It is the intention that this document be used as guidance to support the Military Aviation Authority (MAA), Type Airworthiness Authorities (TAA) and their delegates, and Design Organisations (DO) and their sub-contractors when qualifying and certifying an Additively Manufactured (AM) part as airworthy. It is an extensive document that covers a wide range of topics related to AM technologies and the regulatory frameworks in place to assure the airworthiness of military aircraft.

Owing to the wide scope of the document it is recommended that the reader use the document guide on the following page to identify the information they require.

Please use the numbered buttons as hyperlinks to help navigate the document

MASAAG Paper 124 Issue 2

Guidance on the Qualification and Certification of Additive Manufactured Parts for Military Aviation

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Record of Changes

Issue	Chapters Affected	Reason for Issue	Issuing Authority	Issue Date
1	All	Initial issue – covering Structures, Propulsion and Metals.	Military Aircraft Structures Airworthiness Advisory Group (MASAAG).	17 October 2018
2	Front page	Addition of graphical abstract with hyperlinks to chapters.		
	Executive Summary	Modification of "overview" to account for addition of Polymers and Systems chapters.	Military Aircraft Structures Airworthiness Advisory Group (MASAAG).	31 March 2022
	3, 4	Clarification of Issue / Version number of DefStan 00-970 Part 1 and Part 11 used and referenced in the paper.		
	1.1.1	Change in diagram detailing overview of document and inclusion of "document navigation" section.		
	3, 9	Addition of "Grade A" to recommendation REC 3.1 to highlight that the recommendation only applies to critical structural parts.		
	3.11.1	Removal of "metallic" from REC3.3 to account for inclusion of polymers.		
	4.9.1	Removal of "metallic" from REC4.7 to account for inclusion of polymers.		
	5	Addition of chapter on Airworthiness Assurance For Manufactured Parts (Aircraft Systems).		
	3, 5	Revision to Figure 3-1 and 5-1 to include Regulator in RA5820 flow diagram		
	3, 4, 5	Removal of reference to RN2016/12 and 13 and replacement with reference to Manual of Military Air System Certification		
	7	Addition of chapter on Part Design and Build – Polymers.		
	8.1	Modification of Conclusions to include guidance specific to aircraft Systems.		
	8.1	Removal of omissions to account for addition of Polymers and Systems chapters.		
	8.2	Modification of "further work" section to account for addition of Polymers and Systems chapters.		
	9	Inclusion of recommendations from Chapters 5 and 7.		
	9	Restate that this document is for guidance only in the summary of recommendations.		
	Appendix A	Removal of RA4204. Removal of RA5203. Removal of RA5307, RA5312, RA5313. Revision of RA5305. Removal of RA5601, 5603 and 5615. Update of RA5602. Consolidation of RA5720 and RA5722 (and inclusion of RA5721) into RA5726.		

Overview

The aim of this document is to provide guidance on the qualification and certification of additive manufactured (AM) parts for use in military aviation. This guidance is aimed at the Regulator, Type Airworthiness Authorities (TAA), Design Organisations (DO) and AM Part Suppliers. This paper covers metallic and polymeric parts for aircraft structures (Grade A parts), engines (Critical parts) and systems. Within the paper, the existing military and civil regulatory material, relevant to AM parts, has been reviewed (Chapters 3, 4 and 5). In addition, a significant proportion of the paper (Chapters 6 and 7) has been devoted to describing the various methodologies used for AM part design and build. This has been included to explain the sources of variation in performance of AM parts and to underpin the recommendations made to minimise, measure and account for these performance variations. Where appropriate, existing standards for AM or other relevant manufacturing or test methods have been identified and are referenced within this paper.

In all 116 recommendations have been made. These are divided into those affecting regulation (‘shall’), Acceptable Means of Compliance (AMC) (‘should’) and Guidance Material (GM) (‘may’ or 'could'). The background to each recommendation has been explained within the relevant section and the recommendations have been collated into cross-referenced summary tables in Chapter 9.

For part designers and those involved in Type / Continued Airworthiness the document is a guided walk through the parts of Def Stan 00-970 and the regulations that are especially important for airworthiness of manufactured parts. Taken together with the explanations on AM part design and build (Chapters 6 and 7) the document justifies recommendations that can be used to either set out or evaluate a qualification plan for the part under consideration. One way of approaching the guide is to start with the summary of recommendations in Chapter 9 and if necessary refer back to the text from which each is justified.

Key regulatory recommendations include invoking the use of the Military Certification Review Item (MCRI) process for all Grade A or Critical AM parts, until the technology is sufficiently mature to maintain variability in a predictable and repeatable manner. Moreover, the AM part and the AM process shall be qualified and certified and properties should be measured and factors covering scatter in performance shall be derived rationally.

A key recommendation from the Chapters on Part Design and Build is that for critical AM components a Process Control Document (PCD) shall be supplied as part of the airworthiness documentation. Any changes to the PCD shall be subject to the MCRI process.

This guide considers Grade A or Critical parts; however, it is recognised that early adoption of AM is most likely to occur in non-critical parts. For such applications, it will be necessary to undertake a sub-set of the recommendations tabled here but the extent will need to be appropriate for the consequence of failure of the part and agreed with the TAA.

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1 INTRODUCTION

1.1 BACKGROUND

The aim of this document is to provide guidance on the qualification and certification of metallic and polymeric additive manufactured (AM) parts for use in military aviation.

In the following chapters the document contains an examination of the Military Aviation Authority's (MAA) existing regulatory framework and certification standards for airworthiness assurance of manufactured parts for: (a) aircraft structures; (b) aircraft engines and (c) aircraft systems. From these the regulations, acceptable means of compliance (AMC) and guidance that are especially relevant to AM parts are explained and highlighted. From this activity, the document provides information that may be used to set out a qualification plan for the AM components under consideration, with specific recommendations made and highlighted. The document also contains a review of literature on the design and build of parts using AM, e.g. sources of scatter, methods for monitoring and control, etc., again making and highlighting recommendations.

Additive Manufacturing (AM) is defined by the International Standards Organization (ISO) and the American Society for the Testing of Materials (ASTM) International as "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [1.1]. The term covers many individual AM process technologies. This guidance also covers manufacturing where AM is just one of a sequence of processes used to make a part.

At the Military Aircraft Structures Airworthiness Advisory Group (MASAAG) meeting 78 it was agreed that the manufacture of AM parts included new processes that introduced variability that needed to be understood, quantified and controlled for AM of airworthiness-critical parts to be qualified and certified. Without an appropriate agreed approach to qualification and certification, balancing risk and opportunity, the potential benefits of this technology may not be fully exploited. Subsequent to MASAAG 78, it was agreed that a MASAAG Guidance Note would be compiled, in cooperation with key industrial and MOD stakeholders, to provide the necessary guidance on the qualification and certification of AM parts.

The MASAAG is considered an appropriate vehicle for this task because the purpose of the MASAAG is the development and promotion of best practice in the support of structural integrity of MOD air platforms. The MASAAG provides an element of governance through its advisory role to the Military Aviation Authority (MAA) [1.2]. The MASAAG supports and informs the Joint Air Safety Committee (JASC), acting through the Type Airworthiness Advisory Group (TAAG), on matters affecting the structural airworthiness of military aircraft. The MASAAG is also charged with formulating and endorsing the MOD's technical design and certification standards for military aircraft. The Propulsion Airworthiness Advisory Group (PAAG) has a parallel role for propulsion integrity of MOD air platforms.

The guidance provided in this note has been developed by a specially-convened Working Group of UK industry, academia and government (military and civilian personnel) under the sponsorship of MASAAG. Its development is supported by MOD Air Command as part of its innovative Certification of Novel Technologies work stream (Contract Number DSTL/DTEC/210). Where permitted, acknowledgement is given to authors and contributors whose contributions have been included.

1.2 DOCUMENT NAVIGATION

Figure 1-1 is a schematic of the Guidance Note showing its chapters and appendices. The reader is recommended to navigate the document by first reading the following (highlighted in blue in Figure 1-1):

- Introductory Material
    - Executive Summary
    - Chapter 1 – Introduction
    - Chapter 2 – Intent of the guidance note
- Conclusions and recommendations
    - Chapter 8 - Conclusions and Suggestions for Further Work
    - Chapter 9 – Summary of Recommendations

The remaining chapters are intended as a reference to the background technical information and should be used to provide further justification to the conclusions and recommendations as needed.

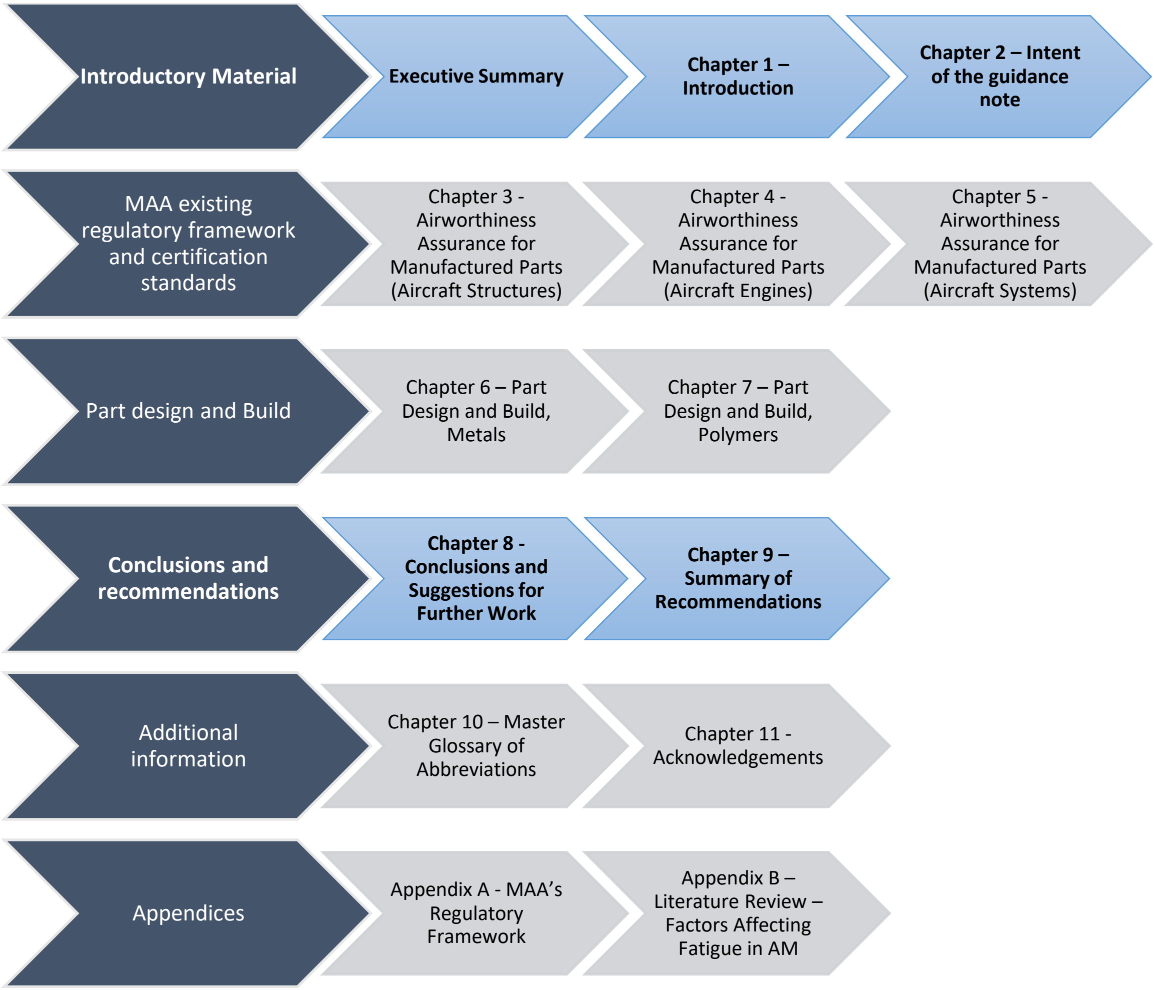

Figure 1-1 - Schematic of the structure of the Guidance Note.

Chapters 3, 4, and 5 and 6 have their own conclusions, summaries of recommendations, glossaries of abbreviations and list of references. Chapters 1 and 2 also have their own list of references. The recommendations are collected together and repeated as a summary table in Chapter 9. A master glossary covering the whole document is provided in Chapter 10.

1.3 TYPES OF PARTS COVERED

The Guidance Note has been written with consideration to the most safety critical parts in the air system. For the aircraft structure these are termed Grade A parts which are defined in the defence standard governing design and airworthiness requirements for fixed wing aircraft (DefStan 00-970 Part 1 Section 4)[1.3] as:

A part shall be Grade A if the deformation or failure of the part would result in one or more of the following:

- Structural collapse at loads up to and including, the design ultimate load;
- Loss of control.
- Failure of motive power.
- Unintentional operation of, or inability to operate, any systems or equipment essential to the safety or operational function of the aeroplane.
- Incapacitating injury to any occupant.
- Unacceptable unserviceability or maintainability (with a specific definition for this term).

Following a Safety Analysis aircraft engine parts are classified according the consequences of failure on the engine, namely: (a) hazardous engine effect; (b) major engine effect; and (c) minor engine effect. Each of these has definitions of effect - and for hazardous and major engine effects maximum permitted probabilities of occurrence. Forgings whose failure could cause a hazardous engine effect are termed Class 1 while for welded structures the term is Group 1 [1.4]. There is no existing classification for AM parts in aircraft engines. This is discussed further in Chapter 4.

This document covers metallic and polymeric parts; ceramic parts are omitted. Primarily the Guidance Note focuses on manufacture of new parts using additive processes, however additive processes are also being developed for repair of parts originally manufactured using established techniques. Therefore additive repair is also considered, especially with respect to aircraft engines.

1.4 DEVELOPMENT OF INTERNATIONAL STANDARDS FOR ADDITIVE MANUFACTURING

At the time of writing, AM technology is developing rapidly. The development and publication of international standards on AM is a necessarily painstaking process which consequently lags behind developments in the technology. Nevertheless international standards and accreditation organisations are developing standards and procedures for AM, for example ASTM International, ISO and the National Aerospace and Defense Contractors Accreditation Program (Nadcap). Organisations are also working together to publish joint AM standards, for example ISO/ASTM 52921-13 Standard Terminology for Additive Manufacturing – Co-ordinate Systems and Test Methodologies [1.5]. A consequence of the rapidly developing technology, and necessarily slower pace of standards publication, is that the references cited in this guidance may quickly be superseded or new standards may emerge that deal with new technologies applicable to AM, for example in-situ monitoring. This is important to note because the use and recording of “recognised standards” is the second of the “four pillars of airworthiness” [1.6] which underpin all the activities related to airworthiness of an aircraft.

1.5 CHAPTER 1 REFERENCES

1.1. BS ISO/ASTM 52900:2015 Additive manufacturing — General principles — Terminology. December 2015.

1.2. https://www.gov.uk/government/organisations/military-aviation-authority/about [08 August 2017].

1.3. Defence Standard 00-970 Design and Airworthiness Requirements for Service Aircraft Part 1 Fixed Wing, Section 4 Design and Construction, Issue 14, 13 July 2015.

1.4. Defence Standard 00-970 Design and Airworthiness Requirements for Service Aircraft Part 11 Engines, Section 3 General Requirements for Aircraft Engines, Issue 6, 13 July 2015.

1.5. ISO/ASTM 52921-13 Standard Terminology for Additive Manufacturing – Co-ordinate Systems and Test Methodologies. June2013.

1.6. RA1220 Project Team Airworthiness and Safety Issue 4, 26 October 2016.

2.1 INTENDED AUDIENCE

As described above the Guidance Note brings together the MAA airworthiness regulations / standards, and AM literature to: (a) provide information that should be used to set out a qualification plan for the AM parts under consideration; and (b) highlight features of AM processes that should be understood, monitored / controlled and recorded to give a level of assurance in the airworthiness of an AM part. While the guidance has been agreed by the MASAAG Working Group of industrial, academic and government contributors, the guidance is suggested “good practice” and its adoption does not guarantee acceptance of an AM part as safe.

The intent is that the guidance can be used to support the MAA, the Type Airworthiness Authority (TAA), Design Organisations (DO) and their sub-contractors when they cooperate to qualify and certify an AM part as airworthy. It is hoped that regulators, and others responsible for the airworthiness of military aircraft, will be informed by the discussions on AM technology, e.g. sources of scatter in AM part properties. Equally manufacturers, especially those less familiar with regulations, will be informed by the guidance on the MAA’s regulatory framework and certification specifications and the paragraphs therein that are especially relevant to AM.

2.2 HIGH LEVEL PROCEDURES AND PROCESSES

2.2.1 HIERARCHY OF DOCUMENT

Guidance Notes and related documents are a means by which the MAA provides peer-reviewed information to support structural integrity and propulsion integrity (and systems integrity) in the MOD’s military aircraft. Figure 2-1 shows how this Guidance Note fits into the regulatory framework – with the relevant Regulatory Article (RA) sitting at the top (see Appendix A for guidance on RAs). While not covered explicitly in this document, systems integrity is also shown since, as mentioned above, this guidance is relevant to manufactured parts in aircraft systems.

The document is for guidance only and does not contain authorised regulations or acceptable means of compliance. Nevertheless the guidance does make specific recommendations that use regulation-type and AMC-type language, namely containing “shall” and “should” respectively. These recommendations are thus classified as either regulation-type or AMC-type. Other recommendations are guidance-type.

2.2.2 CLARIFICATION OF TERMINOLOGY

There are terms used by regulators and industry to describe the processes used to assure the quality of manufactured and assembled parts and systems, e.g. qualification, certification, validation, verification, etc. There is no universally agreed meaning for such terms and clarification is therefore necessary. In this document the terms qualification and certification are used with the following meanings:

- Qualification – the demonstration that the product, process or service conforms to a specified requirement.
- Certification – a procedure by which a third party gives written assurance that a product, process or service conforms to a specified requirement (from BS 3811 - withdrawn [2.1]).

One way of understanding the difference is by considering the activities of different parties in the processes, e.g. a system developer may qualify their system against a standard and then a certification body may look at the qualification evidence and provide assurance through certification.

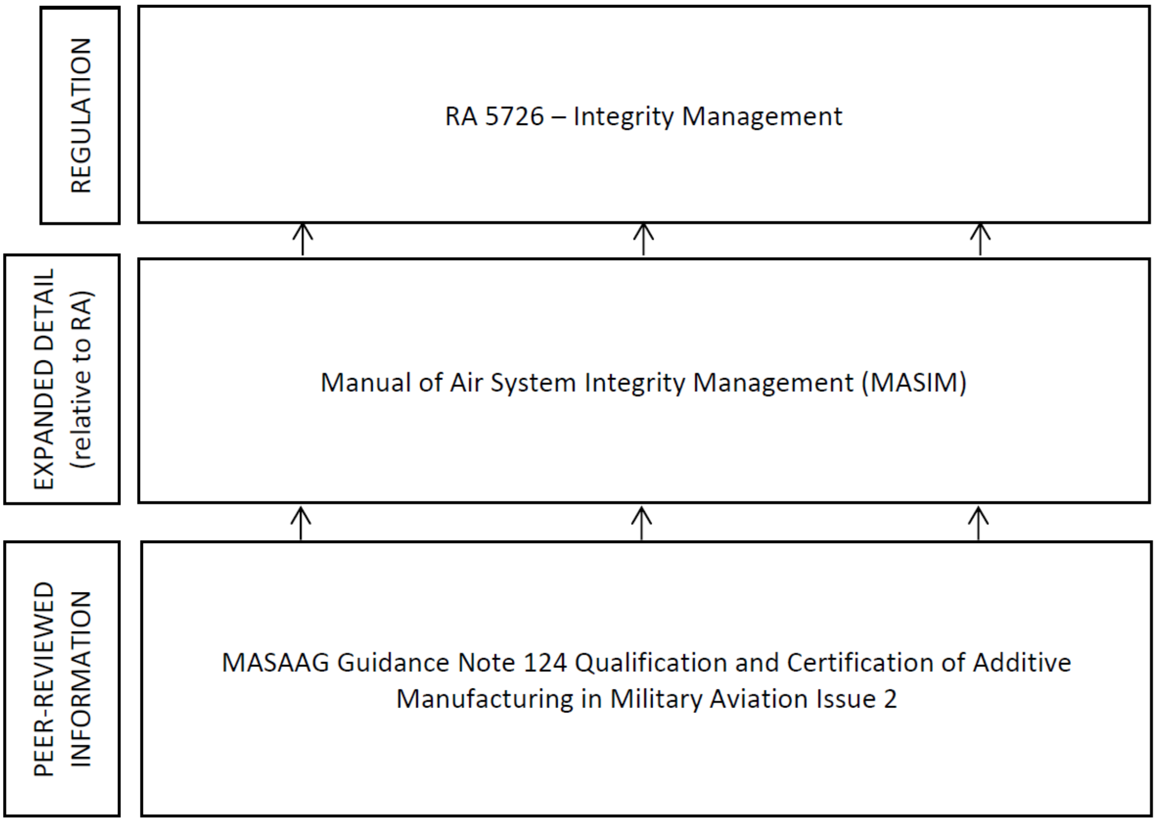

Figure 2-1 – Diagram showing the hierarchy of the Guidance Note with respect to MAA regulations and publications [2.2, 2.3].

2.2.3 USE OF EXTERNAL PUBLICATIONS

In line with current MOD policy, where they exist the document will refer to current standards (either published or in preparation), other open source guidance from respected authorities and peer-reviewed journal articles. This approach is preferred to the presentation of original Working Group guidance, where possible, nevertheless it has been necessary to produce original guidance in many parts of the paper.

The intent is for the paper to act as a bibliography of, and guide to, appropriate publications. However, as discussed previously it is inevitable that in this rapidly developing field references may quickly become obsolete or superseded by updated versions.

2.2.4 INTELLECTUAL PROPERTY

It is not the intent of this document to give any information that could be considered precious intellectual property. In Chapter 6 and 7 variables are presented that it is either known or suspected give rise to variations in part properties and performance. The specific relationships between material, processing parameters, microstructure and properties are not discussed.

2.2.5 APPENDICES

Supplementary information is provided in appendices, which are shown in the Document at a Glance diagram in figure 1-1.

2.3 CHAPTER 2 REFERENCES

2.1. BS3811 Glossary of Terms Used in Terotechnology, 15 December 2003 [withdrawn].
2.2. RA5726 Integrity Management Issue 2, 30 November 2020.
2.3. Military Aviation Authority Manual of Air System Integrity Management (MASIM) Issue 2, 8 December 2020. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/941876/MASIM_Issue_2.pdf [10 November 2021].

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3 AIRWORTHINESS ASSURANCE FOR MANUFACTURED PARTS (AIRCRAFT STRUCTURES)

3.1 INTRODUCTION

Airworthiness is defined as: the ability of an aircraft or other airborne equipment or system to be operated in flight and on the ground without significant hazard to aircrew, ground crew, passengers or to third parties; it is a technical attribute of materiel throughout its lifecycle [3.1].

3.1.1 THE PURPOSE OF THE CHAPTER

The purpose of this chapter is to provide the reader with a guided "walk through" of the regulations and certification standards that are used for the airworthiness assurance of manufactured aircraft structural parts and make specific recommendations with respect to additive manufactured (AM) parts. Where "shall" is used in the recommendation it is underlined because the word "shall" is used in statements for Regulations in Regulatory Articles (RAs) and certification standards, i.e. in this document it is a Regulation-type recommendation. Likewise in recommendations where "should" is used it is Acceptable Means of Compliance (AMC)-type guidance.

In the context of the chapter Additive Manufacturing (AM) is considered as simply another manufacturing process, which will produce scatter in materials properties that need to be accurately represented by the materials allowables and fatigue properties certified for the component. Emphasis is placed on the design, manufacture and certification of aircraft structural parts. The airworthiness regulations for aircraft engine and systems parts are dealt with in separate chapters.

Where considered useful, reference is made to regulations, regulatory articles, standards and advisory/guidance documents of MOD and other bodies, such as the European Aviation Safety Agency (EASA), the Federal Aviation Administration (FAA), the US Department of Defense (DoD) and others. It must be stressed that this overview is for guidance only.

The chapter will focus on Type 1 military aircraft (high manoeuvrability aeroplanes) because their design and construction is unique to the military, i.e. they are not modified civilian designs. However the chapter will be relevant to other military operated aircraft covered by parallel regulations / standards. This chapter is based on Def Stan 00-970 **Part 1 Section 3 Issue 13 (2015)** and **Part 1 Section 4 Issue 14 (2015)**.

The requirements for structural parts are also relevant to aircraft systems components, for example those that make up fuel systems.

3.1.2 CHAPTER AT A GLANCE

Table 3-1 is a concise overview of the chapter and provides a brief description of the purpose of each section.

Table 3-1 – Overview of Chapter 3 and summary of each section.

Section	Title	Description and purpose	Page
3.1	Introduction	MOD's definition of the term Airworthiness. An explanation of the chapter's purpose with a table summarising the chapter's structure.	21
3.2	Overview of qualification process for manufactured parts	A simplified schematic representation of the qualification process for manufactured parts.	23
3.3	The Military Aviation Authority's (MAA) regulatory framework	A high level summary of the MAA's regulatory framework, including an introduction to the four pillars of airworthiness. Regulatory publications that are especially relevant to AM are described in Appendix A.	24
3.4	Certification standards	Introduces MOD's primary standard Def Stan 00-970 but also briefly describes other relevant standards, e.g. those of the European Aviation Safety Agency (EASA).	25
3.5	Noteworthy elements of Def Stan 00-970	Description of Def Stan 00-970 Part 1 Section 3 Structure and Part 1 Section 4 Design and Construction.	28
3.6	Establishing materials allowables	Describes the test and statistical methods that must be used to obtain and derive design values.	37
3.7	Establishing fatigue properties	A description of the fatigue requirements of Def Stan 00-970 and additional information on Safe Life and Damage Tolerant design philosophies.	44
3.8	Discussion on application of Regulatory Articles and Def Stan 00-970 to AM	Highlights points of the proceeding sections that are especially important for AM.	46
3.9	Guidance from other aerospace manufacturing processes	An introduction to Def Stan 00-970 guidance on manufacturing processes that either have features similar to AM or are in some way analogous to AM. Casting, Welding and Polymer Matrix Fibre Composites.	50

3.2 OVERVIEW OF CERTIFICATION PROCESS FOR ADDITIVELY MANUFACTURED PARTS

For an air system to be accepted onto the Military Aircraft Register (MAR) it must go through the Military Air System Certification Process (MACP) as defined in Regulatory Article RA5810 [3.2]. For parts to be used on existing aircraft the use of an AM part is likely to be classed as a major modification from that of its original Military Type Certification (MTC) because it will at least represent a modification to the manufacturing process (and perhaps also design and/or material). Guidance on the classification of changes as major or minor is given in Regulatory Article RA5820 [3.3]. The aircraft will usually have to go through MACP so that the MAA, as an independent authority, can assess whether the Type Airworthiness arrangements in place for the Air System are adequate; if adequate an up-issued MTC will be released. The modification must be justified to the Type Airworthiness Authority (TAA) by the DO [3.4, 3.3]. The Manual of Military Air System Certification (MMAC) provides an explanation of MTCs and approved design changes, as well as guidance on the MACP [3.5].

Figure 3-1 is a simplified schematic of the Military Certification Review Item (MCRI)-process whereby an approved Design Organisation (DO) justifies that a part is airworthy. The process is part of the MACP for either the up-issue of the MTC or the issue of an Approved Design Change Certificate (ADCC) where an MTC does not exist. In either case, this will be underpinned by the production of a Type Certification Report (TCR). An AM part must fulfil the requirements for structural strength and fatigue as specified in Def Stan 00-970 Part 1 Section 3.

Owing to the novel nature of AM it can be assumed that even for new aircraft an AM part will require a MCRI-type process until there are established processes and procedures for the design and certification of parts and the characteristics of the manufacturing process for each. **It is recommended that a Grade A AM part, whether for a new or existing aircraft, shall be subject to the MCRI process until the technology is sufficiently mature to maintain variability in a predictable and repeatable manner (REC3.1)**.

The methods to be used to establish the materials allowables and fatigue properties of parts are specified in Def Stan 00-970 Part 1 Section 4.

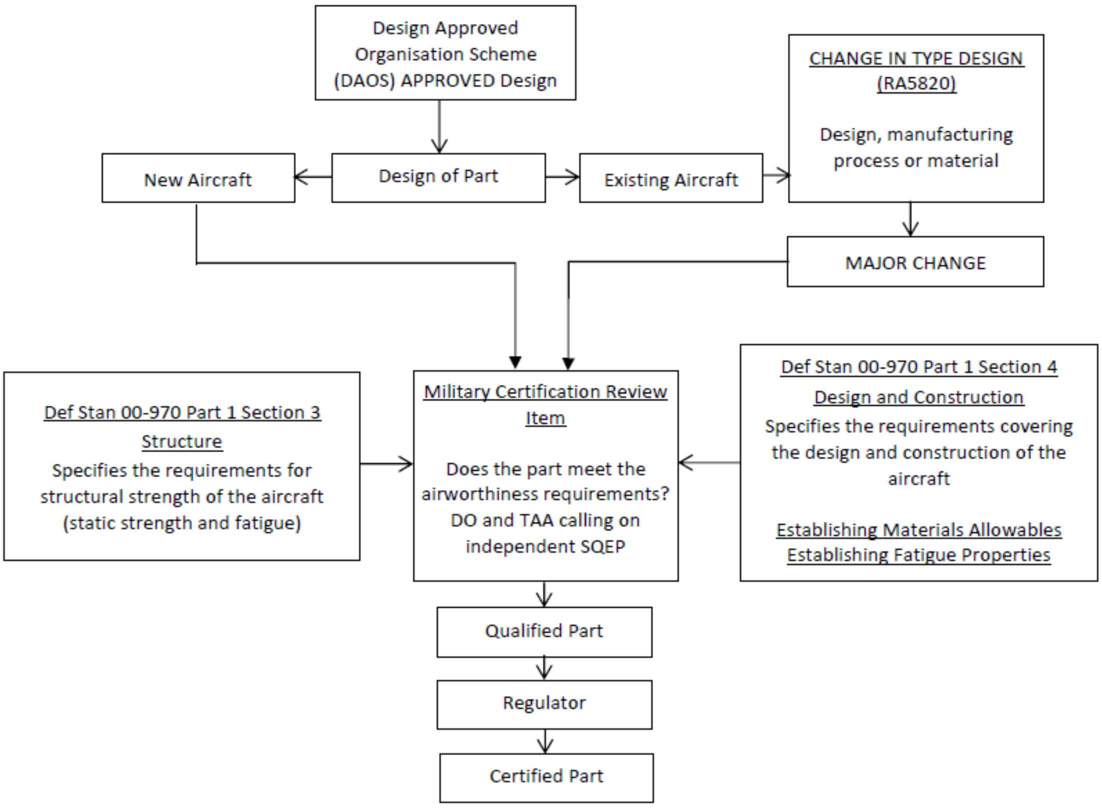

Figure 3-1 – Simplified schematic of the process through which a part may be qualified as airworthy by an approved DO and the TAA, who may call on independent Suitably Qualified and Experienced Person(s) (SQEP) to support the MCRI process. The regulator may then certify the part as airworthy.

3.3 THE MAA'S REGULATORY FRAMEWORK

All aspects of the safety of military aviation are underpinned by the MAA's Regulatory Framework; the scope of the Regulatory Policy is laid out in MAA001 [3.1].

The MAA publishes its regulatory framework as a series of MAA Regulatory Publications (MRPs) in three layers: overarching documents, Regulatory Articles, and manuals [3.6] (The Pocket Guide to MAA Regulation is a concise explanatory guide [3.7]). Readers are encouraged to refer to the most up to date versions of the MRPs by checking the MAA's website [3.6].

For the purposes of the design, manufacture and certification of AM parts, the regulations of primary concern are those associated with Type Airworthiness: these are mainly to be found in the 5000 series, with some aspects also covered in the 4000 series. These, and other regulations that need to be considered, are identified in Appendix A to this Chapter. These further considerations include, but are not necessarily limited to, standardisation, competence, record and configuration management, and approval of manufactured and repaired parts.

The Four Pillars of Airworthiness is an important principle introduced and described in Regulatory Article 1220 [3.8]. It is discussed in Appendix A and summarised here: (1) an effective Safety Management System (SMS) should be established and detailed; (2) Recognised standards should be used and their use detailed; (3) Competence – arrangements for the use and management of competent persons and competent organisations should be detailed; and (4) Independence -

arrangements for ensuring independent assessment, technical evaluation and safety audit should be detailed. The four pillars underpin all the activities related to airworthiness of an aircraft and drive the requirements that will be discussed below; the discussion below concentrates mainly on the standards applicable and how AM components may differ from those manufactured using more established methods.

3.4 CERTIFICATION PROCESS

It is necessary to establish that an aircraft's Type Design meets appropriate airworthiness standards, as required by RA5810 and laid down by the MAA; other Airworthiness Authorities have similar regulations. As part of the TCB a certification process is required to demonstrate that the design meets the requirements established for the equipment. The paragraphs below outline the main design requirements available for aircraft design.

3.4.1 MOD CERTIFICATION SPECIFICATIONS FOR AIRWORTHINESS – DEFENCE STANDARD 00-970

The MAA's RAs provide requirements, AMC and guidance for the design of aircraft to meet the airworthiness requirements for UK military operation. Defence Standard 00-970 (Def Stan 00-970) Design and Airworthiness Requirements for Service Aircraft provides the design standard that must be maintained through the life of the aircraft [3.9]. It is an extensive document: it is divided into eight parts (not including Part 0 - Guidance), covering all types of military aircraft, engines and related equipment, and includes Annexes and Leaflets that provide additional guidance on other applicable and related standards (e.g. US DoD Specifications), as well as guidance on acceptable means of compliance and supplementary technical information.

At a glance the structure of the document is shown in Figure 3-2. The standard contains definitions of different types of aircraft used in military operations and which Part is applicable to each type of aircraft and military usage. For example a summary of aeroplanes (Types 1, 3 and 5) is shown in Table 3-2.

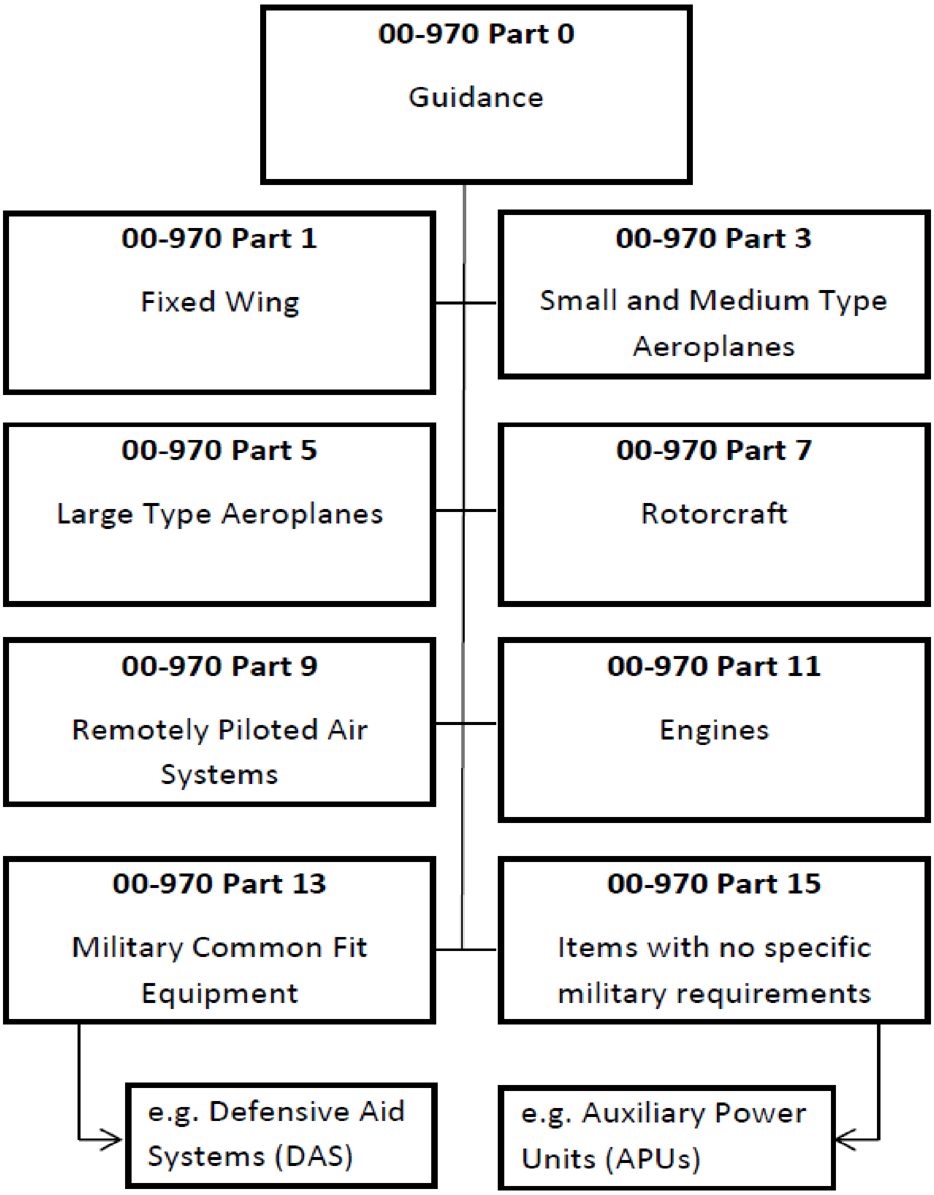

Figure 3-2 - Overview of structure of Def Stan 00-970.

Table 3-2 – Summary of aeroplane types in military operation.

Type	General Description	Examples
1	High manoeuvrability aeroplanes	Fighter/interceptor Attack Tactical reconnaissance Observation Trainers for Type 1
3	Small, light aeroplanes	Light utility Primary trainer Light observation
	Medium weight, low to medium manoeuvrability aeroplanes. Aircraft of this type may be considered for either Type 3 or Type 5 Certification).	Heavy utility/search and rescue Light or medium transport/cargo/tanker Early warning/electronic counter-measures/airborne command, control or communications relay Anti-submarine Assault transport Reconnaissance Tactical bomber Heavy attack Trainer
5	Large, heavy, low to medium manoeuvrability aeroplanes	Heavy transport/cargo/tanker Heavy bomber Patrol/early warning/electronic counter-measures/airborne command, control or communications relay Trainer for Type 5

The UK operates a large range of different aircraft types in different roles, from military-specific fast jets to modified civilian aircraft and for most aircraft/roles UK MOD develops and procures aircraft in collaboration with other nations. Indeed the Def Stan is used as a baseline in establishing appropriate design and airworthiness requirements taking account of the procurement strategy to be adopted. Maximum use is made of EASA Regulations and Certification Specifications where these are applicable to both military and civil roles [3.9]. Consequently it is appropriate to mention related statutory regulations.

3.4.2 EUROPEAN AND US CIVIL REQUIREMENTS

In Europe the aircraft design requirements are issued by the EASA (as Certification Specifications - CSs) [3.10] and in the US by the FAA (as Federal Aviation Regulations - FARs) [3.11]. There is broad equivalence between CS-25 and Def Stan 00-970 Part 5 (Large Type Aeroplanes) and CS-23 and Def Stan 00-970 Part 3 (Small and Medium Type Aeroplanes). For these types of aircraft, there will be additional Military Certification Review Items to be agreed when setting the Type Certification

Basis. While the numbering and titles of many of the EASA and FAA regulations mirror each other their content is not necessarily the same. Examples of EASA and FAA regulations that are of relevance to UK MOD, namely: CS-25/FAR-25 Large Aeroplanes; CS-23/FAR-23 Normal, Utility, Acrobatic, and Commuter Category Airplanes; CS-27/FAR-27 Small Rotorcraft; and CS-29/FAR-29 Large/Transport Rotorcraft [3.10, 3.11]. It should also be noted that there are significant differences in the interpretation of the regulations as applied by the EASA and FAA during certification.

3.4.3 US MILITARY REQUIREMENTS

The DoD Joint Services Specification Guide JSSG-2006 for Aircraft Structures is a specification developed jointly by the US Air Force (USAF) and the US Navy (USN). It establishes the joint structural performance and verification requirements for the airframe [3.12]. Demonstration of compliance with the specification requirements is underpinned by the use of appropriate MIL-STDs and MIL-HDBKs that may be called up when the JSSG is completed for the aircraft under consideration, for example MIL-HDBK-516 (Airworthiness Certification Criteria) to establish the certification basis and MIL-STD-1530 (Aircraft Structural Integrity Program) to set out the framework for the completion of the structural certification activity and the framework for continued airworthiness and structural integrity [3.13, 3.14].

3.5 NOTEWORTHY ELEMENTS OF DEF STAN 00-970

Within each part of Def Stan 00-970 information is presented in clauses and takes the form of:

- **REQUIREMENT** - These requirements affect airworthiness and safety and are normally prefaced by the word “shall.” All requirements must be considered in the procurement of UK military aircraft and subsequent design changes.
- **COMPLIANCE** - Contains information regarding established methods for demonstrating compliance with the requirement. Technology advances may allow the use of alternative methods in achieving the requirement, which should be agreed in advance with the MAA.
- **GUIDANCE** - Will contain the technical justification for the requirement and additional information considered useful in designing a system to meet the requirements. This may include appropriate references, advice on issues that require consideration or advice on typical design solutions that have been applied in the past. Some areas are considered ‘best practice’ by MOD, for example where they may affect survivability of an aircraft.

For the purposes of this document the following Sections are examined in more detail: (a) Def Stan 00-970 Part 1 Fixed Wing Section 3 Structure [3.15]; and (b) Def Stan 00-970 Part 1 Fixed Wing Section 4 Design and Construction [3.16]. A simplified explanation of these sections is:

- Section 3 describes the static strength and fatigue properties required of the aircraft’s structure; and
- Section 4 describes how to demonstrate, with a required level of statistical rigour, that the properties of the structure (and its constituent manufactured parts) meet the requirements from Section 3.

It is helpful to introduce here the grading of aircraft parts and structures into Grade A and Grade B, and the different bases used to define design allowables, even though they are defined in more detail later.

- Grade A is given to parts / structures whose deformation or failure would cause serious consequences for the aircraft, its occupant(s), mission or maintainability. They are the most safety critical parts / structures in the aircraft. Grade B is used for parts / structures that are less safety critical. Definitions are provided in section 3.5.2.1.
- Design allowables for static strength and deformation properties are established based on statistical theory so that, to a particular level of confidence (i.e. 95%), it is possible to state a value above which either: (a) 99% - A-basis; or (b) 90% - B-basis, of the population of the property lies. S-basis design allowables generally define a property minimum and sometimes a property minimum and maximum. An explanation of A, B and S-basis design allowables is given in section 3.6.1.1.

3.5.1 DEF STAN 00-970 PART 1 SECTION 3 STRUCTURE

Section 3.1 Static Strength and Deformation, and Section 3.2 Fatigue state the design allowable basis and lifing approach, respectively, required for the airframe structure, including manufactured components, of military aircraft of Type 1, for example Section 3.1 is shown in Table 3-3 (Section 3.2 is too large to reproduce here).

In Clause 3.1.6, the “B-value” design allowable basis is mandated for each failure mode in Grade A structure. This has consequences for the number and quality of coupon tests required so that statistically rigorous analyses of the data can be made. Further, Clause 3.1.9 states that Allowables shall take account of inherent defects, such as those arising from manufacture, which also has important consequences for manufactured coupons, i.e. they must be truly representative of typical manufacturing, and defect populations.

In this respect it is important to highlight the words in Leaflet 02, paragraph 3.4 [3.17], when considering the scope of the coupon test programme necessary to obtain materials design data, limitations of the applicability of these data to the structural level should be considered. Such limitations may include: (a) scale effects; and (b) differences in variability and properties between the as-received material and the as-manufactured component; differences that could be significant if AM methods are used. These points are discussed in more detail below.

For comparison the US DoD JSSG-2006 states that A-basis design allowables shall be used in the design of all critical parts. A-basis design allowables shall also be used in the design of structure not tested to ultimate load in full scale airframe static testing. B-basis design allowables may be used for all other structure. CS 25 also uses A-basis design allowables.

Table 3-3 - Def Stan 00-970 Part 1 Section 3.1 (Static Strength and Deformation), clauses 3.1.6 to 3.1.10.

STRENGTH

ALLOWABLES

REQUIREMENT	**COMPLIANCE**	**GUIDANCE**
3.1.6 All Grade A structure **shall** be identified; an allowable stress, load or strain shall be determined for each of them, on a 'B' value basis for each failure mode.	Coupon tests shall be done to establish materials allowables on a 'B' basis, where such allowables are not available from an acceptable source, for each potential failure mode. (See Leaflets 01 and 03 for data requirements for derivation of materials allowables and Part 1, Section 4, Clause 4.1 for acceptable sources of metallic materials data). Should this be impractical, the material allowable shall be based on the mean of at least 15 coupon test results. These must be obtained under the most adverse environmental conditions, if such conditions significantly affect the strength. When only 15 coupons are used, these shall comprise at least 5 samples from each source of supply and at least 3 batches of material from each source. Similarly representative samples shall be used, if larger numbers of coupons are tested. Exceptionally, it may be acceptable to allocate allowable values to individual batches of material: in circumstances where the mean strength of the material varies from batch to batch, but the coefficient of variation (c.v.) (based on individual batches) remains reasonably constant, the 'B' value in a given batch of material must be reduced if the mean of the batch in question is lower than that of the batch on which the reference 'B' value is based. No increase in the reference 'B' value is permissible unless it can be shown that other failure modes do not thereby become significant.	A definition of Grade A structure is given in Part 1, Section 4, Clause 4.1
3.1.7 The allowable **shall** be determined under the most adverse environmental conditions arising in the critical design case for the structure in question.		See also Leaflet 02 (which gives guidance on static test philosophy and the test pyramid).
3.1.8 Allowables for each failure mode **shall** take due consideration		

of environmental degradation.		
3.1.9 Allowables **shall** take account of inherent defects, such as those arising from manufacture.		
3.1.10 All static allowable values of load, stress or strain **shall** be based on nominal dimensions, unless adverse tolerances significantly affect the strength.		

Def Stan 00-970 Section 3.2, provides the fatigue design requirements for structures and mechanical components that affect safety, operational capability and supportability (Grade A parts). Generally speaking a Safe Life approach is used to declare the fatigue life of Type 1 aircraft, but there are exceptions to this and clarification is useful.

Clause 3.2.4 states that a Safe Life approach shall always be used for components where fatigue damage cannot be identified readily (which is often the case for components in Type 1 aircraft) but the Def Stan also allows for Inspection-based Substantiation (which is the approach mandated for the most part in civil aircraft regulations, e.g. EASA CS-25 - Sub-Part C Structure paragraph CS-25.571 [3.18]).

For lifing with respect to fatigue the USAF uses a damage tolerant approach which requires regular inspections for cracks, with guidance on this approach contained in the standard MIL-STD-1530C (USAF) (1530C has evolved over time from previous handbooks and standards) [3.13]. The USN on the other hand has an approach that is more similar to the UK's Safe Life approach, albeit using different factors and testing philosophies (termed the strain-life approach or Neuber analysis) [3.19]. Section 3.7 of this document provides an explanation of lifing philosophies with respect to fatigue.

Clauses 3.2.9 to 3.2.11 cover Material Selection and are reproduced here since, while concise, they state some materials requirements in terms of fatigue that will also be important for AM (Table 3-4).

Table 3-4 - Def Stan 00-9710 Part 1 Section 3.2 (Fatigue), clauses 3.2.9 to 3.2.11 Material Selection.

FATIGUE		
MATERIAL SELECTION		
REQUIREMENT	**COMPLIANCE**	**GUIDANCE**
3.2.9 The variability of the manufacturing processes, product forms and material fatigue properties **shall** be accounted for in the fatigue substantiation.		See Leaflet 34.
3.2.10 Materials, in the product forms chosen, **shall** show: (a) good fatigue performance; (b) good resistance and tolerance to damage, in particular, they shall have a high toughness to yield strength ratio; (c) good resistance to environmental degradation.	Exceptionally, materials and components which have identified shortcomings in meeting these criteria (for example, materials with a poor toughness to yield strength ratio or materials with a poor corrosion resistance) may be used with the prior agreement of the Project Technical Lead (PTL). Any shortcomings shall be taken into account in the design and maintenance philosophy.	
3.2.11 Structural components and assemblies **shall** also have: (a) acceptable resistance and tolerance to fatigue crack growth; (b) protection from any effects of environmental degradation, other than those effects which have been accounted for in the substantiation; (c) tolerance to accidental damage.		

Three points are worth highlighting: in essence (a) the inherent variability from manufacturing processes, etc. has to be accounted for in the fatigue substantiation; (b) damage tolerance must be good (fracture toughness to yield strength ratio); and (c) the resistance of the material to environmental degradation must be good.

Environmental degradation covers a large number of phenomena, for example corrosion, stress corrosion cracking, exfoliation corrosion and hydrogen embrittlement. In all cases materials must be protected from this degradation (Clause 3.2.11 b.). More information on environmental degradation and the protection of structure against it is given in Def Stan 00-970 Part 1 Section 4 (discussed below) [3.16].

A structure / component can be either Safe-Life or Inspection-based Substantiated, nevertheless all component fatigue tests must be truly representative of the component (e.g. stress-concentrating features, fretting fatigue, etc.) and material quality (inclusions, residual stresses, etc.). A true comparison of materials for fatigue performance must be done using coupons representative of component condition (including any significant batch effects), loading and environment. Where changes are made to the material processing or manufacturing route, comparative testing must be done under representative conditions to ensure that fatigue performance has not been adversely affected [3.20].

3.5.2 DEF STAN 00-970 PART 1 SECTION 4 DESIGN AND CONSTRUCTION

As stated in its introduction, Section 4 of Def Stan 00-970 specifies the requirements covering the design and construction of the aircraft: “These requirements should be implemented with the aim that no design features or details of the aircraft should be known to be hazardous or unreliable and that areas of doubt concerning design details and parts should be confirmed by test and analysis”. The requirements cover 27 aspects of aircraft design and construction, from Marking of Aeroplane Parts to Design of Undercarriage. Further guidance is provided in the form of 97 leaflets on a large range of topics, for example Leaflet 1 - Grading of Aeroplane Parts and Assemblies.

Some of the Clauses are highlighted because they are particularly relevant to manufactured parts.

3.5.2.1 GRADING OF PARTS AND ASSEMBLIES

In its Requirement, Clause 4.1.4 states that in order to ensure that the material and processes used in the manufacture of a part are of suitable quality and that the part is satisfactory, quality control and testing must be appropriate to the design requirements and the application of the part. To this end all parts, except standard parts as defined in Clauses 4.1.10 to 4.1.12 shall be designated Grade A or Grade B, taking cognizance of strength and stiffness requirements as promulgated in this publication, quality requirements, maintainability and inspectability requirements, and also such factors as failure by leakage, malfunction, or other defect. The grading requirements apply whether the part is designed to Damage Tolerance Requirements or not [3.16].

Clause 4.1.6 defines a Grade A part within the Requirement, with advice on the interpretation of the definitions given in Section 4, Leaflet 1 [3.21]. A part shall be Grade A if the deformation or failure of the part would result in one or more of the following:

- structural collapse at loads up to and including, the design ultimate load;
- loss of control;
- failure of motive power;
- unintentional operation of, or inability to operate, any systems or equipment essential to the safety or operational function of the aeroplane;
- incapacitating injury to any occupant;
- unacceptable unserviceability or maintainability.

A part may be Grade B at the designers’ discretion if none of the provisions of Clause 4.1.6 applies.

3.5.2.2 MATERIALS AND PROCESSES

Clauses 4.1.13 to 4.1.15 are recreated here (in Table 3-5) since in addition to the Requirements they provide important Compliance and Guidance information and are especially relevant to a manufacturer’s use of approved specifications. An important consequence of these three clauses for Grade A AM parts is that until an approved aerospace specification exists for a material or process, a Contractor’s Specification shall be used. The Intellectual Property (IP) considerations around AM are significant and consequently it is most likely that individual contractors will have their own proprietary materials/process specifications, developed through extensive research and development, with an industry-wide approved aerospace specification unlikely in the short to medium term.

3.5.2.3 STRENGTH OF MATERIALS

Clause 4.1.16 (the only clause under this title) refers forwards to Clause 4.5, and within that to 4.5.2 to 4.5.4 for Design Data for Metallic Materials. These clauses are reproduced in Table 3-5 since they provide a concise summary of requirements around manufacturing process considerations and guidance on use of design allowables for metallic parts. The Clause is similar in content to CS 25.613 [3.22].

Clauses 4.5.2 to 4.5.4 contain requirements and guidance that have important consequences when interpreted for AM parts, namely:

- Clause 4.5.2 – the Guidance provides information in combination with Clause 3.1 Structure, and in particular 3.1.6, on the design allowables to be used for Grade A parts and how to generate them to an acceptable level of compliance. The Clause refers to the ESDU Metallic Materials Data Handbook (MMDH) 00932 as the source of definitions for A, B and S-basis values [3.23].
- Clause 4.5.3 – the Guidance states that appropriate (i.e. on white paper) properties for design of metallic details in MMDH 00932 are acceptable but if they are not available, which will be the case for AM, then they can be either (a) (2) obtained or derived from test data, or (a) (3) obtained using approved processes and control specifications to maintain a mechanical property that is more advantageous than that included in MMDH 00932. Further, data obtained as in (a) (2) and (a) (3) shall be derived by the same methods as are used to establish data in MMDH 00932.
- Clause 4.5.4 – the Requirement that adequate allowance shall be made for the effects of all manufacturing processes and environmental conditions on material strength… is followed by Compliance that the B basis values must be associated with a procedure that can monitor that those mechanical properties are being maintained to the appropriate specification.

These points will be discussed in more detail in Section 3.8 of this document.

A more detailed description of A, B and S-basis design values is given in Section 3.6 of this document.

Table 3-5 - Def Stan 00-9710 Part 1 Section 4, Clauses 4.1.13 to 4.1.15 (Materials and Processes).

MATERIALS AND PROCESSES		
REQUIREMENT	**COMPLIANCE**	**GUDIANCE**
4.1.13 For Grade A parts the material and process of manufacture **shall** normally conform to an approved Aerospace Specification (see MAA Regulatory Publication RA 5203 for order of preference). See Appendix A of this document for a description of RA5203.	For ease of reference the situation on some national and international standards is as follows: **Approved Aerospace Specification** British Standards: Aerospace Series, including ISO and EN Standards published by BSI in the Aerospace Series. PR EN Standard Specifications issued by ASD-STAN. DTD Specifications, including DTD 900 (Obsolescent) approvals. **Unapproved**	See Clauses 4.3.11 to 4.3.12 for materials and processes used for protective treatment.
4.1.14 Where it is proposed to use an unapproved material or process specification for a Grade A part, a Contractors' Specification **shall** be used		
4.1.15 Grade B parts may be manufactured from materials specified in Clause 4.1.13, or from less closely controlled materials (e.g. general engineering materials) at the Designer's discretion.		

Table 3-6 - Def Stan 00-9710 Part 1 Section 4, Clauses 4.5.2 to 4.5.4 (Design Data for Metallic Materials).

DESIGN DATA FOR METALLIC MATERIALS		
REQUIREMENT	**COMPLIANCE**	**GUDIANCE**
4.5.2		Clause 3.1 states that 'B' allowable values shall be derived for all Grade A structural details. To calculate these values it is necessary to refer to 'B 'allowable data for structural materials. This Clause provides information on acceptable data for metallic materials. Note: The definitions of A, B and S values are to be found in ESDU Metallic aterials Data Handbook 00932.[
4.5.3		a. Acceptable properties for use in the design of metallic details are as follows: 1. As stated in the ESDU Metallic Materials Data Handbook 00932 obtainable…, or 2. As obtained or derived from test data when not included in ESDU Metallic Materials Data Handbook 00932, or 3. As obtained by using approved (see Clause 4.1) processes and control specifications to maintain a mechanical property which is more advantageous than that included in ESDU Metallic Materials Data Handbook 00932. b. Data obtained as in (a) (2) and (3) above shall be derived by the same methods as are used to establish the data in ESDU Metallic Materials Data Handbook 00932 and specified therein. c. When using data given in ESDU Metallic Materials Data Handbook 00932 under (a) (1) above the following requirements apply: 1. For the design and airworthiness acceptance of all parts the data given on white paper shall be used. Data on grey paper shall not be used. 2. Where no 'B' values are available and only 'S' values are given on white paper then 'S' values are acceptable. Data given on grey paper may be used for preliminary project work only.
4.5.4 Adequate allowance **shall** be made, where applicable, for the effects of all manufacturing processes and environmental conditions on material strength and for all tolerances, ranges, variations, or limitations stated or referenced in ESDU Metallic Materials	The use of 'B' values shall be associated with a procedure to monitor the appropriate specification mechanical properties to ensure and demonstrate that the values are being	

3.5.2.4 PROTECTION OF STRUCTURE

This paragraph (Part 1 Section 4 Paragraph 4.3) covers all factors that must be considered to protect the aircraft structure from environmental degradation, from drainage of contaminating liquids to protective surface treatments. Paragraph 4.3 is extensive covering 134 requirements. Under Choice of Materials in Relation to the Avoidance of Corrosion, Requirement 4.3.11 states: Materials for each given use are chosen in the first place for their appropriate mechanical and other physical properties but their corrosion within the environment of the given use **shall** also be considered. 4.3.11 Compliance: Materials with lower susceptibilities to corrosion, corrosion fatigue, stress corrosion or hydrogen embrittlement should be chosen where possible, and unnecessarily strong but susceptible materials shall be avoided [3.16]. It is possible that AM parts may have microstructures that have a different susceptibility to environmental degradation when compared to conventional forms and **it is recommended that their particular susceptibility should be established (REC3.2)**. Guidance material on degradation phenomena and appropriate mitigation strategies for steels, aluminium alloys and titanium alloys is provided in Leaflets 6 to 9 and 13 of Section 4.

3.6 ESTABLISHING MATERIALS ALLOWABLES

In Def Stan 00-970 Clauses 4.5.2 and 4.5.3 refer to the ESDU Metallic Materials Data Handbook 00932 as the source of historical structural design data for metallic materials from conventional manufacturing.

Where data are not included in MMDH 00932, as will be the case for AM, the data shall be obtained or derived from test data using the same methods as those specified in MMDH 00932 [3.23]; in this context methods means those used to test specimens to recognised standards and the statistical techniques that should be used to describe the resulting data as design values. Consequently MMDH 00932 is a very useful source of guidance on the principles and techniques used to derive design values.

In the US the Metallic Materials Properties Development and Standardization (MMPDS) publication (formerly MIL-HDBK-5) [3.24] is similar to MMDH 00932. It is used in many different commercial and military aerospace applications around the world.

This section will focus on MMDH 00932 because it is the handbook referred to by Def Stan 00-970. Where helpful, reference will be made to MMPDS as an internationally recognised publication that supports the certification of aircraft. Use of the methods in either publication will satisfy the requirements of Def Stan 00-970.

3.6.1 DESIGN DATA

The handbook provides design data on the following property categories:

- Static properties – strength (ultimate tensile stress, tensile and compressive proof stresses - including strength vs. temperature), shear stress, bearing stress, torsion stress and fracture toughness.
- Creep, creep-rupture and stress-rupture properties.
- Fatigue properties.
- Crack propagation properties.
- Physical and characteristic properties (e.g. susceptibility to stress corrosion cracking, weldability, etc.).

3.6.1.1 STATIC PROPERTIES

Static properties are presented in the form of design allowables – A, B or S-basis depending on the availability of data. The availability of sufficient numbers of reliable data points for a particular property determines the design allowable basis that can be quoted (see below).

3.6.1.1.1 A, B AND S-BASIS DESIGN ALLOWABLES

Paragraphs 3.2 to 3.4 of Section 1 of MMDH 00932 Derivation and use of design data define A, B and S-basis design allowables for use in the design and manufacture of aerospace parts from metallic materials.

- A-basis – a (one-sided) lower 95 per cent confidence limit for the value above which 99 per cent of the population lies. This means that there is a 95 per cent probability that at least 99 per cent of the material released will exceed the A value.
- B-basis – a (one-sided) lower 95 per cent confidence limit for the value above which 90 per cent of the population lies. This means that there is a 95 per cent probability that at least 90 per cent of the material released will exceed the B value.
- S-basis – the specified minimum values of an appropriate material specification or standard. A single value indicates a minimum, whereas two values, for example 390-540, indicate a minimum of 390 with a maximum of 540.

Figure 3-3 is a representation of statistical distribution of a property and the position on it of A and B-basis allowables.

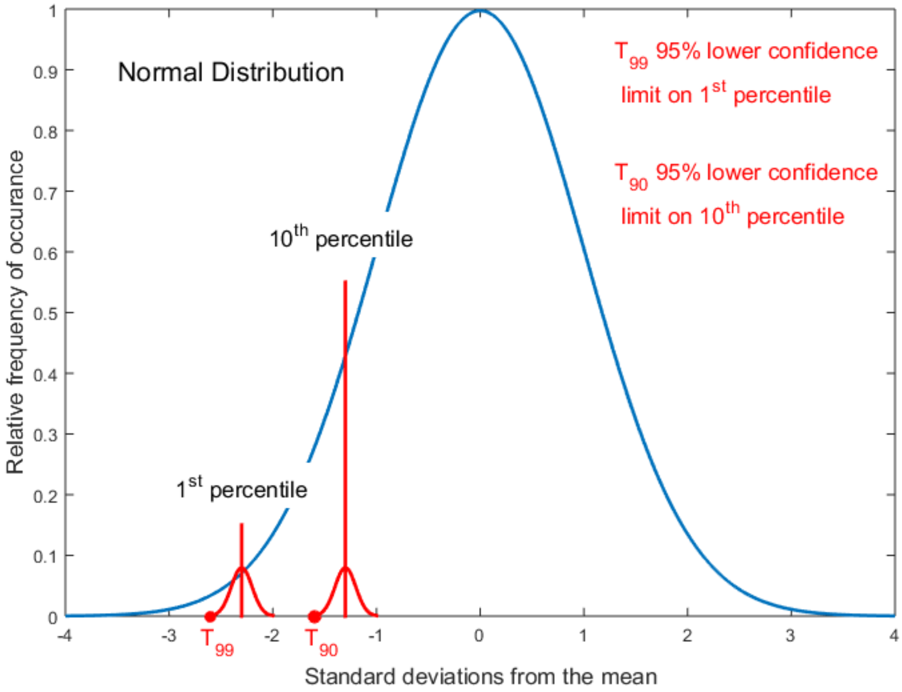

Figure 3-3 – Representation of A and B-basis design allowables from a statistical distribution of a particular property.

Historically a statistical confidence level for S-basis allowables was not known, however since ~1975 the minimum mechanical properties in the Society of Automotive Engineers (SAE)/Aerospace Material Specification (AMS) specifications have been statistically justified with a procedure described in Part F of the SAE/AMS Editorial Style Manual for the Preparation of Aerospace Material Specifications (AMS) Metals and Processes and Non-metallic Materials [3.24, 3.25].

Metals often exhibit anisotropic properties as a consequence of the processing technique used to manufacture a particular product form, for example rolling of aluminium alloy plate. Consequently both MMDH 00932 and MMPDS quote design allowables in different directions, for example ultimate tensile strength in the longitudinal, transverse and short transverse orientations for an aluminium alloy plate in specific thickness ranges in MMDH 00932 (MMPDS has equivalent terminology with Sections 9.2.3.1 and 9.2.3.2 providing useful guidance [3.24]). This has relevance to additive manufactured metals because research has shown that AM specimens/parts often also exhibit anisotropic properties owing to textured grain structures as a result of directional solidification [3.26, 3.27, 3.28].

3.6.1.1.2 STATISTICAL PRINCIPLES AND TECHNIQUES

The statistical principles and techniques employed to establish design allowables are described comprehensively in MMDH 00932 Section 1 Appendix A Statistical Calculations. They are also applicable when a designer wishes to obtain his own design values [3.29]. It is important to highlight some paragraphs since they provide an outline of the requirements for raw data and its statistical analysis, which is useful when discussing their relevance to AM.

Subsection A3 of MMDH 00932 describes the raw data requirements. The overriding thrust is that the raw data used to establish design values should be as representative as possible of the whole range of material accepted to the specification, i.e. the statistical procedures depend for their strict validity on the assumption that the sample data have been obtained by selecting the material to be tested independently at random, i.e. there must be no censoring of data. Only under some special circumstances can data be discarded.

Figure 3-3 illustrates a Normal (Gaussian) probability distribution, which has been shown by experience to model well the mechanical properties of metallic materials (conventional materials / manufacturing). Therefore the statistical procedures in the appendix are based primarily on Normal statistical theory. Below is a list summarising the high level sampling requirements for conventional materials / manufacturing based on this theory (for brevity the sampling requirements for producers, batches and melts, and the definitions of those terms, are not summarised here):

- To derive A and B-basis values directly a minimum of 100 individual measurements should be used (for each property of interest), although higher numbers are desirable.
- When order statistics are used at least 299 results are necessary for an A value and 29 for a B value.
- Exceptionally, as an interim measure until further data become available, 30 individual measurements may be used to derive a B value (at least 30 measurements are required to derive a useful estimate of the coefficient of variation of a property).
- Indirect derivation of A and B values using the ratio method requires a minimum number of results from a specified combination of batches, melts and specimen locations.
- Test results should span the range of material thicknesses to which the A and B values are to be applicable.

MMPDS has the same sampling requirements as those for MMDH 00932 [3.24].

The statistical analysis procedures set out in MMDH 00932 Section 1 Appendix A, and a brief explanation of their function, are summarised below:

1. Calculation of sample mean and standard deviation, to be used (along with sample size) when employing a probabilistic design procedure instead of A, B or S-basis design values.
2. Comparison of samples - to ensure samples are only combined when it can be shown that, with a statistical risk of error, they belong to the same population.

3. Goodness-of-fit testing (the Anderson-Darling test) – to test that the sample supports the hypothesis that it was drawn at random from a given probability distribution (i.e. a Normal distribution).
4. Direct calculation of A and B values, with methods for when either: (i) a normally distributed population is assumed; or (ii) a distribution form has not been established.
5. Calculation of A, B and S values by the ratio method. These are methods to calculate and check design values for some properties based on a particular property relationship with known directly calculated tensile property design values.
6. Estimation of population coefficient of variation. This allows the estimation of the variability of a property, with a statistical level of confidence, to aid safe design.
7. Calculation of lower and upper design values for mechanical properties. A and B values are lower values but designers sometimes require upper design limits for example when designing deliberate weak links.
8. Monitoring material properties by users. These are methods to monitor the material to be used in production to make sure its properties are still valid with respect to the historical A and/or B design values in MMDH 00932. Since AM is a process separate and distinct from conventional processes such as forging, rolling, etc. and is not included in MMDH 00932, these methods are relevant only for the purposes of comparison for information.
9. Vetting of S values. This is a method to test that S values are not too high when compared with the properties of released material.

As stated, the guidance is based on Normal statistical theory. If calculations of skewness and/or kurtosis indicate a non-Normal distribution then an alternative statistical distribution may be indicated, e.g. a Weibull distribution [3.29]. MMPDS Chapter 9 also provides extensive guidance on the statistical analysis of static properties, and Section 9.5.4 describes the procedures to determine whether the form of a distribution is either Normal, Pearson Type III or three-parameter Weibull [3.24].

3.6.1.2 TESTING PHILOSOPHY

Def Stan 00-970 Section 3 Leaflets 01 to 06 provide extensive information relevant to Clause 3.1 Static Strength and Deformation. Leaflet 02 is noteworthy because it describes the route to the certification and qualification of an aircraft component through the use of a 'testing pyramid'. This 'building block' approach starts with simple coupons and leads to elements, details and sub-components, and finally the component and/or airframe static tests. This concept is illustrated schematically in Figure 3-4 – the bulk of the effort, in terms of numbers of tests, will be in the activities below the dotted line. The approach is relevant to AM parts because it allows the manufacturer to establish mechanical properties and design allowables, check how the properties measured in coupons are representative of realistic design features, and eventually to qualify real components.

3.6.1.3 TESTING PROCEDURES

MMDH 00932 Section 5 defines the standardised test procedures to be adopted for determining static properties of metallic materials at sub-zero, room and elevated temperatures which can be employed in the derivation of design data for aerospace purposes; MMPDS contains similar guidance. It does not cover dynamic properties.

Test procedures are defined by recognised standardisation organisations such as BSI (British Standards Institution), ISO (International Organization for Standardization) and ASTM International (American Society for Testing and Materials). The procedures have been designed for conventionally manufactured parts where the relationships between manufacturing process, product form, location, orientation and design of test specimens, and final part properties are well established. This is not the case for AM and great care needs to be exercised in interpreting how to use standardised test procedures to certify an AM part as airworthy. Guidance has been issued by the US National Institute of Standards and Technology (NIST) on the applicability of existing metallic materials testing standards for additive manufacturing specimens. NISTIR 7847 [3.30] provides an overview of ASTM and ISO testing standards for deformation properties (tension, compression, bearing, etc.) and failure properties (fatigue, fracture toughness and crack growth), with an appendix of definitions of materials property terms. These standardised tests are those for properties that are specified in MMDH and MMPDS. NISTIR 8005 [3.31] provides brief guidance on factors that should be considered when assessing the applicability of existing standards for the testing of AM specimens, e.g. anisotropy, porosity, component thickness and sensitivity of materials properties to AM build parameters and initial powder properties. NISTIR 8005 then goes on to list standards for the mechanical testing of metal parts with an assessment of their applicability to AM specimens with useful guidance for each.

NOTE: The United Kingdom Accreditation Service (UKAS) is the sole national accreditation body to assess, against internationally agreed standards, organisations that provide certification, testing, inspection, and calibration services. UKAS is the national signatory, along with other nationally recognised accreditation bodies world-wide, to multilateral agreements for the purposes of mutual recognition through the European Co-operation for Accreditation (EA), the International Accreditation Forum (IAF) and the International Laboratory Accreditation Co-operation (ILAC). Those bodies that are signatory to these agreements are deemed to be equivalent having undergone stringent peer evaluations [3.32]. However it should be noted that UKAS accreditation is a mark of competence of the testing house and does not imply that it will be able to offer suitable advice on the testing of AM specimens.

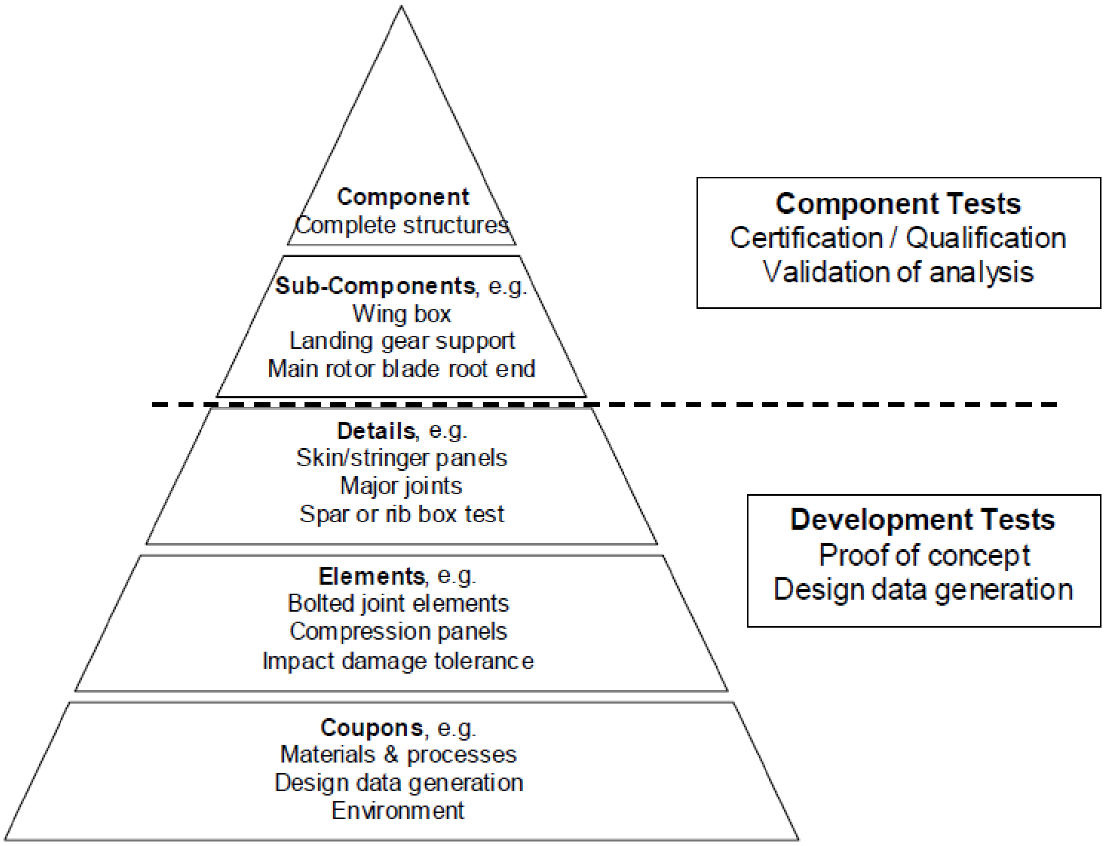

Figure 3-4 – the structural test 'pyramid' [3.17]

3.7 ESTABLISHING FATIGUE PROPERTIES

Fatigue performance is a term defining the resistance of a structural component to the development of cracking under fatigue loading. Under fatigue loading the design allowable stress levels may be considerably lower than those acceptable for static design [3.33].

Good fatigue design is based on the use of a robust, well understood and verifiable design philosophy. There are two main design philosophies, commonly called the Safe Life approach (based on the use of S-N curves) and the Damage Tolerant approach (based on fracture mechanics calculations and $\mathrm{d}a/\mathrm{d}N$ vs. ΔK fatigue crack growth curves). The Safe Life design philosophy is mandated for combat aircraft and rotorcraft since their structures are often compact, inaccessible for inspection and highly stressed. Military transport, light trainer and intelligence aircraft are generally derived from civil designs and are of damage tolerant design, which requires regular inspections to support airworthiness [3.19], except for their landing gear which are Safe Life components.

Def Stan 00-970 Clause 3.2 sets out the fatigue requirements that apply to all Grade A structures and components. The clause is supported by extensive additional information in the leaflets of Section 3, especially Leaflets 34 to 39 which deal with many aspects of fatigue with respect to safe aircraft design and management of airworthiness through life (Leaflet 40 specifically deals with special considerations for fatigue and polymer-matrix fibre-composite components).

Leaflet 34 provides essential guidance on material selection with respect to fatigue. Guidance is given under the topic headings: Fatigue Performance; Fracture Toughness; Impact Resistance; and Fatigue Crack Growth Resistance. Many of the paragraphs in the leaflet have noteworthy relevance to AM parts for example fatigue and the effects of residual stresses and surface finish, the mandated use of representative coupons / conditions to establish fatigue performance, and the use of the fracture toughness / yield strength ratio to determine whether a material will have an acceptable damage tolerance.

The main stipulations of the fatigue design requirements of Def Stan 00-970 are as follows [3.19]:

- Structure and mechanical components shall have an acceptable tolerance of defects and damage.
- The structure or mechanical system as a whole shall have an acceptable Safe Life.
- Structure and mechanical components shall have an adequate residual strength throughout their service life.

Whichever design philosophy is adopted it will be necessary to instigate a comprehensive test programme to establish the necessary fatigue design data, whether S-N curves or $\mathrm{d}a/\mathrm{d}N$ vs. ΔK fatigue crack growth curves. Sufficient S-N or $\mathrm{d}a/\mathrm{d}N$ data must be derived for design purposes using coupons of the material and manufacturing parameters under consideration at constant stress amplitude and at appropriate R ratios; the bottom part of the testing pyramid in Figure 3-4. Eventually fatigue testing of whole components will be required using realistic spectrum loading conditions to verify the actual design with that manufactured component.

3.7.1 THE SAFE-LIFE DESIGN PHILOSOPHY AND SUBSTANTIATION

The Safe Life design philosophy uses factors on S-N curves to allow for scatter in fatigue performance and assumes that this scatter, either in life at a given stress amplitude or stress amplitude at a given life, is normally distributed. Using this distribution the safe life is estimated from the mean, giving a life at which less than 1 in 1000 items should fail. Scatter increases with life (e.g. Figure 3-5) and consequently the concept of the Safe S-N curve is used where, at high stress amplitudes where the fatigue curve is steep the fatigue life factor is based on the life at that stress amplitude – at low stress amplitudes where the fatigue curve is flat and scatter is large the fatigue life factor is based on the stress amplitude at that life.

Def Stan 00-970 Section 3 Leaflet 35 provides extensive guidance on the use of scatter factors to comply with the Safe Life approach. The factors are specific to the types of component/structure, material/manufacturing method and use of testing and monitoring. The leaflet also emphasises that the factors will be judged sufficient only in those circumstances where the Service Spectrum is confirmed by regular sampling of the service loads by Operational Loads Measurement (OLM) or Operational Data Recording (ODR) in compliance with the requirements of Clause 3.2 [3.33].

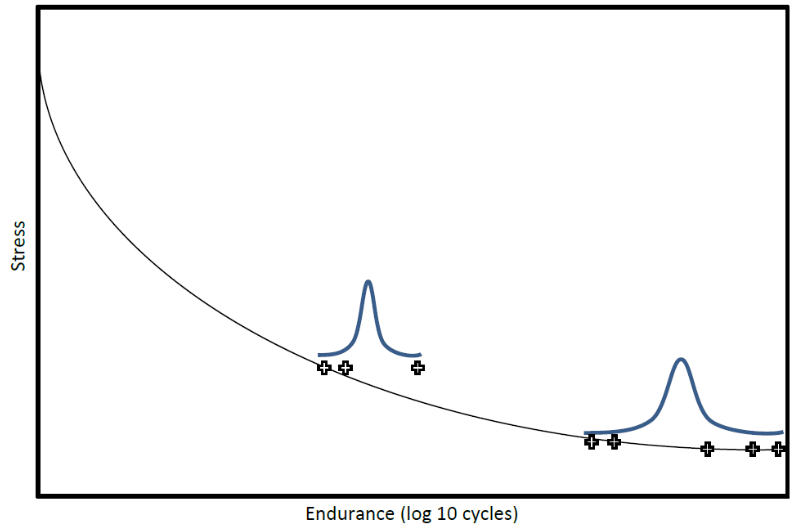

Figure 3-5 - Schematic representation of the scatter in endurance at different stress levels (reproduced from [3.19]).

3.7.2 INSPECTION-BASED SUBSTANTIATION

In certain circumstances the use of inspection-based substantiation (including the Damage Tolerant approach) is permitted for the fatigue design requirements of UK military aircraft. The requirements for inspection-based substantiation are provided in Def Stan 00-970 Section 1 Clause 3.2 [3.15]. It requires directed fatigue-related inspections of structures to support structural integrity in service or to support life extension [3.19]. Consequently a crucial relationship exists between: (i) the crack size that can be reliably detected by non-destructive inspection techniques of accessible aircraft structures; (ii) the crack growth rate determined from testing; and (iii) the critical crack size - this relationship will determine the inspection regime required to support airworthiness. Def Stan 00-970 Part 1 Clause 3.2.20 states – The inspection periodicity **shall** be substantiated by calculations, supported by evidence from relevant crack growth testing, tear-down inspections and in-service inspections. [3.15]. The fatigue crack growth curves used must also take account of environmental or temperature effects where appropriate. The EASA Certification “Specifications and Acceptable Means of Compliance for Large Aeroplanes, CS 25” [3.37], contains relevant information on Damage Tolerance and Fatigue Evaluation of Structure - CS 25.571 and AMC 25.571 [3.18]. It is the certification specification cited in Def Stan 00-970 Part 5 Large Aeroplanes. AMC 25.571 contains the noteworthy statement on damage tolerant fatigue design: … The evaluation should encompass establishing the components which are to be designed as damage-tolerant, defining the loading conditions and extent of damage, conducting sufficient representative tests and/or analyses to substantiate the design objectives (such as life to crack-initiation, crack propagation rate and residual strength) have been achieved and establishing data for inspection programmes to ensure detection of damage. Interpretation of the test results should take into account the scatter in crack propagation rates as well as in lives to crack-initiation. Test results should be corrected to allow for variations between the specimen and the aeroplane component thickness and sizes …

3.8 DISCUSSION ON APPLICATION OF REGULATORY ARTICLES AND DEF STAN 00-970 TO ADDITIVE MANUFACTURING

At a top level, the concept of the four pillars of airworthiness drives all activities related to the establishment and management of the airworthiness of military aircraft. The MAA’s Regulatory Framework provides the requirements, acceptable means of compliance and guidance that when followed will satisfy the principles of the four pillars. The MRPs that are especially relevant to AM have been summarised in Appendix A; one set in particular are noteworthy for this discussion since they apply to design changes.

RA5305 and RA5820 [3.4, 3.3] relate to the management of design changes to an aircraft. Their primary function is to ensure that any design changes do not adversely affect the airworthiness of the aircraft. A dominant theme is the management of design changes through the collaborative efforts of the TAA and DO; however the TAA is ultimately responsible for signing off the change before it is implemented, with the MAA providing independent certification assurance where changes are considered to have a major impact on airworthiness.

An important process is the classification of design changes as either major or minor, as described in RA5820, since this drives the level of assurance to be carried out by the TAA. Annex A of RA5820 gives an example of a major change to aircraft structure as: Changes to materials, processes or methods of manufacture of primary structural elements, such as spars, frames and critical parts… Clearly the introduction of an AM part in place of a part manufactured in a different way for type certification is a major design change and consequently the aircraft must go through the full MACP before its introduction. As part of these assurance procedures, Def Stan 00-970 Part 1 Section 4 provides the methods that must be followed to establish the materials allowables and fatigue properties of a part. The principles embodied in this Def Stan section have important consequences for AM and are discussed below.

3.8.1 MATERIALS ALLOWABLES

It was pointed out in a preceding paragraph that Section 4 Clauses 4.5.3 and 4.5.4 contain requirements and guidance that have important consequences when interpreted for AM parts, namely:

- Clause 4.5.3 – the Guidance states that if appropriate design values are not available from MMDH 00932, which will be the case for AM, then they can be either (a) (2) obtained or derived from test data, or (a) (3) obtained using approved processes and control specifications to maintain a mechanical property that is more advantageous than that included in MMDH 00932. Further, data obtained as in (a) (2) and (a) (3) shall be derived by the same methods as are used to establish data in MMDH 00932.
- Clause 4.5.4 – the Requirement that "adequate allowance shall be made for the effects of all manufacturing processes and environmental conditions on material strength…" is followed by Compliance that the B values must be associated with a procedure that can monitor that those mechanical properties are being maintained to the appropriate specification.

Further guidance from Section 3 Leaflet 02 advises on the limitations of the applicability of coupon test data to the structural level, for example owing to: (a) scale effects; and (b) differences in variability and properties between the as-received material and the as-manufactured component.

The two clauses and Leaflet 02 advice have very important consequences for AM, which are given below:

1. Manufacturers can use their own mechanical properties data for the design of Grade A parts;
2. Manufacturers' own mechanical properties data shall be derived using the same methods as those used in MMDH 00932. Manufacturers must ensure that all sources of variability in the manufacturing process that could affect those properties are represented in the design allowable to a recognised level of statistical rigour (namely that described in MMDH 00932), i.e. the design allowable must always accurately represent the spread in properties achieved by the manufacturing process;
3. Materials properties from many manufacturing processes are affected by the scale of the material or part being processed. This is particularly the case for AM where the scale of the part (and the position of the melt pool on the build volume) will affect the solidification rate and consequently the microstructure and properties, e.g. [3.34]. These scale effects must be accurately represented in the materials allowables of the real part;
4. Materials properties can change over time because of environmental degradation, e.g. corrosion, oxidation, embrittlement, stress corrosion cracking, etc. and this should be reflected in the allowables. Further, different microstructures for the same alloy are affected by the environment differently and this should be understood when a new process, such as AM, is being developed.
5. There must be an appropriate procedure for the manufacturing process to monitor, and thus ensure, that the mechanical properties are being maintained over time.

The guidance in MMDH 00932 has been developed based on conventional materials / manufacturing methods, for example the material forms in Section 4 Limitation and Variation of Allowable Stresses: sheet and strip, plate, bar, forgings and castings. In these cases the terms batch, melt, cast, parent cast and campaign are well-defined. Further, the effect of processing on directionality of properties can be identified and described using a practice that is universally accepted. These two points are not the case for AM which, along with other sources of variability, makes the description of a single population distribution of properties a challenge.

Nevertheless MMDH 00932 does provide guidance, and two paragraphs in Section 1 Appendix A are especially noteworthy in this regard:

A1.7 For novel or unconventional metallic materials [which could be interpreted as also including manufacturing method], for which the appropriate distributional form has not yet been established, the method of analysis should be chosen on the basis of the significance level achieved… When the Normal hypothesis is rejected at the 5 per cent significance level, A and B values should be calculated by a distribution-free technique using order statistics…

A1.4 Samples should only be combined for analysis purposes when there is positive reason to suppose that they have been taken from the same homogeneous population which can be characterised by a single probability distribution…

The significance of these paragraphs for AM is that it is crucial that a single population of a property is defined with confidence – and that censoring or inadvertent omission of data is guarded against.

As mentioned above AM is not currently a well-established manufacturing process with properties that can be compared to large existing data sets with scatter that is understood from test and experience. **Consequently for Grade A metallic aircraft structures it is recommended that both the AM process AND the part shall be qualified and certified to establish, and provide confidence and assurance in, the variability in their properties (REC3.3)**. In time it may be possible to qualify and certify an AM process for a range of different parts – at least within the same part “family” - but this will require comprehensive knowledge and experience of process-property relationships, enhanced control and monitoring of process parameters, and appropriate specimen and part testing to ensure an acceptable level of safety-conservatism is embodied in the part (which must be demonstrated to the satisfaction of the TAA).

3.8.2 FATIGUE PROPERTIES

Paragraph 2.7 of Leaflet 35 states that the scatter factors therein are suitable for use in the design of components manufactured from conventional aluminium alloys, titanium alloys and steels; however they are not necessarily appropriate for those manufactured using additive methods. **For the Safe-Life approach it is recommended that scatter factors for Safe S-N curves for AM parts shall be rationally derived, i.e. they shall be determined from tests of elements that are representative of individual structural features and with the application of customary statistical techniques to give the required probability of failure (REC3.4)**. The test elements should also truly embody all sources of scatter in fatigue that will be in the final part, for example voids, pores, residual stresses, surface roughness, anisotropic properties, scale effects, environmental degradation, to name but a few. Leaflet 35 also provides additional procedures that must be followed for clearance by calculation when no element testing has been done so that additional Factors for Uncertainty can be used (e.g. those shown in Leaflet 35 Table 4 for conventional materials / manufacturing). For AM extreme care must be taken when choosing uncertainty factors – it is emphasised that the factors in Table 4 are minimums; higher values may be appropriate in some circumstances, which could include AM parts. All factors must be agreed with the Project Team (PT). The use of “no test” factors are only really intended for initial design analysis purposes and the overall intention of the regulations is that, particularly for primary structure, there will be supporting tests (all the way up the pyramid shown in Figure 3-4).

For inspection-based substantiation it is crucial that for AM parts fatigue crack growth specimens must be truly representative of the crack growth behaviour of the actual manufactured part, taking into account the same sources of scatter as described above. It must be possible to inspect the part appropriately, which could be difficult for parts where AM has been used to enable a more sophisticated design. If adequate inspection is not possible then Safe-Life Substantiation must be used.

It is known that microstructural characteristics affect the Probability of Detection (POD) in NDE techniques such as ultrasonic detection since they affect backscatter and attenuation [3.35]. **Since AM-produced microstructures can be very different from those from established processes it is recommended that POD characteristics should be established specifically for the part and microstructures of interest (REC3.5)**.

3.8.3 GENERAL COMMENTS

It has been emphasised that the sources of scatter in both static strength and deformation, and fatigue properties could be high in AM parts; higher than is usual for those from conventional manufacturing. Further the properties of an AM part are affected by, amongst many other things, its size, geometry, location in the build volume and orientation to the build direction. Consequently there is a risk that standard type test specimens (at the bottom of the test pyramid - Figure 3-4) do not accurately reflect the properties of the final part (at the top of the test pyramid). **It is therefore recommended that the philosophy of the testing pyramid, with its increasing level of size and feature complexity as specimens and elements become more representative of the final part, should be adopted to provide a level of assurance that these sources of scatter have been captured in the design allowables and fatigue properties (REC3.6)**.

3.9 GUIDANCE FROM OTHER AEROSPACE MANUFACTURING PROCESSES

Guidance material in Def Stan 00-970 and related regulatory documents, e.g. CS 25 Large Aeroplanes, provides information that may be useful when considering how to qualify a part manufactured using an additive process. Manufacturing processes for metals such as casting and welding have some features that are similar to AM, for example cast microstructures and the possible presence of solidification cracks prior to any post-process treatments. In a way the manufacture of structures from polymer-matrix fibre-composites is analogous to AM because the build-up of the material and the creation of the structure are the same process.

The sections below give a brief overview of guidance on these processes, some useful references and an important recommendation.

3.9.1 CASTINGS

It is stated in reference [3.36] that historically in aerospace for the static strength and deformation of castings, large Casting Factors were used because castings displayed considerable variability in properties. Further, uncertainties existed in the accuracy of the non-destructive inspection techniques of the time. The reference cites the British Civil Airworthiness Requirements (BCAR) D3-10 Castings which prescribed a casting factor of 1.5 and FAR 25.621 (Large Aeroplanes, Castings) which used to prescribe a casting factor of at least 1.25 for critical castings along with 100% inspection by approved non-destructive inspection methods. Nowadays in civilian regulations casting factors of 1.0 can be used for premium castings (i.e. very high quality) provided that: (i) it is demonstrated, in the form of process qualification, proof of product, and process monitoring that, for each casting design and part number, the castings produced by each foundry and process combination have coefficients of variation of the material properties that are equivalent to those of wrought alloy products of similar composition…; (ii) each casting receives inspection of 100 percent of its surface…, and inspection of structurally significant internal areas and areas where defects are likely to occur…; and (iii) one casting undergoes a static test and is shown to meet the strength and deformation requirements… [3.37]. It is required that for a particular process and foundry the following is done:

- Qualification of the process.
- Proof of the product.
- Monitoring of the process.

Def Stan 00-970 Part 1 Section 4 provides the requirements, compliance and guidance on the use of Grade A castings in military aviation, for example Allowable A values obtained in accordance with the methods described in ESDU Metallic Materials Data Handbook 00932 Volume 1 Section 1 Appendix A. Values obtained in this way shall be associated only with the one specification and the founder supplying the data until data from other founders has been obtained and included [3.16, 3.38].

For fatigue properties Def Stan 00-970 Part 1 Section 3 Leaflet 35 states that Factors of 10 on life and 2 on stress may be used for the construction of Safe S-N curves for castings, in the absence of rationally-derived scatter factors in the development phase. In all other cases, scatter factors shall be rationally derived, and the factors to be used shall be agreed with the PT... [3.33].

It is clear that the procedures for the qualification and certification of premium castings are especially useful when considering AM parts given potential similarities in microstructures, defects and scatter in properties, and the explicit guidance on process qualification, proof of product and process monitoring. Of significant importance is the emphasis the guidance places on non-destructive inspection. **It is therefore recommended that each Grade A AM part should receive inspection of 100 percent of its surface, and inspection of structurally significant internal areas and areas where defects are likely to occur, using approved non-destructive inspection methods (REC3.7)**. This wording on NDI is taken from CS 25.621 *Premium Castings* and, in the absence of AM-specific guidance, provides a conservative approach to qualification of a part that effectively has no arbitrary scatter factor. Innovations in AM technologies, e.g. in-situ monitoring, could provide alternative means of assuring the defect population of a part without the need for this degree of NDI; nevertheless alternative acceptable approaches must be agreed by the DO and TAA.

3.9.2 WELDING

Def Stan 00-970 Part 1 Section 4 Leaflet 15 gives guidance on the use of fusion welding, friction welding and diffusion bonding in military aviation. Since welding is used to join parent metal into joints for structures, it is only partially relevant to AM where the whole component has a cast microstructure analogous to a weldment. One exception is where an additive process is used to repair an existing part. In that case the guidance on heat affected zones may be useful. The leaflet does provide useful information on the grading of welds and their inspection [3.39].

3.9.3 POLYMER-MATRIX FIBRE COMPOSITES

The FAA’s Advisory Circular 107B Composite Aircraft Structure gives extensive guidance on acceptable means of compliance regarding airworthiness type certification requirements for composite aircraft structures using polymer-matrix fibre-reinforced composites [3.40]. The reason special considerations need to be given to composites is stated as: One of the unique features of composite construction is the degree of care needed in the procurement and processing of composite materials. The final mechanical behaviour of a given composite material may vary greatly depending on the processing methods employed to fabricate production parts. Special care needs to be taken in controlling both the materials being procured and how the material is processed once delivered to the fabrication facility. This reason is analogous to that required of AM parts. A conceptual building block approach has been developed for composite structure qualification, e.g. Figure 3-6 for fixed wing, which may be useful when considering the qualification of AM parts. This is similar to the building block approach described in Def Stan 00-970 Part 1 Section 3 Leaflet 02 (Figure 3-4).

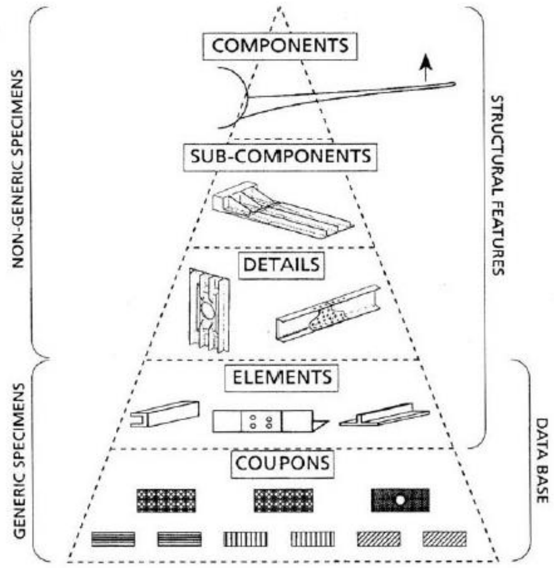

Figure 3-6 – Schematic diagram of building block tests for fixed wing [3.40].

3.10 CHAPTER 3 CONCLUDING REMARKS

Analysis of the UK military aviation regulations, defence standards and supporting information has been used to provide guidance on the assurance of aircraft structural parts with respect to airworthiness and relate these to AM. The qualification and certification that a Grade A manufactured part meets its specification is a deterministic process; the purpose of the pyramid of testing is to determine that all sources of variability have been captured (as far as reasonably possible), including through the use of appropriate and agreed NDE techniques to capture any rogue flaws. Further, aircraft structures will be inspected and maintained as necessary through life to ensure they continue to perform. These are all part of Structural Integrity (SI) Management, which forms part of the first pillar of airworthiness: the establishment and description of an effective Safety Management System (which must be detailed in the airworthiness strategy).

The sections on static strength and deformation, and fatigue show that the properties of manufactured parts follow a probability distribution that can be described using statistical theory to give a quantified level of confidence in a particular risk of failure. The consequence of this approach is that the properties of test specimens and test elements (representative of part features) must truly reflect the scatter in properties of the final part from all sources. The guidance is clear that censoring of data, whether intentional or not, must be guarded against.

The rational derivation of static strength and deformation design allowables, fatigue and / or fatigue crack growth scatter factors is strongly encouraged. The use of arbitrary factors, as was the case historically for aerospace castings, is discouraged since it held back the use of castings in the highly weight sensitive environment of aircraft structures. The use of premium castings without scatter factors (or with a scatter factor of 1.0) is a consequence of large improvements in casting quality and inspection. The guidance for premium castings is helpful since it describes succinctly an appropriate approach for ensuring their quality for a specific process, part, alloy and founder, namely:

- Qualification of the process.
- Proof of the product.
- Monitoring of the process.

The testing pyramid, starting with large numbers of specimens at the bottom through to real parts / structures at the top, is a well-established philosophy that should be adopted for both materials allowables and fatigue properties.

For Grade A metallic aircraft structures, until such time that AM is sufficiently mature, it is recommended that both the AM process AND the part are qualified and certified as a way of establishing and guaranteeing variability.

The approach of the document has been to treat the properties of AM parts in the same way as any other part with properties from material / process combinations. The document has provided a framework for considering all of the factors that should be taken into account; **it is recommended that the relevant sections in the requirements in Def Stan 00-970 Part 1 shall be used to set out a qualification plan for the AM components under consideration. The information in this chapter and Appendix A may be used as a guide to those requirements (REC3.8)**.

The guidance in this chapter considers Grade A parts; however, it is recognised that early adoption of AM is most likely to occur in non-critical parts. For such applications this document (as a whole) can still be used as a guide to the relevant sections in the requirements in Def Stan 00 970 Part 1. It will still be necessary to set out a qualification plan for the AM components under consideration and undertake a sub-set of the recommendations suggested here; the extent will need to be appropriate for the consequence of failure of the part and agreed with the TAA. **It is recommended that the information in this document may be used as a guide to set out an appropriate qualification plan for the non-critical AM components under consideration (REC3.9).**

3.11 CHAPTER 3 – SUMMARY OF RECOMMENDATIONS

In this chapter and Appendix A the airworthiness regulations and certification standards have been discussed with relation to AM parts. While it is considered that the existing regulations / standards are satisfactory for AM, the sources of scatter in AM (discussed in more detail in Chapter 5) are outside of experience compared to those from conventional manufacturing processes and consequently some key recommendations are made. These are summarised below in order from high level to more specific and grouped together as AMC-type recommendations (rather than the order in which they appear in the document):

3.11.1 REGULATION-TYPE RECOMMENDATIONS (CONTAINING "SHALL")

- **REC3.8: The relevant sections in the requirements in Def Stan 00-970 Part 1 shall be used to set out a qualification plan for the Additive Manufactured (AM) components under consideration. The information in this chapter (Airworthiness Assurance of Manufactured Components - Aircraft Structures) and Appendix A (Additive Manufacturing and the Military Aviation Authority's (MAA's) Regulatory Framework) may be used as a guide to those requirements - Section 3.10.**

- **REC3.1: It is recommended that a Grade A Additive Manufactured (AM) part, whether for a new or existing aircraft, shall be subject to the Military Certification Review Item (MCRI) process until the technology is sufficiently mature to maintain variability in a predictable and repeatable manner - Section 3.2.**

- **REC3.3: For Grade A aircraft structures it is recommended that both the Additive Manufactured (AM) process AND the part shall be qualified and certified to establish, and provide confidence and assurance in, the variability in their properties – Section 3.8.1.**

- **REC3.4: For the Safe-Life approach scatter factors for Safe S-N curves for Additive Manufactured (AM) parts shall be rationally derived, i.e. they shall be determined from tests of elements that are representative of individual structural features and with the application of customary statistical techniques to give the required probability of failure – Section 3.8.2.**

3.11.2 ACCEPTABLE MEANS OF COMPLIANCE-TYPE RECOMMENDATIONS (CONTAINING "SHOULD")

- **REC3.6: The philosophy of the testing pyramid, with its increasing level of size and feature complexity as specimens and elements become more representative of the final part, should be adopted to provide a level of assurance that the sources of scatter have been captured in the design allowables and fatigue properties – Section 3.8.3**

- **REC3.2: It is possible that AM parts may have microstructures that have a different susceptibility to environmental degradation when compared to conventional forms and it is recommended that their particular susceptibility should be established – Section 3.5.2.4.**

- **REC3.7: Each Grade A AM part should receive inspection of 100 percent of its surface, and inspection of structurally significant internal areas and areas where defects are likely to occur, using approved non-destructive inspection methods – Section 3.9.1.**

- **REC3.5: Since AM-produced microstructures can be very different from those from established processes it is recommended that non-destructive evaluation (NDE) probability of detection (POD) characteristics should be established specifically for the part and microstructures of interest - Section 3.8.2.**

3.11.3 GUDIANCE-TYPE RECOMMENDATIONS (CONTAINING “MAY” OR “COULD”)

- **REC3.9: The information in this document may be used as a guide to set out an appropriate qualification plan for the non-critical AM components under consideration - Section 3.10.**

3.12 CHAPTER 3 GLOSSARY OF ABBREVIATIONS

AM – Additive Manufactured/Manufacturing
AMC – Acceptable Means of Compliance
AMS - Aerospace Material Specification
ASD-STAN - an association that establishes, develops and maintains standards on behalf of the European aerospace industry
BCAR - British Civil Airworthiness Requirements
BS – British Standard
BSI – British Standards Institute
CRI – Certification Review Item
CS – Certification Specification
DAOS – Design Approved Organisation Scheme
Def Stan – Defence Standard
DO – Design Organisation
DoD – Department of Defense
DTD – Directorate Technical Development
EA - European Co-operation for Accreditation
EASA – European Aircraft Safety Agency
ESDU – Engineering Sciences Data Unit
FAA – Federal Aviation Administration
FAR – Federal Aviation Regulations
IAF - International Accreditation Forum
ILAC - International Laboratory Accreditation Co-operation
JSSG – Joint Services Specification Guide
MAA – Military Aviation Authority
MIL-HDBK – Military Handbook
MIL-STD – Military Standard
MMAC - Manual of Military Air System Certification
MMDH – Metallic Materials Data Handbook
MMPDS - Metallic Materials Properties Development and Standardization
MOD – Ministry of Defence
NIST – National Institute of Standards and Technology
ODR – Operational Data Recording
OLM – Operational Loads Measurement
PR EN – Pre-Standard European Norms
PT – Project Team
RA – Regulatory Article
SAE – [formerly] Society of Automotive Engineers
SI – Structural Integrity
SQEP – Suitably Qualified and Experienced Person(s)
TAA – Type Airworthiness Authority
TCR – Type Certification Report
UK – United Kingdom
UKAS – United Kingdom Accreditation Service
US – United States (of America)
USAF – United States Air Force
USN – United States Navy

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3.37. EASA Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes CS-25 CS25.621 Casting factors, Amendment 18, 22 June 2016.

3.38. Defence Standard 00-970 Design and Airworthiness Requirements for Service Aircraft Part 1 Fixed Wing, Section 4 Design and Construction, Leaflet 21, Castings - Static Strength Approval Of Castings, Issue 14, 13 July 2015.

3.39. Defence Standard 00-970 Design and Airworthiness Requirements for Service Aircraft Part 1 Fixed Wing, Section 4 Design and Construction, Leaflet 15, Processes and Working of Materials Fusion Welding, Friction Welding and Diffusion Bonding, Issue 14, 13 July 2015.

3.40. Federal Aviation Administration Advisory Circular 20-107B Composite Aircraft Structure, 9 August 2009.

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4 AIRWORTHINESS ASSURANCE FOR MANUFACTURED PARTS (AIRCRAFT ENGINES)

4.1 INTRODUCTION

Airworthiness is defined as: the ability of an aircraft or other airborne equipment or system to be operated in flight and on the ground without significant hazard to aircrew, ground crew, passengers or to third parties; it is a technical attribute of materiel throughout its lifecycle [4.1].

4.1.1 THE PURPOSE OF THE CHAPTER

As with Chapter 3 for aircraft structures the purpose of this Chapter is to provide a guided "walk through" the regulations and certification standards that are used for the airworthiness assurance of manufactured gas turbine engine parts and make specific recommendations with respect to additive manufactured (AM) parts. Piston engine parts are not covered, the reason for which is explained in Section 4.4. Where "shall" is used in the recommendation it is underlined because the word "shall" is used in statements for Regulations in Regulatory Articles (RAs) and certification standards, i.e. in this document it is a Regulation-type recommendation. Likewise in recommendations where "should" is used it is Acceptable Means of Compliance (AMC)-type guidance. Other recommendations are Guidance material.

The intention of this Chapter is to be self-contained and for the most part stand-alone from Chapter 3. Consequently there is repetition when introducing and discussing the MOD's regulatory framework since it is applicable to both aircraft structures and aircraft engines. The Military Aviation Authority's (MAA's) Regulatory Publications (MRPs) that are especially relevant to additive manufacturing (AM) (in either aircraft structures or aircraft engines or both) are identified in Appendix A.

Section 4.7 Discussion on application of Regulatory Articles and Def Stan 00-970 **Part 11 Issue 6** (2015) to AM is especially noteworthy because it draws together information presented in the rest of the Chapter and emphasises its importance for AM.

4.1.2 CHAPTER AT A GLANCE

Table 4-1 is a concise overview of the chapter and provides a brief description of the purpose of each section.

Table 4-1 – Overview of Chapter 4 and summary of each section.

Section	Title	Description and purpose	Page
4.1	Introduction	MOD's definition of the term Airworthiness. An explanation of the chapter's purpose with a table summarising the chapter's structure.	61
4.2	Overview of qualification process for manufactured parts	A simplified schematic representation of the qualification process for manufactured parts.	63
4.3	The Military Aviation Authority's (MAA) regulatory framework	A high level summary of the MAA's regulatory framework, including an introduction to the four pillars of airworthiness. Regulatory publications that are especially relevant to AM are described in Appendix A.	65
4.4	Certification standards	Introduces MOD's primary standard Def Stan 00-970 but also briefly describes other relevant standards, e.g. those of the European Aviation Safety Agency (EASA), which may provide Alternative Acceptable Means of Compliance (AAMC).	65
4.5	Noteworthy elements of Def Stan 00-970	Description of Def Stan 00-970 Part 11 Section 3 General Requirements for Aircraft Engines and Part 4 Section 4 Military Requirements for Gas Turbine Engines.	69
4.6	Establishing Predicted Safe Cyclic Life	Describes features of Safe Life and Damage Tolerance Lifing methods. A short introduction to Probabilistic Lifing is provided.	85
4.7	Discussion on application of Regulatory Articles and Def Stan 00-970 Part 11 to AM	Highlights points of the proceeding sections that are especially important for AM.	90
4.8	Chapter 4 Concluding remarks		96
4.9	Chapter 4 Summary of Recommendations		98
4.10	Chapter 4 Glossary of Abbreviations		100
4.11	Chapter 4 References		101

4.2 OVERVIEW OF CERTIFICATION PROCESS FOR ADDITIVELY MANUFACTURED PARTS

For an air system to be accepted onto the Military Aircraft Register (MAR) it must go through the Military Air System Certification Process (MACP) as defined in Regulatory Article RA5810 [4.2], which includes the engines. For parts to be used on existing aircraft engines the use of an AM part is likely to be classed as a major modification from that of its original Military Type Certification (MTC) because it will at least represent a modification to the manufacturing process (and perhaps also design and/or material). Guidance on the classification of changes as major or minor is given in Regulatory Article RA5820 [4.3]. The part will become a Military Certification Review Item (MCRI) and consequently go through an appropriate certification assurance process. The aircraft will usually have to go through MACP so that the MAA, as an independent authority, can assess whether the Type Airworthiness arrangements in place for the Air System are adequate; if adequate an up-issued MTC (or the issue of an Approved Design Change Certificate (ADCC) where an MTC does not exist) will be released. These certificates provide assurance to the Release to Service Authority (RTSA) and Aviation Duty Holder (ADH) that, for the design changes covered by the certificate, the Type Airworthiness arrangements in place have been assessed to be adequate by the MAA. The modification must be justified to the Type Airworthiness Authority (TAA) by the DO [4.4, 4.3]. The Manual of Military Air System Certification (MMAC) provides an explanation of MTCs and approved design changes, as well as guidance on the MACP [4.5]

Figure 1 is a simplified schematic of the MCRI-process whereby a Design Approve Organisation Scheme (DAOS) approved Design Organisation (DO)-Engine Manufacturer justifies that a part is airworthy. The process is part of the MACP for either the up-issue of the MTC or the issue of an ADCC. In either case, this will be underpinned by the production of a Type Certification Report (TCR). Whether an AM part is for a new or existing engine it must be assessed for safety and fulfil the requirements for strength and its life established if it is an Engine Critical Part as specified in Def Stan 00-970 Part 11 Section 3.

Owing to the novel nature of AM, and to provide appropriate assurance, an AM part will require a MCRI-type process until there are established processes and procedures for the design and certification of parts and the characteristics of the manufacturing process for each**. It is recommended that a Critical AM part, whether for a new or existing aircraft engine, shall be subject to the MCRI process until the technology is sufficiently mature to maintain variability in a predictable and repeatable manner (REC4.1)**. The term ‘Critical’ is explained later.

The methods to be used to establish engine failure effects (Safety Analysis), design values and durability (critical part life) of parts are specified in Def Stan 00-970 Part 1 Sections 3 and 4.

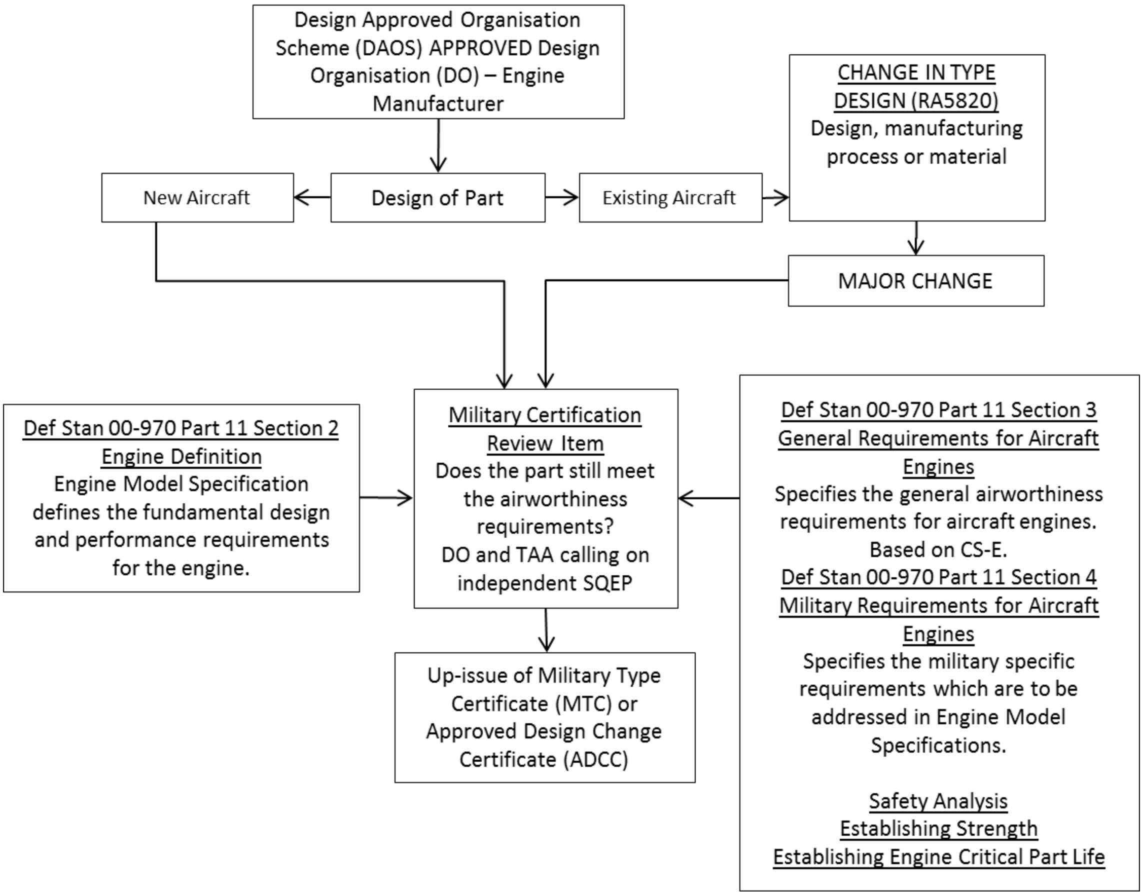

Figure 4-1 – Simplified schematic of the process through which a part may be certified as airworthy by an approved DO –Engine Manufacturer and the TAA, who may call on independent Suitably Qualified and Experienced Person(s) (SQEP) to support the MCRI process.

4.3 THE MAA'S REGULATORY FRAMEWORK

All aspects of the safety of military aviation are underpinned by the MAA's Regulatory Framework; the scope of the Regulatory Policy is laid out in MAA001 [4.1].

The MAA publishes its regulatory framework as a series of MAA Regulatory Publications (MRPs) in three layers: overarching documents, Regulatory Articles, and manuals [4.6] (The Pocket Guide to MAA Regulation is a concise explanatory guide [4.7]). Readers are encouraged to refer to the most up to date versions of the MRPs by checking the MAA's website [4.6].

For the purposes of the design, manufacture and certification of AM parts, the regulations of primary concern are those associated with Type Airworthiness: these are mainly to be found in the 5000 series, with some aspects also covered in the 4000 series. These, and other regulations that need to be considered, are identified in Appendix A to this Chapter. These further considerations include, but are not necessarily limited to, standardisation, competence, record and configuration management, and approval of manufactured and repaired parts.

The Four Pillars of Airworthiness is an important principle introduced and described in Regulatory Article 1220 [4.8].]. It is discussed in Appendix A and summarised here: (1) an effective Safety Management System (SMS) should be established and detailed; (2) Recognised standards should be used and their use detailed; (3) Competence – arrangements for the use and management of competent persons and competent organisations should be detailed; and (4) Independence - arrangements for ensuring independent assessment, technical evaluation and safety audit should be detailed. The four pillars underpin all the activities related to airworthiness of an aircraft and drive the requirements that will be discussed below; the discussion below concentrates mainly on the standards applicable and how AM components may differ from those manufactured using more established methods.

4.4 CERTIFICATION SPECIFICATIONS

4.4.1 DEF STAN 00-970 PART 11 ENGINES

Figure 2 of Chapter 3 gives a summary of the structure of Def Stan 00-970 and shows the Parts that cover different aircraft types and equipment. Def Stan 00-970 Part 11 Engines is a guide to the preparation of an Engine Model Specification. It provides requirements and guidance for the design and testing of aircraft engines to meet the airworthiness requirements for UK military operation [4.9]. It is the primary standard used by UK MOD as the certification basis for engines for military aircraft, and lays the foundation for the management of airworthiness through life. The UK does use alternative certification baselines and Alternative Acceptable Means of Compliance (AAMC), for example those of the US Air Force and US Navy, nevertheless these are currently assessed against Def Stan 00-970 Part 11.

At a glance the structure of Def Stan 00-970 Part 11 is shown in Figure 4-2.

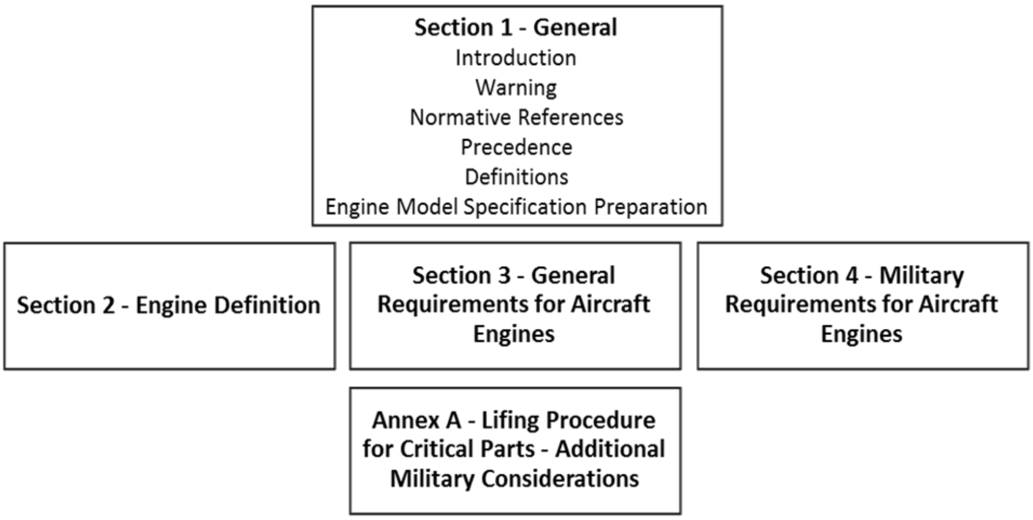

Figure 4-2 - Simplified view of the structure of Def Stan 00-970 Part 11 Engines.

A brief description of each Section is given below

- **Section 1** – General. An introduction to Part 11, its scope, engines for what types of aircraft it covers, its approach to references, and the precedence of other specifications and legal requirements. A very useful definition of engines and terminology is presented. Terms associated with engine Critical Part Lifing are especially important for this Chapter and will be referred to in Section 4.5.
- **Section 2** – Engine Definition. The fundamental design and performance requirements of the engine.
- **Section 3** – General requirements for aircraft engines. This section contains the fundamental airworthiness requirements and is based on the European Aviation Safety Agency's (EASA's) Certification Specification for Engines (CS E) [4.10, 4.11].
- **Section 4** – Military requirements for aircraft engines. This section contains military-specific requirements that are not addressed in Section 3: vectored thrust, reheat lighting and burning, infra-red radiation / suppression, etc.
- **Annex A** – Lifing procedure for critical parts – additional military considerations. The material in this Annex complements EASA CS-E 515, which provides the Requirements (Airworthiness Code in EASA terminology) and Acceptable Means of Compliance (AMCs) to establish and maintain the integrity of Engine Critical Parts.

NOTE: Def Stan 00-970 Part 11 Section 1 Paragraph 1.1.1 Scope, states that: Part 11 details the general requirements for the performance, operating characteristics, design, reliability and maintainability of **gas turbine** aero engines and associated jet pipes for use in UK military aeroplanes and rotorcraft. Therefore piston engines are not discussed in this Chapter with respect to AM and airworthiness [4.9].

Def Stan 00-970 is the default Type Certification Basis (TCB) for air systems on the MAR and is used as a baseline in establishing appropriate design and airworthiness requirements taking account of the procurement strategy to be adopted (in accordance with MRPs RA5810 and RA5820). For Part 11 Engines Section 3, the requirements are as defined in CS-E Certification Specification – Engines, Amendment 3 (dated 23 December 2010)[1]. The paragraph numbers have been defined to be directly compatible with CS-E requirements, e.g. CS-E 515 becomes 3.E515 in Def Stan 00-970 Part 11. It is important therefore to discuss CS-E and also important to mention the US Federal Aviation Administration's (FAA's) equivalent Federal Aviation Regulation-33 (FAR-33) Airworthiness Standards – Engines.

4.4.2 EUROPEAN AND US CIVIL REQUIREMENTS

In Europe the civil aircraft design requirements are issued by the EASA as Certification Specifications (CSs) [4.12] and in the US by the FAA as Federal Aviation Regulations (FARs) [4.13]; generally there is read across in the numbering systems between the two bodies (but not necessarily the content), e.g. CS-25/FAR-25 Large Aeroplanes. For engines, the certification requirements are contained in CS-E and FAR-33.

A simplified schematic representation of CS-E is shown in Figure 4-3. The CS is divided into two Books, with each containing the Sub-Parts A to F: Regulations/Airworthiness Codes in Book 1 and AMCs in Book 2. Piston engines are covered by Sub-Parts A, B and C and turbine engines are covered by A, D, E and F.

FAR-33 Airworthiness Standards – Engines is structured in Sub-Parts A to G plus Appendices A to D:

- Sub-Part A – General.
- Sub-Part B – Design and Construction: General.
- Sub-Part C – Design and Construction: Reciprocating Aircraft Engines.
- Sub-Part D – Block Tests: Reciprocating Aircraft Engines.
- Sub-Part E – Design and Construction: Turbine Aircraft Engines.
- Sub-Part F – Block Tests: Turbine Aircraft Engines.
- Sub-Part G – Special Requirements: Turbine Aircraft Engines.
- Appendix A – Instructions for Continued Airworthiness.
- Appendix B – Certification Standard Atmospheric Concentrations of Rain and Hail.
- Appendix C – Reserved.
- Appendix D – Mixed Phase Ice Crystal Icing Envelope (Deep Convective Clouds).

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[1] As at 8 June 2017, the latest CS-E version is Amendment 4 (12 March 2015). This is being reflected in Def Stan 00-970 Part 11 Issue 7, which is in preparation.

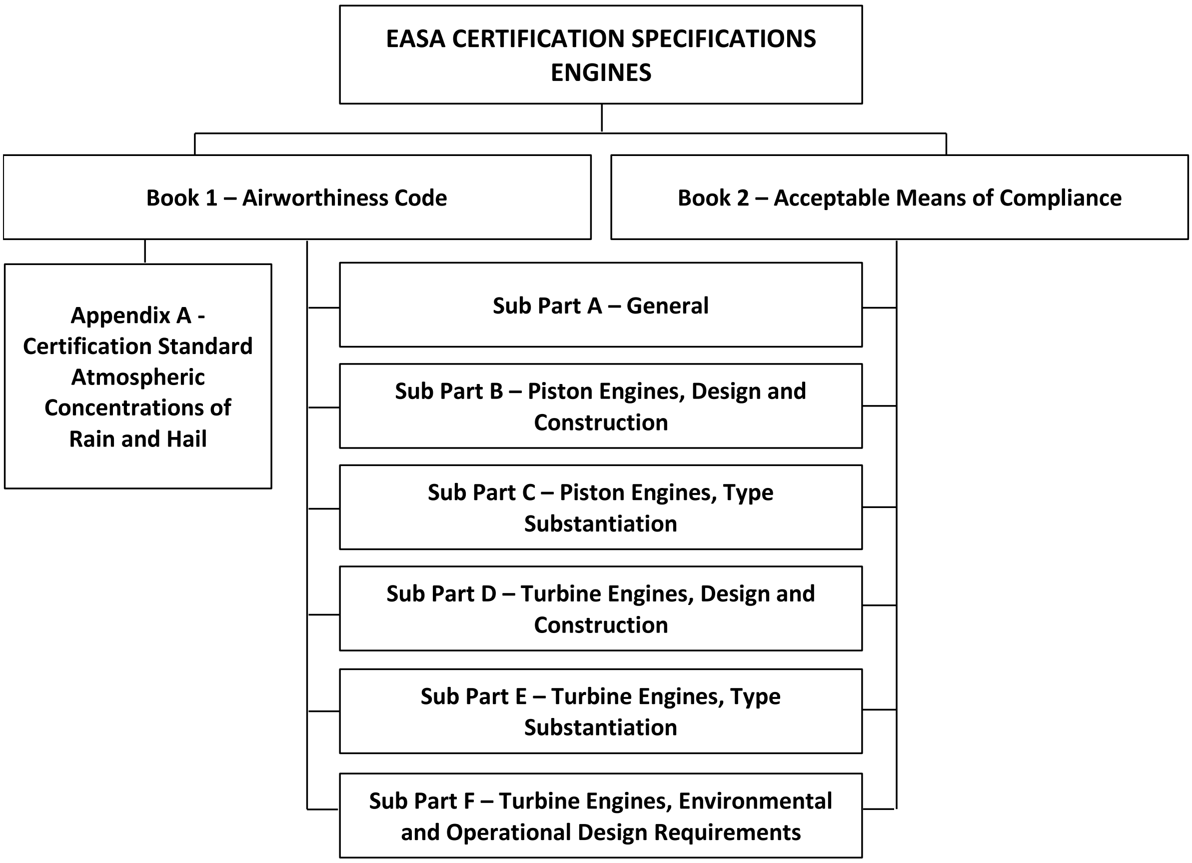

Figure 4-3 - Simplified view of the structure of CS-E.

4.4.3 US MILITARY REQUIREMENTS

The Department of Defense (DoD) Joint Services Specification Guide JSSG-2007A for Aircraft Turbine Engines is a specification developed jointly by the US Air Force (USAF) and the US Navy (USN). JSSG-2007A and its handbook appendices provide rationale, guidance, background, lessons learned, and instructions necessary to tailor sections 3 and 4 of JSSG-2007A for a specific application. These applications include fixed and rotary wing, wide body, manned, and unmanned air vehicles [4.14]. In the United States Air Force (USAF) the demonstration of compliance with the specification requirements is underpinned by the use of MIL-STD-3024 (Propulsion Structural Integrity Program - PSIP) and MIL-HDBK-1783B (Engine Structural Integrity Program - ENSIP) [4.15, 4.16].

4.5 NOTEWORTHY ELEMENTS OF DEF STAN 00-970 PART 11

A summary of Def Stan 00-970 Part 11 Section 1 is provided above. An important section to highlight here is 1.5 Definitions, 1.5.8 Terms associated with Engine Critical Part Lifing since it contains definitions of 21 terms that are commonly used and understood across the aircraft engine airworthiness/safety community. The definitions will not be reproduced here but a useful example at this point in the document is:

1.5.8.5 Critical Part - A critical part as defined in this document is an engine rotating or non-rotating component, which from failure analysis shows that the component must achieve and maintain a particularly high level of integrity if hazardous effects are not to occur at a rate in excess of Extremely Remote [4.9].

Readers are encouraged to refer to the most up to date version of the standard for these definitions by visiting the Defence Standards website [4.17].

Def Stan 00-970 Part 11 Section 2 [4.18] defines the fundamental design and performance requirements for the engine. Compliance with these requirements is substantiated by compliance with the applicable requirements of Sections 3 and 4. Consequently for the purposes of this document and considerations for AM and engine component airworthiness the following discussion will focus on especially relevant paragraphs in Sections 3 and 4 only.

Within each part of Def Stan 00-970 Part 11 Sections 3 and 4, information is presented in paragraphs and takes the form of:

REQUIREMENT - These requirements affect airworthiness and safety and are normally prefaced by the word “shall.” All requirements must be considered in the procurement of UK military aircraft and subsequent design changes.

COMPLIANCE - Contains information regarding established methods for demonstrating compliance with the requirement. Technology advances may allow the use of alternative methods in achieving the requirement.

GUIDANCE - Will contain the technical justification for the requirement and additional information considered useful in designing a system to meet the requirements. This may include appropriate references, advice on issues that require consideration or advice on typical design solutions that have been applied in the past. Some areas are considered ‘best practice’ by MOD, for example where they may affect survivability of an aircraft.

4.5.1 DEF STAN 00-970 PART 11 SECTION 3 - GENERAL REQUIREMENTS FOR AIRCRAFT ENGINES

Figure 4-2 provides an overview of the structure of Def Stan 00-970 Part 11. Sections 1 General and 2 Engine Definition will not be discussed further here since they do not contain information specific to the airworthiness of manufactured parts.

Def Stan 00-970 Part 11 Section 3 contains the general airworthiness requirements for aircraft engines [4.19]. It is based on the relevant sections of CS-E, namely sub-parts A, D, E and F in Book 1 (Requirements/Airworthiness Code), and Book 2 (AMC). In addition to introductory paragraphs, Section 3 has paragraphs numbered 3.E10 to 3.E1040, with direct read across of CS-E 10 to CS-E 1040 (Amendment 3, 23 December 2010) [4.20]. CS-E 200 to CS-E 470 deal with piston engines and are not referred to further in Def Stan 00-970 Part 11 Section 3. CS-E Amendment 4 (12 March 2015) [4.21] also contains CS-E 1050 Exposure to volcanic cloud hazards, which will be included in Issue 7 of Def Stan 00-970 Part 11 when released.

Of the 68 paragraphs in Section 3 a number can be highlighted that are especially important when considering the airworthiness of manufactured parts and implications for AM. They are discussed below, with particular attention paid to: (i) 3.E70/CS-E 70 Material and Manufacturing Methods; (ii) 3.E510/CS-E 510 Safety analysis; and (iii) 3.E515/CS-E 515 Engine critical parts.

4.5.1.1 3.E15/CS-E 15 TERMINOLOGY

This paragraph provides some definitions of important terms for the safety and airworthiness of engines. It should be used in conjunction with the issue of CS-E Definitions current at the date of issue of CS-E 15 [4.10, 4.11]. Readers are encouraged to check the EASA website for the appropriate version of CS-Definitions [4.22].

The paragraph refers to terms used in describing the analysis of engine effects and likelihood of occurrence (see CS-E 510 Safety Analysis), and terms used specifically for Engine Critical Parts (see CS-E 515 Engine Critical Parts). With the exception of the terms Manufacturing Plan and Service Management Plan, the terms described are not specific to the manufacture or repair of parts, nevertheless it is useful to highlight them in this document since they set the scene for proceeding discussions. Turbine engine relevant terms and definitions are shown in Table 4-2.

4.5.1.2 3.E20/CS-E 20 ENGINE CONFIGURATION AND INTERFACES AND 3.E30/CS-E 30 ASSUMPTIONS

These paragraphs will only be mentioned briefly since they do not deal directly with manufactured parts. Their relevance to this document is that they provide the framework to document parts and equipment that constitute the engine design - and interfaces with other aircraft parts and equipment [4.9, 4.10, 4.11]. This may be important when introducing an AM part into an existing design or repairing a part using an AM-type process.

The overall point is that all parts and equipment that constitute the engine design must be established, with reference to drawings, and that parts and equipment that are mounted on or driven by the engine, but not covered by the Engine Type Certificate, must also be identified. Engine performance data (including acceptance and operating limitations) and any assumptions on conditions imposed on the engine must be provided. There are specific requirements and AMCs related to One Engine Inoperative (OEI) ratings. Manuals must be provided containing instructions for installing and operating the engine.

4.5.1.3 3.E25/CS-E 25 INSTRUCTIONS FOR CONTINUED AIRWORTHINESS

This paragraph deals with the establishment and documentation of procedures for ensuring continued airworthiness of the engine [4.9, 4.10, 4.11]. They will only be touched on here - the relevance of the requirements and their AMCs to manufactured parts and AM is around what should be included in manuals, namely:

a. AM parts, or parts that have been repaired using an AM-type process, may require a specific type, degree and periodicity of inspection, which must be established and documented.
b. Details of repair methods for worn or otherwise non-serviceable parts and components along with the information necessary to determine when replacement is necessary must be considered for inclusion in the manuals. Repair methods may include AM-type processes.

4.5.1.4 3.E70/CS-E 70 MATERIALS AND MANUFACTURING METHODS

The requirements set out in this paragraph are brief but embody the importance of material and manufacturing method(s) on part integrity. They are [4.9, 4.10, 4.11]:

a. The suitability and durability of materials used in the engine must be established on the basis of experience or tests. The assumed design values of properties of materials must be suitably related to the minimum properties stated in the material specification.
b. Manufacturing methods and processes must be such as to produce sound structure and mechanisms which retain the original mechanical properties under reasonable service conditions.

The AMC material for CS-E 70 goes into detail on procedures that should be carried out on: (1) castings; (2) forgings; and (3) welded structures and welded components. AM processes are not included in the current version of CS-E [4.21]. It could be reasoned that the AMC material on castings could be used as a guide to parts manufactured wholly by AM because there are some similarities in process features (e.g. cast microstructures, possibility of defects); material on welded structures/components could be used as a guide to parts that have been conventionally-manufactured (e.g. forged) but repaired using an AM-type process – both AM-type repair and welding processes involve the deposition of new material onto an existing part / substrate.

In the current guidance forgings and welded structures/components are classified into Classes or Groups respectively, e.g. forgings, Classes 1 to 3, Class 1 – those parts, the failure of which could hazard the aircraft, i.e. they are Engine Critical Parts. Guidance is not given on a classification system for castings, which it could be inferred means that for engine applications castings are not traditionally used for Engine Critical Parts. Nevertheless it is useful to highlight the AMC for castings. The first part states:

The means of maintaining the required quality of all castings should be established by such methods as analysis for correct chemical composition, tests of mechanical properties, microscopic examination, break-up examination, strength tests, radiographic examination, etc. While other forms of examination may be adequate for most parts of castings, radiographic examination, where practicable, should be carried out on the more highly stressed portions in order to establish that the foundry technique is satisfactory.

The AMC refers to areas of the part that are highly stressed but does not refer to whether the failure of the part would hazard the aircraft. On the other hand the AMC for welded structures / components states that:

Fusion and resistance welds should be classified in accordance with the following:

- Group 1 - those welds the failure or leakage of which could hazard the aircraft.
- Group 2 - highly stressed welds the failure or leakage of which would not hazard the aircraft.
- Group 3 - all other welds.

It could be inferred that treating an AM part as a welded structure/component would allow its use in a Class 1/Group 1-type application.

In the absence of AM-specific AMC and guidance material in CS-E, and in any case, it is recommended that the Design Organisation (DO) (engine manufacturer) shall prove to the TAA, using appropriate and agreed methods, that any AM parts have suitable structural integrity assurance for their Class / Group, or similar classification of effect on failure (REC4.2).

This will be discussed further later.

Table 4-2 - Summary of turbine engine relevant terms and definitions in CS E 15.

(b) All engines	
Extremely Remote	Unlikely to occur when considering the total operational life of a number of aircraft of the type in which the Engine is installed, but nevertheless, has to be regarded as being possible. Where numerical values are used this may normally be interpreted as a probability in the range 10^{-7} to 10^{-9} per Engine flight hour.
Reasonable Probable	Unlikely to occur often during the operation of each aircraft of the type but which may occur several times during the total operational life of each aircraft of the types in which the Engine may be installed. Where numerical values are used this may normally be interpreted as a probability in the range 10^{-3} to 10^{-5} per Engine flight hour.
Remote	Unlikely to occur to each aircraft during its total operational life but may occur several times when considering the total operational life of a number of aircraft of the type in which the Engine may be installed. When numerical values are used, this may normally be interpreted as a probability in the range 10^{-5} to 10^{-7} per Engine flight hour.
(c) Turbine engines	
Hazardous Engine Effect	An effect identified as such under CS-E 510.
Major Engine Effect	An effect identified as such under CS-E 510.
Minor Engine Effect	An effect identified as such under CS-E 510.
(e) Terms associated with engine critical parts	
Approved Life	The mandatory replacement life of a part which is approved by the Agency.
Attributes	Inherent characteristics of a finished part that determine its capability.
Damage Tolerance	An element of the life management process that recognises the potential existence of component imperfections as the result of inherent material structure, material processing, component design, manufacturing or usage and addresses this situation through the incorporation of fracture resistant design, fracture mechanics, process control, and non-destructive inspection.
Engine Critical Part	A part that relies upon meeting prescribed integrity specifications of CS-E 515 to avoid its Primary Failure, which is likely to result in a Hazardous Engine Effect.
Engine Flight Cycle	The flight profile, or combination of profiles, upon which the Approved Life is based.
Engineering Plan	Compilation of the assumptions, technical data and actions required to establish and to maintain the life capability of an Engine Critical Part. The Engineering Plan is established and executed as part of the pre- and post-certification activities.
Manufacturing Plan	A compilation of the part specific manufacturing process constraints, which must be included in the manufacturing definition (drawings, procedures, specifications, etc.) of the Engine Critical Part to ensure that it meets the design intent as defined by the Engineering Plan.
Primary Failure	A Failure of a part which is not the result of the prior Failure of another part or system.
Service Management Plan	A compilation of the processes for in-service maintenance and repair to ensure that an Engine Critical Part achieves the design intent as defined by the Engineering Plan.

4.5.1.5 CS-E 90 PREVENTION OF CORROSION AND DETERIORATION

This paragraph states [4.9, 4.10, 4.11]:

Each Engine component and each item of equipment must be protected from corrosion and deterioration in an approved manner.

Materials which will render the Engine inherently self-protecting against corrosion, without the use of internal and external corrosion inhibitors, must be used wherever possible.

AM processes may result in parts with microstructures that respond differently to the environment compared to conventionally-manufactured parts, e.g. corrosion, oxidation, sulphidation, etc. **It is recommended that the environmental properties of AM parts <u>should</u> be established specifically rather than based on experience of parts from established manufacturing methods (REC4.3)**.

4.5.1.6 3.E100/CS-E 100 STRENGTH

Table 4-3 recreates the text in the standard [4.9, 4.10, 4.11].

Table 4-3 - Def Stan 00-970 Part 11 3.E100 Strength.

3.E100 Strength
Requirement
Compliance
Proof and ultimate tests shall be carried out on the engine mountings and engine structural components as follows: (a) The proof test shall be to loads equal to those specified in Def Stan 00-970 Part 11 Figure 4 with the engine at maximum thrust / power. Following the proof test the test item shall not have suffered permanent distortion; and (b) The ultimate test shall be to loads 1.5 times those specified in Figure 4 with the engine at maximum thrust / power. After the test, the item shall not have failed, but permanent deformation is permissible. Prior to initial flight, an analysis may be carried out to demonstrate that no detrimental blade tip and seal rubs will occur due to ‘g’ loading. Confirmation of satisfactory clearances should be obtained during the flight development programme by exposing the engine to the maximum ‘g’ loading in combination with the worst thermal transients resulting from engine thrust / power condition. Following these tests, the engine should be stripped and inspected. The engine mounts shall be designed to withstand the crash loads discussed in section 2.11.2 (of Def Stan 00-970 Part 11).

Guidance
The engine must be able to withstand the externally applied and induced forces which may result from flight manoeuvres, landings and takeoffs. The values indicated in Figure 4 should be tailored to the particular application. Engine flight loads are increased due to rotations and accelerations that occur during aircraft rolling, pitching and yawing manoeuvres. The engine must be capable of resisting these loads at the limiting conditions.

CS-E 100 Strength provides the certification specifications and text that is also useful for consideration with AM parts [4.10]: (a) The maximum stresses developed in the Engine must not exceed values conforming to those established by satisfactory practice for the material involved, due account being taken of the particular form of construction and the most severe operating conditions. Where a new type of material is involved, evidence must be available to substantiate the assumed material characteristics. For Turbine Engines, due consideration must be given to the effects of any residual stresses in Engine Critical Parts; (b) The Engine components which form part of the Engine mounting and any other parts of the Engine liable to be critically affected must, when the Engine is properly supported by a suitable Engine-mounting structure, have sufficient strength to withstand the flight and ground loads for the aircraft as a whole in combination with the local loads arising from the operation of the Engine; and (c) Each Engine must be designed and constructed to function throughout its declared flight envelope and operating range of rotational speeds and power/thrust, without inducing excessive stress in any Engine part because of vibration and without imparting excessive vibration forces to the aircraft structure.

Unlike for aircraft structures the standards do not prescribe a particular design allowable and statistical method to account for scatter in properties but instead CS-E refers to their establishment by satisfactory practice. For AM parts the engine manufacturer will be required to prove to the TAA that their establishment provides a satisfactory level of safety conservatism, which could be provided by adopting the methods described in Def Stan 00-970 Part 1 Section 4 Design and Construction.

4.5.1.7 3.E110/CS-E 110 DRAWINGS AND MARKING OF PARTS

The essence of this paragraph is that drawings must be provided for each engine component and item of equipment giving the full particulars of the design, including: (a) materials and manufacturing history including protective finishes and surface finishes where applicable; (b) where necessary, risk to incorrect assembly is minimised through design and/or a marking system. The engine manufacturer would normally have a quality system in place containing procedures that satisfy these requirements [4.9, 4.10, 4.11].

4.5.1.8 3.E510/CS-E 510 SAFETY ANALYSIS

The first paragraph in CS-E 510 captures the essence of the requirement. It states that an analysis of the engine, including the control system, must be carried out in order to assess the likely consequence of all failures that can reasonably be expected to occur. It is discussed here because it is applicable to any manufactured part, assembly or sub-system, including by AM. In summary the requirement covers the main points [4.19, 4.23, 4.24]:

a. The equipment and devices that are covered by the requirement, including any equipment on which engine safety depends, e.g. indicating equipment.
b. Multiple and combined failures, consequential secondary failures and dormant failures.
c. Actions on which safety analysis depends, e.g. maintenance actions.
d. Estimating the probability of failure; requirements for probability limits for different failure effects are given.
e. Categorising failure effects.
   - Hazardous engine effects – and their upper probability of occurrence limit (extremely remote – 10^{-7} per engine flight hour).
   - Major engine effects - and their upper probability of occurrence limit (remote – 10^{-5} per engine flight hour).
   - Minor engine effects.

CS-E 510 (g) is highlighted since it provides the definitions of the three engine failure effects (hazardous, major and minor):

For compliance with CS-E, the following Failure definitions apply to the Engine:

1. An Engine Failure in which the only consequence is partial or complete loss of thrust or power (and associated Engine services) from the Engine must be regarded as a **Minor Engine Effect**.
2. The following effects must be regarded as **Hazardous Engine Effects**:
   i. Non-containment of high-energy debris,
   ii. Concentration of toxic products in the Engine bleed air for the cabin sufficient to incapacitate crew or passengers,
   iii. Significant thrust in the opposite direction to that commanded by the pilot,
   iv. Uncontrolled fire,
   v. Failure of the Engine mount system leading to inadvertent Engine separation,
   vi. Release of the propeller by the Engine, if applicable,
   vii. Complete inability to shut the Engine down.
3. An effect falling between those covered in CS-E 510 (g)(1) and (2) must be regarded as a **Major Engine Effect**.

Further, CS-E 510 (a)(2) states that… a summary must be made of those Failures that could result in Major Engine Effects or Hazardous Engine Effects as defined in CS-E 510 (g), together with an estimate of the probability of occurrence of those effects. Any **Engine Critical Part** must be clearly identified in this summary.

Noteworthy paragraphs under Non-containment of high-energy debris are:

Uncontained debris covers a large spectrum of energy levels due to the various sizes and velocities of parts released in an Engine Failure. The Engine has a containment structure which is designed to withstand the consequences of the release of a single blade (see CS-E 810 (a)), and which is often adequate to contain additional released blades and static parts. The Engine containment structure is not expected to contain major rotating parts should they fracture. Discs, hubs, impellers, large rotating seals, and other similar large rotating components should therefore always be considered to represent potential high-energy debris.

Service experience has shown that, depending on their size and the internal pressures, the rupture of the high-pressure casings can generate high-energy debris. Casings may therefore need to be considered as a potential for high-energy debris.

AMC E 510 provides extensive compliance and guidance material, for example referencing typical techniques for safety analysis, e.g. Failure Modes and Effects Analysis, Fault Tree/Dependence Diagrams, etc. Examples of failures and their effects are given.

4.5.1.9 3.E515/CS-E 515 ENGINE CRITICAL PARTS

Def Stan 00-970 Part 11 3.E515 is based on CS-E 515 but has additional compliance and guidance material related to Engine Critical Parts. 3.E515 is shown in Table 4-4 [4.19]. Annex A to 3.E515 is very important for the airworthiness of any manufactured engine part and is discussed in Section 4.5.1.11 below.

Since the failure of an Engine Critical Part is likely to result in a Hazardous Engine Effect, it is necessary to take precautions to avoid the occurrence of failures of such parts. Under CS-E 510 (c), they are required to meet prescribed integrity specifications [4.23, 4.24].

The integrity of the Engine Critical Parts identified under CS-E 510 must be established by:

a. **An Engineering Plan**, the execution of which establishes and maintains that the combinations of loads, material properties, environmental influences and operating conditions, including the effects of parts influencing these parameters, are sufficiently well known or predictable, by validated analysis, test or service experience, to allow each Engine Critical Part to be withdrawn from service at an Approved Life before Hazardous Engine Effects can occur. Appropriate Damage Tolerance assessments must be performed to address the potential for Failure from material, manufacturing and service-induced anomalies within the Approved Life of the part. The Approved Life must be published as required in CS-E 25 (b).
b. **A Manufacturing Plan** which identifies the specific manufacturing constraints necessary to consistently produce Engine Critical Parts with the Attributes required by the Engineering Plan.
c. **A Service Management Plan** which defines in-service processes for maintenance and repair of Engine Critical Parts which will maintain Attributes consistent with those required by the Engineering Plan. These processes must become part of the instructions for continued airworthiness.

The **Engineering Plan**, **Manufacturing Plan** and **Service Management Plan** define a closed-loop system which links the assumptions made in the Engineering Plan to how the part is manufactured and maintained in service; the latter two aspects are controlled by the Manufacturing and Service Management Plans respectively.

AMC E 515 provides the means to establish the three plans; it is an extensive document but covers Engine Critical Parts in the categories:

- Rotating parts.

- Static, pressure loaded parts.
- Other parts (parts other than rotating and static, pressure loaded parts that have been determined Critical by the safety analysis in CS-E 510).

For rotating parts a typical process to establish an Approved Life is described. Its major elements of analysis are: (i) operating conditions; (ii) thermal analysis; (iii) stress analysis; (iv) life analysis; and (v) damage tolerance assessment. Figure 4-4 is a schematic of a typical process containing a variety of analyses that, overall, achieve the five types of analyses.

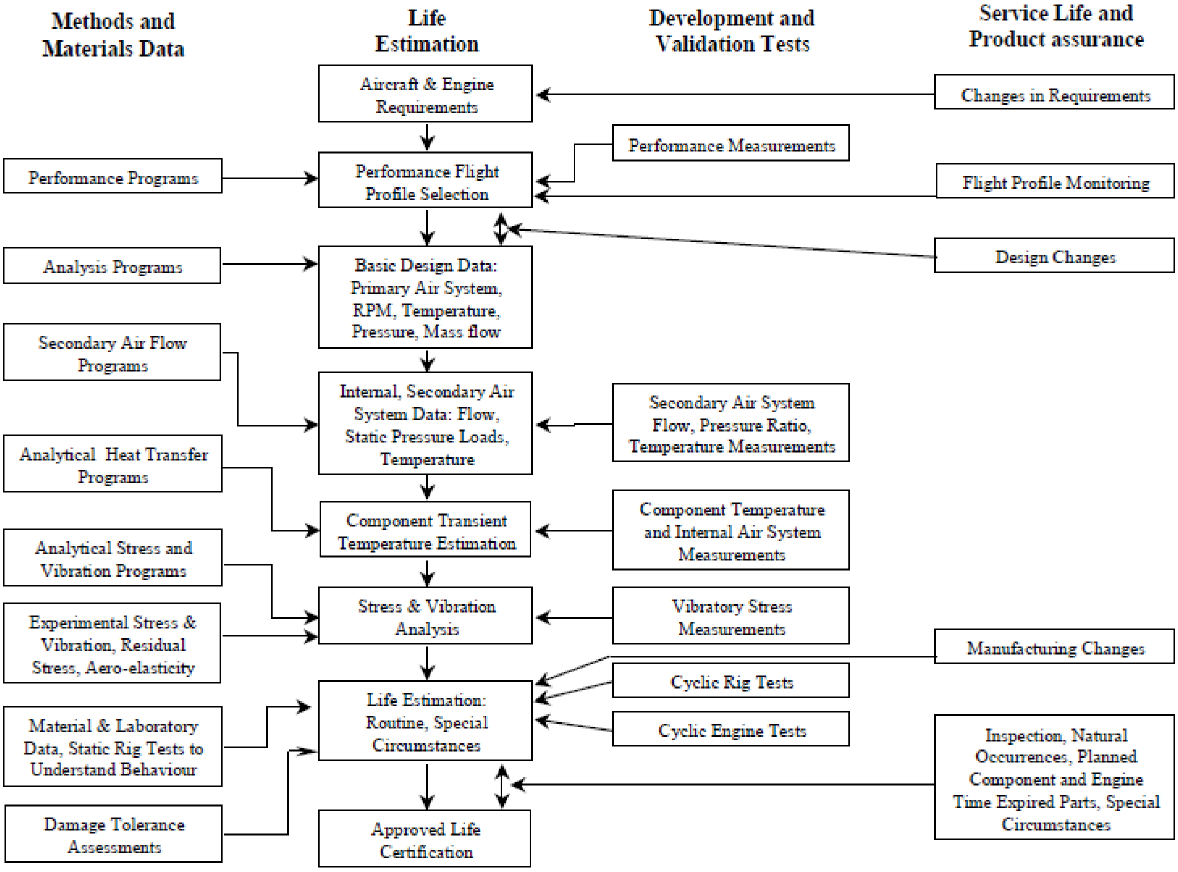

Figure 4-4 - A schematic representation of activities to establish an Approved Life for engine critical rotating parts [4.24].

Table 4-4 - Paragraph 3.E515 Engine Critical Parts.

3.E515 Engine Critical Parts

REQUIREMENT	**COMPLIANCE**	**GUDIANCE**
	(See AMC E 515)	
	When selecting an appropriate lifing methodology additional GM at Annex A should be considered.	The appropriateness of the methodology used to determine the life of engine critical parts should be demonstrated and agreed with the Type Airworthiness Authority. Where a lifing methodology has previously been deemed acceptable by a recognised Aviation Authority, it may be appropriate to present this approval as evidence of compliance/partial compliance with this requirement.
	Owing to the changing nature of military operations a periodic review of the service environment and investigation of service arisings to confirm the predictions concerning duty and capability should be carried out and documented within the Engineering Plan, as per AMC E-515. (AMC E-515 (3) (g))	Airworthiness is underpinned by effective usage monitoring. As such, usage data is to be collected in support of usage monitoring (as per Annex A). Service usage data is to be collected and aircraft usage monitored over a representative range of missions for the purpose of re-qualifying the confidence in the exchange rates. See Annex A Para 3.5 Service Usage Data.

Similar AMC and guidance material is provided for static, pressure loaded parts. For the establishment of an Approved Life for other parts AMC E 515 (3)(f) states [4.24]: It is possible that the Safety Analysis required by CS-E 510 may identify Engine Critical Parts other than rotating parts or static pressure loaded parts. In such instances, a methodology for determining the Approved Life will need to be agreed with the Authority, using the general principles for rotating and static pressure loaded parts as a guideline.

Of the five major elements of analysis to establish an Approved Life of an Engine Critical Part, the assessment of damage tolerance (AMC E 515 (3) (d) (v) [4.24]) is especially relevant to AM since it deals with the potential for failure from material, manufacturing and service-induced anomalies. The damage tolerance assessment complements the fatigue life prediction system (see AMC E 515 (3) (d) (iv) [4.24]). The AMC provides guidance on the seven primary elements of a damage tolerance assessment:

- Anomaly size and frequency distributions.
- Crack growth analysis.
- Inspection techniques and intervals.
- Inspection probability of detection (POD).
- Material anomalies.
- Manufacturing anomalies.
- Service-induced anomalies.

For this document noteworthy text on material, manufacturing and service-induced anomalies is:

Material anomalies - Material anomalies consist of abnormal discontinuities or non-homogeneities introduced during the production of the input material or melting of the material. Some examples of material anomalies that should be considered are hard alpha anomalies in titanium, oxide/carbide (slag) stringers in nickel alloys, and ceramic particulate anomalies in powder metallurgy materials unintentionally generated during powder manufacturing.

Manufacturing anomalies - Manufacturing anomalies include anomalies produced in the conversion of the ingot to billet and billet to forging steps as well as anomalies generated by the metal removal and finishing processes used during manufacture and/or repair. Examples of conversion related anomalies are forging laps and strain induced porosity. Some examples of metal removal related anomalies are tears due to broaching, arc burns from various sources and disturbed microstructure due to localised overheating of the machined surface.

Service-induced anomalies - Service-induced anomalies such as non-repaired nicks, dings and scratches, corrosion, etc. should be considered. Similarity of hardware design, installation, exposure and maintenance practice should be used to determine relevance of the experience.

While AM is not mentioned the principle of the advice is clear; any anomalies in the part (from material, manufacturing and/or induced in service) should be characterised to quantify their effect on the life of the part to complement the fatigue life prediction system. The number of potential sources of anomalies in AM is large (see Chapter 5), whether from the powder or wire feedstock (material) or from phenomena associated with the particular AM process (manufacturing). Consequently extensive activities associated with the minimisation and understanding of anomalies from AM, their quantitative characterisation and their effect on manufactured part properties is required to bring AM into service in aircraft engines. Further, AM processes may result in parts having properties that react differently to in-service conditions/events, e.g. corrosion, foreign object damage (FOD), compared to conventionally-manufactured parts.

4.5.1.10 3.E520/CS-E 520 STRENGTH

This paragraph gives requirements that major rotating components and casings have adequate strength to withstand normal operation and any excessive / abnormal conditions (as considered for Safety Analysis CS-E 510) [4.23, 4.24]. It also deals with fixed structure in close proximity to rotating parts and their possible interaction, for example during bird strike (CS-E 800) [4.25, 4.26] or shedding of blades (CS-E 810) [4.25, 4.26].

The essence is that the interaction of rotating parts, casings and containment, and adjacent fixed parts during normal / abnormal operation and failure should not result in a hazardous engine effect. This has significance for AM in the sense that an AM part may have different properties (physical, mechanical) from conventionally-manufactured parts so their interaction with other parts, debris, etc. should be established explicitly as part of the Safety Analysis. For example AMC E 520 provides particular guidance on high cycle fatigue (HCF), and shedding of blades. AMC 520 (a) Strength – High Cycle Fatigue: In order to minimise the adverse consequences of Failures due to unpredicted high cycle fatigue it is recommended that, normally, the relative fatigue strengths of the blade/disc are graded such that they lie in the ascending order: blade form, blade root, disc blade attachment, disc rim. An AM part may have a microstructure different from that of a conventionally-manufactured version. This could affect its fatigue strength and that strength relative to associated part/assembly sections where the consequences of HCF are typically managed.

Useful examples are given in AMC E 515 (3)(h) Influencing Parts [4.24]: Engine Critical Parts are part of a complex system and other parts of the engine can have an impact on the Engine Critical Parts and their life capability. Therefore, the Engineering Plan needs to address these parts, and particularly changes to them. Examples of influencing parts include a turbine blade, a mating part, and a static part that impacts the environment (temperatures, pressures, etc.) around the Engine Critical Part. Examples of changes to influencing parts include a blade with a different weight, centre of gravity, or root coating; a mating part made from a material having a different coefficient of thermal expansion; and a static part where changes in geometry or material modify the thermal and/or mechanical response of the component and could, as a result, affect the environment around the Engine Critical Part.

4.5.1.11 3.E.540/CS-E 540 STRIKE AND INGESTION OF FOREIGN MATTER

Noteworthy elements of this paragraph for AM are under compliance [4.24]: The engine should be designed to operate for one inspection period as defined in the engine specification after the ingestion of foreign objects which produce damage with a stress concentration factor (K_t) not exceeding 3.0 for fan blades and vanes, and a K_t not exceeding 2.0 for compressor blades and vanes at a location where failure would occur in the most critical mode of vibration, and guidance: as stated in AMC to CS-E 540, the following related paragraphs are sufficient for demonstrating compliance with CS-E 540 (b) for the considered subject. 3.E790 Rain, hail and ice ingestion [4.25, 4.26], 3.E800 Bird Ingestion [4.25, 4.26]. The vibration characteristics and damage tolerance (3.E.515) of AM parts, or those repaired using AM-type methods, could be different from conventional parts and this should be considered with reference to the consequences of ingestion of foreign objects (including rain, hail and ice - 3.E.790, and birds - 3.E.800). In CS-E 800 the "critical impact parameter (CIP)" is defined as a parameter used to characterise the state of stress, strain, deflection, twist, or other condition which will result in the maximum impact damage to the Engine for the prescribed bird ingestion condition. The critical impact parameter is generally a function of such things as bird mass, bird velocity, fan/rotor speed, impact location, and fan/rotor blade geometry. Where for example a part has been manufactured or repaired using AM it is possible that the location of the CIP is different to a conventional part.

4.5.1.12 3.E.810/CS-E 810 COMPRESSOR AND TURBINE BLADE FAILURE TO 3.E.850/CS-E 850 COMPRESSOR, FAN AND TURBINE SHAFTS

This group of paragraphs relates to the effects of failure of rotating parts to the engine and requirements for their integrity and continued operation of the engine following failure: 3.E.810 / CS E 810 Compressor and Turbine Blade Failure [4.19, 4.25, 4.26]; 3.E.820/CS E 820 Over-torque Test (where there is a free power turbine) [4.19, 4.25, 4.26]; 3.E.830/CS E 830 Maximum Engine Overspeed [4.19, 4.25, 4.26]; 3.E.840/CS E 840 Rotor Integrity [4.19, 4.25, 4.26]; and 3.E.850/CS-E 850 Compressor, Fan and Turbine Shafts [4.19, 4.25, 4.26]. They should be interpreted with the additional guidance of 3.E.510/CS-E 510 Safety Analysis [4.19, 4.25, 4.26], 3.E.515/CS-E 515 Engine Critical Parts [4.19, 4.25, 4.26] and 3.E.520/CS-E 520 Strength [4.19, 4.25, 4.26]. The significance for AM parts is that the location specific nature of microstructures should not produce parts with location specific properties that could cause a hazardous or major engine effect greater than the probabilities specified in the standard. For example for containment of blades it is advised that to minimise the likelihood of multiple blade failures (and hence uncontained failure) being triggered by a single blade failure, blades should be designed such that they will fail in the aerofoil rather than in the root fixing.

4.5.1.13 DEF STAN 00-970 PART 11 ANNEX A – LIFING PROCEDURE FOR CRITICAL PARTS – ADDITIONAL MILITARY CONSIDERATIONS

This annex offers enhanced guidance material for the determination of an Approved Life for a rotating or non-rotating Engine Critical Part. It complements 3.E515 / CS-E 515 – namely the establishment of engine integrity by an Engineering Plan, a Manufacturing Plan and a Service Plan.

At a glance, the structure of Def Stan 00-970 Annex A is shown in Table 4-5 [4.27].

The annex contains extremely important information regarding life determination and management of Engine Critical parts, albeit in a succinct five page document (plus two tables). Rather than recreate the document here readers are encouraged to consult the latest version of the Annex by visiting the Defence Standards website [4.17]. With respect to any manufactured part, whether AM or any other process, Paragraphs A.2.1.1 and A2.1.2 provide the reader with the essence of the process:

A.2.1.1 The determination of critical part lives is based on demonstrating an understanding of the component operational environment and validation of the component life when operating in that environment. Life validation is based on cyclic testing of representative component features, the lives of which are factored to account for material scatter and to provide a safety margin.

A.2.1.2 A margin of safety in addition to the allowance for material scatter is required to achieve acceptable failure rates in service. This is normally provided by a period of stable crack propagation between crack formation and component dysfunction (see Def Stan 00-970 Part 11 Section 1 for definitions of terms [4.9]).

Table 4-5 - Overview of the structure of 3.E515 Annex A

Lifing Procedure for Critical Parts (see 3.E515) Additional Military Considerations
A.1 Introduction
A.2 Life Determination
A.2.1 Additional Considerations
A.2.2 Analytical Modelling Methods
A.2.3 Retirement for Cause
A.3 Life Management Plan
A.3.1 Sample Inspections
A.3.2 Service Usage Data
A.3.3 Technical Life Reviews

As for fatigue design of aircraft structures (Chapter 3), the fatigue design of Engine Critical Parts can be based on either a Safe Life or a Damage Tolerance approach, i.e. either S-N curves or fracture mechanics-based respectively. The UK uses Safe Life for its military aircraft engines – these days the 2/3 Dysfunction criterion to provide the margin of safety, namely that the probability of a component exceeding 2/3 of the dysfunction life in service at its predicted safe cyclic life (PSCL), or predicted safe cyclic damage tolerant life (PSCDTL), is less than or equivalent to 1 in 750 at 95% confidence. This will be explained in more detail in Section 4.6.

4.5.2 Def Stan 00-970 Part 11 Section 4 - Military Requirements for Aircraft Engines

Section 4 covers 13 subjects in its paragraphs 4.1 to 4.13:

1. Vectored Thrust
2. Reheat Lighting and Burning
3. Infra-Red Radiation / Suppression
4. Nuclear Weapons Effects
5. Armament Gas Ingestion
6. Steam Ingestion
7. Reduction of Vulnerability to Battle Damage
8. Electro-Magnetic Compatibility
9. Corrosion
10. Sand and Dust Ingestion

11. Prototype Flight Clearance
12. Accelerated Simulated Mission Endurance Test
13. Noise

Of these paragraphs those covering Corrosion (4.9) [4.28] and Sand and Dust Ingestion (4.10) [4.28] may have considerations that are specific to AM parts since corrosion properties and susceptibility to erosion by sand and dust will both be affected by part microstructure and variations in microstructure across the part – which may be different for AM parts, or those repaired using AM-type processes. The requirements, compliance and guidance given provide the requirements for performance and the testing procedures to assess them, including for example definitions of sand characteristics for ingestion testing. The essence of the two requirements is stated in their opening paragraphs:

- 4.9.1 Operating characteristics, structural integrity, durability, component life and maintenance shall not be adversely affected while operating in or after exposure to salt laden air. Any requirement for washing shall be stated in the Engine Model Specification.
- 4.10.1 Engines intended to operate for significant periods in desert environments shall operate satisfactorily with air containing sand and dust …

4.6 ESTABLISHING PREDICTED SAFE CYCLIC LIFE (PSCL)

4.6.1 INTRODUCTION

As previously discussed the establishment of the PSCL of a critical component brings together the: (i) operating conditions; (ii) thermal analysis; (iii) stress analysis; (iv) life analysis; and (v) damage tolerance assessment. In essence, from the operating environment we determine the stress and temperature environment of the part and use it, with the performance of the material (in that environment) and its scatter in properties, to determine the PSCL. The analyses use a combination of testing and analytical modelling techniques. For example, in UK military engines the life of aircraft engine discs is ultimately determined from spin tests of real discs. The critical areas of the disc are determined by modelling and, since real spin tests are expensive, overstress conditions are used to allow multiple critical areas to be tested on one test (to acceptable maximum overstress levels - see Def Stan 00-970 Part 11 Annex A, Table A-B [4.27]).

Using an engine disc as an example the following is a brief explanation of the Safe Life approach to Engine Critical Part Lifing – both Life to First Crack (LTFC) and 2/3 Dysfunction, since LTFC provides the background and rationale for 2/3 Dysfunction. Further, fracture mechanics and probabilistic based lifing methodologies are introduced briefly to allow discussion of lifing with respect to AM parts. The themes raised in this Section will be used to discuss factors to consider when lifing AM parts in Section 4.7.

In advanced turbine engines, both military and civil, manufacturers use nickel superalloy turbine discs produced through a powder metallurgy route. A concern in establishing a safe life for these parts is the presence of material anomalies unintentionally generated during the powder production process, for example small inclusions and pores. Inclusions are usually in the form of ceramic particles generated by erosion of the melt crucible liner by the molten metal during the process. Pores are usually from entrapment of atomising gas within individual powder particles on solidification; these considerations are identical to a sub-set of those for critical AM parts (see Chapter 5). EASA has provided advice, in addition to its regulations, through a Certification Memorandum (CM-PIFS-013, Issue 01 *The integrity of nickel powder metallurgy rotating critical parts for gas turbines*), on the development of a lifing system for powder metallurgy rotating parts, including advice on anomaly characterisation, fatigue testing, probabilistic treatment of inclusions, etc. [4.29]. It is a very important advisory document, which has relevance to AM and **it is recommended that EASA Certification Memorandum CM–PIFS-013, Issue 01 may be used to help those involved in qualification and certification of critical AM aero engine parts to set out an appropriate plan for the establishment of safe cyclic life (REC4.4)**.

4.6.2 SAFE LIFE APPROACH

4.6.2.1 LIFE TO FIRST CRACK (LTFC)

In this methodology failure is defined as the occurrence of an engineering crack of specified depth. The approach relies on rig spinning of actual engine discs under stress and temperature conditions similar to those experienced in the engine to determine the cyclic life to the formation of an ‘engineering’ crack 0.38 mm deep. A PSCL is then declared by applying statistically derived safety factors to the test results such that at this life, to a 95% confidence level, not more than 1 in 750 discs would be expected to contain a crack of depth greater than 0.38 mm. Figure 4-5 provides a representation of the S-N curve and statistical scatter factors associated with the test of a disc to the point of failure (when an engineering crack of 0.38 mm depth occurs).

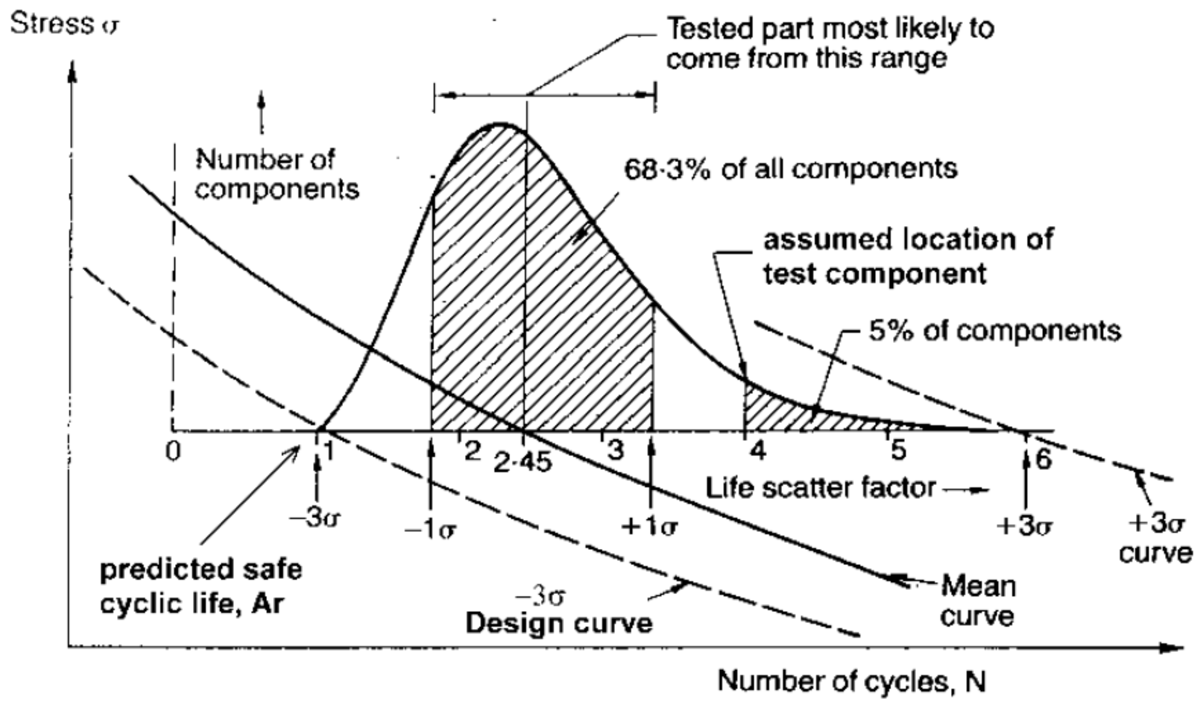

Figure 4-5 - Derivation of the material design curve and predicted safe cyclic life [4.32].

From experience the scatter in fatigue lives of metals is well described using a log normal distribution and at a 1 in 750 probability of failure there is a 6x scatter in lives between the +3σ and -3σ standard deviations [4.30]. By locating the test result at the best 5% (i.e. for an infinite number of tests it has been decided that 95% of them would fail under these conditions), a distribution can be constructed. Given this assumed scatter factor of 6 the life corresponding to the lower 1/750 quantile is located at a factor of √6 (= 2.449) below the geometric mean of the LTFC. This lower confidence bound corresponds to a factor in life of:

$$6^{\left(1.645/6\sqrt{n}\right)} \tag{1}$$

where n is the number of test results. 95% confidence translates to 1.645 standard deviations. It can be seen that Equation 1 is a decreasing function with respect to increasing sample size. In summary, a PSCL is calculated by an equation of the type:

$$\mathrm{Ar} = \frac{\sqrt[n]{\prod_{i=1}^{n} N_i}}{2.449 \times 6^{\left(1.645/6\sqrt{n}\right)}} \tag{2}$$

Where N_i are the individual LTFC test results and Ar is Area Safe Cyclic Life (the safe life predicted for a critical area in reference cycles). For one test Ar is a factor of ~4 below the test result.

Through using ‘first crack’ as the basis for the calculation, the additional life taken to grow to the critical size associated with dysfunction acts as a further margin of safety. Ultimately, it is this, in combination with the two factors in the denominator of Equation 2, that define the actual safety level inherent in the application of this method [4.31].

4.6.2.2 2/3 DYSFUNCTION

The rate of fatigue crack propagation from first / engineering crack to the critical crack size (dysfunction) – where unstable crack growth ensues - is material and geometry dependent. In conventional disc materials the ratio of the life - LTFC/dysfunction - is typically about 1/3. However in more modern high strength / temperature-capable materials operating under applicable conditions the critical crack size for the onset of rapid fatigue crack propagation can be significantly smaller than 0.38 mm. As a consequence the UK adopted the 2/3 Dysfunction criterion where the ratio of the declared life and the dysfunction life are a constant ratio of 2/3 which ensures a more consistent safety margin; at PSCL there is still 50% life in hand. Application of 2/3 Dysfunction enables modern high strength / temperature alloys to be exploited safely [4.32].

Both LTFC and 2/3 Dysfunction methodologies are permitted in AMC E 515 (3)(iv).

4.6.3 FRACTURE MECHANICS BASED METHODS

4.6.3.1 DATABANK OR CORRELATION

In this approach, a model is used to bring the results from different disc designs and features into a correlation for a given material. Such models can account for variations in stress field and geometry and offer a means of combining the results from different disc designs and large specimens. A correlating parameter is developed which could be as simple as Effective Initial Flaw Size (EIFS) as in the fracture mechanics Databank approach or more complex models including initiation and propagation and effects of inelasticity, non-proportionality, etc. A statistical prediction is then made of the minimum fatigue life of a component feature as a function of the correlating parameter. Hence, the benefit is all results can be collected into a common database for the material and analysed statistically to establish a lifing model that represents the quality of the material and of the disc manufacturing process [4.31, 4.32].This model is then used to predict the maximum allowable life to dysfunction, where 2/3 is applied.

4.6.3.2 DAMAGE TOLERANCE LIFING

Damage Tolerance lifing is used by the US Air Force for its Engine Critical Components and originates from the Engine Structural Integrity Program (ENSIP) [4.16]. Rather than determining a life to first / engineering crack it is assumed that all components have some form of initial damage. The declared service life of the component is therefore taken as a set fraction (typically ½) of the mean number of cycles required to grow the crack from a proven non-destructive inspection (NDI) crack detection size (typically corresponding to 90% probability of detection to 95% confidence) to a critical crack size – based on the largest / most damaging crack that would be undetected. It is assumed that even if such a crack fails to be detected, the component will be re-inspected or retired from service before dysfunction occurs [4.32].

Damage tolerance reflects the safe period of operation from assumed pre-existing flaws or damage, whether material, manufacturing or handling. In the context of current critical parts it is an additional requirement to safe life, not an alternative means of compliance, which addresses the requirement not to have failure from damage.

4.6.3.3 RETIREMENT FOR CAUSE

This is a development of Damage Tolerance lifing that allows the safe extension of discs beyond their initial PSCL. It involves scheduled inspections of discs to allow progressive life extensions and involves the explicit calculation of risk (per unit of flight service) based on missions and stress analyses, fracture mechanics, probability of detection, the scatter in these elements and the number of discs in the analysis [4.33].

NOTE: Different aircraft missions impose different severities of fatigue cycles on the Engine Critical Parts, i.e. combinations of major cycles (major throttle movements for acceleration, e.g. take-off) and minor cycles (minor throttle adjustments and vibration). To account for this a factor called the Exchange Rate is used, which relates the relative damage accumulation in the mission to reference cycles used in the lifing tests. Def Stan 00-970 Part 11 Section 1 Paragraph 1.5.8.8 states: Exchange Rate (ER) - A damage or usage factor defining the number of reference units used per hour (or flight as appropriate). There will usually be a different value for each critical area. For specification purposes, the ER shall be determined from predicted mission profiles, and shall be modified in the light of development flight experience and data from service usage monitoring. In fatigue minor cycles are relatively more damaging in crack propagation than crack initiation. Consequently during crack propagation (either in Damage Tolerance lifing or beyond 0.38 mm crack depth in 2/3 dysfunction or owing to necessary life extension in LTFC), separate initiation and propagation factors must be calculated for the mission Exchange Rate, or an appropriate compound factor of the two calculated [4.9].

4.6.3.4 PROBABILISTIC LIFING

This lifing approach is briefly introduced to aid discussion with respect to AM in Section 4.7. LTFC and 2/3 Dysfunction (Safe life) methodologies are essentially safety factors and do not quantify the risk of failure per flying hour. An alternative approach currently used for damage tolerance (particularly of melt anomalies) is based on the use of probability density functions to quantify the combined risk from different input variable such as anomaly size, position, initiation life, propagation life, etc. Where behaviour is well enough characterised this approach could be expanded to include many different sources of uncertainty; e.g. scatter in materials properties (inherent, from finishing and machining, from residual stresses, etc.), volume effects on fatigue and fatigue scatter (real components *vs*. test specimens), engine usage (real *vs*. anticipated, unintended, etc.), and non-destructive evaluation NDE detection.

4.7 DISCUSSION ON APPLICATION OF REGULATORY ARTICLES AND DEF STAN 00-970 PART 11 TO ADDITIVE MANUFACTURING

4.7.1 INTRODUCTION

At a top level the concept of the four pillars of airworthiness drives all activities related to the establishment and management of the airworthiness of military aircraft. The MAA's Regulatory Framework provides the requirements, acceptable means of compliance and guidance that when followed will satisfy the principles of the four pillars. The Military Regulatory Publications (MRPs) that are especially relevant to AM have been summarised in Appendix A; one set in particular are noteworthy for this discussion since they apply to design changes.

RA5305 (In-Service Design Changes) and RA5820 (Changes In Type Design) [4.4, 4.3] relate to the management of design changes to an aircraft. Their primary function is to ensure that any design changes do not adversely affect the airworthiness of the aircraft. A dominant theme is the management of design changes through the collaborative efforts of the TAA and DO, however the TAA is ultimately responsible for signing off the change before it is implemented, with the MAA providing independent certification assurance where changes are considered to have a major impact on airworthiness.

An important process is the classification of design changes as either major or minor, as described in RA5820, since this drives the level of assurance to be carried out. Annex A of RA5820 gives an example of a major change to aircraft structure as: Changes to materials, processes or methods of manufacture of primary structural elements, such as spars, frames and critical parts… Clearly the introduction of an AM part in place of a part manufactured in a different way for type certification is a major design change and consequently the requisite assurance procedures must be followed before its introduction. As recommended previously (REC4.1), until such time as AM is sufficiently mature, an AM part should always be subject to a MCRI-type procedure. As part of these assurance procedures Def Stan 00-970 Part 11 Sections 3 provides the methods that must be followed to establish Approved Life for a rotating or non-rotating Engine Critical Part. Principles embodied in this Def Stan section (and CS E) have important consequences for AM and are discussed below.

4.7.2 ENGINE CRITICAL PARTS

4.7.2.1 CLASSIFICATION OF PARTS

As described above it is mandatory for propulsion integrity that an analysis of all failures (that are reasonably expected to occur) is carried out to determine their consequences and probability. Parts and integrated sub-parts must be categorised according to the severity of the consequences of their failure, i.e. Hazardous Engine Effect, Major Engine Effect and Minor Engine Effect. Maximum permitted probabilities of failure are required for Hazardous and Major Engine Effects. Failures that could lead to a Hazardous Engine Effect are Engine Critical Parts and must be lifed according to recognised and approved methods; Def Stan 00-970 Part 11 prescribes a Safe Life approach.

Engine critical parts are further sub-divided into rotating parts (e.g. discs and blisks[2]), static, pressure loaded parts (e.g. casings) and other parts. This classification system and the regulatory framework have some important consequences for critical part lifing and strength with respect to AM.

The engine parts that are critical will be identified in the Safety Analysis (3.E510) however the Engineering Plan must also address "influencing parts" that could have an impact on the critical parts, especially changes to them. For example an AM part, or its premature failure, could change the stress or temperature environment around the critical part and its resulting response. Changes to materials, processes or methods of manufacture are classified as major design changes in RA5820 and require the prescribed assurance processes before introduction.

Guidance in 3.E70/AMC E 70 on materials and manufacturing methods describes the classification of forgings and welds into three different Classes or Groups respectively. Failure of Class/Group 1 parts could hazard the aircraft and are therefore Engine Critical Parts. Given that AM in aerospace applications is at the early development stage there is no classification system in the current standard for AM parts. Welding and casting processes have some characteristics that are similar to AM, for example cast microstructures and in some cases rapid solidification. Welded parts can be classified as Group 1 (i.e. Critical) whereas cast parts are not classified using such a system which could be inferred as meaning that castings are not used in Class 1 / Group 1-type applications. On the other hand Def Stan 00-970 Part 1 Section 4 provides the Requirements, AMC and Guidance for the use of Grade A castings in military aircraft structures (premium castings) (see [4.34] for definition of Grade A) and the approach described in the standard, its Leaflet 21 and CS 25.621 is potentially helpful when considering the use of AM parts in aircraft engines [4.34, 4.35, 4.36]. In fact AM processes have a combination of characteristics that make them unique to other manufacturing methods (and each other), e.g. feedstocks (either powder or wire), layer-wise lay-down of material, in some cases fairly rapid solidification and cooling, and power source/feedstock interactions to name but a few. The consideration of other manufacturing processes featuring some similar phenomena, or in some way being analogous to AM (see Chapter 3 Section 3.9), is helpful in thinking through the whole process of manufactured part assurance, nevertheless **it is anticipated and recommended that AM will require unique AMC and guidance material, with its own Class / Group classification (based on the Safety Analysis), to be included in the standard (REC4.5)**. In any case the Design Organisation (DO) (engine manufacturer) will be required to prove to the TAA, using appropriate and agreed methods, that any AM parts have suitable structural integrity assurance for their Class / Group, or similar classification of effect on failure.

In aircraft engines in particular AM-type processes are being developed for the repair of parts, for example the aerofoils on compressor blisks. Conventional discs, with aerofoils slotted into grooves in the rim, are Engine Critical Parts since failure might not be contained. In blisks where the aerofoils are integral to the disc the standard prescribes treating the entire blisk as an Engine Critical Part [4.24], even if only an aerofoil is being affected by a repair. This brings with it the requirements set out in RA5820 on Changes in Type Design and RA5865 on Repairs, and the necessary and appropriate level of assurance set out in 3.E515/AMC E 515. AMC E 515 (5) on determining the

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[2] Integrally bladed discs/integrally bladed rotors.

acceptability of repair and maintenance processes provides important guidance. Repair and maintenance processes should be reviewed by the following skills:

- Engineering (Design & Lifing).
- Material Engineering.
- Non-Destructive Inspection.
- Quality Assurance.
- Product Support Engineering.
- Repair Development Engineering.

The role of this cross-functional review is consistent with that laid out for the Manufacturing Plan. The review should include process validation, change control and non-conformance to ensure the product of any repair or maintenance is consistent with the engineering specification. The intent is that:

- Repair and maintenance processes and practices are developed with the appropriate level of oversight, and with due regard to their possible impact on the life capability of the part.
- Substantiation programmes are agreed up-front and executed as part of the validation process.
- Changes to such processes and practices are visible to all parties, and are not made without cross-functional review and approval.
- When a suspected non-conformance event occurs, it is reviewed with the appropriate skill mix prior to disposition.

4.7.2.2 LIFING OF ENGINE CRITICAL PARTS

Total fatigue life (N_T in cycles) is the fatigue crack initiation life (N_i) plus the fatigue crack propagation life (N_p).

$$N_\mathrm{T} = N_\mathrm{i} + N_\mathrm{p} \tag{3}$$

In the LTFC approach the PSCL is effectively the fatigue crack initiation life; the propagation life is only utilised as an additional factor of safety. Conversely in Damage Tolerance the PSCL is based solely on measurements and calculations of fatigue crack propagation from assumed pre-existing flaws based on proven NDE capabilities.

Nevertheless engine manufacturers carry out extensive research, development and testing to try to understand and quantify the different phenomena of fatigue crack initiation AND fatigue crack propagation - the more economically to life their engines. Fatigue crack propagation can also be divided into short and long crack growth with each affected by microstructure and engine conditions / environment differently. A further complication is that at high temperatures effects of fatigue, creep and environmental degradation interact. The study of fatigue in Engine Critical Parts is therefore an extremely complex subject that requires an understanding of how microstructure, stress, temperature, environment, stress / temperature profiles, and different combinations thereof interact.

Generally speaking the UK MOD develops and procures engines in partnership with other nations, and procures civil-based engines, e.g. for its large type aircraft. Consequently the MOD may have to assess the critical part lifing methods and standards of other nations or organisations, e.g. Damage

Tolerance-based, against the requirements of Def Stan 00-970 Part 11 to understand whether their approach provides an acceptable level of risk to airworthiness.

Taken together the above paragraphs provide an appreciation of factors that should be considered when establishing the integrity of an Engine Critical Part, whatever lifing methodology is used.

In AM the feedstock materials and specific features of the build process can result in microstructures that are different from those from established manufacturing, i.e. castings, forgings and welded structures (see Chapter 5 for guidance). **Consequently it is recommended that properties and scatter in properties of an AM part (i.e. that design / material / application combination) shall be measured and rationally derived rather than assumed from previous experience (REC4.6)**; properties can include but are not limited to mechanical (including fatigue and time dependent properties such as creep and stress relaxation), physical properties (e.g. coefficient of thermal expansion) and resistance to environmental degradation (e.g. corrosion susceptibility). For example some AM processes / parameters and alloys result in anisotropic grain structures [4.37, 4.38, 4.39] which will affect the mechanical and physical properties and their directionality, e.g. mechanical, creep and low cycle fatigue strength, stiffness and coefficient of thermal expansion. It is useful to repeat 3.E70/CS-E 70 Materials and Manufacturing Methods:

a. *The suitability and durability of materials used in the engine must be established on the basis of experience or tests. The assumed design values of properties of materials must be suitably related to the minimum properties stated in the material specification.*
b. *Manufacturing methods and processes must be such as to produce sound structure and mechanisms which retain the original mechanical properties under reasonable service conditions*.

For metallic aircraft engine parts that could result in a hazardous engine effect it is recommended that both the AM process AND the part shall be qualified and certified to establish, and provide confidence and assurance in, the variability in their properties (REC4.7). In time it may be possible to qualify and certify an AM process for a range of different parts – at least within the same part "family" - but this will require comprehensive knowledge and experience of process-property relationships, enhanced control and monitoring of process parameters, and appropriate specimen and part testing to ensure an acceptable level of safety-conservatism is embodied in the part (which must be demonstrated to the satisfaction of the TAA).

In fatigue, especially for fatigue crack initiation, anomalies (in addition to any fatigue-initiating characteristics of the microstructure) are extremely important. Hence as discussed above they should be minimised and their characteristics quantified using appropriate destructive and non-destructive techniques. In line with a recommendation made in Chapter 3 on aircraft structures, and based on guidance on the use of premium castings in aircraft structures, **it is recommended that each Class 1/Group 1-type AM part should receive inspection of 100 percent of its surface, and inspection of structurally significant internal areas and areas where defects are likely to occur, using approved non-destructive inspection methods (REC4.8)**. **)**. This wording on NDI is taken from CS 25.621 *Premium Castings* and, in the absence of AM-specific guidance, provides a conservative approach to qualification of a part that effectively has no arbitrary scatter factor. Innovations in AM technologies, e.g. in-situ monitoring, could provide alternative means of assuring the defect population of a part without the need for this degree of NDI; nevertheless alternative acceptable approaches must be agreed by the DO and TAA.

Microstructures from AM are strongly dependent on the position of the particular part volume element within the whole build volume and its relationship to adjacent volumes, e.g. changes in cross section, part surface or interior, etc. Further, fatigue and scatter in fatigue is highly dependent on the volume of material being tested. Consequently it is essential that appropriate assurance is achieved that properties and scatter in properties from test specimens truly reflect those of the final part. Defence Standard 00-970 Part 1 Section 3 Structure, Leaflet 02 provides a useful philosophy based on a testing pyramid where the scale and representativeness of specimens increases up the pyramid (see Figure 4-6) [4.40]. In engines Critical Part Life is established ultimately by testing real components.

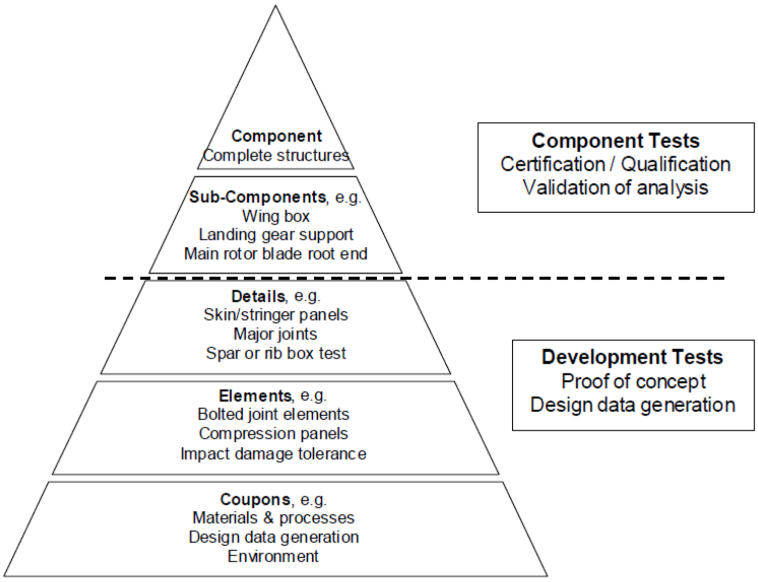

Figure 4-6 – the structural test 'pyramid'.

It is recommended that the philosophy of the testing pyramid, with its increasing level of size and feature complexity as specimens and elements become more representative of the final part, may be adopted for AM to provide a level of assurance that these sources of scatter have been captured in the design values and fatigue properties (REC4.9).

For aircraft structures the guidance on the derivation of design allowables and fatigue scatter factors is explicit; acceptable means of compliance on testing and statistical methods are provided in Def Stan 00-970 Part 1 Sections 3 and 4. Its statistical methods are based on Normal statistical theory and methods are given to determine whether the population of a property exhibits a Normal distribution. Similarly fatigue lifing methods whether Safe Life (based on S-N curves) or Damage Tolerance (based on fracture mechanics) also require the establishment of scatter factors based on the generation of materials databases and statistical analysis to determine the distributional form of the population. For example the scatter in the Safe Life methodologies for aircraft engine discs is based on the materials / forms exhibiting a log-normal distribution, which may not be appropriate for parts made by AM. While the 2/3 Dysfunction methodology applies a single factor to provide safety its validity, and confidence in its level of safety, relies on materials properties with understood behaviour with regard to fatigue crack initiation and propagation and the ratio of the two. Damage Tolerance methods will require fatigue crack propagation rates and their scatter to be measured and understood, i.e. rationally derived for AM parts. Probabilistic methods require databases and scatter factors for fatigue crack initiation and propagation, volume effects, probability of (NDE) detection, etc. Further, as the drive to increase hot section temperatures continues fatigue interacts with creep and environmental (e.g. oxidation) processes and linear elastic fracture mechanics is not sufficient to derive lives. In this case non-linear stress analysis is also required [4.41].

AM microstructures may create different environmental properties for the part, for example resistance to corrosion, oxidation and sulphidation. The properties and performance should be understood with respect to management of airworthiness through the life of the engine.

It is known that microstructural characteristics affect the Probability of Detection (POD) in NDE techniques such as ultrasonic detection since they affect backscatter and attenuation [4.42]. **Since AM-produced microstructures can be very different from those from established processes it is recommended that POD characteristics should be established specifically for the part and microstructures of interest (REC4.10)**.

It was mentioned previously that the different level of damage accumulation from different aircraft missions / manoeuvres is accounted for using the Exchange Rate. In fatigue, minor cycles are relatively more damaging in fatigue crack propagation than initiation and consequently separate Exchange Rate factors are used for them. As with other factors it cannot be assumed that those for AM parts are the same as those based on experience from established processes. **It is therefore recommended that consideration is given to the choice of appropriate exchange rates for fatigue crack initiation and propagation in AM critical parts (REC4.11).**

The international nature of aircraft engine development and procurement will require an understanding of how the consequences of AM-produced properties affect the elements of different lifing methodologies differently; in simple terms their relationship with fatigue crack initiation and fatigue crack propagation and the variability in each. **Even though the UK standard specifies a Safe Life approach, e.g. 2/3 Dysfunction, it is nevertheless recommended that the fatigue crack initiation and propagation characteristics of critical AM parts should be rationally derived to provide a level of assurance in the inherent safety of different lifing approaches (REC4.12).**

4.8 CONCLUDING REMARKS

Analysis of the UK military aviation regulations, defence standards and supporting information has been used to provide guidance on the assurance of aircraft engine parts with respect to airworthiness and relate these to AM. The qualification and certification that an Engine Critical Part meets its specification is a deterministic process; the purpose of establishing a Predicted Safe Cyclic Life (PSCL) is to determine that all sources of variability have been captured (as far as reasonably possible), including through the use of appropriate and agreed NDE techniques to capture any rogue flaws. Further, aircraft engines will be inspected and maintained as necessary through life to ensure they continue to perform. These are all part of Propulsion Integrity (PI) Management, which forms part of the first pillar of airworthiness: the establishment and description of an effective Safety Management System (which must be detailed in the airworthiness strategy).

An important part of the safety assurance of engines is the Safety Analysis, which provides the classification system and maximum acceptable risk of failures for different categories of failures. Parts whose failure could result in a Hazardous Engine Effect are Engine Critical Parts, and must have a risk of failure not exceeding 10^{-7} per engine flying hour. Parts are grouped into: (a) rotating parts; (b) static, pressure loaded parts; and (c) other parts - “influencing parts” that could affect Engine Critical Parts must also be considered.

Engine Critical Parts must have an Engineering Plan, Manufacturing Plan and Service Management Plan as part of their assurance right through life from design through to disposal, which will include details of any manufacturing processes and controls (e.g. in-service inspections). Their life must be established using an appropriate method that provides an adequate factor of safety, for Def Stan 00-970 Part 11 3.E.515 using a Safe Life approach established from experience or test. Other lifing methodologies exist that may need to be considered during procurement and through life since military engine procurements are often multi-partner in nature. The LFTC and 2/3 Dysfunction methodologies depend for their validity that material failures follow a log-normal distribution. The understanding of risk in the 2/3 Dysfunction is also based on an understanding of the values and spread associated with fatigue crack initiation and propagation lives. Damage Tolerance, and 2/3 Dysfunction beyond 0.38 mm crack depth, require the fatigue crack propagation rates and their scatter to be rationally derived. Further, the exchange rates applied to major and minor cycles during fatigue crack initiation and propagation should be appropriate for how the two elements of fatigue life are affected by those cycles.

All materials properties and their scatter that need consideration in the Safety Analysis and Engine Critical Parts activities should be rationally derived. Appropriate consideration should be made to scale effects, i.e. how AM part properties can be affected by build volume and build location; the properties of test specimens and test elements (representative of part features) should truly reflect the scatter in properties of the final part from all sources. Censoring of data, whether intentional or not, should be guarded against, so that a level of risk of failure to a given level of confidence can be established and assured.

The approach of the document has been to treat the properties of AM parts in the same way as any other part with properties from material / process combinations. The document has provided a framework for considering all of the factors that should be taken into account; **it is recommended that the relevant sections in the requirements in Def Stan 00-970 Part 11 shall be used to set out a qualification plan for the AM components under consideration. The information in this chapter and Appendix A may be used as a guide to those requirements (REC4.13)**.

The guidance in this chapter considers Critical parts; however, it is recognised that early adoption of AM is most likely to occur in non-critical parts. For such applications this document (as a whole) can still be used as a guide to the relevant sections in the requirements in Def Stan 00 970 Part 11. It will still be necessary to set out a qualification plan for the AM components under consideration and undertake a sub-set of the recommendations suggested here; the extent will need to be appropriate for the consequence of failure of the part and agreed with the TAA. **It is recommended that the information in this document may be used as a guide to set out an appropriate qualification plan for the non-critical AM components under consideration (REC4.14).**

4.9 CHAPTER 4 SUMMARY OF RECOMMENDATIONS

In this chapter and Appendix A the airworthiness regulations and certification standards for aircraft engines have been discussed with relation to AM parts. On the whole it is considered that the existing regulations / standards are satisfactory for AM, except the classification of an AM part using a Class / Group-type approach based on the Safety Analysis. Nevertheless the sources of scatter in AM (discussed in more detail in Chapter 5) are outside of experience compared to those from established manufacturing processes and consequently some key recommendations are made. These are summarised below in order from high level to more specific and grouped together as AMC-type and Guidance-type recommendations (rather than the order in which they appear in the document):

4.9.1 REGULATION-TYPE RECOMMENDATIONS (CONTAINING "SHALL")

- **REC4.13: The relevant sections in the requirements in Def Stan 00-970 Part 11 shall be used to set out a qualification plan for the Additive Manufactured (AM) components under consideration. The information in this chapter and Appendix A may be used as a guide to those requirements – Section 4.8.**

- **REC4.1: A Critical Additive Manufactured (AM) part, whether for a new or existing aircraft engine, shall be subject to the MCRI process until the technology is sufficiently mature to maintain variability in a predictable and repeatable manner– Section 4.2.**

- **REC4.7: For aircraft engine parts that could result in a hazardous engine effect it is recommended that both the Additive Manufactured (AM) process AND the part shall be qualified and certified to establish, and provide confidence and assurance in, the variability in their properties – Section 4.7.2.2.**

- **REC4.6: The properties and scatter in properties of an Additive Manufactured (AM) part (i.e. that design / material / application combination) shall be measured and rationally derived rather than assumed from previous experience – Section 4.7.2.2.**

- **REC4.2: In the absence of Additive Manufactured (AM)-specific acceptable means of compliance (AMC) and guidance material in CS-E, and in any case, the Design Organisation (DO) (engine manufacturer) shall prove to the Type Airworthiness Authority (TAA), using appropriate and agreed methods, that any AM parts have suitable structural integrity assurance for their Class / Group, or similar classification of effect on failure – Section 4.5.1.4.**

4.9.2 ACCEPTABLE MEANS OF COMPLIANCE-TYPE RECOMMENDATIONS (CONTAINING "SHOULD")

- **REC4.12: Even though the UK standard specifies a Safe Life approach, e.g. 2/3 Dysfunction, it is nevertheless recommended that the fatigue crack initiation and propagation characteristics of critical AM parts should be rationally derived to provide a level of assurance in the inherent safety of different lifing approaches - Section 4.7.2.2**.

- **REC4.3: It is recommended that the environmental properties of AM parts should be established specifically rather than based on experience of parts from established manufacturing methods – Section 4.5.1.5.**

- **REC4.8: it is recommended that each Class 1/Group 1-type AM part should receive inspection of 100 percent of its surface, and inspection of structurally significant internal areas and areas where defects are likely to occur, using approved non-destructive inspection methods – Section 4.7.2.2.**

- **REC4.10: Since AM-produced microstructures can be very different from those from established processes it is recommended that non-destructive evaluation (NDE) probability of detection (POD) characteristics should be established specifically for the part and microstructures of interest (REC4.7) – Section 4.7.2.2.**

4.9.3 GUIDANCE-TYPE RECOMMENDATIONS

- **REC4.4: it is recommended that EASA Certification Memorandum CM–PIFS-013, Issue 01 may be used to help those involved in qualification and certification of critical AM aero engine parts to set out an appropriate plan for the establishment of safe cyclic life - Section 4.6.1.**

- **REC4.9: The philosophy of the testing pyramid, with its increasing level of size and feature complexity as specimens and elements become more representative of the final part, may be adopted to provide a level of assurance that sources of scatter have been captured in the design values and fatigue properties – Section 4.7.2.2.**

- **REC4.5: It is anticipated and recommended that AM will require unique AMC and guidance material, with its own Class / Group classification (based on the Safety Analysis), to be included in the standard – Section 4.7.2.1**.

- **REC4.11: It is recommended that consideration is given to the choice of appropriate exchange rates for fatigue crack initiation and propagation in AM critical parts – Section 4.7.2.2.**

- **REC4.14: The information in this document may be used as a guide to set out an appropriate qualification plan for the non-critical AM components under consideration - Section 4.8.**

4.10 CHAPTER 4 GLOSSARY OF ABBREVIATIONS

ADH – Aviation Duty Holder
AM – Additive Manufactured/Manufacturing
AMC – Acceptable Means of Compliance
AMS - Aerospace Material Specification
Ar - Area Safe Cyclic Life
CIP – Critical Impact Parameter
CRI – Certification Review Item
CS – Certification Specification
CS E - Certification Specification - Engines
DAOS - Design Approve Organisation Scheme
Def Stan – Defence Standard
DO – Design Organisation
EASA – European Aircraft Safety Agency
EIFS – Effective Initial Flaw Size
ENSIP – Engine Structural Integrity Program
ER – Exchange Rate
FAA – Federal Aviation Administration
FAR – Federal Aviation Regulations
JSSG – Joint Services Specification Guide
LTFC – Life to First Crack
MAA – Military Aviation Authority
MIL-HDBK – Military Handbook
MIL-STD – Military Standard
MMAC - Manual of Military Air System Certification
MOD – Ministry of Defence
MRP – MAA's Regulatory Publications
NDE – Non-destructive evaluation
NDI – Non-destructive inspection
N_i – Fatigue crack initiation life
N_p – Fatigue crack propagation life
N_T – Total fatigue life
OEI – One Engine Inoperative
PI – Propulsion Integrity
POD – Probability of Detection
PSCDTL – Predicted Safe Cyclic Damage Tolerant Life
PSCL – Predicted Safe Cyclic Life
PSIP – Propulsion Structural Integrity Program
PT – Project Team
RA – Regulatory Article
RTSA – Release to Service Authority
SQEP – Suitably Qualified and Experienced Person(s)
TAA – Type Airworthiness Authority
TCB – Type Certification Basis
TCR – Type Certification Report
UK – United Kingdom
US – United States (of America)
USAF – United States Air Force

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5 AIRWORTHINESS ASSURANCE FOR MANUFACTURED PARTS (AIRCRAFT SYSTEMS)

5.1 INTRODUCTION

Airworthiness is defined as: *the ability of an Air System or other airborne equipment or system to be operated in flight and on the ground without significant hazard to aircrew, ground crew, passengers or to third parties; it is a technical attribute of materiel throughout its lifecycle* [5.1].

5.1.1 THE PURPOSE OF THE CHAPTER

The purpose of this chapter is to provide the reader with a guided “walk through” of the regulations and certification standards that are used for the airworthiness assurance of manufactured components for aircraft systems. In the context of the chapter Additive Manufacturing (AM) is considered as simply another manufacturing process, which will produce scatter in materials properties that must be accurately represented by the materials allowables and fatigue properties certified for the component. Emphasis is placed on the design, manufacture, and certification and qualification of structural components for use in aircraft systems; the focus is on structural components within any aircraft system that may have an impact on airworthiness. The airworthiness regulations for aeroengine parts and aircraft structure are dealt with in separate chapters. Where considered useful, reference is made to regulations, regulatory articles, standards and advisory/guidance documents of MOD and other bodies, such as the European Aviation Safety Agency (EASA), the Federal Aviation Administration (FAA), the US Department of Defense (DoD) and others. It must be stressed that this overview is for guidance only.

The chapter will focus on Type 1 military aircraft (high manoeuvrability combat air systems) since their design and construction is unique to the military, i.e. they are not modified civilian designs. However the chapter will be relevant to other military operated aircraft covered by parallel regulations / standards, with the exception of rotorcraft mechanical systems, where there may be additional considerations due to the loading environment.

5.1.2 CHAPTER AT A GLANCE

Table 5-6 is a concise overview of the chapter and provides a brief description of the purpose of each section.

Table 5-6 – Overview of Chapter 5 and summary of each section.

Section	Title	Description and purpose	Page
1.1	Introduction	MOD's definition of the term *Airworthiness*. An explanation of the chapter's purpose with a table summarising the chapter's structure.	103
1.2	Overview of certification and qualification process for manufactured system components	A discussion of the certification and qualification process for additively manufactured system components.	105
1.3	The Military Aviation Authority's (MAA) regulatory framework	A high level summary of the MAA's regulatory framework, including an introduction to the four pillars of airworthiness. Regulatory publications that are especially relevant to AM are described in Appendix A.	107
1.4	Certification standards	Introduces MOD's primary standard Def-Stan 00-970 but also briefly describes other relevant standards, e.g. those of the European Aircraft Safety Agency (EASA).	107
1.5	Noteworthy elements of Def-Stan 00-970	Description of the applicable requirements of Def-Stan 00-970. Note this may cross-refer to structural requirements in Def Stan 00-970, where requirements are applicable to systems components.	108
1.6	Establishing materials allowables and fatigue properties	Describes the test and statistical methods that must be used to obtain and derive design values.	110
1.7	Discussion on application of Regulatory Articles and Def-Stan 00-970 to AM	Highlights points of the proceeding sections that are especially important for AM.	110
1.8	Guidance from other aerospace organisations	This outlines other available sources of guidance on the certification and qualification of AM parts	112
1.9	Chapter 5 Concluding remarks		114
1.10	Chapter 5 Summary of Recommendations		115
1.11	Chapter 5 Glossary of Abbreviations		117
1.12	Chapter 5 References		118

5.2 OVERVIEW OF CERTIFICATION AND QUALIFICATION PROCESSES FOR ADDITIVELY MANUFACTURED SYSTEM COMPONENTS

For an Air System to be accepted onto the Military Aircraft Register (MAR) it must go through the Military Air System Certification Process (MACP) as defined in Regulatory Article (RA) RA5810 [5.2]. For systems to be used on existing aircraft, the use of an AM part is likely to be classed as a major modification from that of its original Military Type Certification (MTC) because it will at least represent a modification to the manufacturing process (and perhaps also design and/or material). Guidance on the classification of changes as major or minor is given in Regulatory Article RA5820 [5.3]. The system will become the subject of a Military Certification Review Item (MCRI) and will consequently go through an appropriate certification assurance process. The aircraft will usually have to go through MACP so that the MAA, as an independent authority, can assess whether the Type Airworthiness arrangements in place for the Air System are adequate; if adequate an up-issued MTC will be released. The modification must be justified to the Type Airworthiness Authority (TAA) by the Design Organisation (DO) [5.3, 5.4]. The Manual of Military Air System Certification (MMAC) provides an explanation of MTCs and approved design changes, as well as guidance on the MACP [5.5].

Figure 5-1 is a simplified schematic of the MCRI-process whereby an approved DO justifies that a part is airworthy. The process is part of the MACP for either the up-issue of the MTC or the issue of an Approved Design Change Certificate (ADCC) where an MTC does not exist. In either case, this will be underpinned by the production of a Type Certification Report (TCR).

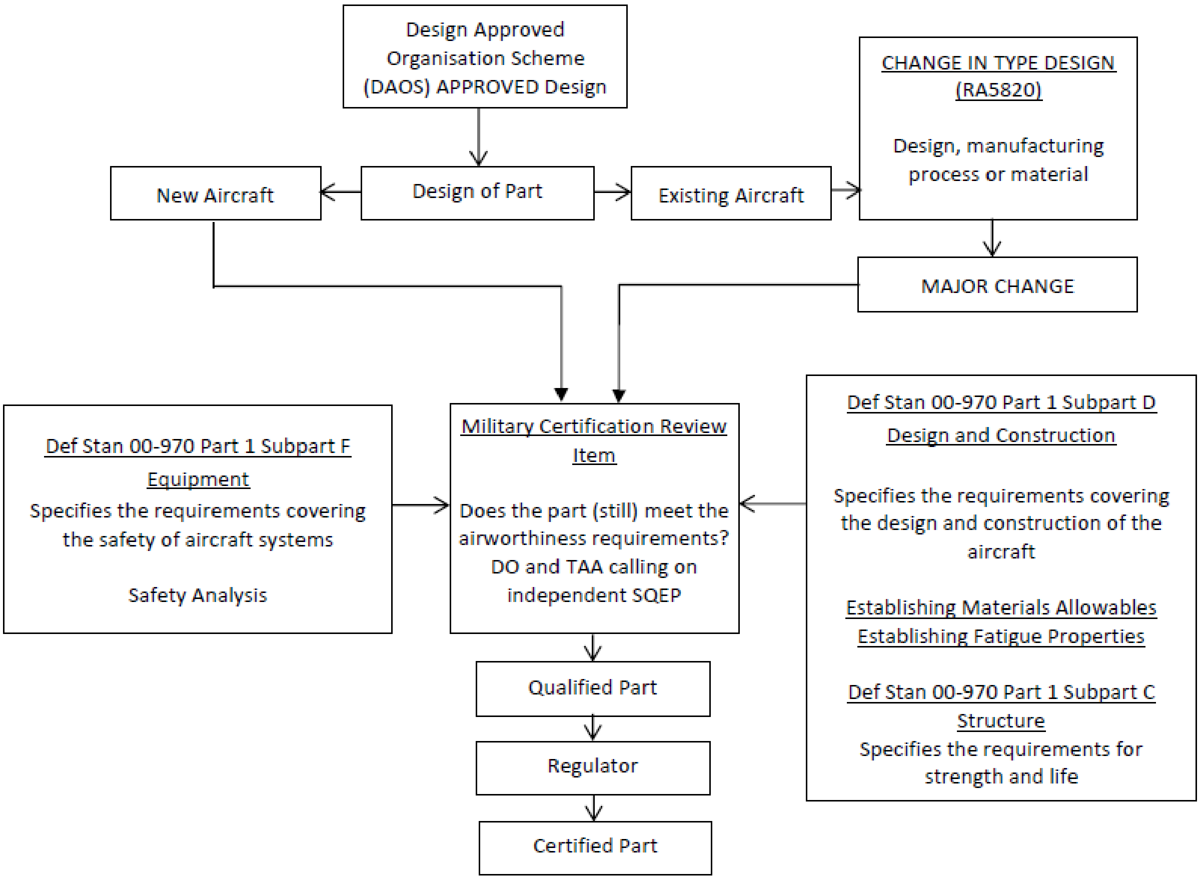

Figure 5-1 – Simplified schematic of the process of system component certification

Whether an AM part is for a new or existing system, it must be assessed for safety and must fulfil its function within the overall system design: regardless of the fabrication method for parts in an assembly and system, determination of the part criticality level is determined by the required function of the system.

Owing to the novel nature of AM, it can be assumed that even for new aircraft an AM part will require an MCRI-type process until there are established processes and procedures for the design and certification of parts, and the characteristics of the manufacturing process for each. **It is recommended that a Critical AM part, whether for a new or existing aircraft, shall be subject to the MCRI process until the technology is sufficiently mature to maintain variability in a predictable and repeatable manner (REC5.1)**. The term 'Critical' is explained later.

The methods to be used to establish system failure effects, materials allowables and fatigue properties of parts are specified in Def Stan 00-970 Part 1 Subparts C, D and F.

As discussed in Section 5.4 below, Def Stan 00-970 sets out the certification requirements for the air system, i.e. the overall airworthiness requirements. Within the certification basis, system components are qualified, i.e. it must be demonstrated that they meet their specification requirements in terms of showing that they exhibit the required properties and performance.

5.3 THE MAA'S REGULATORY FRAMEWORK

All aspects of the safety of military aviation are underpinned by the MAA's Regulatory Framework; the scope of the Regulatory Policy is laid out in MAA001 [5.6].

The MAA publishes its regulatory framework as a series of MAA Regulatory Publications (MRPs) in three layers: overarching documents, Regulatory Articles, and manuals [5.7]. Readers are encouraged to refer to the most up to date versions of the MRPs by checking the MAA's website.

For the purposes of the design, manufacture and certification of AM parts, the regulations of primary concern are those associated with Type Airworthiness: these are mainly to be found in the 5000 series, with some aspects also covered in the 4000 series. These, and other regulations that need to be considered, are identified in Appendix A to this Paper. These further considerations include, but are not necessarily limited to, standardisation, competence, record and configuration management, and approval of manufactured and repaired parts.

The Four Pillars of Airworthiness is an important principle introduced and described in Regulatory Article 1220 [5.8]. It is discussed in Appendix A and summarised here: (1) an effective Air Safety Management System (ASMS) should be established and detailed; (2) Recognised standards should be used and their use detailed; (3) Competence – arrangements for the use and management of airworthiness competent persons and competent organisations should be detailed; and (4) Independence – arrangements for ensuring independent assessment, technical evaluation and safety audit should be detailed. The four pillars underpin all the activities related to airworthiness of an aircraft and drive the requirements that will be discussed below; the discussion below concentrates mainly on the standards applicable and how AM components may differ from those manufactured using more established methods.

5.4 CERTIFICATION BASIS

It is necessary to establish that an aircraft's Type Design meets appropriate airworthiness standards, as required by RA5810 and laid down by the MAA; other Airworthiness Authorities have similar regulations. As part of the certification process a Type Certification Basis (TCB) shall be established to demonstrate that the design meets the requirements for the equipment. The paragraphs below outline the main design requirements available for aircraft design.

5.4.1 MOD CERTIFICATION SPECIFICATIONS FOR AIRWORTHINESS – DEFENCE STANDARD 00-970

The MAA's RAs provide requirements, acceptable means of compliance (AMC) and guidance for the design of aircraft to meet the airworthiness requirements for UK military operation. Defence Standard 00-970 (Def Stan 00-970) Certification Specifications for Airworthiness provides the design standard that must be maintained through the life of the aircraft.

Figure 2 of Chapter 3 gives a summary of the structure of Def Stan 00-970 and shows the Parts that cover different aircraft types and equipment. Def Stan 00-970 is the default TCB for air systems on the MAR and is used as a baseline in establishing appropriate design and airworthiness requirements, taking account of the procurement strategy to be adopted (in accordance with MRPs RA5810 and RA5820). Def Stan 00-970 Part 1 (Fixed Wing Combat Air Systems) at Issue 17 has been rewritten to make maximum use of EASA Regulations and Certification Specifications (CSs) where these are applicable to both military and civil roles [5.9]. Consequently it is appropriate to mention related statutory regulations.

5.4.2 EUROPEAN AND US CIVIL REQUIREMENTS

In Europe the aircraft design requirements are issued by the EASA (as CSs) [5.10] and in the US by the FAA (as Federal Aviation Regulations - FARs) [5.11]. There is broad equivalence between CS-25 and Def Stan 00-970 Part 1 (Fixed Wing Combat Air Systems) and Part 5 (Large Type Air Systems) and CS-23 and Def Stan 00-970 Part 3 (Small and Medium Type Aeroplanes). For most types of military aircraft, there will be additional MCRIs to be agreed when setting the TCB. Similar requirement numbering to the EASA CSs has now been adopted within all Parts of Def Stan 00-970, unless a specific military requirement is applicable.

While the numbering and titles of many of the EASA and FAA regulations mirror each other, their content is not necessarily the same. Examples of EASA and FAA regulations that are of relevance to UK MOD, namely: CS-25/FAR-25 Large Aeroplanes; CS-23/FAR-23 Normal, Utility, Acrobatic, and Commuter Category Airplanes; CS-27/FAR-27 Small Rotorcraft; and CS-29/FAR-29 Large/Transport Rotorcraft [5.10, 5.11]. It should also be noted that there are significant differences in the interpretation of the regulations as applied by the EASA and FAA during certification.

5.4.3 US MILITARY REQUIREMENTS

The DoD Joint Services Specification Guide JSSG-2009A [5.12] for Air Vehicle Subsystems is a specification developed jointly by the US Air Force (USAF) and the US Navy (USN). It, and its appendices, covering different subsystem types, establishes the joint performance and verification requirements for the various air vehicle subsystems, including hydraulic power, auxiliary power, environmental control, fuel, mechanical, aerial delivery and other subsystems. Demonstration of compliance with the specification requirements is underpinned by the use of appropriate MIL-STDs and MIL-HDBKs that may be called up when the JSSG is completed for the aircraft under consideration, for example MIL-HDBK-516 (Airworthiness Certification Criteria) [5.13] to establish the certification basis and MIL-STD-1798C (Mechanical Equipment and Subsystems Integrity Program) [5.14] to set out the framework for the completion of the certification activity and the framework for continued airworthiness and systems integrity.

5.5 NOTEWORTHY ELEMENTS OF DEF-STAN 00-970

Within each part of Def Stan 00-970, information is presented in paragraphs and takes the form of:

- **REQUIREMENT** - These requirements affect airworthiness and safety and are normally prefaced by the word “shall.” All requirements must be considered in the procurement of UK military aircraft and subsequent design changes.

- **COMPLIANCE** - Contains information regarding established methods for demonstrating compliance with the requirement. Technology advances may allow the use of alternative methods in achieving the requirement.
- **GUIDANCE** - Will contain the technical justification for the requirement and additional information considered useful in designing a system to meet the requirements. This may include appropriate references, advice on issues that require consideration or advice on typical design solutions that have been applied in the past. Some areas are considered ‘best practice’ by MOD, for example where they may affect survivability of an aircraft.

For the purposes of this document the following Subparts are examined in more detail: Part 1 Fixed Wing Combat Air Systems Subparts C, D and F. A simplified explanation of these sections is:

- Subpart C describes the static strength and fatigue properties required of the aircraft’s structure, and is also applicable to structural parts of systems;
- Subpart D describes how to demonstrate, with a required level of statistical rigour, that manufactured parts meet the requirements from Subpart C;
- Subpart F describes the requirements for the integrity of aircraft systems.

Although these terms are no longer explicitly used in Def Stan 00-970, it is helpful to introduce here the grading of aircraft parts into Grade A and Grade B depending on their criticality, and the different bases used to define design allowables, even though they are defined in more detail in Chapter 3. The consideration of the criticality of a part within any system is implicit in the requirement of CS25.1309.

- Grade A is given to parts whose deformation or failure would cause serious consequences for the aircraft, its occupant(s), mission or maintainability. They are the most safety critical parts in the aircraft. Grade B is used for parts that are less safety critical. Definitions are provided in section 3.5.2.1.
- Design allowables for static strength and deformation properties are established based on statistical theory so that, to a particular level of confidence (i.e. 95%), it is possible to state a value above which either: (a) 99% - A-basis; or (b) 90% - B-basis, of the population of the property lies. S-basis design allowables generally define a property minimum and sometimes a property minimum and maximum. An explanation of A, B and S-basis design allowables is given in section 3.6.1.1.

The requirements of Def Stan 00-970 primarily impacted by AM are CS 25.571, CS 25.603, CS 25.605, and CS 25.613. These requirements deal with design and construction, and materials processes and properties.

An important consequence of these requirements for Grade A (critical) AM parts is that until an approved aerospace specification exists for a material or process, a Contractor’s Specification shall be used. The Intellectual Property (IP) considerations around AM are significant and consequently it is most likely that individual contractors will have their own proprietary materials/process specifications, developed through extensive research and development, with an industry-wide approved aerospace specification unlikely in the short to medium term.

CS25.605 covers the requirement to protect parts from environmental degradation. It is possible that AM parts may have microstructures that have a different susceptibility to environmental degradation when compared to conventional forms and **it is recommended that their particular susceptibility should be established (REC5.2)**.

5.6 ESTABLISHING MATERIALS ALLOWABLES AND FATIGUE PROPERTIES

For a summary of materials allowables and their derivation, refer to Chapter 3.6. For a summary of methods to establish the fatigue performance of Grade A (critical) parts, refer to Chapter 3.7.

5.7 DISCUSSION ON APPLICATION OF REGULATORY ARTICLES AND DEF-STAN 00-970 TO ADDITIVE MANUFACTURING

At a top level, the concept of the four pillars of airworthiness drives all activities related to the establishment and management of the airworthiness of military aircraft. The MAA's Regulatory Framework provides the requirements, acceptable means of compliance and guidance that when followed will satisfy the principles of the four pillars. The MRPs that are especially relevant to AM have been summarised in Appendix A; one set in particular are noteworthy for this discussion since they apply to design changes.

RA5305 (In-Service Design Changes) and RA5820 (Changes in Type Design) [5.4, 5.3] relate to the management of design changes to an aircraft. Their primary function is to ensure that any design changes do not adversely affect the airworthiness of the aircraft. A dominant theme is the management of design changes through the collaborative efforts of the TAA and DO, however, the TAA is ultimately responsible for approving the change before it is implemented, with the MAA providing independent certification assurance where changes are considered to have a major impact on airworthiness.

An important process is the classification of design changes as either major or minor, as described in RA5820, since this drives the level of assurance to be carried out. Annex A of RA5820 gives an example of a major change to aircraft system. The applicable principle here is that the classification of systems is based on the functional aspects of the change, and its potential effect on safety. If the effect of failure is 'major' or above and aspects of the compliance demonstration use means or methods that have not been previously accepted for the nature of the change to the system, the change will be considered to be a major design change. Clearly, the introduction of an AM part in place of a part manufactured in a different way for type certification is a major design change and consequently the requisite assurance procedures must be followed before its introduction. As recommended previously (REC5.1), until such time as AM is sufficiently mature, an AM part should always be subject to a MCRI-type procedure. As part of these assurance procedures Def Stan 00-970 CS25.1309 provides the methods that must be followed to establish the performance of parts.

5.7.1 PROCESS AND PART QUALIFICATION

As discussed in Chapter 3, AM is not currently a well-established manufacturing process with properties that can be compared to large existing data sets with scatter that is understood from test and experience. Consequently, **for critical Air System parts it is recommended that both the AM process AND the part shall be qualified to establish, and provide confidence and assurance in, the**

variability in their properties (REC 5.3). In time it may be possible to qualify and certify an AM process for a range of different parts – at least within the same part “family” - but this will require comprehensive knowledge and experience of process-property relationships, enhanced control and monitoring of process parameters, and appropriate specimen and part testing to ensure an acceptable level of safety-conservatism is embodied in the part (which must be demonstrated to the satisfaction of the TAA).

5.7.2 MATERIALS AND DESIGN ALLOWABLES

In AM, the feedstock materials and specific features of the build process can result in microstructures that are different from those from established manufacturing, i.e. castings, forgings and welded structures (see Chapter 5 for guidance). Furthermore, the discussion relating to the determination of materials properties and allowables in Chapter 3 is equally applicable to Grade A (critical) system components. **Consequently it is recommended that the properties and scatter in properties of an AM part (i.e. that design / material / application combination) shall be measured and rationally derived rather than assumed from previous experience (REC 5.4)**; properties can include but are not limited to mechanical (including fatigue and time dependent properties such as creep and stress relaxation), physical properties (e.g. coefficient of thermal expansion) and resistance to environmental degradation (e.g. corrosion susceptibility).

Microstructures from AM are strongly dependent on the position of the particular part volume element within the whole build volume and its relationship to adjacent volumes, e.g. changes in cross section, part surface or interior, etc. Further, fatigue and scatter in fatigue is highly dependent on the volume of material being tested. Consequently it is essential that appropriate assurance is achieved that properties and scatter in properties from test specimens truly reflect those of the final part. **It is recommended that the philosophy of the testing pyramid, with its increasing level of size and feature complexity as specimens and elements become more representative of the final part, should be adopted for critical AM components to provide a level of assurance that these sources of scatter have been captured in the design values (Rec 5.5).**

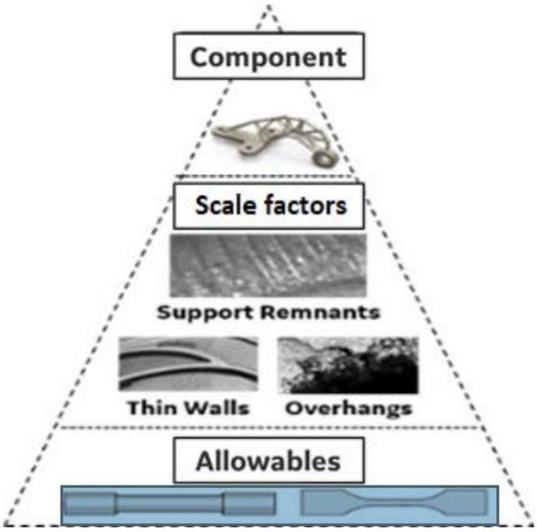

Figure 5-2 – the test ‘pyramid’

5.7.3 COMPONENT INTEGRITY

It is clear that the procedures for the qualification and certification of premium castings are especially useful when considering AM parts given potential similarities in microstructures, defects and scatter in properties, and the explicit guidance on process qualification, proof of product and process monitoring. Of significant importance is the emphasis the guidance places on non-destructive inspection. **It is therefore recommended that each Grade A (critical) AM part should receive inspection of 100 percent of its surface, and inspection of structurally significant internal areas and areas where defects are likely to occur, using approved non-destructive inspection methods (REC5.6)**.

5.7.4 OTHER CONSIDERATIONS

Although there is an emphasis in this document on determining the mechanical properties and controlling variability of components, it is also important to consider the certification and qualification of other component characteristics that are not necessarily explicitly required by Def Stan 00-970. Nevertheless, any such additional testing should be agreed as part of the certification basis.

Depending on the function and criticality of the component, additional testing such as vibration, pressure, shock or environmental (temperature range, corrosion) testing should be considered, as discussed in the Chapters on polymer and metallic components. Suitable means of compliance, environmental test conditions, test methods and guidance are given in standards such as Def Stan 00-035 [5.15], MIL-STD-810 [5.16] and RTCA DO-160 [5.17]. The first two of these standards include military-specific requirements, such as resistance to gunfire shock, and contain extensive guidance on the planning of test programmes, whereas RTCA DO-160 is a civil standard generally accepted by the civil airworthiness authorities.

5.8 GUIDANCE FROM OTHER AEROSPACE ORGANISATIONS

Since the initial publication of MASAAG Paper 124, other regulatory organisations, notably the US Air Force Structures Division [5.18] and EASA [5.19], have published guidance on the certification and qualification of AM parts. The Aerospace Industries Association (AIA) has also published recommendations [5.20]. Although the FAA participated in the preparation of the AIA recommendations, the AIA report does not constitute official guidance for the demonstration of compliance with airworthiness regulations.

The purpose of the guidance document issued by the US Air Force Structures Division [5.18] is to establish requirements for Durability and Damage Tolerance (DADT) certification of aircraft structural metallic parts fabricated using an AM process. Essentially, the approach taken in this guidance note is very similar to that applied to conventionally manufactured structure (as is the case in this MASAAG Paper) with an emphasis placed on the important aspects to be considered for AM parts. The guidance given is applicable to demonstrating compliance with the requirements of the US Air Force Aircraft Structural Integrity Program, but is equally applicable to all aircraft parts.

Similarly, the EASA Memorandum [5.19] sets out to provide complementary guidance regarding the introduction and use of AM technologies in products (aircraft, rotorcraft and propulsion) and Parts and Appliances subject to EASA Type Certification. It is noted in the Memorandum that all aviation parts and products are required to meet the relevant certification specifications, regardless of the material and process combination used to generate the engineering properties. In this respect, the EASA Memorandum also expects AM components to be treated no differently to conventionally manufactured parts.

The AIA recommendations [5.20], although not published by a regulatory authority, were the result of a collaboration to address the unique aspects of certifying AM components for aerospace applications. Guidance is provided on considerations and best practice in the areas of material/process development, part/system qualification, and development of material allowables and design values. In these respects, the AIA report [5.20] can be considered to provide the basis for an acceptable means of compliance to the applicable (civil) regulations.

5.9 CONCLUDING REMARKS

Analysis of the UK military aviation regulations, Defence Standards and supporting information has been used to provide guidance on the assurance of aircraft system structural parts with respect to airworthiness and relate these to AM. The qualification of a Grade A (critical) manufactured part to demonstrate that it meets its specification is a deterministic process; the purpose of the pyramid of testing is to determine that all sources of variability have been captured (as far as reasonably possible), including through the use of appropriate and agreed NDE techniques to capture any rogue flaws. Further, aircraft system parts will be inspected and maintained as necessary through life to ensure they continue to perform. These are all part of Integrity Management (IM), which forms part of the first pillar of airworthiness: the establishment and description of an effective Air Safety Management System (which must be detailed in the airworthiness strategy).

The properties of manufactured parts follow a probability distribution that can be described using statistical theory to give a quantified level of confidence in a particular risk of failure. The consequence of this approach is that the properties of test specimens and test elements (representative of part features) must truly reflect the scatter in properties of the final part from all sources. The guidance is clear that censoring of data, whether intentional or not, must be guarded against.

The rational derivation of static strength and deformation design allowables, fatigue and / or fatigue crack growth scatter factors is strongly encouraged.

The testing pyramid, starting with large numbers of specimens at the bottom through to real parts at the top, is a well-established philosophy that should be adopted for both materials allowables and design properties.

For Grade A (critical) parts, until such time that AM is sufficiently mature, it is recommended that both the AM process AND the part are qualified and certified as a way of establishing and guaranteeing variability.

The approach of the document has been to treat the properties of AM parts in the same way as any other part with properties from material / process combinations. The document has provided a framework for considering all of the factors that should be taken into account. **It is therefore recommended that the relevant sections in the requirements in Def Stan 00-970 Part 1 shall be used to set out a qualification plan for the AM components under consideration. The information in this chapter and Appendix A may be used as a guide to those requirements (REC5.7)**.

5.10 CHAPTER 5 SUMMARY OF RECOMMENDATIONS

In this chapter and Appendix A the airworthiness regulations and certification standards have been discussed with relation to AM parts. While it is considered that the existing regulations / standards are satisfactory for AM, the sources of scatter in AM (discussed in more detail in Chapter 5) are outside of experience compared to those from conventional manufacturing processes and consequently some key recommendations are made. These are summarised below in order from high level to more specific and grouped together as AMC-type recommendations (rather than the order in which they appear in the document).

5.10.1 RECOMMENDATIONS CONTAINING "SHALL"

REC5.7: The relevant sections in the requirements in Def Stan 00-970 Part 1 shall be used to set out a qualification plan for the Additive Manufactured (AM) components under consideration. The information in this chapter (Airworthiness Assurance of Manufactured Components - Aircraft Systems) and Appendix A (Additive Manufacturing and the Military Aviation Authority's (MAA's) Regulatory Framework) may be used as a guide to those requirements - Section 5.9.

REC5.1: It is recommended that an Additive Manufactured (AM) part, whether for a new or existing aircraft, shall be subject to the Military Certification Review Item (MCRI) process until the technology is sufficiently mature to maintain variability in a predictable and repeatable manner - Section 5.2.

REC5.3: For Grade A (critical) parts it is recommended that both the Additive Manufactured (AM) process AND the part shall be qualified and certified to establish, and provide confidence and assurance in, the variability in their performance – Section 5.7.1.

REC 5.4: it is recommended that the properties and scatter in properties of an AM part (i.e. that design / material / application combination) shall be measured and rationally derived rather than assumed from previous experience – Section 5.7.2.

5.10.2 RECOMMENDATIONS FOR ACCEPTABLE MEANS OF COMPLIANCE

REC5.5: The philosophy of the testing pyramid, with its increasing level of size and feature complexity as specimens and elements become more representative of the final part, should be adopted for critical parts to provide a level of assurance that the sources of scatter have been captured in the design allowables – Section 5.7.2.

REC5.2: It is possible that AM parts may have microstructures that have a different susceptibility to environmental degradation when compared to conventional forms and it is recommended that their particular susceptibility should be established – Section 5.5.

5.10.3 GUIDANCE-TYPE RECOMMENDATIONS

REC5.7: The information in this document may be used as a guide to set out an appropriate qualification plan for the non-critical AM components under consideration – Section 5.9.

5.11 CHAPTER 5 GLOSSARY OF ABBREVIATIONS

AM – Additive Manufactured/Manufacturing
AMC – Acceptable Means of Compliance
ADCC - Approved Design Change Certificate
AIA – Aerospace Industries Association
ASMS – Air Safety Management System
CS – Certification Specification
DAOS – Design Approved Organisation Scheme
DO – Design Organisation
DoD – Department of Defense
EASA – European Aviation Safety Agency
FAA – Federal Aviation Administration
FAR – Federal Aviation Regulations
IM – Integrity Management
IP – Intellectual Property
JSSG – Joint Services Specification Guide
MAA – Military Aviation Authority
MACP – Military Air System Certification Process
MAR – Military Aircraft Register
MCRI – Military Certification Review Item
MIL-HDBK – Military Handbook
MIL-STD – Military Standard
MMAC - Manual of Military Air System Certification
MRP – Military Regulatory Publications
MTC – Military Type Certificate
RA – Regulatory Article
TAA – Type Airworthiness Authority
TCB – Type Certification Basis
TCR – Type Certification Report
UK – United Kingdom
US – United States (of America)
USAF – United States Air Force
USN – United States Navy

5.12 CHAPTER 5 REFERENCES

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5.2. RA5810 Military Type Certificate (MRP 21 Subpart B) Issue 3, 30 November 2020.

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6.1 INTRODUCTION

6.1.1 PURPOSE OF THE CHAPTER

The purpose of this chapter is to provide a guide for those involved in the design or redesign of a component to be produced using additive manufacturing (AM). This includes the Design Organisation (DO) and the Production Organisation (PO), which could both be from the same organisation. In designing or redesigning a component, those involved will agree manufacturing specifications to control the variables within the process and outline testing methods and the number of tests required to give confidence that the material is within the specification. The specification will then be agreed on a part by part basis depending on the part and its function.

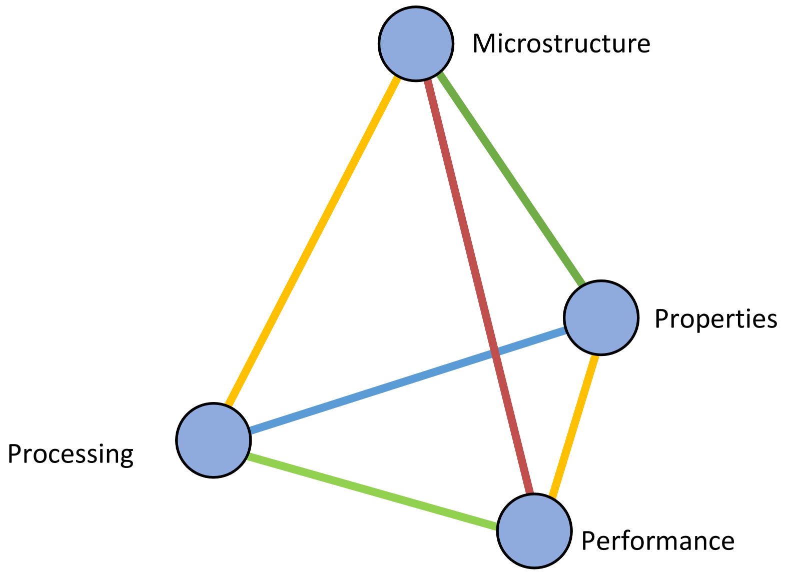


Figure 6-1 - The traditional materials tetrahedron representing the four key aspects of metallic materials development [6.1]

As Figure 6-1 demonstrates materials development in metals requires a complex relationship between the microstructure of the metal and the processing parameters to produce the required properties and performance. AM processes are in general complex and there are many interconnected process variables associated with the technique. This section of the guidance document will outline each variable, explaining why it may be important before discussing how a manufacturer might control or measure the variable. This guidance is not expected to be a process specification but gives information and guidance for the PO, DO and the Type Airworthiness Authority (TAA) when assessing the airworthiness of a part produced using AM.

For the purpose of this guidance document the AM process will be categorised using the different stages of a build as an outline. Some of these stages are similar to other manufacturing processes while others are unique to AM. In chronological order these are:

1. Part design – the generation of a suitable computer aided design (CAD) model based on the part specification and manufacturability.
2. Build design – the process of taking a CAD model and determining how it will be built using AM e.g. support structure, part location
3. Build – any processes or sources of variability experienced during the build, i.e. whilst the machine is functioning e.g. feedstock variability.
4. Post processing – any processes performed on the part once it has been built using AM e.g. machining, surface finishing, stress relieving.
5. Part validation – testing of both the final part and any test specimens to determine whether the part meets the specification.
6. Component handover – documentation and test results required when a final part is handed over to the user.

While for clarity this section is sub-divided into these stages, in developing an AM process it is common to consider all the stages together. For example, part design cannot be determined without knowing the AM method that will be used and its capabilities and installation.

As discussed in Chapter 3, the guidance for premium castings is helpful in developing an appropriate approach to ensuring quality in AM parts based on a specific process, part, alloy and founder. These can be summarised as three key aspects of qualification:

- Qualification of the process.
- Proof of the product.
- Monitoring of the process.

This means that, similar to castings, the AM process is important to the properties and scatter in properties of the final part. For critical AM components **a Process Control Document (PCD) shall be supplied as part of the airworthiness documentation. Any changes to the PCD shall be subject to the Military Certification Review Item (MCRI) process. The contents of the PCD should be written based on the recommendations outlined within this document. The Process control document could include but not be limited to details of the control of:**

- **AM machine.**
- **Build strategy.**
- **Testing.**
- **Post-processing (REC6.1).**

Although standards are mentioned within this document where applicable, **it is recommended that existing, recognised standards (e.g. ASTM, ISO, BSI) are used where available to inform the qualification and certification of AM components (REC6.2).** It is expected that as AM develops; more AM-specific standards will be produced.

6.1.2 CHAPTER AT A GLANCE

Table 6-1 is a concise overview of the chapter and provides a brief description of the purpose of each section.

Table 6-1 – Overview of Chapter 4 and summary of each section.

Section	Title	Description and purpose	Page
6.1	Introduction	An introduction to airworthiness aspects of additive manufacturing including common defects and an outline of solidification and melting in additive manufacturing.	119
6.2	Part Design	An outline of the additional aspects for consideration when designing a part for additive manufacturing including the physical and mechanical properties, part geometry requirements and designing for anisotropy.	133
6.3	Build design	An outline of all aspects of build design from machine choice and aspects of health and safety to the part configuration and build parameters.	136
6.4	Build Key performance variables	An outline of the key performance variables during the AM build including control of the feedstock and calibration of the machine.	146
6.5	Post-processing techniques	Additional post processing that may be required for AM components and how these should be recorded and measured.	162
6.6	Component validation	Destructive and non-destructive testing techniques and how their recording or use may be different for additive manufacturing.	169
6.7	Component handover	Information about additional documentary evidence required for additive manufacturing.	177
6.8	Chapter 5 Summary of Recommendations		178
6.9	Section references		185

6.1.3 ADDITIVE MANUFACTURING TERMINOLOGY

Table 6-2 – An overview of standard terminology for AM processes used throughout this report.

ASTM name (used through this report)	**Powder Bed Fusion (PBF)**		**Direct energy Deposition (DED)**	
Feedstock	Powder	Powder	Powder	Wire
Power source	Laser	Electron beam	Laser	Plasma arc
Other given names	Selective laser melting (SLM), Selective Laser Sintering (SLS)	Electron beam melting (EBM)	Laser Blown Powder, Laser Melt Deposition (LMD)	Wire arc additive manufacturing (WAAM)

6.1.4 COMMON DEFECTS IN MATERIALS PRODUCED USING AM

For the purposes of this section, the term defects is used to group together unintended macroscopic, microscopic and chemical heterogeneities in the build that may cause it to be out of specification. Surface roughness is discussed separately in Section 6.5.3. Several defects can be observed in parts made using AM processes. While some, such as porosity, are routinely observed in other metal manufacturing processes other defects, such as delamination, are generally only seen in metals in AM. The types of defects in AM can be split into four main types: porosity, distortion, chemical defects and stoppage defects [6.2]-[6.5].

6.1.4.1 VOIDS

Voids are particularly concerning defects within metals since they can have a significant effect on the variability of the mechanical properties of the final part. As discussed later in this chapter voids can be reduced once the part has been built through processes such as hot isostatic pressing (HIPping) which closes pores within the part. Surface connected voids are more difficult to rectify: when larger voids are observed in castings they are often filled by welding the surface of the part.

Three main types of voids are observed in additive manufacturing: (i) gas porosity (ii) process-induced voids, and (iii) cracking. Gas-induced porosity is often observed in powder bed systems and is owing to gas bubbles that were entrapped in the feedstock material which remain when the material is melted, e.g. argon bubbles in gas atomised titanium alloys. These pores are usually small and spherical when observed.

Process-induced porosity can come from several sources within the AM process and is typically observed as more irregular/ elongated defects in the material. One source of such defects is lack of fusion, which can occur because of unsatisfactory melting and/or as a result of insufficient material being fed/applied to the region. In powder bed fusion (PBF) systems insufficient material feed/application could be a consequence of poor packing in the feedstock; in direct energy systems it may be because too wide a gap has been set between build passes. Another lack of fusion phenomenon is caused when too high laser power levels are used in powder bed systems. In these cases regions are depleted of material through either vaporisation (so-called “keyholing” – a term from key-hole welding) or ejection of powder (spatter ejection) [6.6]. Keyholing can also create spherical gas pores at the bottom of the melt pool due to the vaporisation of elements. Melt pool turbulence can cause gas entrapment within the build. This is observed in PBF at high scanning speeds or by using thick powder layers and is also observed in laser blown powder where there is the incorrect combination of parameters.

As with casting and other molten metal processes, cracking can occur in AM. Several types of cracking are observed as the metal solidifies and cools. For example solidification cracking effects are typically because of the stresses induced in the material between solidified and molten zones. This can then cause either high strain on the melt pool or an insufficient amount of liquid material to supply the solidifying zones. Grain boundary cracking occurs at the interface between different crystallographic grains and is dependent on the phases formed during solidification, for example grain boundary carbides. Post-process cracking (cracking during post-AM heat treatment) can also occur and is common in high gamma prime Ni-superalloys. Liquation cracking, where cracks are formed from the migration of lower melting point metals from the alloy is also common in blown powder and some wire techniques, especially in some Ni-superalloys.

6.1.4.2 DISTORTION / RESIDUAL STRESSES

A simplified explanation of distortion and residual stresses is that they are manifestations of the same phenomenon, where stresses act on a part as a consequence of a process, such as a build pass in AM. Stresses that remain in the part once the source is removed are residual stresses. They can be large enough to cause distortion (elastic only or elastic and inelastic strains). This has the effect of reducing the residual stresses in the part and therefore residual stresses and distortion can be thought of as balancing each other. Unlike microscopic defects such as porosity, distortions are macroscopic defects in the part. If predictable and sufficiently small, distortions can be planned-for and corrected using post-build machining. Larger distortions cannot usually be rectified and will result in a failed build. Some residual stresses are within the part and so do not result in a distortion, instead affecting the mechanical properties of the part. These should therefore be considered during analysis and design of components, particularly when the component is not undergoing thermal post-processing discussed later on in this chapter.

There are many specific sources of distortion / residual stresses in AM depending on the features of the part and process, nevertheless all are related to the highly localised nature of heating / cooling, melting / solidification and constraint. For example most AM systems rely on a substrate material, which may or may not be the same as the material being built. As the material being built immediately on the substrate solidifies and cools it will contract relative to its volume at the point that solidification finishes. As the solidified material cools its strength will increase and a stress will start to be imposed on it and the substrate since it is contracting and is constrained by the substrate. This stress can remain as a residual stress and/or manifest as distortion in either the substrate, build volume or both. As discussed later on in this chapter the residual stress can be controlled or managed using a heated build plate. This process continues with each successive build layer, with the added complication that reheating of previous layers as the build progresses can relieve residual stresses. Build volume is defined by the scan strategy which is discussed in more detail in Section 6.3.3. Incomplete fusion of adjacent layers in the build can lead to inter-layer delamination when sufficient build-up of stresses causes local distortions.

6.1.4.3 STOPPAGE DEFECTS

Although not strictly separate defects, the impact of stoppages in the machine operation on the properties of the part is such that they can be discussed as a separate defect here. Stoppages could be because feedstock has run out or because of a machine failure or power outage. When the machine is stopped, whether planned or unplanned, the material has the chance to cool to ambient temperature which could cause microstructural in-homogeneities in the part (in addition to those that would exist in an unstopped build). If the machine is open to the environment when there is a machine stoppage there could also be uncontrolled contamination of the material in the chamber (e.g. oxidation, rogue particles, etc.). Both of these incidents could introduce points of weakness in the part that would affect its mechanical properties and performance [6.7]. Unplanned stoppages will inevitably lead to problems with the build, nevertheless even with planned stoppages it is extremely difficult to control all the sources of variability that may result. Stoppages, both planned and unplanned should be recorded during part manufacture. Some AM techniques require long build times, particularly large parts. **If the machine is unattended during a build time, procedures <u>should</u> be put in place to detect unplanned stoppages and report them (REC6.3).**

It is recommended that stoppages during the build <u>should</u> be avoided; if stoppages are unavoidable it <u>should</u> be demonstrated that they are not detrimental to the properties and scatter in properties of the final part (REC6.4).

6.1.4.4 CHEMICAL DEFECTS

As well as physical defects in the part (porosity and distortion) chemical defects in the final part are also observed during AM. Amongst other things chemical defects will affect the microstructure of the part which can in turn affect its mechanical properties.

Two main sources of chemical defects are observed:

The first source is contamination in the original feedstock. In powders this may be owing to insufficient cleaning of previously used powders which could lead to out-of-specification powder material within a powder batch. In direct energy deposition systems, feedstocks can be contaminated, which is generally owing to poor quality control where unwanted elements have contaminated the original feedstock.

The second source of chemical defects is due the high energy heat sources used in AM which can lead to vaporisation of some high vapour pressure elements e.g. aluminium and chromium. This can cause two main negative effects within the AM part:

a. Elements that are vaporised are no longer within the alloy deposited and consequently the elemental composition of the part may not be within the specified value. Compositions are specified because they affect mechanical properties of the part significantly (through various strengthening mechanisms).
b. Vaporised elements such as aluminium can react with other elements e.g. oxygen from the build atmosphere. Even in the very low oxygen concentrations in vacuum and inert atmosphere systems (e.g. argon inert gas systems typically have oxygen levels in at the 20 parts per million level [6.8]), this may lead to the formation of oxides which can be incorporated into the final part.

For PBF systems defined earlier in this chapter, additional chemical defects can occur, these include:

a. Contamination due to different metals being used in the same machine. If a machine is used for several different alloys and not sufficiently cleaned between alloys, powder from previous builds can contaminate the build. **It is recommended that for critical components, calibration builds <u>should</u> be performed on AM powder bed machines if there is a changeover of metal alloy types (REC6.5).**
b. Degradation due to repeated re-use of powders. As a powder is re-used it can pick up oxygen as a contaminant in the build.

6.1.5 AN INTRODUCTION TO MELTING AND SOLIDIFICATION DURING AM

The thermal processes undertaken during AM of metals are complex but vital to the quality of the part that is being built. Unlike conventional subtractive manufacturing techniques for metals where the part is machined from a pre-qualified material, in AM processes the precursor material is re-melted for each different part built. This means that, similar to casting, the final quality of the part is profoundly affected by the melting and solidification processes undertaken during AM. The delicate balance of thermal properties is in turn influenced by the sources of variability that must be controlled during an AM build process and will be discussed later on in this chapter.

There is currently a large amount of research effort to determine the exact thermal processes that are happening during AM. As well as modelling and simulation of the AM systems, the research is influenced by current understanding of the thermal processes involved in both welding and casting. In this section we will seek to describe these balances to help the reader understand why AM is different when compared to other manufacturing processes and to understand why and how methods of control should be applied.

6.1.5.1 MELTING

A key parameter that influences the quality of any AM parts is the nature of the melt pool, the material melted by the primary heat source during the AM process. The melt pool size and shape is important because it influences the thermal profile of the melting and cooling material which can in turn affect a range of properties including residual stress, surface roughness and the geometry and microstructure of the part. The melt pool is primarily determined by the amount of energy applied to the part by the heat source. Several models have been generated to understand the energy inputs and outputs to the process of generating a melt pool in powder bed systems and although there is not agreement as to the exact relationship, they give a good outline of the important parameters when determining the amount of energy put into melting the part. The energy gains and losses for most types of AM are similar but they may be more or less important depending on the technique [6.6]; [6.9]-[6.12].

The four main AM processes covered in this guidance note each have three different primary heat sources:

- Laser - laser powder bed fusion , Laser blown powder direct energy deposition
- Electron beam - electron beam powder bed fusion
- Arc - wire arc direct energy deposition

In addition to the energy provided by the primary heat source there are also losses in the system. A good comparison is with arc welding where the arc weld power is not the same as the arc energy which is determined from the efficiency of the arc and a range of parameters covering travelling speed, efficiency and layer height [6.13].

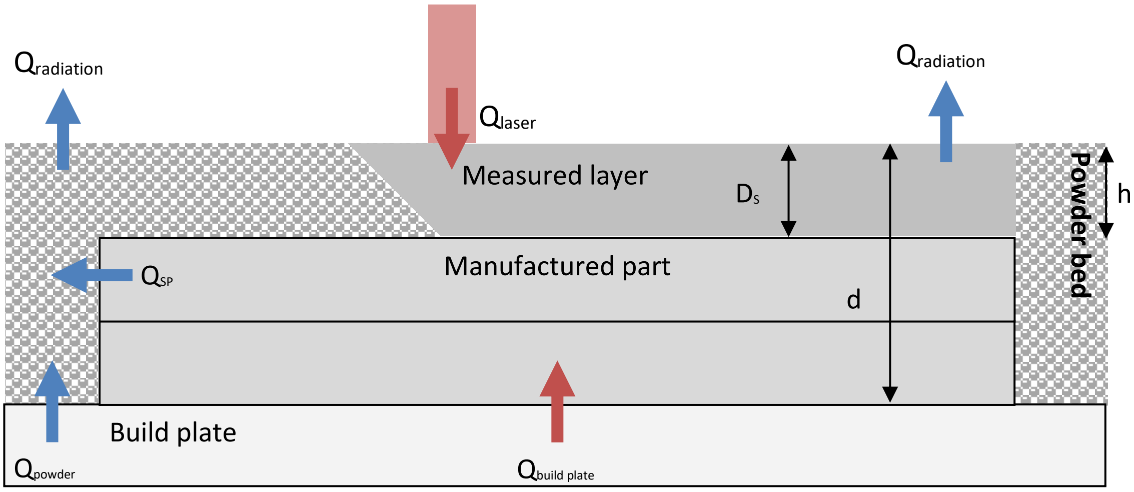


Figure 6-2 - An example of the energy inputs and losses during laser powder bed AM [6.12]

As Figure 6-2 demonstrates, for a powder bed type system the heat flow to form the melt pool can be found by deducting the heat losses (Q_{powder} and $Q_{radiation}$) from the heat inputs (Q_{laser} and $Q_{build\ plate}$) to the system. The heat flows in direct energy deposition systems are similar but with three key differences. Firstly, the absence of the powder material around the part removes conduction to the powder as a heat loss mechanism from the material. Secondly, as base plates are usually not heated, heat will be lost to the baseplate in direct energy deposition rather than input by it. Finally, an additional heat loss mechanism can be observed due to higher gas flows in direct energy deposition systems [6.6]; [6.9]; [6.14].

6.1.5.1.1 ENERGY INPUT: PRIMARY HEAT SOURCE

The best understood AM systems for energy input to melt the material are those processes that are derived from existing welding processes, WAAM and laser blown powder. The total energy input by the primary heat source during arc welding is typically defined based on the power of the primary heat source divided by the speed of movement of the arc to give an energy input value in J mm^{-3}.

This relationship is also valid for laser blown powder systems where the method of application is similar to the arc welding systems.

Despite their difference to the more welding-like systems, the energy input during powder bed processes such as E-beam and SLM is derived from similar equations. In addition to a beam velocity term, they also include terms relating to the size of the beam. The energy applied to melt the precursor material in both electron beam and laser powder bed fusion systems can be determined as follows:

$$E = \frac{P}{vht}$$

E is energy density in J mm^{-3}, *P* is the power of the beam in *W*, *v* is the beam velocity in mm s^{-1}, *h* is the line offset (hatch distance) in mm and *t* is the layer thickness in mm [6.11]; [6.15]; [6.16].

There are however complications to this equation and consequently it does not give a complete understanding of the energy input supplied to generate the melt pool. Firstly, the equation considers the energy supplied as a point source where the energy across the beam is the same. In reality this is not the case for many systems. For lasers, for example there may be a Gaussian distribution with the highest energy in the centre of the beam, decreasing towards the edge of the beam. We also observe differences in the shape of the beam due to focussing, increasing this effect further. There is also sometimes a tail on the beam following the direction of motion which can influence the energy inputted to generate a melt pool.

As discussed previously, the high energy heat sources used in AM, combined with systems held below atmospheric pressure can lead to the vaporisation and then oxidation of some elements leading to oxidation of some elements which can become defects if entrapped in the part. The evaporated material can also form a plasma when it is hit by the laser. This generates pressure on the melt pool which can affect the microstructure and properties of the final part. For laser systems there are two types of beam available, pulsed or continuous wave beams. A pulsed beam may be used to enhance the quality of the final part by applying a series of packets of high intensity light to the part instead of applying a continuous wave. This affects the interaction time between the material and the laser. The peaks involved in a pulsed laser can enhance the vaporisation effects mentioned above [6.17].

It is also important to consider the interaction of the heat source with the precursor material. The thermal properties of the precursor material such as absorbance, melting point, reflectivity and thermal conductivity will be affected by the properties discussed later on in this chapter. For laser systems in particular the reflectivity or absorptivity of the feedstock material is an additional factor in the overall energy applied. If the powder is highly reflective such as in aluminium, it will reflect back some of the energy applied by the beam thus reducing the total absorbed power and affecting the melt pool. This can also be observed in electron beam melting when electrons are backscattered (rather than reflected), reducing the energy absorbed. For both systems the reduction in energy can be modified in build planning by increasing the beam power for certain materials but could be an additional source of variability if the powder surface varies, affecting the reflectivity or backscatter. The laser absorptivity and thermo-physical properties can also be affected by powder particle morphology (spherical, irregular, faceted, etc.) and the powder size distribution (Gaussian, bimodal, etc.). As with other feedstock interaction parameters this can be controlled and measured using the parameters discussed in part 6.4 of this guidance [6.17].

6.1.5.1.2 ENERGY INPUT: THE BUILD PLATE AND CONSOLIDATED MATERIAL

In addition to the energy input by the primary heat source, for some methods of AM energy input to the material is also observed through preheating of the build plane. Although these temperatures are not typically high enough to melt the powder, they are used to reduce strain and residual stresses in the part. In powder bed systems the extra energy provided by a heated build plane can reduce the power required to melt the material. This is less likely to be used in direct energy systems and is applied at lower temperatures (Currently ≤ 550°C [6.18]) in laser powder bed systems and higher temperatures (Currently ≤ 1100°C [6.19]) in electron beam powder bed systems.

6.1.5.1.3 ENERGY LOSSES

Two main mechanisms are available for the melt pool to lose heat during the AM process, conduction and radiation. Radiation is emitted during the process at visible and infrared (heat) wavelengths. Radiation is strongly influenced by the temperature of the material but can also be affected by part material properties such as emissivity

Some of the heat energy that has been input to the material will conduct to the already solidified materials that make up the part and the base plate. Often this conduction leads to temperatures that are high enough to re-melt already solidified layers below. As demonstrated in Figure 6-2, in powder bed systems some of the energy is also transferred to the surrounding powder through conduction [6.20]. In electron beam melting systems the powder may be pre-sintered to improve electrical conductivity and limit the build up of charge in the powder. This can also enhance thermal conduction paths to the surrounding material. Direct energy systems, do not have feedstock material surrounding the part and do not see this type of conduction.

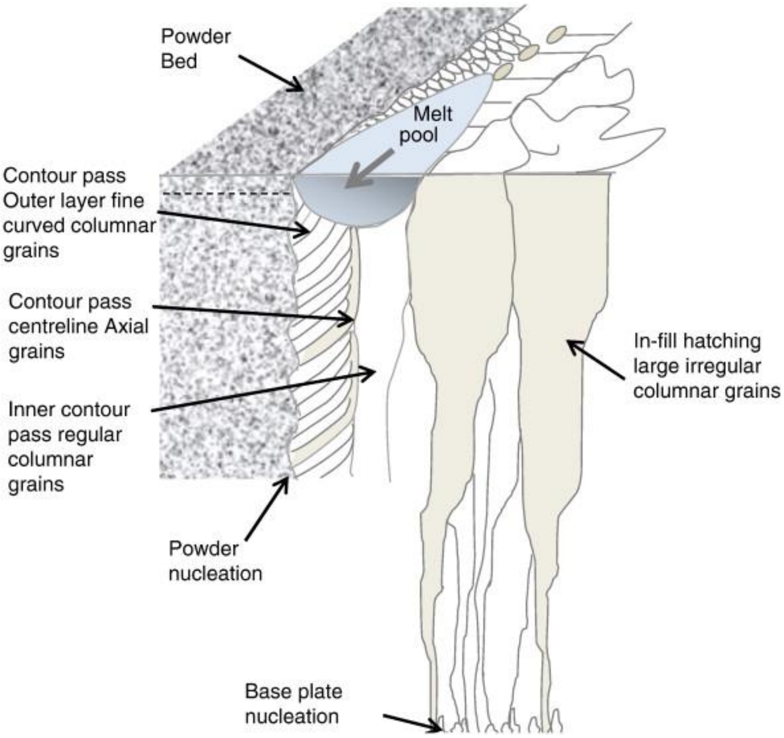


Figure 6-3 - Microstructure evolution during powder bed AM [6.20].

6.1.5.1.4 OTHER FACTORS THAT CAN AFFECT THE MELT POOL FORMATION

The relatively small size and low mass of powder particles means that their interaction with a beam during melting can be more complex than wire feed systems; with sufficient force particles can be ejected. Four main mechanisms exist for particles to be ejected during AM across the three powder techniques covered by this guidance note:

- Convective transport of liquid or vaporised metal out of the melt pool (or spatter ejection).
- Electrostatic repulsion of powder particles in electron beam PBF.
- Kinetic recoil of powder in laser blown powder DED.
- Enhanced convection of powder in gas streams [6.6].

Spatter ejection can also happen in direct energy deposition systems and welding systems leading to porosity and surface roughness.

Some of the molten material will be vaporised and ejected from the melt pool. This creates the white “sparks” often seen in AM which can lead to variation in the amount of material being formed into the final part, which can directly lead to porosity and build failures. The vaporised material can also be incorporated as defects in the part through the formation of oxides. As discussed previously, if the power of the heat source is too high an effect called keyholing (a term borrowed from keyhole welding) can occur. In this effect a high power laser can lead to enough evaporation of the metal to create a void in the layer below. The molten metal will then solidify over the void creating trapped porosity within the material [6.21].

How the powder packs together and the thermal properties of its packed volume are also important in forming a stable melt pool. If the particles have loose packing the thermal conductivity between the particles may be lower, varying the melt pool size for a given laser power. This could be controlled by specifying the powder packing properties through tap density measurements to ensure repeatability of the melt pool. Powder properties are discussed in more detail in Part 6.4 of this guidance.

In powder bed systems the ejected particles can be dispersed in the area above the build plane and block out some of the laser power or blur the laser definition. This can lead to variation in melting in the part which can affect the microstructure and porosity of the final part. This blur is countered through flowing gas across the surface of the powder bed to remove any powder. The gas is then filtered to remove the powder before being recycled in the machine. It is also important to ensure that the gas flow is not too high since this can also remove powder from the powder bed leading to a reduction in material deposited with consequences for porosity and build geometry.

In laser blown powder systems the gas flow is used to apply the powder and should be carefully controlled to ensure that the powder is not applied with too much force such that the powder undergoes kinetic recoil where the applied powder bounces away from the part before it can melt. This is compensated for through careful control of the laser blown powder system. Once the flow rate has been set the variability in the powder flow can be controlled and measured using the parameters discussed in part 6.4 of this guidance.

6.1.5.2 SOLIDIFICATION

Solidification in metals is extremely complex and strongly dependent on alloy chemistry among other factors. Consequently it is outside the scope of this guidance to discuss this in detail. Instead this guidance will focus on a general discussion of the factors in AM that relate to solidification. Solidification history is crucial in determining the microstructure of the metal. The microstructure is then important in determining the mechanical properties of the final part and consequently variation in solidification can have a direct impact on its quality. In alloys solidification history also determines the characteristics of various phases in the alloy. Poor solidification control can lead to precipitation of phases that have characteristics that do not give the requisite mechanical properties and performance. In addition solidification can also influence the formation of defects such as porosity and delamination or residual stresses and distortion which can lead to the part not meeting its specification (mechanical, dimensional, etc.).

Three key features of solidification in AM are observed to be different from other processes (e.g. casting):

- The cooling rate in AM is much faster than in conventional manufacturing because the surface area to volume ratio in a layer will be significantly higher than a larger cast shape. This could affect the microstructure and character of the phases present in the final part.
- The layer by layer manufacturing technique means that the melting of subsequent layers can re-melt the layers below them leading to solidification and subsequent phase field cycling. This is illustrated in Figure 6-4 which shows a representative solidification mechanism for laser PBF of Ti-6Al-4V alloy.

- Many metals and alloys solidify along a preferential crystallographic growth direction. The complex nature of heat flows in AM, and its variation through the build volume, will lead to localised crystallographic anisotropy i.e. localised texture in the part.

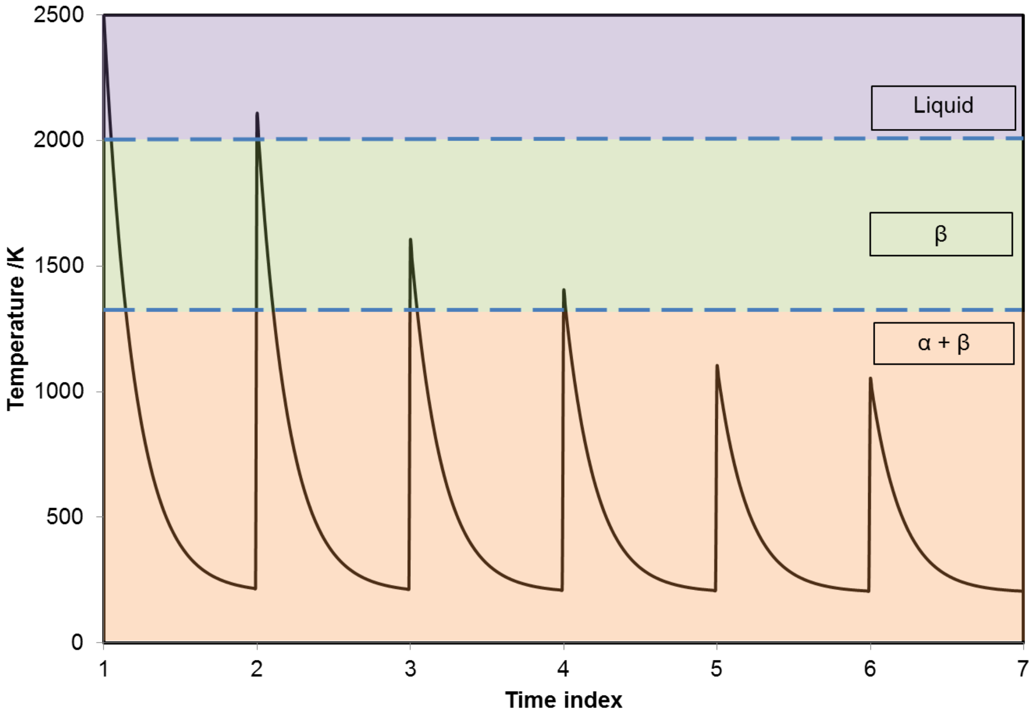


Figure 6-4 - Representative solidification mechanism for Ti-6Al-4V during laser PBF AM.

Figure 6-4 is a representative solidification mechanism for Ti-6Al-4V during laser PBF AM. The time index represents subsequent layers of material being added onto the layer of material depicted in the diagram. Step one shows initial solidification, in step two the layer is remelted and solidifies because of the next pass building the layer above. Passes three and four cycle the layer in and out of the β phase field. Passes five onwards are thermally cycled but remain in the α + β phase field [6.9]; [6.16].

6.1.6 SUMMARY AND APPLICATION OF MELTING AND SOLIDIFICATION IN AM

Some key conclusions can be drawn from this brief discussion into the melting and solidification processes involved in AM:

- The thermal balances during melting and solidification processes are complex and are not yet fully understood in AM but they highlight the influence of a complex balance of machine parameters on the microstructure / defect population and mechanical properties of the final part.
- The properties of each layer in AM are not only affected by its geometry but also the previous and subsequent layers. This gives each part and orientation a potentially different thermal history which affects its microstructure, defects, residual stress and mechanical properties. Consequently any change in geometry or orientation could lead to different part properties.

- Powders as a feedstock add extra complexity since they may interact differently with the primary heat source and transfer energy to the surrounding powder. This suggests careful control of powder properties in particular is required to reduce variation in the final part.

6.2 PART DESIGN

As discussed in the previous section, the complex thermal processes involved in AM mean that part design is particularly important to the properties. Similar to composite materials, for each part the material can be considered as built new so the material has the potential to be different each time. This is different from conventional subtractive machining where the microstructure of the material is determined during the thermomechanical processing of the starting material (forging, plate). In subtractive machining, with the exception of surface defects, the machining has no effect on microstructure and thus properties of the final part.

There is a wide range of guidance on design for AM and most organisations and machine manufacturers will have their own design guide to determine which parts can and cannot be built using their machine. The constraints of AM systems when considering residual stress in particular may mean that it is necessary to re-design the part to be manufactured using AM.

6.2.1 PHYSICAL AND MECHANICAL PROPERTIES

The development of a part's physical and mechanical properties is important in any process. The development of design allowables for the physical and mechanical properties of a part is discussed at length in Chapter Three of this document so will not be discussed here. It is however of use to reiterate some of the physical and mechanical properties considered during manufacture of structural components:

- Static properties – strength (ultimate tensile stress, tensile and compressive proof stresses - including strength vs. temperature), shear stress, bearing stress, torsion stress and fracture toughness.
- Creep, creep-rupture and stress-rupture properties.
- Fatigue properties.
- Crack propagation properties.
- Physical and characteristic properties (e.g. susceptibility to stress corrosion cracking, weldability, etc.).

6.2.2 PART GEOMETRY

The geometry of a part that can be built will be strongly influenced by the AM machine choice. Table 6-3 demonstrates some of the geometric limitations of the different types of AM. As the table shows these values can vary widely so should be considered in the part design stage, especially when deciding on the type of machine to use.

Table 6-3 - Typical layer thicknesses and minimum feature sizes of powder bed fusion (PBF) and Direct energy deposition (DED) processes [6.6].

Machine type	Typical layer thickness /µm	Minimum feature size or beam diameter /µm
PBF –SLM e.g. Renishaw	10–50	75–100
PBF –EBM e.g. ARCAM	50	100–200
DED – wire fed e.g. WAAM	3000	16 000
DED – powder fed e.g. Laser blown powder	250	380

The part geometry is also important because there can be a significant deterioration in properties at certain part geometries. Of particular importance are overhangs where an overhang is defined as any area where instead of building directly onto another layer of the part below, the material is built directly onto the powder. Insufficient support for the overhanging layer as it is built can create distortions in the part due to residual stress. This distortion can be overcome through the addition of support structures and different AM systems allow different levels of overhanging structures before additional supports must be added. In general supports are avoided as much as possible in part design as they can negatively affect the surface properties of the part. Overhangs can be minimised by careful orientation of the part in the build volume [6.22].

Another consideration in designing for powder AM is the removal of powder once the part has been built. For this reason completely enclosed structures should be designed with consideration for powder removal to avoid the powder being trapped inside. As well as enclosed structures, powder can also be difficult to remove from open ended narrow structures, e.g. pipes, since the powder compacts and cannot be easily removed. Design changes could include the adding of a hole in the part design for powder to escape or consideration of post machining to remove the powder. The size of any spaces to remove powder should also be considered since even where a hole exists to remove the powder, the nature of the powder packing may make complete powder removal impossible [6.22];[6.23].

For some AM processes the difference in density of the molten material leads to shrinkage during melting which can distort the part from the required geometry. If this adversely affects key features of the part, it may need additional material adding to these features which can then be machined to the correct geometry. In addition, it may be possible to modify the CAD model to take shrinkage into consideration. However this is a relatively complex operation requiring simplified models that are currently only partially representative [6.24].

6.2.3 DESIGN FOR ANISOTROPY

It may be necessary to design the part considering anisotropy of the AM process which as previously mentioned can be a feature of AM. Similar to composite materials the part may be designed to optimise the anisotropy and enhance mechanical properties in a particular direction. There is currently limited understanding of the solidification and melting processes within AM but in the future greater understanding and modelling of the processes involved may lead to greater control of the microstructure in the part design stage, enhancing and potentially tailoring mechanical properties. **If a part is designed and qualified to optimise properties in a particular direction then any change in orientation or build methodology for the part (discussed later on in this chapter) will particularly affect the properties of the final part and <u>should</u> not be altered from the optimised orientation (REC6.7).**

6.3 BUILD DESIGN

An important step in any manufacturing process is the development of the process from an initial CAD model or drawing. In this document the build design stage of manufacture is anything that is done in the planning stages before the button is pressed to initiate the build. The use of computer-control in AM does not remove the build design stage of the manufacture, in fact it is more important in AM since human control is more difficult once the computer has initiated the build.

The section on build key process variables (KPVs) refers specifically to the sources of variability whilst the machine is in use and usually can only be controlled or recorded by the computer or automated system. The manufacture of parts using AM can however be an iterative process with the build key process variables and final part properties influencing the build design and requiring multiple builds to develop a production quality part. Although this is an advantage of AM, it must be considered in the same way as any manufacturing technique and any changes to the build process should be considered from an airworthiness perspective before being applied to the final part.

As with other manufacturing processes, for example welding, for additive manufacturing the operator can be a source of variation in the final part. **All operators should be shown to be suitably qualified to use the additive manufacturing machine.** This is important primarily for safe operation of the machine but also an inexperienced operator may lead to differences in the control of the AM machine that could lead to variation in the final part. Much af the variation observed between AM operators is in the design of the build volume, discussed later on in this section and so can be limited by recording aspects of the build layout in the process control document. **If variation between operators is still deemed a significant source of scatter, it may be necessary to specify named operators to build a critical part (REC6.7).**

6.3.1 MACHINE CHOICE

Machine choice is a crucial step in build planning and the machine type and model should be recorded in any qualification /certification document. Several factors relating to the final part must be considered when deciding which machine to use:

- Size of part – Will it fit within the required build volume?
- Material – e.g. Specific alloys can only be produced using certain machines
- Surface finish – i.e. maximum un-machined surface roughness acceptable for the part
- Build resolution – Layer height, beam size and minimum feature size. Will the part be built to the specified level of detail? Particularly important for small parts.

Within the same machine type, there can be significant machine to machine variation so **if a part will be produced on different machines to those used for qualification and certification, all machines should undergo a pre-qualification process with calibration builds to show that any variation is within an acceptable range (REC6.8).**

6.3.2 FACILITIES ASPECTS

The effect of ambient temperature, storage and humidity changes on the final build quality is not yet fully understood but for some AM systems the change of these parameters within a facility can affect the final build quality. It is most likely that these conditions primarily affect the feedstock material which in turn could affect build quality [6.25]. As such an AM system should sit within an environment with limited significant heat and moisture fluctuations. This may mean that the manufacturing is performed in a climate controlled atmosphere but could mean that temperature and moisture levels are measured and recorded during builds. Within powder systems there is an increasing use of closed loop powder handling systems where the powder is never exposed to the air to limit the effects of moisture and temperature control on the build quality.

6.3.2.1 HEALTH AND SAFETY CONSIDERATIONS

In addition to common factors associated with any manufacturing or laboratory environment, several specific safety factors must be taken into consideration when using an AM machine. Please note that the safety guidance provided in this document is included for guidance only. In applying AM a user must ensure that local safety protocols are followed and applied. The safety factors associated with AM can be divided into four main sections: Heat source, Robotic systems, atmospheric risks and safety factors associated with the feedstock.

The safety considerations for powder-bed systems that occur within an enclosed machine are significantly different to those for direct energy deposition techniques such as WAAM which can be used in the open on a factory floorplate. A lot of the safety risks associated with powder bed AM are controlled at the machine design level and are mitigated through machine interlocking systems and gas sensors. Despite this it is important to outline some of the risks involved both inside and outside of the machine in case modifications on future machines limit some of these safety systems.

Directed energy AM systems are often based on existing robotic welding systems and so safety practises for these systems transfer across to their AM counterparts. This includes enclosures for the system to restrict access during a build.

6.3.2.1.1 HEAT SOURCES

The nature of most AM processes means that heat sources are almost always associated with the production of the part and these pose a risk to the AM machine user and any surrounding equipment or facilities. The following heat sources pose a risk in an AM operation:

- Heated bed or build plate.
- Melt pool generation by lasers, electron beams etc.
- Heat processes during part break out.

The main heat risk of an AM system is the heat required to melt the material, particularly metals. As well as posing a risk during the build this can also lead to latent heat sources which may remain when the machine is no longer running.

Lasers used in laser powder bed AM would be identified as class 4 lasers if used on an open bench top. By government guidelines this means they pose the following risk: “Class 4 lasers are capable of causing injury to both the eye and skin and will also present a fire hazard if sufficiently high output powers are used [6.26].” Despite the high power of lasers used for AM, safety procedures and engineering systems are put in place by manufacturers which mean that during conventional operation the lasers in AM machines can be considered as safe class 1 lasers [6.27]. Such procedures could include an automated shut off when a build chamber door is open and interlocks that mean the laser can only be accessed directly during calibration and maintenance. It is the responsibility of the machine manufacturer to determine the laser safety classification of the equipment [6.28].

Users should however be vigilant to any change in a laser based systems through malfunction or modification of a system. If any modifications of a previously classified piece of equipment affect their performance or intended functions, the person or organization performing the modification is responsible for ensuring the reclassification and relabelling of the laser product [6.28].

Melt pool generation by electron beam systems follow a different mechanism to laser-based systems. In electron beam systems, electrons are fired at a surface and the transference of their kinetic energy into the surface generates a temperature rise in the material. In addition to the heat generated, a by-product of the high energy collision of electrons is the generation of X rays which are ionising and thus pose a greater hazard. These hazards are controlled in electron beam melting systems by containing the electron source and shielding the user from any ionising radiation.

In addition to the direct hazards of the heat source, the reflectivity of the metal base plate can lead to indirect hazards to people and equipment, particularly for laser-based systems. The angles of reflectivity should be considered during build design and additional safety features such as barriers and screens may be required [6.29].

The main approach to mitigating the risks posed by heat sources is to limit access to the heat source itself. This is mainly done through engineering controls of AM systems. Restricted access facilities and Personal Protection Equipment (PPE) may be required where engineering controls are not practical.

6.3.2.1.2 ROBOTIC SYSTEMS

The computer controlled elements of AM and other risks involved means that AM systems rely on a significant level of robotic systems in the control and manipulation of the material.

For enclosed systems such as powder bed systems the interlocks in the system should limit access during operation and any maintenance and calibration of the machine should also check any safety systems associated with the machine. Direct energy systems, which are based on automated welding tools can be operated in a more open environment and as such pose a greater risk. The risk can be reduced by following guidelines such as the BSI guidelines for industrial robotics followed [6.30] the risks can be reduced. The guidelines include ensuring emergency stops for the system and operating the system in a separate area clearly marked with the possible hazards.

6.3.2.1.3 ATMOSPHERIC RISKS

The reactivity of metals to oxygen means that some AM systems function in an inert atmosphere, using gases such as argon or nitrogen. These gases may pose a risk to operators because if they escape from the build chamber they exclude the oxygen from the room which cause breathing difficulties in anyone present at the time of release. Oxygen sensors are often placed in the room where the AM build takes place to protect against the risks of asphyxiant gases. The different densities of these gases mean that these sensors should be placed at different heights in the room.

For powder bed systems the risk is through accidental release and care must be taken when purging systems and connecting gas cylinders to ensure the gases are not released to the environment. For direct energy systems where the manufacture may occur in the open environment these gases are used as a shield gas and the gas is released to the environment. The risk through release of these gases is mainly mitigated by ensuring that the action is performed in a large space where the released gas can escape. HSE has further guidance on the measurement and mitigation of risks for these and other welding systems [6.31].

Further, the fumes produced during operation can pose a risk if inhaled. For powder bed systems the extraction and filtration systems employed can mitigate this risk but filtration systems should be to a defined standard and should be calibrated to ensure safe operation [6.32]. For direct energy systems where manufacture may be performed in an open space, the controls around welding could be used including extraction systems and PPE such as respiratory protection masks. Further guidance on control and hazards relating to welding fumes can be applied to direct energy deposition systems and can be found on the HSE website [6.33].

6.3.2.1.4 FEEDSTOCK

Many of the feedstock materials used in AM offer chemical safety risks and as with any manufacturing process these risks should be assessed as per local guidelines and through Control of Substances Hazardous to Health (COSHH) guidelines. Further information on these guidelines can be found at 6.3.4. A Materials Safety Data Sheet (MSDS) should be provided from the manufacturer with any feedstock material and risk and safety guidance on the MSDS should be followed, including appropriate PPE [6.35].

In addition to any chemical hazards powder feedstocks are a particular risk when manufacturing using powder bed AM system. Three key risks are evident when using powders for AM [6.35].

- Explosion – the high surface area to volume ratio of all powders means they can pose an explosion risk. Reactive metal powders such as titanium are particularly susceptible to explosion when mixed with air.
- Powder inhalation risks.
- Metal powder causing a short circuit.

To minimise the risk of sparks which could cause an explosion in powder feedstock, anti-static protection through e.g. antistatic clothing or antistatic mats may be required. Where powder handling in the open is unavoidable, appropriate personal protective equipment (PPE) such as respirators and gloves should be worn. To mitigate the significant risks in powder AM systems, as much powder handling as possible is undertaken in a closed loop. In this system all operations – sieving, loading, storage etc. are undertaken in sealed vessels often held under an inert atmosphere.

6.3.3 PART CONFIGURATION AND BUILD SUPPORTS

Once a part has been designed and the machine has been identified, then the AM user must decide how the part will be built by the AM machine. For most AM systems this is done either computer aided manufacturing (CAM) software or directly by the AM machine that converts the computer aided design (CAD) file into instructions and parameters for the AM machine to run.

6.3.3.1 FILE CONVERSION

Most AM systems run on the .STL (abbreviated from stereolithography) file input which exchanges pure geometric coordinates from the CAD file to the AM machine. It works by converting boundary surfaces of the CAD file into triangles or facets and describing these as vectors. If the file conversion is not performed correctly it can introduce errors to the part which will need to be corrected before the build can proceed. Table 6-4 below demonstrates some common errors in transferring data to the STL file type and their effect on final part quality. Further guidance on the effects of file type can be found in BS ISO 17296-4:2014 which covers general principles relating to data processing for AM [6.36].

Table 6-4 - The effect of different STL file conversion errors on the part and process during AM [6.36].

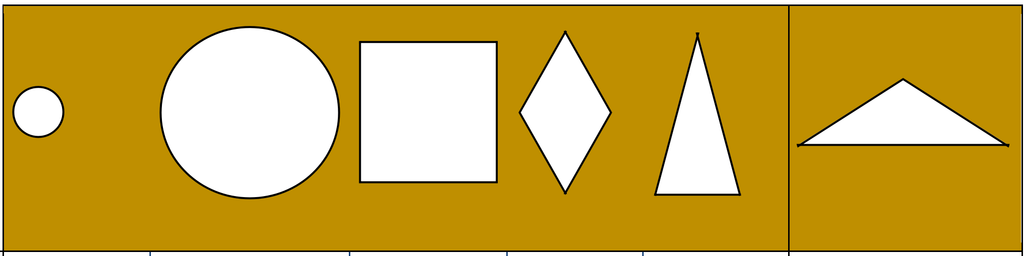
Formatting error	Process effect	Part affect	Possible measures
Too coarse triangulation	None	Poor approximation of the actual geometry	STL generation with adjusted resolution
Too fine triangulation	Excessive computing time, long construction times Process errors due to large volumes of data	Defects caused by process errors	STL generation with adjusted resolution
Uneven and/or untrimmed surfaces in the CAD model	Process errors caused by undefined parts definition	Geometric distortion defects	Repair = clean cut “closed volumes”
Incorrect orientation of the surfaces in the CAD model	Process errors caused by empty layers or undefined parts definition	Geometric distortion defects Delamination and loss of strength in z-direction (axis)	Check normal vectors “Closed volumes”

If the file conversion from CAD to STL or similar has a significant effect on the required properties of the final part the AM producer <u>should</u> ensure that the converted file used to build the qualified part is the same as the file used for production builds. (REC6.9).

6.3.3.2 PART ORIENTATION

As discussed in section 6.1 the thermal processes the part undergoes during the layer by layer build process can lead to anisotropy and variation in properties in the build direction (sometimes referred to as the z direction) in particular. This means that the orientation of the part when it is being built using AM is very important in determining final part properties. In the future it may be possible through modelling to optimise part orientation to minimise the negative effects of any anisotropy during build using AM. However, **if the variation due to orientation of the part leads to a scatter of properties greater than those allowed by the design authority then it may be necessary to record and maintain the orientation of the part used during qualification and certification throughout all part manufacture (REC6.10).**

As discussed previously the geometry of the part may be determined by the limitations of the AM machine. For some systems this may limit the use of certain shapes. The orientation of the part is also important when considering overhanging structures. Some example enclosed overhanging shapes and an indication of whether they can be built without support structure is shown in Figure 6-5.



Support structure recommended?	NO	YES	YES	NO	NO	YES

Figure 6-5 - Some example hole geometries and an indication of whether they can be built without support structure using AM [6.37].

Supports are used extensively in powder bed AM systems but are less likely to be used in the directed energy systems such as WAAM. The supports are thin sections of material that are built with the part to support overhanging structures. As well as providing a physical support, they can also be useful in conducting away any excess heat built up during the build process to the build plate. At the end of the build, usually after stress relief has been performed, the supports are removed and are not present in the final part. The effect of the removal of these supports will be discussed in a later section of the document. **If supports are used, their structure and shape <u>should</u> be recorded along with any CAD models of the part to ensure that the support structure used in qualification and certification is repeated for each part built (REC6.11).**

Some powder systems use a re-coater blade to apply each layer of powder. When the re-coater blade passes across, the small layer height means the blade can be very close to the previous melted and solidified layer. There is a risk that the close proximity of the previous layer can lead to dysfunction of the re-coater operation, e.g. mis-coating, damage to the previous layer, damage to the re-coater, etc. Parts are orientated to minimise this effect by, for example, orientating to ensure long edges of the part are not in line with the re-coater.

Another factor that must be considered in AM is stepping. This occurs at certain geometries where the detail level of the AM process is not sufficient to maintain the angle required. This leads to steps on the surface of the part which affects surface roughness and therefore potentially fatigue properties. EOS for example recommends that flat surfaces are orientated at 0^{o} or greater than 20^{o} to ensure a surface quality without stepping. Post-machining can be used to remove surface defects if they are known to affect final part performance. This is often performed with DED systems where the lower resolution achieved can lead to unwanted surface features.

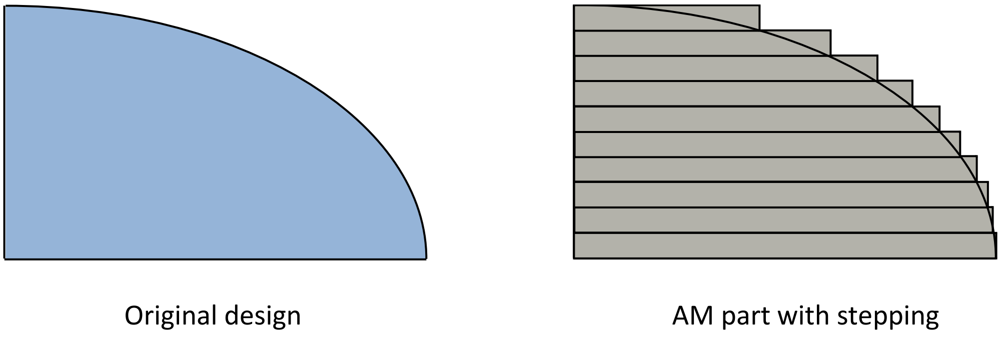


Figure 6-6 - Diagram to demonstrate the effect of stepping on a final part quality.

6.3.3.3 PART LOCATION

For powder bed systems where often multiple parts are being built the user will also determine how these parts and any test specimens are located and nested in the build volume. This is often optimised to maximise the number of parts being built and also to reduce the height of the build to reduce the amount of powder being used. As discussed previously the thermal properties of the melt pool are affected by how the energy is input to and lost from the part. It is possible that other parts being built near each other may act as a heat source or sink to another item within the build. This can in turn affect the formation of the melt pool and also affect the solidification of those parts, affecting final build properties such as residual stresses, surface roughness and porosity [6.9].

There can also be variation in part quality across the build plane due to aspects of powder flow and beam power. This can affect the microstructure and consequently the mechanical properties of the final part. Indeed it may be the case that some locations for the build plane must be avoided to ensure a quality part. This phenomenon is dependent on the characteristics of an individual AM machine (e.g. powder feed and laser system characteristics). For example multi-laser PBF systems, can lead to regions of poor part quality where lasers overlap.

Part location is also important in powder bed systems because of its effect on the order that the part is built. Generally the electron beam or laser will start in one corner of the build plane and build parts in a set pattern. This means that parts nearer that corner will be built first and those furthest away built last. This could lead to a subtle difference between the thermal histories of each of these parts, affecting final part quality.

In multiple part builds the number of parts being built could also have an effect since there is a significant time difference between layers when building one part in the bed when compared to building five parts for example. This is considered to have a greater effect in DED AM systems where the build rate is slower so the time between layers could be considerable. The layers tend to be thicker than in powder bed systems so the cooling rate is slower. PBF systems additionally have a faster build rate so are less affected by the use of multiple parts. Powder bed systems also have additional time between layers owing to the deposition of the next powder layer. This can have a cooling effect since cold powder is added to the cooling material.

If the variation due to location and number of parts leads to a scatter of properties greater than those allowed by the design authority then it may be necessary to record and maintain the build plan used during qualification and certification throughout all part manufacture (REC6.12).

6.3.3.4 TEST SPECIMENS

In addition to as-built AM test specimens, witness specimens may be used. These are designed to be more representative of the final part and may be machined to make standard test specimens. They are particularly important in AM where the thermal history of the part can affect its properties. This means that tensile coupons with their particular thermal history could have different mechanical properties to the final part. **If witness specimens are used to reduce the number of whole-part cut ups, evidence should be produced to demonstrate that the witness specimens are representative of the final part (REC6.13).** Although witness specimen design may be based on modelling, physical evidence should be provided to validate that the witness specimens are representative of the final part.

As with manufactured parts, build location and orientation should be considered for witness and test specimens so that they more accurately reflect this source of scatter during the qualification process (REC6.14). Witness and test specimens should also undergo the same processes as the AM part.

6.3.3.5 SCAN STRATEGY

The pattern of how the AM layers are applied; the scan strategy, is important for all types of AM. For PBF systems in particular there is greater control and more parameters for scan strategy than for DED systems. Nevertheless scan pattern design is also a variable for direct energy deposition.

The first parameter to consider in developing a melting strategy is the scan spacing, as discussed further in the section on solidification and melting, it is the distance between the individual passes of the AM system and is important because it is one of the parameters that determine energy density; with consequences for defects such as porosity, lack of fusion, etc. The scan spacing will consequently affect the microstructure and mechanical properties of the part. The scan spacing is usually specified for the feedstock and the type of AM machine [6.38].

Once the scan spacing has been decided, in considering the scan strategy for some AM systems each layer of the part may be considered as two main sections, the central section which contains the bulk of the material, and the edges – often called the shell. The scan strategy dictates how both sections are applied using AM. The relative areas of central and shell sections are determined by the part dimensions and the scan strategy used for its build. Any change to part shape may require a different scan strategy and different core/shell form, which could affect part properties.

Several different fill patterns are in use across AM. One of the most common in powder bed systems is the island pattern which fills using a checkerboard of orthogonal laser directions as in Figure 6-7. In the island strategy each square is often scanned in a random rather than specific sequence. This has been shown to help limit residual stress and gives each square some time to solidify before applying an adjacent square. Further, islands on subsequent layers are often offset by a given distance and direction relative to the one below [6.24].

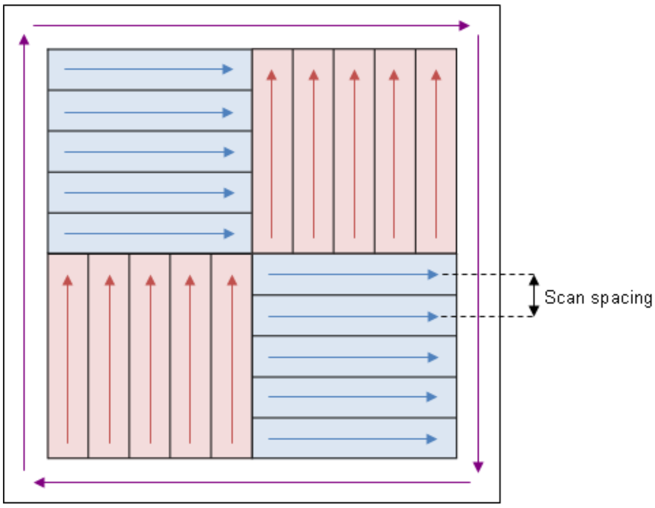


Figure 6-7 - Schematic representation of a checkerboard scan strategy typically used in powder bed systems. The arrows represent the scan vectors with the distance between these vectors defined as the scan spacing. The purple arrow demonstrates a single contour scan around the part.

As Figure 6-8 shows, the scan pattern used can also have an effect on microstructure of a build. Owing to the factors discussed in the earlier section on melting and solidification of metals during the AM process. Microstructure can have an influence on the final mechanical properties of the part. **If the effect of scan strategy is observed to be significant it may be necessary to record and maintain the scan strategy used in qualified builds in all subsequent part manufacture (REC 5.15).**

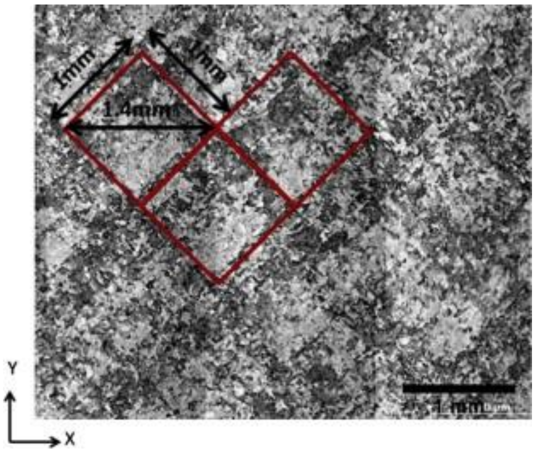


Figure 6-8 - Micrograph showing the 1 mm repeating pattern in the X–Y plane in a laser PBF fabricated nickel superalloy [6.39].

The edges of the part may be treated differently to the central section and in powder bed systems in particular a process called edge contouring is used to optimise surface quality vs. build speed. In this process a single or double wall of material is melted on the edge of the part layer before the central section is filled. A final application of the beam may also be used after the central section has been filled to further improve the surface roughness of the part. **The effects of surface roughness on fatigue in particular means that this edge contouring could have a significant effect on the scatter in mechanical properties. If this is the case, the method of edge contouring used should be recorded and the same technique used for all qualified builds (REC6.16).**

6.3.4 BUILD PARAMETERS / PARAMETER SET

In addition to scan strategy which was discussed in the previous section, typically three main build parameters are considered when producing parts through AM:

- Build speed – how fast the heat source moves
- Heat source power and spot shape – the power applied by the heat source and the area to which it is applied.
- Layer thickness – the thickness of material deposited for each layer

As discussed earlier, these parameters affect the melting, solidification and cooling of the local build volume which in turn will influence a range of mechanical and geometric properties of the final part. In the build design stage these parameters provide an energy input/output balance and are optimised on a machine by machine basis to produce the desired properties in the final part. This means for AM parts the build parameters are very important in determining the properties of the final part.

The build parameters used (e.g. heat source power, build speed) should be recorded and maintained for any qualified build since any change in these parameters defined by the AM process may affect the mechanical properties, geometry and defects, and their scatter in the final part (REC6.17).

6.3.5 SUMMARY OF BUILD DESIGN GUIDANCE

The effects of part configuration, build supports, scan strategy and build parameters on the thermal history of the part could lead to a significant scatter in relevant part properties. Consequently these variables should be fixed to those optimised in the design phase of the build and then qualified for the part.

6.4 BUILD KEY PERFORMANCE VARIABLES (KPVS)

When discussing the key process variables for AM it is easy to be overwhelmed by the many different types of inputs and their effect on the final part. Key to all the variables within AM is the thermal processes during the build. The introduction to this chapter began with an initial discussion of some of the thermal interactions taking place during an AM build and their effect on the microstructure and properties of the part. These thermal interactions are in turn determined by the build key performance variables, this section will discuss these variables and how they are managed at a machine level.

One of the key features of AM is the element of computer control that the machines use. Generally, by the time the build has started the parameters required for the build are locked in and any variation in them is a consequence of a machine or software action and not from a direct action of the operator. Hence application of good practice is the primary method to manage most build KPVs, namely:

- Regular calibration and maintenance of the machine. **As with any machine the calibration routine should show control over all aspects that are critical to the final part. The frequency of re-calibration should be sufficient to provide confidence that unacceptable changes have not occurred between calibrations (REC6.18).**
- An understanding of how software updates and changes to the machine might impact the final build quality. **The software version used to produce qualified AM builds should be recorded and any change in software should be shown not to be detrimental to the properties and the scatter in the final part (REC6.19).**
- Installing and operating the machine as much as possible within the machine manufacturer’s specifications.

Several broad standards exist to give guidance for machine operation, calibration and diagnostics such as BS ISO 17359:2011 [6.40]. The guidance below will focus on the AM specific aspects of variation during builds.

6.4.1 FEEDSTOCK

Almost all AM processes are reliant on a feedstock material from which a computer controlled system produces the final part. This guidance will focus on two main feedstock materials for AM:

- Metal powder.
- Metal wire.

As set out in the introduction to this document (chapter one) other feedstock materials such as polymer materials will not be addressed in this document. Although it is the aim of this document to be process agnostic, nevertheless the specific challenges of feedstock control in each system means that for some KPVs the guidance will be divided into powder and wire feedstocks.

6.4.1.1 CHEMICAL COMPOSITION AND ENTRAPPED POROSITY

The chemical composition of a feedstock is the constituent elements or molecules of the alloy used. The chemistry of these materials affects the composition, microstructure and ultimately the properties of the final part.

Non-destructive techniques to measure chemical composition of the feedstock material include: Energy dispersive X-ray spectroscopy (EDS), X-ray photoelectron spectroscopy (XPS), atomic adsorption spectroscopy (AAS) and X-ray fluorescence analysis (XRF). Destructive techniques to measure chemical composition of the feedstock material include: Inductively coupled plasma mass spectrometry (ICP-MS). Gases such as oxygen, nitrogen and hydrogen can be measured within a sample using a technique such as inert gas fusion (IGF).

Since feedstocks, whether powder or wire, have a large surface area to volume ratio a particular concern is their surface chemistry. If it is significantly different from the bulk chemistry, feedstock materials may not consolidate as expected leading to porosity and/or inclusions in the final part; especially the case for metal powders. For example, in some metal alloy powders high levels of surface oxygen, either dissolved or present as oxides, can affect the mechanical properties of the final part [6.10];[6.41];[6.42].

Welding wires typically used in wire-based AM may be manufactured using drawing where the metal is pulled through a die to make a narrow wire. The drawing process may use e.g. oil-based lubricants which are then left on the surface of the wire. The surface contaminants can then be included in the final part, affecting its mechanical properties. Cleaning processes may be applied to remove these surface contaminants before the wire is used.

Additional sources of chemical variability are chemical changes during the melt processes such as evaporation of volatile elements or oxidation of elements. To control the chemistry of the final part these effects should be accounted for in feedstock materials planning.

During powder manufacture through gas atomisation, gases can become entrapped within the material as pores. These gases can incorporate into the final part build leading to porosity in the material. This inherent porosity can be determined by preparing a cross section of the material through polishing and then through optical or scanning electron microscopy of the cross-section. Gas pycnometry can also be used to measure the powder effective density, This identifies entrapped pores in the powder since the density will be lower than the theoretical density of the alloy [6.43].

6.4.1.2 STORAGE

The large surface area of AM feedstocks and the narrow property distribution requirements of many AM machines mean that feedstock material storage conditions are especially important. Changes to the feedstock material if stored under inappropriate conditions can severely affect the chemistry of the material and ultimately the quality of the final part. For powder materials humidity control during storage is particularly important since moisture can additionally affect flow by altering the electrostatic charge on the powder particle or through capillary action [6.43];[6.44]. **Evidence that properties have not deteriorated during storage <u>should</u> be provided when undertaking any project**

using AM as well as information about the storage conditions and timings in which the feedstock properties remain within a specification. Storage conditions should take into account storage at the powder manufacturer/provider, during transport and at the part manufacturing facility (REC6.20).

It is recommended that powders of some alloys such as titanium alloys are stored and handle under inert gas e.g. argon (REC6.21). If the feedstock (e.g. titanium) or process (e.g. PBF) are moisture sensitive, evidence should be provided that moisture levels in the feedstock environment or feedstock are below a value that will affect the properties and scatter of the final part (REC6.22). Desiccant bags that absorb moisture may be included with powder batches to reduce moisture content.

6.4.1.3 KEY PROCESS VARIABLES RELATING TO POWDER FEEDSTOCKS

6.4.1.3.1 METHOD OF POWDER MANUFACTURE

Whether produced directly in powder form or produced from an ingot of bulk material, the method of manufacture of a powder can have a considerable effect on its morphology, chemistry and flow properties which will in turn affect the quality of the final part. Any change in the powder production process should be recorded and further tests may be required to ensure the powder properties have not deviated from those specified. Before use powders are typically processed through sieving and blending to give the required size distribution. Sieving and blending will not affect the microstructure of the powder particles and may not affect their shape.

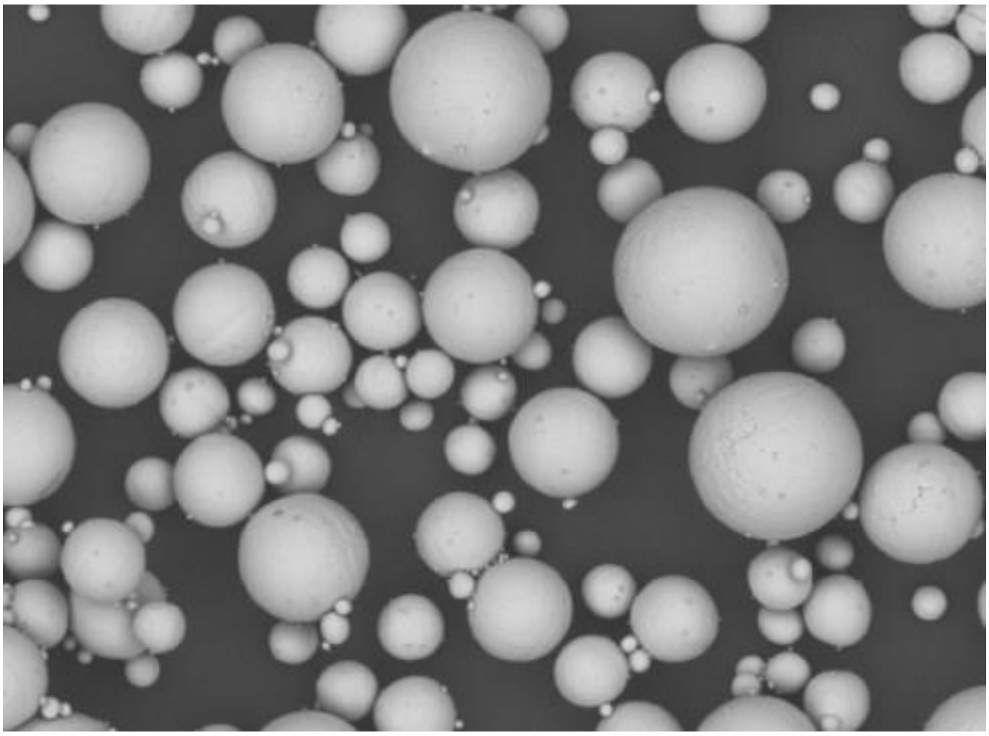


Figure 6-9 - Example of metal powder for AM [6.45].

Metal powders for AM are usually manufactured using an atomisation technique. In atomisation the metal ingot is melted and then enters an atomisation chamber from above. In the chamber it falls through different cooling mechanisms depending on the atomisation type. The solid powder is then collected at the base of the chamber and processed to the required size.

Three main atomisation techniques exist. In water atomisation the molten metal particles are sprayed with water to cool and atomise them as they fall. As well as leading to contamination in some particles the water atomisation technique can also lead to significant differences in morphology than other powder production techniques. Gas atomisation is similar to water atomisation except a gas is used to cool and atomise the particles. This gives greater control of the chemistry of the powder than other techniques.

In plasma atomisation, solid material is fed into a chamber in solid form where it is simultaneously melted and atomised by coaxial plasma torches and gas jets. In addition to providing the advantages of the gas atomisation techniques, this technique leads to highly spherical particles. A subset of the plasma atomisation method is Plasma Rotating Electrode Process (PREP) which uses a rotating bar as a feedstock. Plasma is used to melt the end of the bar and the rotation ejects the molten material which will solidify before hitting the chamber walls [6.43]; [6.46].

6.4.1.3.2 RHEOLOGY E.G. FLOW, TAP DENSITY, ANGLE OF REPOSE

All powder AM systems are strongly reliant on the ability of a powder to flow. In blown powder systems, the flow of the powder affects the rate that the powder is applied to the surface which affects several properties including density and surface roughness of the final part; these in turn will affect its mechanical properties. In powder bed systems the powder flow affects the packing of the powder in the AM chamber which will in turn affect the density of the final part. In powder bed systems the flow also affects the spreadability of the powder and the angle a pile of powder forms when the powder coater moves across. Powder rheology is a study of the flow properties of powder systems. Traditionally powders are characterised using the following measurements techniques:

- Hall flow – the speed of flow of the powder through a standard funnel.
- Angle of repose – The angle formed by the pile of powder when it flows through a funnel.
- Tap density – The density of the powder after it has been tapped a known number of times.

Although these techniques have some merit as a cross-check of powder system degradation, more recently dynamic powder rheometers that use a rotating blade or drum have been deployed and offer a more repeatable test of a powder’s resistance to flow whilst the powder is in motion, the powder’s shear strength and bulk powder density, compressibility and permeability. The main advantage of these systems is that they are able to distinguish between smaller variations in powder rheology and also provide a more realistic flow environment [6.47]; [6.48].

6.4.1.3.3 PARTICLE SIZE DISTRIBUTION

The particle size distribution of powder materials is important in determining the thickness and quality of each layer in the AM process which can in turn affect a wide range of properties in the final parts. The size distribution of a powder feedstock material is often specified by the machine manufacturer and the maximum resolution of the part is determined by the particle size.

Several techniques exist for measuring particle size distribution and different measurements can give slightly different results owing to the assumptions applied in the measurement or analysis of particles, and other sources of error [6.49]; [6.50]. The two most commonly used methods for AM powders are outlined here. The size distribution and morphology of a powder can be measured using microscopy. In this technique a scanning electron microscope or optical microscope are used to take an image of a single layer of particles on a plate. Image processing can then be used to determine the size distribution of a sample of particles. Another technique that can be used to measure the size distribution is using light scattering techniques in which the light scattered by an individual particle is measured giving a size distribution [6.51].

The main technique used to control particle size is sieving of the powders in which different sieves are used to remove powder particles above and below the required size. Powder morphology can affect the results of sieving since elongated particles may pass through the sieve despite being oversized.

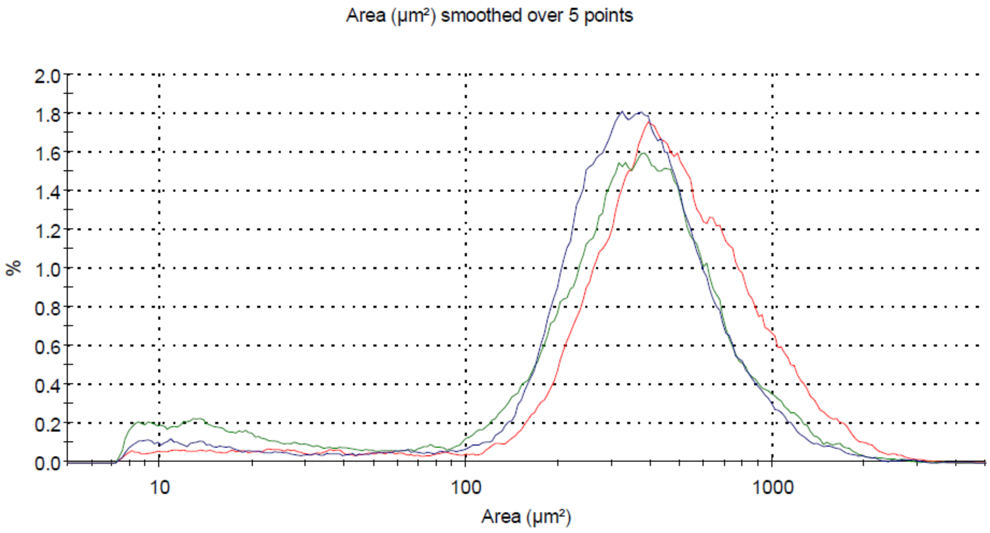


Figure 6-10 - Example of the size distribution of three metal powder samples based on the area of the particle. The microscopy method was used to determine particle size distribution.

6.4.1.3.4 PARTICLE MORPHOLOGY

Powder particle morphology, the shape of the powder, is also important for the flow of the powder and can have an impact on the surface roughness of the part. Particle morphology is typically measured using microscopy as described in the previous section, image processing can then be used to determine shapes of particles in addition to size. Particles can then be characterised based on a range of geometric properties including:

- Circularity – how close the shape of a particle is to a perfect circle.
- Aspect ratio – the ratio of width to the height e.g. circle has an aspect ratio of one and a line has an aspect ratio of zero.

- Area – the total area covered by the particle.

As with particle size, results are typically reported as a distribution. Sieving is typically used to control powder properties for additive manufacturing and although this is useful in controlling particle size, it does not affect the morphology of the particles since elongated particles, for example, can pass through the sieve despite having a large size. If morphology has deteriorated to be outside of the specification set by the machine manufacturer or the Production Organisation, plasma spheroidisation can be used to produce powders of the required morphology.

6.4.1.3.5 POWDER REUSE, RECONDITIONING AND BATCH CONTROL

In order to keep material costs to a minimum, most of the AM systems that use a powder bed technique will undergo a process to reuse powders. The reused powder is defined as any powder that has been through the AM machine but has not been formed into the consolidated part. This can then be mixed with known quantities of virgin / unused powder to be re-used in the machine. Some AM systems offer "closed-loop" powder handling which is beneficial for safety and to minimise contamination from outside sources. The computer controlled aspects of closed loop powder handling means, however, that the operator may not be aware of how many times powder has been used and the nature of blending operations performed. Eventually a powder's properties may have deteriorated through reuse to a point where they are no longer within specification and could affect the quality of the final part. At that point, the powder is considered degraded and should cease being used to manufacture that part.

It is recommended that for critical components, the powder quality <u>should</u> be tracked through sampling and testing to ensure the powder does not fall outside of specification. Example powder specification measurements <u>should</u> be determined by the component manufacturer but could include measurements of chemical composition, particle size distribution and flow and packing properties (REC6.23).

Powder samples for testing <u>should</u> be representative of the powder used in the final part (REC6.24). Many different types of powder samplers exist which enable sampling from different locations through the depth of a batch of powder. The powder from each sampling location is mixed and then used to produce a representative sample.

Where different powder batches, whether virgin or used are mixed, both powders <u>should</u> be confirmed as within specification or the new mixture of powders <u>should</u> be re-tested to confirm the powder properties are within specification (REC6.25). The complexities of powder batch control mean that software is sometimes applied in the tracking powder batches and quality.

In some cases the lifetime of the powder may be extended through reconditioning before reuse for AM Techniques for reconditioning include the following:

- Sieving – passing the powder through a sieve of a known pore size to make sure the powder used remains within the size distribution specified by the AM machine manufacturer or the AM part supplier.
- Moisture removal – heating the powder in an inert atmosphere to remove any moisture that has been absorbed by the powder during storage.

– Plasma spheroidisation – a process that uses a plasma source to remove surface impurities and improve morphology and flow characteristics of the powder [6.45].

6.4.1.4 KEY PROCESS VARIABLES RELATING TO WIRE FED SYSTEMS

It is apparent from the discussion above that powder feedstocks have a large number of characteristics whose variability may affect build quality. Wire feedstocks have fewer sources of variability; nevertheless these must also be considered, measured and controlled for consistent build quality.

Many wire-fed systems use wire with properties to welding standards such as BS EN ISO 544 (e.g. diameter tolerances) [6.52] and BS EN ISO 18273, BS EN ISO 14341 (e.g. composition) [6.53]; [6.54] however caution must be exercised when using welding wire standards for AM. Welding wire standards have been developed over many years to support the production of joints of adequate and repeatable quality, mainly by manual methods and for non-aerospace applications. For some characteristics specified tolerances are fairly tight, e.g. for Metal Inert Gas (MIG) welding wire diameter of 3.0 mm +0.01 to -0.07 mm [6.52], while for others guidance is fairly loose, e.g. the surface of the welding consumables shall be free from contamination and surface defects that can adversely affect welding. Any surface finish is allowed, provided that the welding operation and the properties of the weld metal are not adversely affected [6.52]. For wire-fed AM processes it is likely that the length of wire used is large compared to welds since it is building up a whole three dimensional structure. It is also a feature of any consumable that there may be supplier to supplier and batch to batch variation, with some batches (or parts of the length) sitting outside the current specifications. **For the AM of aerospace parts using highly controlled and repeatable robotic welding systems the characteristics of the wire <u>should</u> be controlled to a much higher level of consistency along the length than is typical for welding. This could include properties such as diameter, composition, surface quality (kinks and nicks), surface contamination, etc. (REC6.26).** As wire-fed AM develops it is anticipated that there will be concomitant development in wire specifications by suppliers and users [6.55].

6.4.1.4.1 WIRE FEED RATE

The feed rate of the wire feedstock is monitored and controlled through the robotic welding machine and is an important parameter in controlling part quality. In coordination with the travel speed it determines the quantity of material deposited and, along with other weld parameters, the characteristics of the “weld bead”. Too low a feed rate will result in insufficient material being deposited and potentially the wire melting too far back from the melt pool. Too high a feed rate can result in lack of fusion defects owing to penetration of the arc into the base plate or previously deposited material [6.14]. **Wire feed rate <u>should</u> be recorded for each build as one of a number of parameters that demonstrate that the part is being built in accordance with its qualification (REC6.27).**

6.4.1.4.2 WIRE ELECTRICAL CONDUCTIVITY / RESISTIVITY

For some types of WAAM the wire feedstock also acts as the electrode, wire electrical conductivity / resistivity is rarely mentioned as a variable for consideration in the literature on WAAM. It is suggested that major differences in wire composition, from those for which the process has been optimised, would be required to have a significant effect on electrical properties, and that these would be detected during chemical analysis. An experimental technique known as induction-assisted WAAM has been reported where induction heating is used to manage the build-up of residual stresses in the part [6.56]. The electrical resistivity of the wire is only indirectly relevant since the wire becomes the substrate, within which electromagnetic heating is induced.

6.4.1.4.3 WIRE DIAMETER

In choosing the wire for WAAM, as with arc welding, consideration must be taken of the feed rate of the system and the energy supplied by the arc. At smaller wire diameters the feed rate will have to be increased to deposit the same amount of material than that for larger diameters. How the wire melts must also be considered as larger diameter wires may not fully melt if the energy of the arc is not adjusted [6.14].

In addition to choice of wire diameter, variation of wire diameter (tolerance) within a wire batch and between wire batches should also be considered (see BS EN ISO 544 [6.52]). Wires should be at the diameter and tolerance specified on purchase. Diameters outside the tolerances specified by the purchaser may lead to variable melt pools and inconsistent lay down of material, which in turn could lead to poor build quality (surface roughness, porosity, etc.).

Diameter measurement should be undertaken based on relevant standards for example BSI EN 13479. In BSI EN 13479, diameter is measured using a micrometer screw gauge at five random points within a batch. Other, automated, diameter measuring systems are available including laser systems. The wire manufacturer should provide the wire to a standard specification agreed with the purchaser which will cover properties such as diameter, diameter tolerances and chemical composition. **The wire manufacturer, diameter measuring system and specification agreed and followed for each numbered batch <u>should</u> be recorded for each batch used for the manufacture of AM components (REC6.28)** [6.54]; [6.57].

6.4.1.4.4 CROSS-SECTIONAL SHAPE

The cross-sectional shape of feedstock can also be an important variable in wire feedstocks and care should be taken to ensure that there are not any kinks or nicks that could affect the properties of the final part.

Kinks in the wire can affect the feeding mechanism which can also cause problems with amount of molten metal applied, affecting build quality. It is possible to identify some kinks through visual inspection of the wire and, while not a quantitative technique, it will give an indication of the quality of the wire.

Most current AM wire feedstocks are based on wires for welding and are circular in cross-section. Depending on the requirements of the user it may be necessary to inspect the shape by taking cross-sectional samples and using appropriate mounting and microscopy techniques.

6.4.2 HEAT SOURCE

As discussed above the thermal processes involved in AM are fundamental in controlling microstructure and defects and as a consequence, mechanical properties. Any variation in the heat source (and interaction with the feedstock and substrate) can lead directly to variation and scatter in the mechanical properties of the part.

The theory of formation of the melt pool in AM was discussed briefly above. In an ideal AM system in-situ monitoring and control would allow real time adjustment of the machine to give an optimum and constant melt pool. This is not currently possible and optimisation is achieved by performing parametric studies on the parameters that are used to control the heat source and then inputting these into a calibrated machine. While machine types, heat sources and feedstocks in AM differ it is helpful to consider just three parameters that are commonly used to control the melt pool: (a) build speed; (b) heat source power and focus (spot size and shape); and (c) layer thickness.

As with any mechanised manufacturing method, confidence in KPV control and measurement methods (and their variability) is by scheduled calibration. Records of any calibrations should be retained to provide the evidence that important KPV parameters are as defined and inputted, and their variability is within acceptable limits. It should be a feature of the AM part qualification process that there is agreement on those parameters/systems requiring calibration, the appropriate method and frequency of calibration and how and what records are kept for parts and specimens. Standards exist on the competence of testing and calibration laboratories [6.58].

For most AM systems, build speed is typically measured by the AM machine which records the length of material deposited over a known time. As with welding, build speed can be confirmed using a ruler and a stop watch to measure the time taken to deposit a known length of material [6.55]. When considering the other aspects of the heat source for AM there are differences between heat sources – feedstock interactions. Consequently it is necessary to split the guidance into two categories:

- Powder bed systems where the material is deposited first before being melted directly by the beam e.g. SLM, EBM.
- Powder or wire fed systems where the substrate is melted and material is added to the melt pool e.g. WAAM, laser blown powder.

This distinction is also necessary because the control and measurement methods for each are significantly different.

NOTE: Calibration builds are a key aspect to AM machine calibration; they are parts and test specimens built to known parameters and geometries that enable the user to identify and track any changes in the machine. They are also used in welding calibration and are used to determine the size and position of the weld. Calibration builds will be discussed in section 6.4.4 of the guidance; this section will instead focus on direct techniques for measuring variation in the AM machine input parameters.

6.4.2.1 POWDER BED SYSTEMS

The powder bed systems for metallic parts use either a laser or an electron beam as their heat source. In qualifying AM the variability of the beam should be understood. For example the characteristics of a beam could change through time (power, focus, shape, etc.) or could change depending on the position it is focused on in the build. This also implies that any differences between inputted / assumed power cf. power at the location-specific melt pool should be understood. As discussed in the previous section calibration may involve direct access to the beam which is hazardous and requires override of interlock systems and should only be done by qualified personnel and with the machine manufacturer's support/guidance.

6.4.2.1.1 LAYER THICKNESS

For most powder bed systems the build plate lowers by a specified amount before a layer of powder is applied by spreading it across the build plane using either a roller or blade (which also expels excess powder). The layer thickness is primarily defined by the depth of the build plate drop. The layer thickness is important since it determines the amount of material to be melted and the resulting beam power density required at the working volume (the layer thickness is also influenced by powder properties - see Section 1.1.2). Consequently it may be important to ensure a correct and consistent drop over time and at positions in the build plane by routine calibration.

6.4.2.1.2 LASER BEAM CALIBRATION

For laser powder bed systems the laser is focussed using physical lenses to give a small spot size to provide the level of detail in the AM part. Over time the focal point may shift leading to a change in diameter of the spot and a potential change in the applied heat density of the laser. The focal point is calibrated using the focus offset which is the distance in mm that the laser focal point is from the build plane. By moving the laser focal point up and down the location in the z axis of this minimum diameter region can be determined and then altered to give the required spot size (see Figure 6-11). For some applications the part may be built with a particular focus offset to use a more diffuse laser as determined from build optimisation studies. The beam diameter can be calibrated by using several filters to significantly reduce the power of the beam so it can be measured by a charge coupled device (CCD) camera. The CCD camera gives the beam diameter, which can be measured at different powers and focus offset values [6.59].

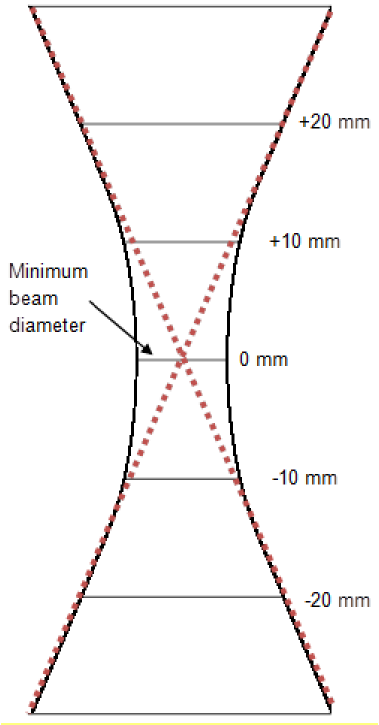


Figure 6-11 - Diagram to demonstrate focus offset in laser beam systems

The laser power is measured using a laser power meter. The laser power is then calibrated based on requested vs. actual power. Equipment is also available to measure the profile of the laser, for example the shape of the beam intensity across the spot area. The dimensional accuracy of the laser can be calibrated by scanning a pattern over a thin layer of material. The laser removes the thin layer of material where it hits and the deviation in the subsequent pattern can be used to calibrate the dimensional accuracy.

The laser beam for laser powder bed systems <u>should</u> be calibrated at least annually to ensure that its characteristics do not change through time to reduce scatter in the properties of the final part (REC6.29). Further guidance on the calibration of high power lasers (>2 W) is provided in NIST publication 250-77 [6.60].

NOTE: Developments in laser-based AM systems could include dynamic control of laser power and spot size, which may require consideration with respect to qualification and certification.

6.4.2.1.3 ELECTRON BEAM CALIBRATION

For EBM AM methods electron beams are focussed using electromagnetic lenses rather than the physical lenses used in laser optics. The beam focus offset may also be altered in EBM to maintain a consistent melt pool. During contouring the beam may have no focus offset before being defocussed to produce the core of the part [6.11]. The parameters used to determine electron beam melt pool characteristics are similar to those used for laser beam melting, i.e. (a) build speed; (b) heat source power and focus (spot size and shape); and (c) layer thickness, nevertheless there is a fundamental difference in how the melt pool is controlled. In laser beam melting, a heat source with a constant voltage and current is used whereas in electron beam melting complex algorithms are used to alter these values to maintain a consistent melt pool [6.11]:

- Current compensation algorithm – beam current is altered based on the length of the hatch line with higher currents on longer hatch lines to allow for the effects of heat dissipation.
- Speed function – beam velocity is also varied based on the beam current to maintain a consistent melt pool size.
- Turning point function – reduces the beam energy near the start of a hatch line where the melt pool is adjacent to the end of another hatch line and so there is not time for the heat to dissipate before applying the beam.
- Thickness function – This accounts for the lower conductivity of the sintered powder underneath a thinner sample, the speed is increased which reduces the heat input to prevent heat accumulation [6.61].

Electron beam powder bed systems should be calibrated at least annually to ensure that parameters such as electron beam power, speed and motion are within acceptable limits as part of the assurance that the part has the specified properties (REC6.30).

6.4.2.2 DIRECT ENERGY SYSTEMS

Variation in the weld for direct energy additive systems is determined primarily by three key parameters:

- Stability of the weld – maintenance of a continuous weld path without any gaps or defects in the material.
- Size of the melt pool – the size and depth of the base plate / substrate that is melted before the material is added.
- Accuracy of the computer controlled movement system – how the computer controlled systems for direct energy systems move and how this varies.

Since some direct energy deposition systems are based on welding process they could be calibrated using the same or modified methods. For arc welding, calibration typically focuses on the voltage and current of the arc using measurements at different input values to confirm that the required current or voltage is being generated. Standards such as BS EN ISO 15609-1:2004 [6.62] and BS EN 50504:2008 [6.63] have further guidance on arc welding qualification and validation. It is common to calibrate welding systems by determining penetration depth and position of the weld using non-destructive testing. Other AM-type systems, especially those used for repair, are similar to laser cladding where standards such as BS EN ISO 15609-4:2009 [6.64] may be useful.

Available standards should be applied to calibration of Direct Energy Deposition techniques. Arc welding AM systems such as WAAM should be calibrated with standards such as BS EN ISO 15609-1:2004 [6.62] and BS EN 50504:2008 [6.63] as a guide. Blown powder systems which are similar to laser cladding should use standards such as BS EN ISO 15609-4:2009 [6.64] to guide in calibration (REC6.31).

6.4.2.2.1 CALIBRATION OF ROBOTIC MOVEMENT SYSTEMS

Direct energy systems typically use computer controlled positioning systems such as robotic arms or multi-axis rotation devices. How these systems move will affect the geometry of the final part and could also affect how the heat is applied to the deposited zone. The calibration of the industrial robotic movement systems is described in BSI BS EN ISO 9283 and uses a range of test movements to cover two key aspects of the calibration:

- Pose accuracy – the ability of the robotic system to move to a static position and how the robot holds that position over time.
- Path accuracy – the ability of the robot to move along a required path and any deviations from that path observed at corners, for example [6.66].

Both calibration items will usually include both position and orientation of the robot. Although some characteristics can be measured manually, increasingly automated measurement systems that employ touch probes or laser scanners are used to calibrate the movement of the robot.

For wire fed systems calibration of the welding part of the robot typically focuses on the travel speed and wire feed speed of the robotic system and both can be measured based on the length of material deposited over a known time period [6.67]. For laser blown powder systems the accuracy of the laser is calibrated by reproducing some standard test patterns and measuring the deviation from the requirements. Further guidance can be found in BS EN ISO 22827 for Nd:YAG lasers [6.68]; [6.69] and BS EN ISO 15616 for CO_2 lasers [6.70]-[6.72]. Both standards use calibration builds to determine the accuracy of the movement of the laser system and check geometric deviations from the expected build. Further details of geometric tolerance measurement are in Section 6.4.4 of this guidance note. **Calibration builds should be used to determine the geometric accuracy of robotic movement systems for direct energy deposition techniques (REC6.32).**

6.4.2.3 MATERIAL PRE-HEATING

For many AM processes a heated build bed is used to heat up the feedstock, base plate or already built material before the next layer is added. At lower temperatures (100-200°C), and depending on the material, the heat provided removes moisture from the material and has a minimal effect on the thermal properties during melting. This is particularly important in powder bed systems since the high surface area of powder particles means they can adsorb a lot of moisture. A variation in this pre-heat time could mean that there is greater moisture content in the material which could lead to porosity and deviations in chemical composition, for example in hydrogen content which can cause embrittlement and cracking in some alloys. Pre-heating at these low temperature ranges can be measured using temperature sensors within the build plane and controlled by increasing or decreasing the level of heating accordingly.

In systems such as the Arcam electron beam melting AM machine the pre-heating step is performed by the electron beam and the pre-heated material can reach relatively high temperatures, e.g. as high as around 1000°C for nickel-based superalloys [6.19]. Depending on the temperature used the alloy can become sintered where it becomes loosely joined together through surface melting. The sintering step reduces the need for supports and pre-heating and sintering can reduce the levels of residual stresses and/or distortion in the part. These relatively high preheating temperatures will also affect the microstructural evolution of the material, owing to time at temperature and solidification and cooling rate [6.24]. Consequently in systems such as EBM deviation in the pre-heating regime of the powder bed can have a significant impact on the mechanical properties of the final part and should be controlled. This control is usually performed at machine level by tracking the temperature of the build volume and any calibration should ensure that the pre-heating step does not vary significantly between builds.

If certification is based on a pre-heated build plane, the pre-heating temperature of the build plane should be calibrated to ensure it is at the correct temperature and does not vary to a point where the scatter in material properties could be affected (REC6.33).

6.4.3 ENVIRONMENT

The environment, both external to the AM machine and within its confines can have an effect on the final properties of the part and can lead to inter-machine variability. The environment primarily has an effect on the chemistry of the final part and of greatest importance is the gas atmosphere in which the part is manufactured.

Most metals will oxidise when exposed to air and this process is accelerated at the high temperatures required to melt metals. Consequently many AM processes are performed within an inert atmosphere by either using a shield gas or using a sealed build chamber filled with the inert gas. In some cases nitrogen can be used as an inert gas; however the tendency for nitrogen to react with some metal systems means that argon is used much more widely. The inert atmosphere is usually moisture controlled to reduce the moisture take up of the feedstock material during the build. While EBM is carried out under vacuum a small amount of inert helium gas is usually injected to prevent charging of the build chamber.

The effect of the gases used on the chemistry and mechanical properties of the final part means that in all AM systems the gases are key. **Where used to produce an inert atmosphere, the oxygen content within gases and containment systems should be monitored and should be handled so as not to be contaminated (REC6.34).**

The detrimental effects of oxygen during heating, melting, solidification and cooling of metals (e.g. oxidation, dissolution of oxygen so as to act as an unintended alloying addition) means that many AM systems have an oxygen sensor that is used to ensure oxygen levels are below values that would be detrimental to part quality**.** For some alloys such as titanium alloys the operating procedure for the part build may specify that the part cannot be built until the oxygen levels are below a set value. **Any oxygen sensors used to confirm oxygen content should be calibrated regularly to ensure continuing compliance of AM builds, further guidance on oxygen sensor systems can be found in BS EN 50104:2010 (REC6.35) [6.73**].

Some direct energy systems use shielding gases to control the environment around the part being built. In direct energy systems in general the shielding gas can also play a role in cooling the sample before the next layer of material is added. As discussed in the section on melting and solidification, this can have an effect on the melt pool formation which can affect the microstructure, defects and mechanical properties of the final part. As well as affecting the chemical composition and cooling in the final part, for laser blown powder systems the shield gas is used to control the flow rate of the powder which could in turn affect the amount of material deposited. **For direct energy systems the flow rate of the gas should be controlled and calibrated to ensure it is constant (REC6.36).**

In powder bed systems the effect of the powders in the environment should also be considered a variable. During the AM process the small powder particles can be dispersed into the atmosphere above the build plane which can diffuse the beam leading to a decrease in the amount of energy applied. Most powder systems use a gas flow across the surface of the powder and have a filtration system to remove any stray powder from the atmosphere. **The device filtration system should be qualified to an approved standard such as the British standard for HEPA filters and should have a regular maintenance and calibration regime to ensure that the filter does not become clogged with powder and ineffective. Filters should be monitored and handled so as not to introduce additional contamination and variability into the machine and ultimately the part (REC6.37) [6.32**]; **[6.74].**

6.4.4 CALIBRATION BUILDS

Calibration builds are used in additive manufacturing to test the performance of the machine and confirm there has not been a drift in parameters through monitoring a range of geometric, mechanical and materials properties. In direct energy deposition systems they are used to confirm the amount, mechanical strength and microstructure of material deposited. In powder bed systems they also confirm how these properties vary through the build volume. Standard geometric test pieces such as the NIST test artefact have been used to compare the geometries produced by different machines. **It is recommended that calibration builds should be used to calibrate all types of additive manufacturing machines used to build critical parts. The frequency and format of these builds should be determined based on the part requirements and the change in properties over the lifetime of the machine. Example properties that could be measured from calibration builds include geometric, mechanical and microstructural properties (REC6.38).**

6.4.5 IN LINE MEASUREMENT AND CONTROL

AM systems rely on a range of inline measurement and control systems to monitor/control parameters from gas concentrations to the power of the primary heat source. Research is underway on inline measurement and control of the melt pool geometry so that instead of inputting parameters that control melt pool, which are then fixed through the build, a user will instead specify a particular melt pool, e.g. temperature and size, and parameters may be automatically changed to maintain that melt pool. Another inline measurement and control system in development is the use of automatic defect recognition in the layers as they are built. The AM machine will then “fill in” defect areas or re-process them in some way to produce a better quality part. These sophisticated inline measurement and control systems are still in the early stages of development and may have consequences for qualification and certification. For example since parameters are not fixed additional assurance may be required to ensure and certify repeatability.

At the moment most AM machine manufacturers are developing inline monitoring systems that measure the temperature of the layer being built, use of image processing to find defects, etc. This information is used to inform the user and potentially stop a failing build before it wastes material. For qualification and certification it is envisaged that these inline measurement systems may add to the evidence that the porosity and internal geometry of a built part is within those outlined in the design stage.

6.4.6 SUMMARY OF BUILD KPVS

The variation of properties during the AM build is the most important source of scatter in the properties of the AM part. However, as many of these sources of variation are machine operated they can be the most difficult to control. The use of robust methods to calibrate AM machines is strongly recommended to track properties of the heat source, for example, over time and ensure part quality does not degrade between builds. The application of additional test coupons to track any potential degradation is also recommended and will be discussed later on in this chapter.

Another key source of variation within the build volume comes from the feedstock material. These materials, whether wire or powder, have a high surface area in relation to their volume so require careful storage to minimise contamination. Powders in particular offer a source of variation in addition to changes in chemical composition. Flow and packing of powder is additionally important to the quality of the final part. Environmental controls within the build are used to ensure that feedstock material does not degrade through reaction with oxygen, for example.

6.5 POST PROCESSING TECHNIQUES

Once a part has been built using AM, a range of processes may be performed on the as-fabricated part to improve the properties of the final part. This section will outline some common post processing techniques and discuss how they may influence the variability of the properties of the final part.

6.5.1 PART REMOVAL FROM BUILD PLATE

The first step in post processing is to remove the part from the AM machine. For powder bed fusion processes the part removal process can be more labour intensive since any excess powder and support structure will need to be removed from the part and the build plate. For laser powder bed the powder is generally removed by vacuuming the system. This process is usually done within the machine to limit the escape of powder to the environment. For electron beam powder bed systems the high temperature pre-heating step means the powder is sintered so is loosely joined together. This powder is usually removed by blasting the part with powder particles of the material with which they are built. This breaks up the sintered material, leaving the fully melted and solidified part to be processed further. In Direct Energy Deposition systems the parts are not usually encased in powder so require minimal part clean-up [6.6].

The next step in part post processing is to remove the part from the build plate, if used. For powder bed fusion techniques the part may be either directly attached to the build plate or attached using support structure. For Direct Energy Deposition techniques, part removal may not be required since for these techniques the material is generally deposited onto a plate of the same material that will be used in the final part. For some parts removal from the base plate may be delayed until after thermal processing techniques have been performed such as stress relieving. **Any stress relieving step performed before removing the part from the build plane <u>should</u> be recorded and monitored to ensure repeatability (REC6.39)** since it could have a significant effect on the residual stress in the part.

The basic method to remove the part from the baseplate is to cut the part off using either mechanical methods or electric discharge machining. Electrical discharge machining (EDM) is a technique where the part is immersed in a dielectric liquid and an electrode is passed near the point to be machined. A current is then generated across the gap that removes or "erodes" the material near the electrode. Many different electrode shapes are used for different applications; for removal of AM parts from a base plate an appropriate electrode may be a continuously fed wire that allows a large flat cut to be made. EDM can however affect the surface of the material, for example creating a thin "re-cast" layer, and it is therefore **recommended to consider the effect of any EDM artefacts on final properties, recording and monitoring where EDM is used (REC6.40).** While micro-EDM has been developed, standard EDM machines may be difficult to control for more intricate geometries and may not be appropriate for removing the support structure from some part locations.

The often manual nature of part and support structure removal has the potential to induce a wide variability in the surface properties of the final part. **Surface finishing techniques may be required on surfaces where support structure has been removed (REC6.41).** A subsequent sub section will outline some techniques that may be used to improve the surface finish of the part.

6.5.2 THERMAL POST-PROCESSING

The second type of post-processing is the thermal techniques. Several techniques exist; Table 6-5 shows some typical techniques and their procedures for two common alloys. The heat treatments are used to improve mechanical properties and reduce their scatter. Many of the techniques are common with conventional manufacturing methods therefore this section will seek to outline the available techniques and why they may be applied to AM parts in particular.

Table 6-5 - Typical post-processing procedures for Ti–6Al–4V and Inconel 718 [6.6].

Alloy	Ti–6Al–4V	Inconel 718
Stress relief	2 hours, 700–730°C [6.75]	0.5 hours at 982°C [6.76] 1065 ± 15°C for 90 min (−5±15 min) [6.77]
Hot isostatic pressing (HIP)	2 hours, 900°C, 900 MPa [6.75] 180 ± 60 min, 895–955°C, >100 MPa [6.78]	4 hours at 1120°C, 200 MPa [6.77]
Solution treat (ST)	Not typical	1 hour at 980°C [6.79]
Aging	Not typical	8 hours at 720°C Cool to 620°C Hold at 620°C for 18 hours total [6.79]

6.5.2.1 HEAT TREATMENTS

Fast cooling rates and local constraint within AM can lead to high levels of residual stresses in the final part. Residual stresses are stresses that persist in the material after the original cause of the stress has been removed. They can cause deformation of the part (both elastic and inelastic) which can manifest as distortion of the finished component. Residual stresses can also cause local hardening of metals through their effects on the microstructure. Unrelieved residual stresses will also superimpose on those that are externally applied, which can cause unforeseen failure if their presence has not been accounted for or managed [6.6].

The main technique to relieve stress in a part is through a carefully controlled heat treatment (a form of annealing). The part is heated to below a critical temperature; the critical temperature will depend on the metallurgy of the alloy but could be associated with a phase transformation or recrystallization. At the stress relieving temperature the atoms have more energy to diffuse within the structure and move, reducing residual stress. In some cases a part may be heat treated above the recrystallization temperature to cause significant changes to the microstructure, for example elongated to equiaxed grains, large deformed to small un-deformed grains, strongly textured to weakly textured grain structures, etc. Any change in microstructure will change mechanical properties and should be accounted for [6.6]; [6.80].

6.5.2.2 HOMOGENISATION AND NORMALISATION

Following solidification (or a heat treatment in a high temperature phase field), the metallurgy of some alloys results in microstructures that are highly chemically segregated, for example dendrite structures in nickel-based superalloy castings. In many cases such microstructures are undesirable, for example because they can lead to large microstructural-level inhomogeneities in properties and changes in properties over time in elevated temperature service. In these cases homogenisation is done to allow diffusion of elements to a more uniform distribution. Normalisation is a term often applied to ferrous alloys where heat treatment following austenitising is used to allow diffusion of elements to form the final desired microstructure. As with any process involving heating, temperature hold and then cooling it must be carefully controlled to manage final residual stresses and any interactions with the environment, e.g. oxidation. Processing parameters, equipment, etc. should be controlled/recorded as part of the manufacturing plan.

6.5.2.3 HOT ISOSTATIC PRESSING (HIP)

In addition to applying a heat treatment, Hot Isostatic Pressing or HIP will apply pressure to the sample. For example titanium is commonly processed for both AM and conventional samples in the temperature range of 890 to 955 °C under pressurised argon, with pressures ranging from 70 to 105 MPa (10 to 15 kpsi) for 2 to 4 h [6.81]. While HIPing will have an effect on any residual stresses, and potentially microstructure depending on parameters, its main function is to close pores and cracks within the part. HIPing cannot however close surface connected pores which must be closed through an additional surface treatment, such as grit blasting, prior to HIPing.

Although the PO should attempt to use standard post-processing techniques where possible, the HIP process has been shown to have a different effect on AM samples than on conventionally made parts and consequently may need to be designed specifically for the AM parts [6.82]. The temperature, atmosphere, pressure, time and position in the HIP vessel with respect to other parts should be measured and recorded for any HIP process performed on the samples and test specimens.

6.5.2.4 SOLUTION TREATMENTS AND AGING

Many alloys derive their strength from precipitation strengthening / age hardening, for example 2000, 6000 and 7000-series aluminium alloys and many nickel-based superalloys such as IN718. Typically the alloy is solutionised above the solvus temperature of the precipitate phase(s) followed by controlled, often rapid, cooling. The alloying elements are then in supersaturated solid solution and can be precipitated as strengthening phases using a carefully controlled ageing treatment at a temperature well below the solvus. For such alloys the as-manufactured precipitate microstructure following AM may not be that desired for service and a solution treatment and aging process will be required. The process should be carefully controlled and recorded as part of the manufacturing plan.

6.5.2.5 COLD WORKING

In addition to thermal post-processing techniques to relieve stress and modify microstructures, cold working techniques may be used to improve the microstructure / mechanical properties of the final part at the surface in addition to closing pores at the surface of the part. Cold working may be performed before or after heat treatments. Several cold working techniques exist in metals manufacturing however this section will only cover the two most likely to be used in AM parts.

Peening is a cold working technique in which the surface of the material is struck in a controlled way to induce compressive stresses in the surface of the part. Peening can also be used to close surface porosity in the part which cannot be closed through heat treatments such as HIPping. Several peening techniques exist, the three most common are:

- Hammer peening - a small hammer is used to input the compressive stress in the part. A disadvantage of this technique for AM is that it requires access to the surface which may not be possible in complex AM parts.
- Shot peening – small beads or metal shot are fired at the sample.
- Laser shock peening – while strictly not cold working, this process uses a laser to induce deep compressive residual stresses in the surface by creating a local shock wave.

Peening processes require careful control and may use computer control to ensure repeatability of the process.

Another technique that can be used is rolling of metal parts. In rolling a wheel passes over the surface of the part and the applied pressure improves the microstructure and mechanical properties whilst reducing porosity. A notable application is in the WAAM method where rolling between deposition passes has been shown to improve microstructure / properties of the final part [6.83].

6.5.3 SURFACE FINISHING

Surface finishing describes a range of processes that reduce the surface roughness of the part and may also remove any surface impurities that have accumulated during heat treatments. Surface roughness is a measure of how much the surface of a material varies from a smooth, flat surface [6.84]. Although for some applications and features, the surface roughness is acceptable, AM components can have a higher level of surface roughness than components that have been machined using subtractive techniques. The design freedoms of AM could enable more complex parts to be built but as a consequence it may be more difficult to produce the required surface finish using conventional finishing techniques. Techniques that do not require machine access to internal surfaces, for example, may be more applicable to these complex parts. For less complex parts conventional machining requiring machine access may be preferred since it is widely available and technologically advanced (precise numerical control, range of machining tools, etc.). The methods for measuring surface roughness will be discussed later on in this section [6.86].

This section will discuss some common surface finishing techniques used in AM components. Details of the surface finishing processes used for both the final part and any test specimens should be recorded since they will have an influence on the fatigue performance and residual stress in the final part. As with any process used the surface finishing technique should be calibrated to ensure that the finish provided by the process is consistent and does not vary by an amount greater than allowed.

Increased design complexity may mean that machine access for surface finishing is not possible, for example where fine internal structures or obscured surfaces are present. In these cases non-conventional techniques are sometimes used. Table 6-6 shows some example surface finishing techniques. Electrochemical techniques for example do not require line-of-sight access to the surface and thus may be more appropriate for complex parts. However if a fine, carefully controlled and reproducible surface finish is important, including on internal / obscured structures, it may be necessary to redesign the part to enable machine access for conventional machining operations.

Table 6-6 - A summary and description of the types of surface finishing available [6.87].

	Technique	Description
Mechanical	Milling	Surface roughness is reduced using a multi-axis cutter that cuts away the surface of the material creating a smoother surface.
	Abrasive Flow machining	Surface roughness is reduced by blasting the sample with an abrasive material using pressurized air or fluid. For PBF, the powders for AM can be used as the abrasive media.
	Vibratory or rotary grinding	Part is placed in a bowl or drum with an abrasive grinding media which is then vibrated or rotated, using the relative movement of the media and the part to reduce surface roughness in the part.
	Micro machining process	An oscillating or rotating abrasive tool is used to improve surface roughness. Material removal can be performed in a stepwise process with each step further improving surface roughness.
Thermal	Thermal deburring	The part is placed in a pressure chamber, which is filled with a gas mixture of oxygen and fuel gas. The gas is ignited and due to limited heat conduction and the high temperature, burrs are oxidized and removed.
	Laser polishing	A laser is used to melt a thin layer on the surface of the material leading to reduced surface roughness in the part due to the surface tension of the molten zone [6.86].
Electrochemical	Electro polishing	Cathode surfaces are placed in an electrolyte material with the part as the anode and a current is applied. There is an increase in current density at features such as surface roughness peaks and burrs which will remove them, reducing surface roughness the part.
	Chemical milling	The part is immersed in a strong acid material which is temperature controlled. The chemical preferentially dissolves the peaks due to surface roughness, smoothing the surface.

6.5.4 SUMMARY OF POST PROCESSING TECHNIQUES

Post-processing can have a significant effect on the properties of an AM component. Three key recommendations can be drawn from the information presented here on removal of the part:

- **Any stress relieving step performed before removing the part from the build plane should be recorded and monitored to ensure repeatability Surface finishing techniques may be required on surfaces where support structure has been removed (REC6.39).**
- **It is recommended to consider the effect of any EDM artefacts on final properties, recording and monitoring where EDM is used (REC6.40).**
- **Surface finishing techniques may be required on surfaces where support structure has been removed (REC6.41).**

As with conventional manufacturing techniques post processing techniques should be recorded and carefully calibrated to ensure there is consistency in their application. In addition, any test specimens should have the same post-processing treatments as the final part. Details of the parameters of post-processing techniques should be recorded and the technique used should be calibrated to ensure repeatability. Post processing techniques include but are not limited to:

- **Thermal techniques – e.g. Solution treatments and aging , Homogenisation and normalisation**
- **Hot Isostatic Pressing (HIP).**
- **Surface finishing.**
- **Cold working (REC6.42).**

6.6 COMPONENT VALIDATION

6.6.1 TEST SPECIMENS

In order to reduce the numbers of high cost final parts being tested while facilitating airworthiness assurance, the "pyramid of testing" concept has been developed. Testing becomes more representative of the final part and test article numbers become fewer as one moves up the pyramid. Figure 3-4 shows testing of coupons, elements, details, sub-components and the final part. As such, test specimens are vital in developing a broad data set and in providing confidence in the properties and scatter of properties of the final part. As discussed in Chapters 3 and 4 a key aspect of the regulations is that the properties of test specimens and test elements (representative of part features) must truly reflect the scatter in properties of the final part from all sources.

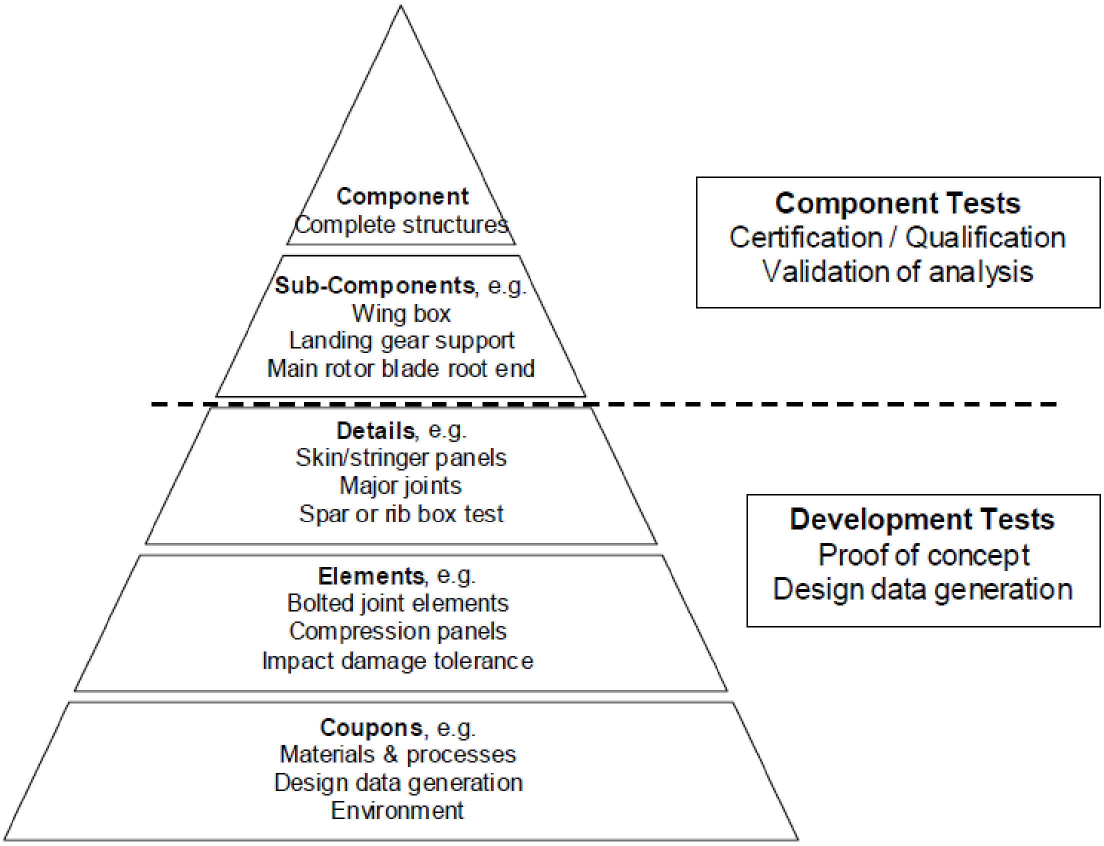


Figure 6-12 – The structural test 'pyramid' [4.34].

In additive manufacturing in particular, the geometry of the part being built may affect its thermal history which could in turn affect its microstructure and mechanical properties. As-built standard test coupons that have a different thermal history may therefore not be representative of the microstructure and properties of the final part. In this case, coupons may be machined from a specimen that has been produced to be more representative than as-built coupon geometry. These specimens are designed to include a microstructure that is representative of the final part, sometimes referred to as a microstructural standard.

In addition to initial qualification specimens, test specimens may be included with each AM build. Their primary use is as a representation of the final part or part features which can be cut up and used to track variation in part properties whether between locations in the build volume or between builds. For powder bed systems some typical specimens included with each build could include but are not limited to:

- Small cube to confirm density of deposited material.
- Powder capsule.
- One set of tensile test coupons [6.88].

As well as standard coupons, the variability in AM processing with geometry may mean that witness or test specimens are designed to be more representative of the final part. The design of witness / traveller specimens may be informed by modelling, nevertheless physical testing should be used to confirm that their properties and scatter in properties are representative of the final part. **For powder bed systems it is recommended that test specimens should be built with each build to track variability between builds. The test specimens should be representative of the final part with microstructure and mechanical properties used to confirm this (REC6.43).**

6.6.2 INSPECTION

Inspection procedures are important in contributing to manufactured part quality control. Manufactured parts are visually inspected initially and this enables the PO to identify any major geometric problems and any obvious surface defects such as cracks, bands of discolouration (possibly indicating unacceptable oxidation), or gross surface roughness. Depending on requirements the part may then either go through further post processing or be scrapped.

6.6.3 PART GEOMETRY

The geometry and tolerances of AM parts are typically set in the design phase of development and are often based on a wide range of mechanical properties and geometric requirements. Once a part has been built and post-processed, several techniques are available to measure the final part geometry.

Manual measurement techniques such as calipers, micrometers and gauges have typically been employed in measuring the geometry of specific features and not for an overall view of the part geometry. This is particularly important where a feature will need to join with another part.

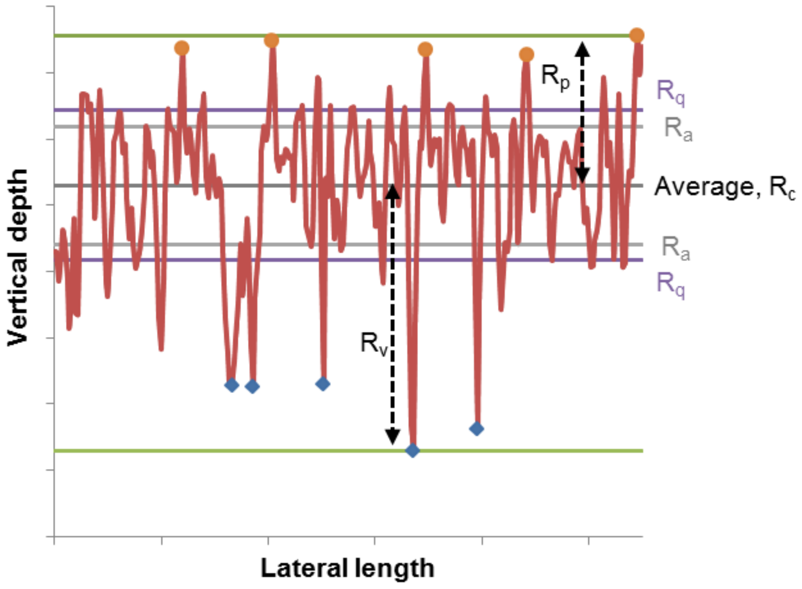
The digital nature of design and manufacture within AM means that increasingly automated measurement techniques are employed to determine the part geometry. This enables direct comparison with the original CAD files and is also able to be applied to the complex geometries that are enabled by the added design freedoms of AM. Typical automated measuring techniques include:

- Laser Scanners.
- Structured light scanning systems.
- Coordinate measuring machines.
- On-machine probes.

- Laser Trackers.
- X-ray computer tomography (a non-destructive technique discussed later in this section).

6.6.4 SURFACE FINISH

Surface roughness is generally measured using a profilometer. For lower levels of detail a manual probe is used, where the tip is run across the sample and small changes in its height are measured. For higher resolution one technique uses a white light interferometer where the constructive and destructive interference of reflecting light is used to determine the vertical depth across a sample. The effect of surface roughness on fatigue performance of materials is especially important. The depth parameters can then be plotted as shown in Figure 6-13 and statistical methods used to calculate several parameters that are used to quantify different parameters associated with the surface roughness (explained further in Figure 6-13).



R_c – the average depth based on all recorded values

Rt – the difference between R_p and R_v.

R_a – is the arithmetic average of the absolute values of the profile heights divided by the evaluation length.

R_q – the root mean square average of the profile heights, y divided by the evaluation length
Roughness

R_z – The sum of the absolute values of the 5 highest peaks and the 5 lowest troughs divided by 5.

Figure 6-13 - Representative cross section through a surface showing surface roughness and some common values used in quantifying surface roughness

6.6.5 DESTRUCTIVE TESTING

Some parts and test specimens must be tested to destruction to provide confidence in the properties and scatter in properties of the final part. There is a wide range of destructive testing techniques depending on the properties to be measured so it is not within the scope of this document to discuss all of the available techniques. One of the four pillars of airworthiness is the use of recognised standards therefore this section will focus on those test standards and their applicability to additive manufacturing.

6.6.5.1 MECHANICAL PROPERTIES

A wide range of mechanical properties and test methods exist and the appropriate test methods should be agreed based on the final requirements for the part. It is outside of the scope of this document to outline all available mechanical test standards but ASTM F3122 gives guidance on the applicability of standard tests to AM components [6.90] and further guidance can be found in NISTIR 8005 document [6.91]. **From both of these documents it is clear that most mechanical test standards can be applied to AM specimens but with the following guidance:**

- **Care must be taken in using flat plate or thin specimens since these samples may be difficult to build using AM and consequently test coupons may not be representative of the AM parts.**
- **Test reports should include the location and orientation of parts within the build volume of the AM system used, as outlined in ISO/ASTM 52921 [6.92].**
- **Test methods with strict requirements for isotropy such as ASTM E1875 (Dynamic Young's modulus) may be difficult to apply if the AM process produces samples that are anisotropic.**
- **Post processing of specimens may be required for some test methods such as ASTM E0399 (Linear-Elastic Plane-Strain Fracture Toughness) and ASTM E0384 (Knoop and Vickers hardness) to achieve the required surface roughness for some tests.**
- **Notches and pre-cracks may need to be machined to give accurate results for tests such as ASTM E1820 (Fracture Toughness) and ASTM E1457 (Creep Crack Growth Times in Metals) [6.90] (REC6.44).**

6.6.5.2 COMPOSITION

As with any metal part manufacture, it is important to ensure that the composition of the metal is within the specification for that alloy. While AM specifications exist for common alloys such as Ti6Al4V [6.93] and stainless steel 316L [6.94] the requirements for chemical composition of these AM materials do not differ from those specified for wrought or cast materials.

Many techniques exist for determining the chemical composition of metals and which technique used should be determined by the chemical elements under study and the accuracy of measurement required. Some typical techniques are discussed in the feedstock section of this document.

For example, for AM of Titanium-6 Aluminum-4 Vanadium alloys the following elements and ASTM standard chemical tests are recommended by the ASTM standard F2924 [6.93]:

- Carbon – E1941 Combustion Analysis.
- Hydrogen – E1447 Inert Gas Fusion Thermal Conductivity/Infrared Detection Method.
- Oxygen and Nitrogen – E1409 Inert Gas Fusion.
- Other elements surface - E539 X-Ray Fluorescence Spectrometry.
- Other elements bulk - E2371 Direct Current Plasma and Inductively Coupled Plasma Atomic. Emission Spectrometry (Performance-Based Test Methodology).

Chemical analysis is typically performed on a test ingot which is produced in the same build as the final part. Although it is good practice that any test specimen undergoes the same post processing as the final part, for some elements it is possible to test the ingot in the as built condition. An exception to this is that hydrogen content in particular should be analysed after the final heat treatment and final surface treatment [6.95].

6.6.5.3 MICROSTRUCTURE

Determining how processing parameters and part / specimen build design affects microstructure is crucial in understanding part properties, performance and scatter. For microstructural evaluation the part or test coupon is sectioned to reveal the areas / orientations of the part to be imaged. These planes are then ground and polished to produce a smooth surface [6.96]. It is usually necessary to etch the surface of interest to reveal microstructural features of interest, e.g. grain boundaries. Standard metallographic etches using different acids exist for the familiar structural metals. Electrolytic etches are sometimes required to reveal particular microstructural features in some alloys [6.97].

Three main techniques can then be used for determining the microstructure of the part:

- Optical microscopy – A light microscope can be used to image features of the microstructure. Different lightning conditions and contrast techniques are used to improve contrast between features.
- Scanning Electron Microscopy – A Scanning Electron Microscopy (SEM) uses electrons to generate images to higher resolutions relative to an optical microscope. Different imaging modes exist, i.e. secondary and backscattered electron imaging, which provide contrast from different electron / specimen interaction phenomena. Further, most SEMs also have hardware and software that uses these phenomena to enable chemical composition measurement (however caution should be exercised when using these measurements for certain elements).
- Electron Backscatter Diffraction (EBSD) – EBSD is a technique that uses those electrons that are backscattered from the specimen at special diffracting angles to allow the measurement of crystallographic information. This can be used to determine the types of phases present in the microstructure and their crystallographic orientation relative to a specific direction, e.g. the Z direction in the AM build, providing the specimen orientation in the build has been accurately recorded.

Anisotropic microstructures can be a feature of AM parts and specimens depending on alloy type and solidification. Consequently **if parts are to be built in different orientations the microstructure <u>should</u> be determined in each build orientation to make sure there is a true picture of its three-dimensional nature, e.g. grain structures, cracks and delaminations (REC6.45).** Guidance on characterisation of AM microstructures, utilising existing standards, is available in [6.98].

6.6.6 NON-DESTRUCTIVE EVALUATION

Non-Destructive Evaluation (NDE) is used across manufacturing processes to check for defects and provide quality assurance. Some typical defects that can be present in AM parts are outlined in section 7.1.7 of this guidance. As Figure 6-14 demonstrates, the Non-Destructive Testing (NDT) technique used is largely dependent on the resolution required to resolve defects and the depth into the part that inspection is required. These techniques can be categorised into surface (e.g. Dye Penetrant Inspection (DPI)), surface/near surface (e.g. Eddy Current Testing (ECT)) and volumetric (e.g. Ultrasound Testing (UT) and X-Ray Computed Tomography (XRCT)) measurements [6.1]; [6.2]. Surface roughness techniques discussed previously have a very high resolution but will only be able to give information about the surface finish of the part. This sub section will briefly discuss each of these NDT techniques and their application in additive manufacturing.

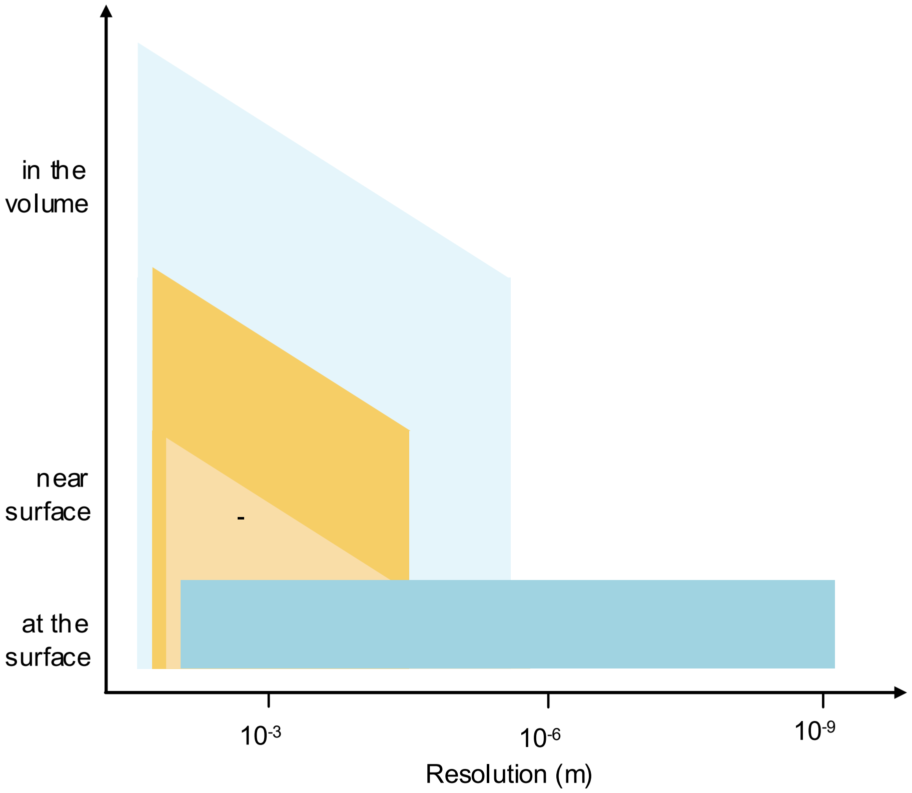


Figure 6-14 - Resolution and depths for different NDE techniques applied to additive manufacturing [6.7]; [6.99].

In dye penetrant testing, a dye is applied on to the part which enters into any surface breaking defects that may exist. Excess dye that remains on the surface is then washed off before a developer is used to draw the dye out from the surface-breaking defects so they can be viewed under ultraviolet or white light, depending on the type of dye used -fluorescent or non-fluorescent (visible). Despite its wide use in the inspection of surface-breaking defects, the irregular or rough surfaces sometimes present in AM parts makes penetrant testing on as-built parts very difficult. Instead, penetrant testing may be used on machined parts to determine surface-breaking defects [6.100].

Eddy Current Testing is a widely used technique that detects surface and near surface defects in electrically conducting materials. When an alternating current flows through a coil that is placed close to the surface of the sample, the accompanying magnetic field will induce circular currents (eddies) in the sample, generating its own magnetic field that will interact with the coil magnetic field. Where defects exist, the current and magnetic fields are disrupted. These changes can be measured and provide information on the size of surface and near surface defects. As with other metallic components, the surface finish and grain structure play a role in how successful ECT is at detecting defects, so eddy current testing may need to be performed on a machined sample and may need to take into account the differences in microstructure observed in AM [6.100]

UT uses the propagation of ultrasonic waves and the time-spacing between reflected signals to detect and locate defects in a sample and derive the elastic properties of a material. Ultrasonic testing can be divided into contact, non-contact immersion, and non-contact in air depending on how the acoustic signal is applied to the sample. As discussed previously, the surface roughness in many AM parts can affect contact techniques so it may be necessary to machine samples before testing. In addition UT can also be affected by the anisotropic microstructures sometimes observed in AM which could interfere with the passage of ultrasonic waves through the part. Ultrasonic waves can be generated using a single transducer, an array or via a laser and are typically of three types, longitudinal, shear and surface waves. The wave speed and attenuation of the ultrasonic reflected signals can been used to correlate to material characteristics such as average porosity and grain size. Further, by combining different wave types correlations have also been made to mechanical properties such as yield strength, fracture toughness and hardness. There are however limitations of the application of ultrasonic testing to determine these properties and destructive testing may be required to calibrate the ultrasonic measurement [6.4]. **It is recommended that surface finishing is applied to any region of an AM component where NDT techniques requiring contact with the surface, e.g. ECT, UT, are undertaken (REC6.46).**

In all radiographic techniques, such as Computed Tomography (CT), the internal structure of a sample can be determined by firing X-rays through the sample and measuring the resulting penetration, providing information on the density and porosity of the sample. In X-ray computer tomography (XRCT), several images are taken at different angles through the sample being reconstructed to form a 3D image of the sample. As Figure 6-14 demonstrates, XRCT can be used to find defects both at the surface and in the volume of the part at a wide range of resolutions. Micro XRCT scanning is capable of giving micron-scale resolution. Another advantage of CT scanning is that it is non-contact so issues due to surface roughness seen in many other NDT techniques are not observed.

The application of CT measurement is discussed further in BS EN 16016 [6.101] but there are three main issues with the application of CT for qualification of AM parts:

- AM design organisations generally have yet to define a minimum defect size for CT imaging so pores or defects too small to be imaged by the CT scanner could be missed and still affect the mechanical properties of the part.
- Noise and artefacts of the measurement in the image affecting results.
- Image conversion and the reliance on user input.

The resolution of XRCT measurements obtained is depends on the spot size of the x ray source, the detector size, the magnification and the number of images used to reconstruct. The quality of the images in XRCT is typically optimised through altering the power of the X-ray source. In addition, consideration must be given to the time taken to perform the measurement which will depend on the size of the part. For larger parts, higher resolutions may not be available without performing the measurement for a long time period. Equally, for highly absorbing metallic materials, the X-rays may not penetrate into the centre of the sample without the use of a higher power X-ray. CT scanning is an imaging technique and like any imaging technique may not give a true picture of the object under study. This could induce artefacts including noise onto the image that are not in the part. An example is ring artefacts which are caused by defective pixels, as the X-ray source rotates around the sample these defects also rotate creating the appearance of high density rings in the sample.

Once an X-ray image has been generated, digital image processing techniques can then be used to determine properties such as porosity and measure internal and external geometries of the part. The reliance of these techniques on manual input to find edges in the part could lead to inaccuracies. Automatic thresholding techniques do exist but may not give an accurate measure of the edge of the part or feature [6.101]; [6.102]. Validation components with similar size to the part and defects of a known size may be used to validate the CT scanning information and its ability to find defects.

6.6.7 RESIDUAL STRESS DETERMINATION

Residual stresses are a feature of many techniques used to process metals and manufacture parts and in some AM methods they can be relatively severe. As discussed above unrelieved residual stresses can lead to distortion and/or superimpose on the stresses applied to the part changing the overall stress state the material experiences. The approaches to measuring the residual stress in a part can be split into three main types:

- Non-destructive techniques e.g. X-ray and neutron diffraction, optical, magnetic or ultrasonic methods.
- Semi-destructive techniques e.g. centre-hole and deep-hole drilling, and the ring core method.
- Destructive techniques e.g. block removal, splitting and layering and the contour method [6.103].

Non-destructive techniques typically use the effect of residual stress on the crystallography of a material, e.g. X-rays or a neutron beam are diffracted differently depending on the stress state of the material and this can be quantified using appropriate methods. X-rays and neutrons will penetrate to different depths in the material depending on many factors (e.g. beam energy, material type and microstructure) which should be considered when planning such methods.

Semi-destructive and destructive techniques use material removal to a lesser or greater degree to infer a residual stress from the strain that is measured in either the removed or remaining material. Material can be removed in a range of shapes depending on the tests. High levels of anisotropy may make some techniques inapplicable to some AM parts, e.g. hole drilling [6.92].

6.7 COMPONENT HANDOVER

6.7.1 RELEASE DOCUMENTATION

The digital nature of additive manufacturing and the wide numbers of parameters that can be recorded may mean that it may be difficult to process and record all the associated data. What is key is that the part producer and the design authority agree the appropriate data to collect and record to give confidence in the properties and scatter in properties of the final part. Based on the guidance in this document it is clear that in comparison to conventional components additional data will be required for AM parts to give confidence in the scatter of properties of both the part and any test coupons. The process control document should be used as the primary means to give evidence of the controls in place to reduce the scatter in properties during manufacture and to outline the testing required confirming properties are not deviating from those measured during initial qualification.

In addition ISO/ASTM 52901 has a great deal of detail on how to outline the requirements for purchased AM parts and <u>should</u> be used as a further guide on the handover of purchased AM components (REC6.47). The required documentation is divided into three separate sections:

- Part ordering information – standard information which would be required to order a part such as the number and type of parts required, identification of the part (marking or tagging) and details of manufacturing and purchasing organisations.
- Definition of the part to be manufactured – details of the part to be built and process specifications to meet the required part properties. This should include part geometry and tolerances but could also include surface texture, build orientation, feedstock, acceptable imperfections or deviations and process control information.
- Part characteristics, functionality and performance – the required properties of the part, depending on the part requirements but covering aspects such as dimensional accuracy, defects, mechanical properties, residual stress, or chemical composition [6.104].

Another useful standard is BSI ISO 17359:2011 which states that records of parameters for condition monitoring and diagnostics of machines should include, as a minimum, the following information:

- Essential data describing the machine.
- Essential data describing operating conditions.
- The measurement position.
- The measured quantity units and processing.
- Date and time information.

The quoted values should also outline details of the measuring systems used to obtain each value and the accuracy of the measuring system [6.40].

6.8 SUMMARY OF RECOMMENDATIONS

6.8.1 REGULATION-TYPE RECOMMENDATIONS

REC6.1: For critical AM components a Process Control Document shall be supplied as part of the airworthiness documentation. Any changes to the process control document shall be subject to the Military Certification Review Item (MCRI) process. The contents of the Process control document should be written based on the recommendations outlined within this document. The Process control document could include but not be limited to details of the control of (refer to Section 6.1.1.):

- **AM machine.**
- **Build strategy.**
- **Feedstock.**
- **Post-processing.**
- **Testing.**

6.8.2 AM MACHINE

6.8.2.1 AMC-TYPE RECOMMENDATIONS

REC6.3: If the AM machine is unattended during a build time, procedures should be put in place to detect unplanned stoppages and report them – Section 6.1.1.3.

REC6.4: Stoppages during the build should be avoided; if stoppages are unavoidable they should be demonstrated not to be detrimental to the properties and scatter in properties of the final part - Section 6.1.1.3.

REC6.7: All AM machine operators should be shown to be suitably qualified to use the additive manufacturing machine. If variation between operators is deemed a significant source of scatter, it may be necessary to specify named operators to build a critical part – Section 6.3.

REC6.8: If a part will be produced on different machines to those used for qualification and certification, all machines used should undergo a pre-qualification process with calibration builds to show that any variation is within an acceptable range – Section 6.3.1.

REC6.18: As with any system the calibration routine should show control over all aspects that are critical to the final part. The frequency of re-calibration should be sufficient to provide confidence that unacceptable changes have not occurred between calibrations – Section 6.4.

REC6.19: The software version used to print qualified AM builds should be recorded and any change in software should be shown not to be detrimental to the properties and scatter of the final part – Section 6.4.

REC6.29: The laser beam for laser powder bed systems should be calibrated at least annually to ensure that its characteristics do not change through time to reduce scatter in the properties of the final part – Section 6.4.2.1.2.

REC6.30: Electron beam powder bed systems should be calibrated at least annually to ensure that parameters such as electron beam power, speed and motion are within acceptable limits as part of the assurance that the part has the specified properties – Section 6.4.2.1.3.

REC6.31 Available standards should be applied to calibration of Direct Energy Deposition techniques. Arc welding AM systems such as WAAM should be calibrated with standards such as BS EN ISO 15609-1:2004 [6.62] and BS EN 50504:2008 [6.63] as a guide. Blown powder systems which are similar to laser cladding should use standards such as BS EN ISO 15609-4:2009 [6.64] to guide in calibration – Section 6.4.2.2.

REC6.32: Calibration builds should be used to determine the geometric accuracy of robotic movement systems for direct energy deposition techniques - Section 6.4.2.2.1.

REC6.33: If certification is based on a pre-heated build plane, the pre-heating temperature of the build plane should be calibrated to ensure it is at the correct temperature and does not varying to a point where the scatter in material properties could be affected – 5.4.2.3.

REC6.34: Where used to produce an inert atmosphere, the oxygen content within gases and containment systems should be monitored and should be handled so as not to be contaminated – Section 6.4.3.

REC6.35: Any oxygen sensors used to confirm oxygen content should be calibrated regularly to ensure continuing compliance of AM builds, further guidance on oxygen sensor systems can be found in BS EN 50104:2010 – Section 6.4.3 [6.73].

REC6.36: For direct energy systems the flow rate of the gas should be controlled and calibrated to ensure it is constant – Section 6.4.3.

REC6.37: The device filtration system should be qualified to an approved standard such as the British standard for HEPA filters and should have a regular maintenance and calibration regime to ensure that the filter does not become clogged with powder and ineffective. Filters should be monitored and handled so as not to introduce additional contamination and variability into the machine and ultimately the part – Section 6.4.3 [6.32]; [6.74].

REC6.38: It is recommended that calibration builds should be used to calibrate all types of additive manufacturing machines used to build critical parts. The frequency and format of these builds should be determined based on the part requirements and the change in properties over the lifetime of the machine. Example properties that could be measured from calibration builds include geometric, mechanical and microstructural properties – Section 6.4.4.

6.8.3 BUILD STRATEGY

6.8.3.1 AMC-TYPE RECOMMENDATIONS

REC6.6: If a part is designed and qualified to optimise properties in a particular direction then any change in orientation or build methodology for the part (discussed later on in this chapter) will

particularly affect the properties of the final part and should not be altered from the optimised orientation – Section 6.2.3.

REC6.9: If the file conversion from CAD to STL or similar has a significant effect on the required properties of the final part the AM producer should record the file and not reconvert from CAD data once the part has been qualified – Section 6.3.1.1.

REC6.11: If supports are used, their structure and shape should be recorded along with any CAD models of the part to ensure that the support structure used in qualification and certification is repeated for each part built – Section 6.3.3.2.

REC6.14: Build location and orientation should be considered for test specimens so that they more fairly reflect this source of scatter during the qualification process – Section 6.3.3.4.

REC6.16: The effects of surface roughness on fatigue in particular means that this edge contouring could have a significant effect on the scatter in mechanical properties. If this is the case, the method of edge contouring used should be recorded and the same technique used for all qualified builds – Section 6.3.3.5.

REC6.17: The build parameters used (e.g. heat source power, build speed) should be recorded and maintained for any qualified build since any change in these parameters defined by the AM process may affect the mechanical properties, geometry and defects, and their scatter in the final part – Section 6.3.4.

6.8.3.2 GUIDANCE-TYPE RECOMMENDATIONS

REC6.10: If the variation due to orientation of the part leads to a scatter of properties greater than those allowed by the design authority then it may be necessary to record and maintain the orientation of the part used during qualification and certification throughout all part manufacture – Section 6.3.3.2.

REC6.12: If the variation due to location and number of parts leads to a scatter of properties greater than those allowed by the design authority then it may be necessary to record and maintain the build plan used during qualification and certification throughout all part manufacture – Section 6.3.3.3.

REC6.15: If the effect of scan strategy is observed to be significant it may be necessary to record and maintain the scan strategy used for all part manufacture – Section 6.3.3.5.

6.8.4 FEEDSTOCK

6.8.4.1 AMC-TYPE RECOMMENDATIONS

REC6.2: Evidence that properties have not deteriorated during storage should be provided when undertaking any project using AM as well as information about the storage conditions and timings in which the feedstock properties remain within a specification. Storage conditions should take

into account storage at the powder manufacturer/provider, during transport and at the part manufacturing facility – Section 6.1.1.

REC6.21: Powders of some alloys such as titanium alloys should be stored and handle under inert gas e.g. argon – Section 6.4.1.2.

REC6.22: If the feedstock (e.g. titanium) or process (e.g. PBF) are moisture sensitive, evidence should be provided that moisture levels in the powder environment or powder are below a value that will affect the properties and scatter of the final part – Section 6.4.1.2.

REC6.23: For critical components, the powder quality should be tracked through regular sampling and testing to ensure the powder does not fall outside of specification. Example powder specification measurements should be determined by the component manufacturer but could include measurements of chemical composition, particle size distribution and flow and packing properties – Section 6.4.1.3.4.

REC6.24: Powder samples for testing should be representative of the powder used in the final part – Section 6.4.1.3.4.

REC6.25: Where different powder batches, whether virgin or used are mixed, both powders should be confirmed as within specification or the new mixture of powders should be re-tested to confirm the powder properties are within – Section 6.4.1.3.4.

REC6.26: For the AM of aerospace parts using highly controlled and repeatable robotic welding systems the characteristics of the wire should be controlled to a much higher level of consistency along the length than is typical for welding. This could include properties such as diameter, composition, surface quality (kinks and nicks), surface contamination, etc. – Section 6.4.1.4.

REC6.27: Wire feed rate should be recorded for each build as one of a number of parameters that demonstrate that the part is being built in accordance with its certification – Section 6.4.1.4.1.

REC6.28: The wire manufacturer, diameter measuring system and specification agreed and followed for each numbered batch should be recorded for each batch used for the manufacture of AM activity components – Section 6.4.1.4.3.

6.8.5 POST-PROCESSING

6.8.5.1 AMC-TYPE RECOMMENDATIONS

REC6.39: Any such stress relieving step performed before removing the part from the build plane should be recorded in the manufacturing plan and monitored to ensure repeatability Surface finishing techniques may be required on surfaces where support structure has been removed – Section 6.5.1.

REC6.40: The effect of any EDM artefacts on final properties should be considered, recording and monitoring where required – Section 6.5.1.

REC6.42: Post processing techniques should be recorded and carefully calibrated to ensure there is consistency in their application. In addition, any test specimens should have the same post-processing treatments as the final part. Details of the parameters of post-processing techniques should be recorded and the technique used should be calibrated to ensure repeatability. Post processing techniques include but are not limited to:

- **Thermal techniques – e.g. Solution treatments and aging, homogenisation and normalisation.**
- **Hot Isostatic Pressing (HIP).**
- **Surface finishing.**
- **Cold working – Section 6.5.4.**

6.8.5.2 GUIDANCE-TYPE RECOMMENDATIONS

REC6.41: Surface finishing techniques may be required on surfaces where support structure has been removed to maintain consistency – Section 6.5.1.

6.8.6 TESTING

6.8.6.1 AMC-TYPE RECOMMENDATIONS

REC6.5: For critical components, calibration builds should be performed on AM powder bed machines if there is a changeover of metal alloy types – Section 6.1.3.4.

REC6.13: If witness specimens are used to reduce the number of whole-part cut ups, evidence should be produced to demonstrate that the witness specimens are representative of the final part – Section 6.3.3.4.

REC6.43: For powder bed systems it is recommended that test specimens should be built with each build to track variability between builds. The test specimens should be representative of the final part with microstructure and mechanical properties used to confirm this – Section 6.6.1.

REC6.45: If parts are to be built in different orientations, the microstructure should be determined in different build orientations to make sure there is a true picture of its three-dimensional nature, e.g. grain structures, cracks and delaminations – Section 6.6.5.3.

REC6.46: Surface finishing should be applied to any region of an AM component where NDT techniques requiring contact with the surface, e.g. ECT, UT, are undertaken – Section 6.6.4.

6.8.6.2 GUIDANCE-TYPE RECOMMENDATIONS

REC6.44: Most mechanical test standards can be applied to AM specimens but with the following guidance:

- **Care must be taken in using flat plate or thin specimens since these samples may be difficult to build using AM and consequently test coupons may not be representative of the AM parts.**
- **Test reports should include the location and orientation of parts within the build volume of the AM system used, as outlined in ISO/ASTM 52921 [4.34].**

- **Test methods with strict requirements for isotropy such as ASTM E1875 (Dynamic Young's modulus) may be difficult to apply if the AM process produces samples that are anisotropic.**
- **Post processing of specimens may be required for some test methods such as ASTM E0399 (Linear-Elastic Plane-Strain Fracture Toughness) and ASTM E0384 (Knoop and Vickers hardness) to achieve the required surface roughness for some tests.**
- **Notches and pre-cracks may need to be post machined to give accurate results for tests such as ASTM E1820 (Fracture Toughness) and ASTM E1457 (Creep Crack Growth Times in Metals) [6.86] – Section 6.6.5.1.**

6.8.7 COMPONENT HANDOVER

6.8.7.1 AMC-TYPE RECOMMENDATION

REC6.47: ISO/ASTM 52901 has a great deal of detail on how to outline the requirements for purchased AM parts and should be used as a further guide on the handover of purchased AM components – Section 6.7.1.

6.9 CHAPTER 6 GLOSSARY OF ABBREVIATIONS

AAS - Atomic Adsorption Spectroscopy
AM - Additive Manufacturing
ASTM - American Society for the Testing of Materials
BSI - British Standards Institute
CAD - Computer Aided Design
CAM - Computer Aided Manufacturing
CCD -
COSHH - Control of Substances Hazardous to Health
CT - Computed Tomography DED - Direct Energy Deposition
DO - Design Organisation
DPI - Dye Penetrant Inspection
EBM - Electron Beam Melting
EBSD - Electron Backscatter Diffraction
ECT - Eddy Current Testing
EDM - Electro-discharge Machining
EDS - Energy Dispersive Spectroscopy
HEPA - High Efficiency Particulate Air
HIP - Hot Isostatic Pressing
HSE - Health and Safety Executive
ICP-MS - Inductively coupled plasma mass spectrometry
IGF - Inert Gas Fusion
ISO - International Standards Organisation
KPV - Key Performance Variable
MCRI - Military Certification Review Item
MIG - Metal Inert Gas
MSDS - Materials Safety Data Sheet
Nd:YAG - Neodymium: Yttrium Aluminium Garnet
NDE - Non-destructive Evaluation
NDT - Non-destruction Inspection
NIST - National Institute of Standards and Technology
PBF - Powder Bed Fusion
PCD - Process Control Document
PO - Production Organisation
PPE - Personal Protective Equipment
SEM - Scanning Electron Microscopy
SLM - Selective Laser Melting
ST - Solution Treat
TAA - Type Airworthiness Authority
UT - Ultrasound Testing
WAAM - Wire Arc Additive Manufacture
XPS - X-ray Photoelectron Spectroscopy
XRCT - X-Ray Computed Tomography
XRF - X-ray Fluorescence Analysis

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7 PART DESIGN AND BUILD - POLYMERS

7.1 INTRODUCTION

7.1.1 PURPOSE AND SCOPE OF THE CHAPTER

The purpose of this chapter is to provide a guide for those involved in the design or redesign of a component to be produced using polymer additive manufacturing (AM). This includes the Design Organisation (DO) and the Production Organisation (PO), which could both be from the same organisation. In designing or redesigning a component, those involved will agree manufacturing specifications to control the variables within the process and outline testing methods and the number of tests required to give confidence that the material is within the specification. The specification will then be agreed on a part by part basis depending on the part and its function.

Although several polymer AM techniques exist this document will focus on material extrusion (also referred to as Fused Deposition Modelling or Fused Deposition Manufacturing) and laser powder bed fusion techniques. These are described in more detail later on in this chapter.

AM processes are in general complex and there are many interconnected process variables associated with the technique. This chapter of the guidance document will outline each variable, explaining why it may be important before discussing how a manufacturer might control or measure the variable. This guidance is not a process specification but gives information and guidance for the PO, DO and the Type Airworthiness Authority (TAA) when assessing the airworthiness of a part produced using AM.

Chapter 3 section 2 figure 3-1 of this document outlines the process through which a part is qualified as airworthy by an approved Design Organisation (DO) and the Type Airworthiness Authority (TAA). For new aircraft all components must go through the Military Certification Review Item (MCRI) process. For replacement components for existing aircraft the change can be marked as a major or minor change. For major changes the item must go through the MCRI process and are classified as such if there is a change in the design, manufacturing process or material. As stated in recommendation 3.1 in that chapter: **It is recommended that an AM part, whether for a new or existing aircraft, <u>shall</u> be subject to the MCRI process until the technology is sufficiently mature to maintain variability in a predictable and repeatable manner**.

As discussed in the metals chapter of this document for the purpose of this guidance document the polymer AM process will be categorised using the different stages of a build as an outline. These are outlined and defined further in the metals chapter.

For polymer AM, as with metal AM the process is important to the properties and scatter in properties of the final part. This means for critical AM components in both polymer and metal **a Process Control Document (PCD) <u>shall</u> be supplied as part of the airworthiness documentation. Any changes to the PCD shall be subject to the Military Certification Review Item (MCRI) process. The contents of the PCD should be written based on the recommendations outlined within this document. The Process control document could include but not be limited to details of the control of:**

- **AM machine.**
- **Build strategy.**
- **Testing.**
- **Post-processing.**

Although standards are mentioned within this document where applicable, **it is recommended that existing, recognised standards (e.g. ASTM, ISO, BSI) <u>should</u> be used where available to inform the qualification and certification of AM components (REC7.1).**

It is expected that as AM develops, more AM-specific standards will be produced.

7.1.2 CHAPTER AT A GLANCE

Section	Title	Description and purpose	Page
7.1	Introduction	An introduction to airworthiness aspects of additive manufacturing including common defects and an outline of solidification and melting in polymer additive manufacturing.	192
7.2	Part design	An outline of the additional aspects for consideration when designing a part for polymer AM including the physical and mechanical properties, part geometry requirements and designing for anisotropy.	220
7.3	Build design	An outline of all aspects of build design from machine choice and aspects of health and safety to the part configuration and build parameters.	226
7.4	Build key performance variables	An outline of the key performance variables during the AM build including control of the feedstock and calibration of the machine.	236
7.5	Post-processing techniques	Additional post processing that may be required for polymer AM components and how these should be recorded and measured.	245
7.6	Component validation	Destructive and non-destructive testing techniques and how their recording or use may be different for polymer AM.	249
7.7	Component handover	Information about additional documentary evidence required for polymer AM.	258
7.8	Chapter summary of Recommendations		268
7.9	Glossary of abbreviations		267
7.10	Section references		259

7.1.3 INTRODUCTION

Additive manufacturing (AM) of polymers is a more mature technique than AM for metals discussed in the previous chapter and has seen application in non-safety critical parts, commonly referred to as tertiary structures, within aircraft for some time now [7.1]. Some proposed applications of polymer AM in aerospace systems include:

- Environmental Control System (ECS) ducting [7.2]
- Interior cabin structure [7.3]
- Brackets/clamps/support struts [7.4]
- Electronics housing [7.4]

As with metal additive manufacturing polymer additive manufacturing is a series of different technologies that can be divided into larger sub-groups. Some of the sub-groups are common with metal additive manufacturing, while others are not. In AM, as with other manufacturing processes, polymers are used in two key forms: thermosetting and thermoplastics.

Thermosetting polymers are typically cured during the AM process and cannot be melted once this chemical reaction has occurred. Two key additive manufacturing technologies cure thermosetting resins in this way:

- Vat photopolymerisation
- Inkjet photopolymerisation

Thermoplastics are polymers that can be re-melted once they have been solidified and like metals are re-melted during the AM process. The AM sub-groups are as follows:

- Powder bed fusion (PBF) (Figure 7-1)
- Material Extrusion – also referred to as Fused Deposition Modelling (Figure 7-2)

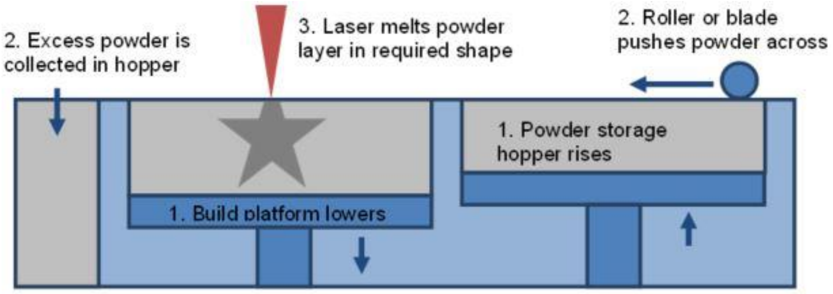

Figure 7-1 - General schematic of an laser PBF AM machine.

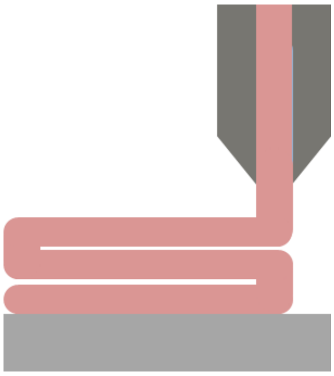

Figure 7-2 - Schematic illustration the deposition of polymer via the nozzle of a material extrusion additive manufacture machine.

Important thermoplastics used in additive manufacture and a selection of their typical properties when used in conventionally manufactured parts is shown in Table 7-1:

Table 7-1 - Data relating to key thermoplastics. This data was derived using ASTM standards and taken from the Modern Plastics Handbook [7.5]

7.1.4 INTRODUCTION TO MELTING AND SOLIDIFICATION IN POLYMERS

Melting and solidification play a central role in additive manufacture processes that utilise thermoplastic polymers. Thus, by gaining a greater understanding of how and why these processes occur in polymers the relevance of additive manufacturing processing parameters become more apparent.

To understand how and why melting and solidification occur in polymers it is first useful to appreciate the underlying physical properties that contribute to these phase transitions, as well as how these properties are described. This section will therefore aim to explain polymer properties that relate to melting and solidification before going on to examine the processes at play during the phase transitions themselves. The ultimate aim will be to provide a reference that gives a useful outline of these properties, while at the same time supplying enough depth that the reader will become familiar with some of the terms and concepts a polymer engineer is likely to use when discussing the melting and solidification of polymers.

7.1.4.1 PHYSICAL PROPERTIES

Polymer Type	T_m (°C)	Tensile strength at break (MPa)	Elongation at break (%)	Tensile yield strength (MPa)	Compressive strength (MPa)	Flexural strength (MPa)	Tensile modulus (MPa)	Compressive modulus (MPa)
Acrylonitrile butadiene styrene (ABS)	110-125	23-55	1.5-80	28-51	45-52		1861-2758	896-2137
Polyamide (Nylon 12)	160-209	35 - 69	250-390	21-42		10-56	248-1241	
Polycarbonate	126	26 - 30	300-380	12-17		14-16	207-276	214
Polyetherether ketone (PEEK)	334	70 - 103	30-150	91	124	110		
Polyetherimide (PEI)	215-217	97	14000	105	151	152	2965	3309

7.1.4.1.1 MOLECULAR WEIGHT

One of the key metrics used to describe a polymer that directly affects its melt and solidification properties is its molecular weight. A polymer's molecular weight is the product of the degree of polymerisation (DP)-*n,* i.e. the number of repeating units (monomers), and the molecular weight of each repeating unit. As an aside, polymers containing more than one distinct monomer species are termed copolymers. As well as melt and solidification, molecular weight will also affect mechanical properties with larger, higher weight polymer chains expected to be entangled to a greater extent, therefore producing higher tensile strengths

As most synthetic polymers contain a mixture of chain lengths, the use of an average value for molecular weight is required. Commonly stated values include: molecular weight average (Eq. 1), number-average molecular weight (Eq. 2) and the weight average molecular weight (Eq. 3). It is also useful to be able to describe the dispersity of molecular masses within a polymer using the polydispersity index (PDI), defined as the ratio of the weight average molecular weight to the number average molecular weight (Eq. 4). For context, PDI values tend to unity as the molecules become more consistent in size (monodisperse). (DP)-*n* can also be calculated from the number average by simply dividing it by the molecular weight of each repeating unit.

$$\sum_{i=0}^{\infty} \boldsymbol{P_i x_i}$$

Equation 1 **-** Equation describing the molecular weight average: P_i = probability of the occurrence of the particular mass x_i.

$$\boldsymbol{M_N = \frac{\sum_{i=1}^{\infty} M_i N_i}{\sum_{j=1}^{\infty} N_i}}$$

Equation 2 **-** Equation describing the number-average molecular weight where the total weight of polymer is divided by the total number of molecules: N_i = the number of molecules with weight M_i.

$$\boldsymbol{M_W = \sum_{i=1}^{\infty} w_i M_i}$$

Equation 3 **-** Equation describing the weight average molecular weight which is weighted according to weight fractions: w_i = the weight fraction of molecules with weight M_i.

$$\boldsymbol{PDI = \frac{M_W}{M_N}}$$

Equation 4 - Equation describing the polydispersity index which is equal to the ratio of the weight average molecular weight to the number average molecular weight.

7.1.4.1.2 CRYSTALLINITY

Another important property to consider when thinking about a thermoplastic polymer's melt and solidification properties is its degree of crystallinity (Eq. 5). Crystallinity can be generally defined as a measure of the long range order found in a material with an increase in polymer crystallinity generally leading to a higher melting point (T_m), higher densities, a higher Young's modulus, lower impact resistance and lower solvent permeability. Most thermoplastic polymers can be defined as either totally amorphous (0% crystallinity) or semi-crystalline (Figure 7-3).

$$\%\boldsymbol{Crystallinity} = \frac{\boldsymbol{\rho_c(\rho_s - \rho_a)}}{\boldsymbol{\rho_s(\rho_c - \rho_a)}} \times \mathbf{100}$$

Equation 5 - Equation describing the degree of crystallinity: ρ_c = the density of the completely crystalline polymer, ρ_a = the density of the completely amorphous polymer, ρ_s = the density of the sample polymer.

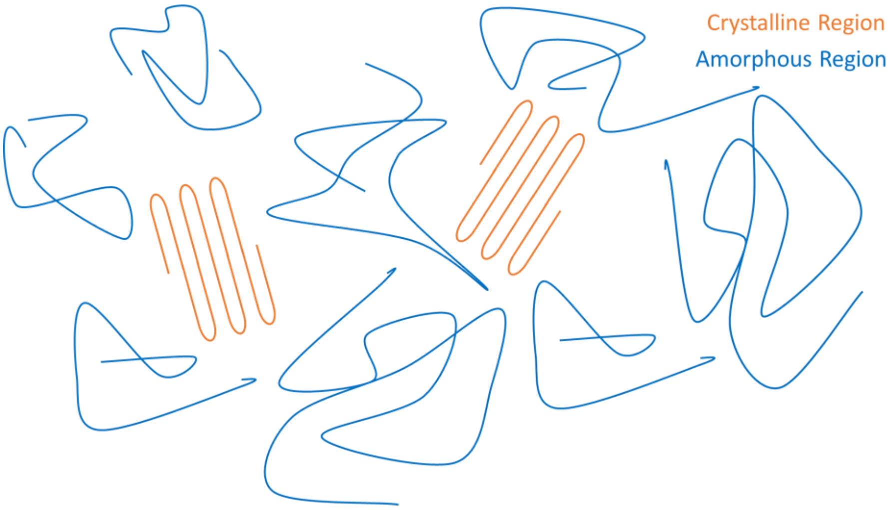

Figure 7-3 **-** Schematic illustrating the degree of molecular order in a semi crystalline material

Polymers that display higher degrees of crystallinity tend to allow for closer packing of molecules into crystalline lamellae. Closer packing is favoured for molecules that have fewer and shorter sidechains, more regular copolymer arrangement and more regular stereochemistry. To expand on the nomenclature of polymer stereochemistry, a polymer is said to be isotactic when polymer side groups are arranged with the same orientation along the polymer backbone, syndiotactic when the side group orientations alternate and atactic when side groups orientations are random. Isotactic polymers are therefore said to have a more regular stereochemistry.

The formation of crystalline lamellae can also be enhanced by employing longer polymer cooling times from a molten state. Conversely, if the polymer is quenched from the molten state then there will be less time for crystalline growth, meaning the amorphous content will be high. During the crystallisation process crystalline lamellae grow radially from a nucleation point to form spherical structures known as spherulites (Figure 7-4). These crystalline spherulites are usually surrounded by amorphous (non-crystalline) material, producing a semi-crystalline material. Consequently, it is important to note that in a semi-crystalline material there will be regions with differing physical properties, corresponding to the differing regions of crystallinity. It is also important to note that if preferred orientation of crystallites is introduced, through processing for example, a material with anisotropic properties will result.

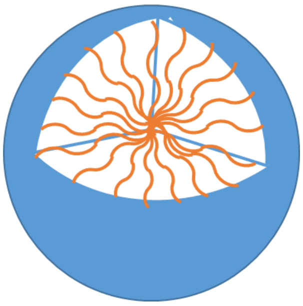

Figure 7-4 - Schematic of a spherulite illustrating polymer chain growing radially from a nucleation point

7.1.4.2 THERMAL PROPERTIES

7.1.4.2.1 MELTING

The AM techniques discussed in this document deal solely with thermoplastic polymers due to their melting and solidification properties. It is therefore useful to have an understanding of what makes a polymer either thermosetting or thermoplastic and how this affects their thermal properties.

Polymers can generally be classified as either thermosetting or thermoplastic. In a thermosetting polymer covalent bonds are formed between polymer chains in a process known as crosslinking. This results in a permanently rigid molecular structure that does not allow for melting on heating. A thermoplastic polymer on the other hand is not subject to crosslinking, meaning its long chain molecules are held together only by the weak attraction provided by Van Der Waals forces. This weak attraction is overcome when a thermoplastic polymer is heated to its melting temperature (T_m), allowing the molecules enough degrees of freedom to enter a molten state in which they can freely flow. Thus, the requirement for free flowing molecules during the melting process means that inhibiting the flexibility of the polymer backbone acts to increase the melting temperature. For example, double bonds, aromatic groups and other bulky side groups, such as those found in high performance polymers such as polyetherketoneketone (PEKK) and polyetheretherketone (PEEK), can all contribute to higher melting temperatures. Conversely, factors that contribute to weaker intermolecular attraction, such as extensive branching, can act to reduce the melting temperatures. This is not the case for a thermoset polymer, where strong covalent bonds must be broken before melting can be achieved, meaning decomposition occurs before melting is possible.

Mechanical strength is higher for a thermosetting polymer, with strength in polymers generally following the trend: crosslinked > branched > linear. The trend can be explained by the relative forces holding the chains together in each case. A small caveat to this is the case of elastomers.

Elastomers contain relatively few crosslinks so that while individual polymer chains are not able to flow when they are in a molten state, they are able to undergo significant changes in their conformation, or, in other words, rotate about their C-C single bonds. They are therefore capable of being far softer and more elastic than thermoset polymers, which as a result makes them slightly more ductile and gives them good resistance to crack growth and good impact properties.

7.1.4.2.2 GLASS TRANSITION TEMPERATURE

Glass transition is a phenomenon observed in amorphous polymers and the amorphous regions of semi-crystalline polymers. In an amorphous polymer (or amorphous region) at temperatures below the glass transition temperature (T_g), the material is typically hard and rigid because polymer chain molecules do not have sufficient thermal energy to overcome their intermolecular attractive forces. At temperatures above T_g, but below T_m, the polymer enters a "rubbery state" because there is sufficient thermal energy to overcome the intermolecular forces (Figure 7-5).

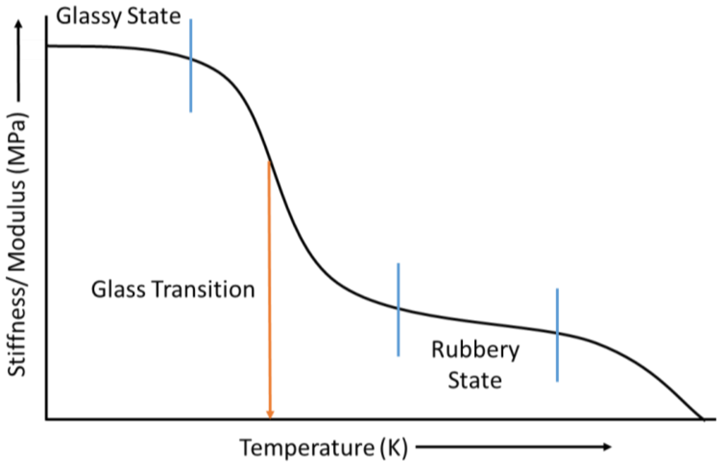

Figure 7-5 **-** Diagram showing the change in stiffness as a function of temperature as a material passes through a glass transition

The value of T_g can depend on a variety of factors. The strength of any intermolecular interactions will have a direct effect on T_g, meaning polymers containing strong dipoles, for example, generally have a higher T_g. The flexibility of the polymer backbone is another important characteristic. When chain flexibility is reduced by the presence of chain stiffening groups such phenylene, carbonyl, sulfone and amide groups T_g can again be expected to rise due to the increased energy required for conformational change. Similarly, crosslinking can restrict rotation about C-C single bonds, raising T_g. T_g can also be linked to molecular weight by the Fox-Flory equation (Eq. 6) with an increase in T_g observed as molecular weight increases. The Fox-Flory equation also takes into account the free volume within a polymer, with free volume being directly related to the number of chain ends found on a polymer molecule. Thus, extra branching can act to reduce T_g, as long as the side braches are not large enough to sterically hinder rotational motion. It is also possible to reduce T_g by incorporating plasticisers which disrupt the attractive intermolecular forces occurring between polymer chains.

$$\boldsymbol{T_g = T_{g,\infty} - \frac{K}{M_n}}$$

Equation 6 **-** Fox-Flory equation relating T_g to molecular mass: $T_{g\infty}$ = polymers T_g at a molecular weight of infinity, K = (Fox-Flory parameter) which is related to the free volume within the polymer, M_n = number average molecular weight.

7.1.4.2.3 SOLIDIFICATION

The solidification of a polymeric liquid is a thermodynamically driven process with solidification becoming thermodynamically favourable as the liquid is cooled to its T_m. However, the nature of the properties of the solid phase can be largely dependent on kinetic factors, i.e. the rate at which they occur as cooling proceeds.

In order for a crystalline (or semi-crystalline) solid to form, nucleation of small crystallite particles must first occur. This requires the energy cost of creating a solid-liquid interface to be overcome by a "driving force". As a consequence nucleation occurs at $T<T_m$ and, depending on the rate of this nucleation, a "super-cooled", also termed "undercooled", liquid can exist at temperatures below T_m. Nucleation is then followed by a period of thermally driven crystal growth. Therefore, cooling rates and the duration a polymer is held between T_g and T_m, will influence the degree of crystallinity and the size of crystalline regions. In turn, this will affect the material's physical and mechanical properties.

Forming a fully amorphous, glass-like solid requires a much faster quenching process. This process can be thought of as preventing polymer molecules from having time to arrange themselves into a crystalline structure before losing thermal mobility, therefore preventing nucleation and fixing them into a disordered "glassy" state.

Amorphous materials have a tendency to be isotropic meaning their mechanical properties are the same in all directions. In contrast, crystalline / semi-crystalline polymers can have either anisotropic or isotropic properties depending on the degree of randomness of crystallite orientations. Fully random orientations, leading to isotropic properties, is in reality difficult to achieve when processing a polymer. For example, passing a molten polymer through an aperture, such as an additive manufacturing nozzle, as it cools may introduce a preferred crystalline orientation, resulting in a material with anisotropic mechanical properties.

7.1.4.3 ADDITIONAL CONSIDERATIONS FOR TWO MATERIAL SYSTEMS

Although multi-material 3D printing research is being undertaken for many different material types, polymer AM, particularly Material Extrusion is unique in offering commercially available multi-material 3D printers. Most industrial scale polymer Material Extrusion printers have a dual nozzle, which enables a second material to be printed along with the main material. In most cases for material extrusion the second material is a support material but could be a material with different functional or mechanical properties.

The choice of second polymer will depend on the required properties of the system but a key point to consider is how or if the two materials with adhere to each other during the build. This is in some part due to the chemical compatibility of the two materials but also can be due to the melting and solidification properties. As such, **when planning a two material build differences in the melting and solidification properties of both polymers should be considered as this can lead to localised differences in crystallinity and distortion if those properties are significantly different (REC7.2).**

Typical parameters that may be considered for a multi-material build include:

- Coefficients of thermal expansion (CTE) – A significant mismatch in the way both polymers expand and contract on heating or cooling can lead to distortion in the polymer.
- Melting and glass transition temperatures – If a higher melting point layer is deposited it could lead to melting in the previously applied polymer layer.
- Thermal conductivity – If one polymer is more conductive than the other it may lead to distortion through heat concentration at e.g. joins between the two materials.[7.6, 7.7]

7.1.5 SUMMARY AND APPLICATION OF MELTING AND SOLIDIFICATION IN AM

The majority of polymer additive manufacturing processes involve the melting and solidification of thermoplastic polymers and consequently their control through machine design is key. The following sub-sections examine how common polymer additive manufacturing systems monitor and control melting and solidification, and how process variables can affect printability and the quality of the final printed part. This will provide an understanding of how the processes can be controlled by the user. However, it is important to emphasise that while the following information can be used as a guide and reference for developing a greater understanding, it is not exhaustive and formal training will be required prior to manufacturing parts on a particular machine.

7.1.5.1 ENERGY INPUT – INTRODUCTION

7.1.5.1.1 POWDER BED FUSION

In polymer additive manufacturing both thermal and optical methods are used to heat and melt polymers. Powder Bed Fusion techniques usually employ the “bulk heating” of the polymer powder to just below the polymer T_m, via thermal energy input, leaving it in rubbery state. This process is usually aided by the presence of conductive heating elements wrapped around the feed and build pistons. Selective radiative heating, via optical energy input using e.g. a laser, is then used to induce melting for part manufacture (Figure 7-6).

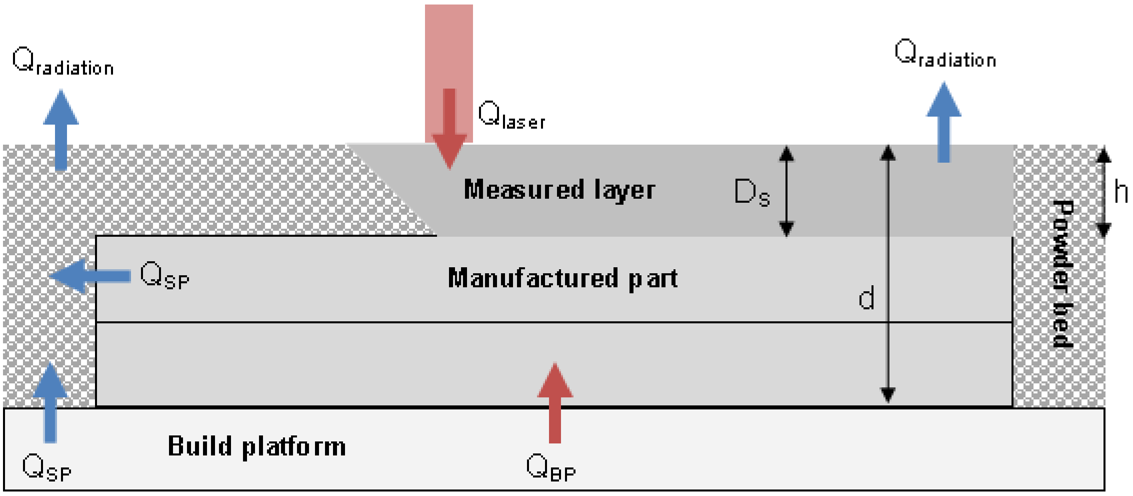

Figure 7-6 - Diagram illustrating heat flow in an L-PBF process. Heat is supplied to the bulk powder by the build bed and associated conductive heating elements. Heat is then supplied selectively to the measured layer above the manufactured part, by a laser, to induce sintering of the following layer.

Powder bed fusion machines can vary in their operation with a primary difference being their selective heating source:

- Laser Powder Bed Fusion (L-PBF) – Utilises a scanning laser to supply selective radiative heating.
- High Speed Sintering (HSS) – Utilises infra-red lamps that heat and melt areas of polymer in which a radiation absorbing material (RAM) has been deposited by a series of print heads.

By preheating the polymer to just below the polymer T_m, a smaller thermal gradient is experienced between the melt powder and the powder in the immediate vicinity, reducing the likelihood of the part distorting as each layer solidifies. It also means that a smaller energy input is required to melt the polymer resulting in the potential for faster scan speeds that allow for material to be built up more quickly. However, it is important to note that maintaining the temperature of a polymer above its T_g for extended periods of time may result in unintended side reactions that alter the molecular weight of the polymer and therefore alter its chemical and physical properties (see section 7.1.4.1.1). This can be mitigated by storing the material in the feed piston at slightly lower temperature than the material in the build piston (if this approach is used then a dwell period is required to ensure the material in the build piston reaches the required temperature prior to selective heating). **Temperature gradients between the feed and build pistons should be recorded and carefully controlled for polymer L-PBF to reduce the risk of geometric distortions in the printed part (REC7.3).**

In order for selective heating by laser scanning to produce a well-defined boundary between the part and the surrounding powder, a well-defined melt pool must be created and the material immediately next to the beam path must not melt. Consequently a polymer with a high heat of fusion and a narrow melting point range is preferable [7.8]. Unfortunately, the literature does not yet contain significant quantitative studies into the exact relationship between these properties and the dimensional accuracy of additive manufactured parts. **A well-defined melt pool should be used to allow for good dimensional accuracy. This may be achieved by selecting a polymer with a high heat of fusion and a narrow melting point range (REC7.4).**

Effective thermal conductivity, namely, the combination of the polymer thermal conductivity, surrounding gas thermal conductivity and the powder bed packing efficiency [7.9], is another important factor contributing to the formation of a well-defined melt pool. **The effective thermal conductivity will play a major role in determining temperature distribution during a selective heating process and thus <u>may</u> prove a valuable consideration when planning key process variables (REC7.5)**.

The rate of energy input is also an important parameter. For example, rapid beam scan speeds can result in an increase in porosity [7.10] in the final part since less time is spent imparting energy to a given area. Lexow *et al.* have demonstrated an inverse relationship between laser scan speed and density and tensile strength [7.11].

7.1.5.1.2 MATERIAL EXTRUSION

Material Extrusion, also known as Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF) is in essence a melt extrusion process. A feedstock thermoplastic polymer filament is fed into the “cold end” of the melt liquefier/print head assembly using an electric motor and pushed into the “hot end” which consists of a heating chamber and the print head nozzle. The molten polymer is then pushed out of the print head nozzle by the solid portion of the filament and deposited onto a build platform. In order to print the desired part geometry the print head assembly is moved across a gantry that allows for movement in the x-y plane of the build platform. Once a layer of polymer has been deposited, depending on the design of the machine, the print head or the build platform can then be moved in the z direction to enable the deposition of subsequent layers. This mechanism provides the means to build up the printed part in a layer by layer fashion.

In a Material Extrusion process the primary mode of thermal energy input is provided by the melt liquefier, with the exact temperature used in the melt liquefier being dependent on the choice of printing polymer and its T_m. The temperature used in the liquefier is commonly referred to as the extrude temperature.

The liquefier itself is generally composed of a metal block with a machined channel to allow for the flow of filament/melt and heat is applied in the form of the resistive heating of either a coiled heating element or cartridge heaters. The entire melt system is designed to maintain a constant temperature through the use of a controller and usually a single thermocouple [7.12].

Secondary mode of energy input can come in the form of a heated build chamber, which can benefit interlayer fusion, or heated build platform. The temperature of this platform is commonly referred to as the bed temperature and plays a vital role in the adhesion of the polymer to the build platform. The build platform material and temperature must allow for enough adhesion so that the part does not move during the printing process while also allowing for the part to be removed at the end of the process. A list of commonly used extrude and bed temperatures can be seen in Table 7-2 [7.13].

The substrate material on which the part is built is another key factor in achieving a good level of adhesion between the part and the build bed. The selected material must allow for good adhesion during the manufacture process but thought must also be put into how the part will be removed. If the build bed to part bond is very strong the build bed material may need to be treated as sacrificial and the part removed via machining. Common bed materials include: glass, aluminium, stainless steel, PET tape, PEI film and BuildTak. However, there is no universally preferred material across all polymers, instead specific polymers can be paired with preferred bed materials for optimum performance.

Table 7-2 - Data relating to the optimal extrude and bed temperatures of some common Material Extrusion filament polymers.

Polymer	Extrude Temperature (°C)	Bed Temperature (°C)
Acrylonitrile butadiene styrene(ABS)	220-250	95-110
Polyactic acid (PLA)	190-220	45-60
Polyethylene terephthalate (PETG)	230-250	75-90
Nylon	220-270	70-90
Polycarbonate	260-310	80-120
Polypropylene	220-250	85-100
Polyvinyl alcohol (PVA)	185-200	45-60

The extruder temperature and the build bed temperature <u>should</u> be matched to the specific polymer in use (REC7.6).

7.1.5.2 ENERGY INPUT – PRINTABILITY PROPERTIES

7.1.5.2.1 POWDER BED FUSION

When considering powder bed fusion variants of polymer additive manufacturing there are some core process variables that can be manipulated. These include bulk polymer temperature, optical energy intensity, scan speed and hatch spacing. It is important to understand how these variables interact with the chosen polymers properties, such as thermal transitions, optical absorptivity at the chosen selective heating wavelength and thermal parameters such as heat capacity (C_p) and heat of fusion (Δh_f).

In the case of polyamide, preheating the material eventually leads to a “glaze point” in which the surface of the material begins to glisten directly prior to melting. The phenomenon can be used by operators to ensure that they do not fuse the entire powder bed, during preheating, by ensuring they do not heat the material past this point. **Careful temperature control should be used to ensure that the powder bed does not fuse during preheating. In polyamide the glaze point could be used to identify the appropriate powder bed temperature and a temperature of 12 °C below the glaze point has been shown to limit this effect [7.10] (REC7.7)**.

A stable sintering region (SSR) can also be identified for polymers, generally defined as the temperature region between T_m and 1% material degradation. This region allows for the efficient fusion of particles without significant losses of material [7.14]. Additional consideration on this subject is usually given to polymers with a high T_m such as poly(aryl ether ketones) (PAEKs), where the thermal characteristics of the polymer, such as melting range, are used precisely to target the most optimal heat input.

With these temperature effects in mind it is important to consider how the energy being delivered, which can be tightly controlled with machine parameters, relates to the energy required to melt the polymer. Assuming a 100% conversion of optical energy into thermal energy this relationship is described by the energy melt ratio (*EMR*). To calculate this value the first parameter of importance is the volume energy density (ED_{vol}) (Eq 7.), which considers the energy density of the laser (*ED*) (Eq.8) and the layer thickness (*z*). The second parameter of importance in the volume energy required to melt the material (Eq. 9). The *EMR* is, in effect, the ratio between these two parameters. This value used in conjunction with the *EMR* for degradation (Eq.11) can help determine the amount of energy required to heat a polymer to a temperature within its SSR [7.14].

$$ED_{vol} = \frac{ED}{z} \qquad \left[\frac{J}{mm^3}\right]$$

Equation 7 - Equation describing volume energy density ED_{vol}: ED = energy density (J mm^{-2}), z = layer thickness (mm)

$$ED = \frac{P\,C}{S\,v} \qquad \left[\frac{J}{mm^2}\right]$$

Equation 8 - Equation describing the energy density (*ED*): P = laser power (J s^{-1}), C = scan count (unitless), S = scan spacing (mm), v = scan speed (mm s^{-1})

$$E_m = \left[C_p(T_m - T_b) + h_f\right] Q\,\Phi \qquad \left[\frac{J}{mm^3}\right]$$

Equation 9 - Equation describing volume energy required to melt a material (E_m): C_p = specific heat capacity (J g^{-1} K^{-1}), T_m = melting temperature (K), T_b = powder bed temperature (K), h_f = enthalpy of melting (J g^{-1}), Q = bulk density (Kg mm^{-3}), Φ = packing fraction (unitless)

$$EMR = \frac{ED_{vol}}{E_m} = \frac{ED}{E_m z} = \frac{\frac{P\,C}{S\,v}}{\left[C_p(T_m - T_b) + h_f\right] Q\,\Phi\,z}$$

Equation 10 - Equation describing the energy melt ratio (*EMR*)

$$EMR_{deg} = \frac{\left[\left(T_{DegOnset} - T_m\right) C_p + \frac{E_A}{M_w}\right] Q}{\left[C_p(T_m - T_b) + h_f\right] Q\,\Phi}$$

Equation 11 - Equation describing the energy melt ratio for degradation: $T_{degonset}$ = temperature for the onset of degradation (K), E_A = activation energy for degradation (J mol^{-1}), M_w = weight average molecular weight (g mol^{-1}).

While not accounted for in the energy melt ratio equations the absorption coefficient of a polymer at incident radiation wavelengths is nevertheless an important factor. If the energy absorption is high at the chosen wavelength then the amount of energy input can be minimised [7.15]. Another important and related observation is that the beam radius to particle size ratio can affect the degree of energy absorption [7.16].

To summarise these points: **The following guidance may be considered when deciding on selective heating parameters:**

a) **Operating the process within the stable sintering region of the feedstock polymer;**
b) **Optimising the wavelength of the incident radiation to the absorption coefficient of the feedstock polymer;**
c) **Ensuring the incident beam radius is appropriate for the feedstock polymer particle size (REC7.8).**

7.1.5.2.2 MATERIAL EXTRUSION

In order to print a part in a Material Extrusion process the melt liquefier must provide enough heat flux to melt the feedstock polymer. The amount of molten polymer in the liquefier is therefore determined by the filament feed rate and the heat flux provided. **The lack of a distinct melting point in amorphous polymers means that for Material Extrusion melt liquefier temperatures and filament feed rates <u>may</u> require fine-tuning to give optimal results (REC7.9).**

In general, a higher melt temperature leads to better interlayer fusion and, consequently, improved strength in the final part. However, high temperatures can also result in the degradation of the polymer resulting in a part with poor properties [7.12]. **During Material Extrusion care <u>should</u> be taken not to induce thermal decomposition of the polymer. This may be particularly relevant when maximising melt temperature in order to achieve a high degree of interlayer fusion (REC7.10).**

Printability performance can also start to degrade with time and use. In a Material Extrusion system the print head and nozzle geometry coupled with the viscosity of the molten polymer have a direct effect on the amount of force required to extrude the polymer and the general performance of the print head. Consequently, the build-up of residue in the print head, which can be exacerbated by polymer degradation, can lead to poor builds. Thermal cycling effects can also become detrimental to the print head through extended use. **For Material Extrusion the impact of head degradation should be considered since head degradation can have a detrimental effect on the properties of the final part (REC7.11).**

7.1.5.3 ENERGY INPUT – PRINTED PART PROPERTIES

7.1.5.3.1 POWDER BED FUSION

The majority of thermal energy delivered in a PBF AM process is delivered during the preheating of the powder bed prior to selective heating, either in the feed piston, build piston or commonly a combination of the two. The importance of the resulting build temperature has been highlighted in the literature. If using a low build temperature, a fast build process will require a rapid selective heating rate, which has been shown to result in a part with poor toughness [7.11]. Further, the build temperature has been shown to affect the dimensional accuracy of the part, its hardness and its final density [7.17]. These factors highlight the need for accurate control of the powder bed temperature as well as a achieving a uniform temperature across the powder bed.

The mechanical properties of a final part are dependent on the energy density delivered during selective heating, i.e. the tensile strength of printed parts has been shown to reach a maximum at a given energy density [7.18]. For example the maximum tensile strength of Nylon 12 is achieved when the energy delivered is approximately 30% in excess of what is required to initiate melting [7.18]. Consequently an overall optimum EMR value, i.e. when polymer degradation is also accounted for, is reported as 1.4 in work by Zarringham *et al.* [7.19]. **The optimal ratio between energy supplied and energy required to the melt the polymer (EMR) may be used in order to maximise the mechanical properties of a printed part (REC7.12).**

Interestingly, while EMR values incorporate a combination of processing parameters, work has also been performed in which the effect of individual processing parameters has been explored, with respect to shrinkage in particular. Work performed by Raghunath *et al.* has shown that laser power is related to shrinkage in the X-direction, laser power and beam speed is related to shrinkage in the Y-direction and beam speed and hatch spacing affects shrinkage in the Z-direction [7.20]. Further, hatch spacing has been shown to have the most pronounced effect on the geometric accuracy of a printed part [7.21]. It also important to note that there does not appear to be a lower limit on beam speed with respect to the resulting properties of a printed part. In fact, reduced scan speeds are associated with smoother surface finishes and an increase in crystallinity [7.22]. Too high a beam speed on the other hand, results in decreased melt pool depth [7.11] and when attempting to compensate for this by increasing the laser power there is a noticeable degradation in part quality. **When considering the beam speed parameter the compromise between build speed and part quality <u>should</u> be considered. For example a high beam speed will result in a faster build rate but will generally lead to a deterioration in build quality (REC7.13).**

7.1.5.3.2 MATERIAL EXTRUSION

As in PBF processing, final printed part properties are highly dependent on the strength of interlayer bonding and it has been shown that an additional heat source (additional to the melt liquefier and heated build bed) can improve interlayer fusion. For example, it has been demonstrated that by preheating the polymer surface with an IR lamp prior to depositing a new layer the fracture energy of the final part can be improved (as well as the surface finish). By tuning the light intensity and deposition rate, the authors of this work claimed to have achieved a 200% improvement [7.23]. It is also not uncommon for heated build chambers to be employed, with temperatures as high as 90°C commonly used when printing with ABS. Research has also shown that preheating the polymer surface with lasers prior to new layer deposition can lead to improvements in interlayer bonding and corresponding improvements in mechanical properties in the z direction in particular [7.24]. The authors were able to show even better results when combining laser heating with the tuning of other variables such as layer thickness, laser power, print speed and deposition rate.

Research has also shown that the incorporation of carbon fibres into ABS polymer filament can reduce distortions while improving the thermal conductivity of the filament, thereby reducing its thermal expansion rate. This reduced the need for secondary energy input in the form of a heated build chamber [7.25].

7.1.5.4 COALESCENCE, COOLING AND CRYSTALLIZATION – INTRODUCTION

7.1.5.4.1 POWDER BED FUSION

Above T_m, where the polymer is molten, the fusion of molten particles can occur whereupon the fused material will solidify on cooling below T_m. The rate of energy transfer to the polymer and the duration at which the polymer is held in a molten state, which can both be controlled, directly affects the degree of particle fusion and therefore the density and strength of the printed part.

The rate at which the polymer then cools can also have a significant effect on the properties of the final part, for example crystallinity. During cooling of a PBF part there are two distinct stages that the part experiences: (a) the cooling of selectively heated material back to the build temperature; and (b) the final cooling of build material at the end of the build process. These cooling rates can be controlled through PBF processing parameters and therefore optimised for the properties of the polymer and the desired properties of the final printed part.

Since the coalescence of particles is strongly dependant on heating rate it can be useful to combine processing parameters such as laser power and scan speed to give a single resultant heating rate measurement, as suggested by Laumer *et al.* [7.26]. This value must then be related to key material based timescales, of which there are two for PBF: (1) the timescales for melting of particles; and (2) the timescales for macroscale flow of the material. Consideration of these timescales and the thermal characteristics of the polymer is necessary to achieve a high quality build. Thermal characteristics include but are not limited to the heat transfer through the bulk of a particle and the rate of change of material viscosity and thus flow characteristics for void filling.

Coalescence behaviour is also influenced by a polymer’s crystallisability, crystallinity and crystallisation rate. Since PBF utilises an isothermal build station , the temperature of fused material can be carefully controlled. This means that a good level of control can be exercised over crystallisation processes. For example, crystal nucleation and growth rate will both be reduced as the build station temperature approaches the polymer’s equilibrium T_m. As described in section 1.2.2.2.3, to provide sufficient driving force to form solid liquid interfaces during crystallite nucleation “super-cooling” of the polymer is required. Thus, crystallisation rate reaches a maximum at some point between the T_m and T_g and can be optimised around this maximum with sufficient understanding and control of the process. For example work by Kruth *et al.* highlights the advantage of a slower crystallisation rate during PBF [7.27]. The authors claimed that by restricting the formation of intra-layer crystals the introduction of internal stress fields, and thus delamination in the part, could be avoided.

It is also important to consider the polymorphism of a polymer because different polymorphs may convert optical energy to thermal energy at different rates (where polymorphism refers to a polymer having different crystal structures for the same composition). For example, commonly printed polymers such as polyamides and Nylon-12 are polymorphic [7.28] [7.26] [7.29]. This means it is possible that different batches of feedstock may contain differing polymorph ratios and therefore display different melting, solidification and crystallisation properties. **To fully understand the thermal properties of the feedstock polymer it may be necessary to consider the polymorphic state of the polymer at each stage of the manufacture process (REC7.14).**

Thermoplastic polymers in a PBF system are typically subject to shrinkage on solidification and cooling and also may be prone to geometric distortion. Shrinkage and distortion can occur during both the build stage and the coalescence/cooling stage [7.30]. While cooling and particle fusion lead to an increase in density and therefore shrinkage, the main contribution to shrinkage is crystallisation [7.31]. This again highlights the need for careful consideration of crystallisation processes and the potential advantage of printing using an amorphous polymer such as amorphous polystyrene [7.27] [7.32]. However, if shrinkage is a significant problem, mitigation methods include increasing the initial powder volume and introducing fillers into the powder. **The effect of shrinkage should be considered and accounted for prior to part manufacture (REC7.15).**

7.1.5.4.2 MATERIAL EXTRUSION

The literature contains very few reports into the effects of coalescence and cooling in Material Extrusion processes compared to PBF. This is mainly because of the rapid speed with which polymers are heated and cooled in Material Extrusion, making accurate measurement difficult. The ability to make such measurements would aid greatly in process monitoring and control.

This also makes the resulting properties of the printed parts produced by a given set of Material Extrusion process parameters hard to predict. Efforts to improve the understanding of the extrusion process have been attempted in the form of studies into Material Extrusion heat transfer [7.33] and filament bonding/coalescence [7.34]. However, the results of these studies have not been translated into models that can be used to predict final part properties with a good degree of reliability.

7.1.5.5 COALESCENCE AND COOLING – PRINTABILITY PROPERTIES

7.1.5.5.1 POWDER BED FUSION

In addition to the kinetics of polymer crystallisation, rheological, or flow, properties are also important. With respect to the rheological properties of a polymer, the concept of the SSR can be expanded. During solidification, coalescence and cooling there is a temperature range within which the rheological properties are optimum, which is just below the SSR range at temperatures lying between the onset of melting and the onset of super-cooling-driven crystallisation. In this range the rheological properties of the polymer can be sufficient to support the build as it forms, without curling. [7.35][7.14]

With respect to crystallisation kinetics a particular printability challenge faced in PBF AM is the difficulty in keeping the large volume of powder in the powder bed at a precise and homogeneous temperature. This can become problematic when the polymer in use has a T_m and an onset of crystallisation temperature (T_c) separated by only a few degrees because inconsistencies in temperature can lead to inconsistencies in the rate of crystallisation. This can result in defects in the printed part such as curling [7.16]. These effects tend to be exacerbated by faster processing windows.

Polymer viscosity can also represent a challenge, because for maximum mechanical properties high molecular weight polymers are necessary. High molecular weight polymers generally have high melt viscosities and consequently can have long coalescence times which can prove problematic [7.27]. **The melt shear velocity should be considered for optimum PBF AM particle coalescence. For example. a sufficiently high shear storage modulus in the molten state and an associated low melt shear viscosity, 60 Pa s in the case of nylon-12 [7.31], may be desirable [7.16] (REC7.16).**

7.1.5.5.2 MATERIAL EXTRUSION

Owing to the fundamental process of fused deposition modelling, thermal gradients are unavoidable in parts as they are being manufactured. If these thermal gradients become too large warping / distortion of the final part may result [7.35]. To combat this many premium Material Extrusion machines employ a temperature controlled printing chamber. The temperature is generally controlled using air flow, the aim of which is to cool the part, as it is being printed, thus mitigating the effects of heat build-up from the print head / melt liquefier assembly.

Non-premium Material Extrusion machines may use the cheaper approach of incorporating a heated build plate. A consistent supply of heat minimises the thermal gradient between the base of the part and freshly printed layers, which mitigates part warping. However, while heated build plates are useful in smaller machines they impose a practical limit on the size of the build plate and therefore the build envelope of premium machines. Heated build plates can also be ineffective when working with polymers that have a high T_m because they require a high extrude temperature and consequently the thermal gradient may still be too large.

7.1.5.6 COALESCENCE AND COOLING – PRINTED PART PROPERTIES

7.1.5.6.1 POWDER BED FUSION

Slower rates of post build cool down have been linked to reducing residual stress in printed parts [7.36] as well as increasing tensile strength while reducing elongation at failure [7.37] making cooling rate a parameter to consider when planning a build

Another phenomenon observed for nylon 12 powders is the incomplete melting of particles. When such particles coalesce it is only the melted shell regions that actually coalesce leaving the particle cores existing effectively as an unmelted secondary phase. The interfaces between the melted and unmelted phases can then act as areas of structural weakness [7.19] [7.38]. Researchers were able to monitor this effect in detail because the processed nylon 12 exists in a different crystal structure (polymorph) to the virgin powder found in the unmelted cores. **It is therefore important that the energy delivered to the polymer should be sufficient to melt polymer particles fully (REC7.17).**

Particle coalescence is also affected by physical build parameters such as build orientation. Build direction, for example, is known to result in a directional bias in surface finish [7.39] [7.40] [7.41]:

- When a curved surface is printed in the XY plane it tends to produce a smoother surface finish.
- When a curved surface is printed in the ZY or ZX planes the stair-casing effect starts to become apparent resulting in an increase in surface roughness [7.42].

Part density on a build bed can also play an important role in particle coalescence. It has been reported that when multiple parts are being printed simultaneously the resulting parts appear to have less porosity than a single part printed on its own. This effect has been attributed to the observation that the laser follows a longer path over a given area, thereby increasing the local area temperature [7.43]. As an extension of this principle, it also follows that a reduction in porosity is seen as the density of parts on a build bed is increased.

The orientation and build packing of parts should be considered and, if necessary, established and fixed for a particular part, or part family, depending on part criticality (REC7.18).

7.1.5.6.2 MATERIAL EXTRUSION

When a layer is printed in a Material Extrusion process it is printed directly onto the previous layer which is ideally still in a molten state. The molecular freedom of motion permitted in the molten state allows the polymer chains to arrange themselves in a way that maximises intermolecular attraction providing strong bonding in the material on macroscopic level. However, if the previous layer cools too quickly it is possible that it will solidify before the layers can fuse effectively, resulting in voids in the final printed part. Consequently, a higher average temperature is advantageous in relation to fusion.

Related to this is the interlayer cooling time. Increasing the interlayer cooling time means that the previously deposited layer temperature will be lower when a new layer is deposited. This will disfavour the fusion of layers, hence the overall strength and ductility of the part will be reduced. **For Material Extrusion the fusion between deposited layers should be considered since this can have a significant impact on mechanical properties. This may be achieved by reducing the overall cooling of material between layer depositions, which can be achieved by increasing the raster speed and/or layer thickness and decreasing the interlayer cooling time (REC7.19).**

7.1.6 USE OF FILLERS FOR POLYMER AM

Fibre, micro-particle and nano-particle fillers are all commonly added to polymers, including those used in AM, with the goal of improving various aspects of performance through the tuning of properties. These properties cover mechanical, magnetic, thermal, electrical and more. Improving these properties can be highly desirable from an airworthiness perspective. However, care must be taken to ensure than when forming a polymer filler composite part, the filler does not introduce sources of scatter into critical part properties.

This section will first give examples for the use of three key filler morphologies and then explore the challenges associated with incorporating fillers when considering property scatter and consistency in part performance.

7.1.6.1 FILLER TYPES

7.1.6.1.1 FIBRE REINFORCEMENT

Fibre reinforcement is becoming ever more popular in applications in which high mechanical performance is required. The replacement of metallic parts in Formula SAE race cars [7.44], Airbus A359XWB planes [7.45] and cement mortars [7.46] are a few examples.

While the incorporation of fillers has been shown to increase the viscosity of polymers the effect has been shown to be most pronounced for 1 dimensional fillers [7.47] i.e. fibres and as the filler becomes more rigid. Conversely, shear thinning which results in a lowering of viscosity under shear strain has been shown to be greatest for longer fibres. These effects warrant consideration when selecting fibre type and whether to utilise either short or continuous forms.

Fibres can be made from both synthetic materials such as glass, Kevlar, nylon and manufactured carbons, as well as natural materials such as bamboo, hemp and flax. While synthetic materials can offer impressive improvement in mechanical properties, natural fibres such as bamboo fibres [7.48] can offer slightly more modest improvements in mechanical performance, but do not come at the cost of a reduction in the biodegradability of the part.

In all cases in which fibres are utilised the orientation of the fibres is key to achieving the desired directional properties. For this reason, fibre reinforcement is most commonly employed in material extrusion AM, as deposition process allows for a degree of control over fibre alignment. For a material extrusion process the flow field of the extruded polymer will help determine the alignment of the fibre however it is important to note that the shear flow through the nozzle aperture is likely introduce randomisation in fibre alignment, so again a balance will need to be struck here.

As a result, the direction in which the fibres are deposited relative to the intended mechanical loading direction <u>should</u> be a key consideration when planning a build as should the material flow rate and size of the nozzle aperture (REC7.20).

7.1.6.1.2 MICRO-POWDER REINFORCEMENT

Particle reinforcement using inorganic/metallic particles is another approach that is becoming more wide spread. The dimensional properties of particles offer the advantage of being easier to disperse in a polymer than fibres making them suitable for both AM by materials extrusion and PBF. The dimensional properties of particles also lead to less dramatic impacts on isotropy than high aspect ratio fibres.

The wide spectrum of available materials, particle sizes and particle loading factors is another key advantage to a materials engineer, offering a lot options for the tuning of polymer composite properties. For example, in addition to mechanical properties, particles have been used to affect a range of other key material properties: Stainless steel particles have been used to enhance the thermal properties of ABS [7.49]; Magnetite (Fe_3O_4) particles have been added to polymers to utilise their magnetic properties for EM shielding [7.50]; hollow microspheres have been added to polymers to reduce density [7.51].

On the other hand, sensible limits on properties such as particle size may be useful. Hackly [7.52] and Atanasio [7.53] for example have both stated that the aperture of an extrusion device should be 3-5 times larger than the maximum particle size for optimal material flow.

7.1.6.1.3 NANO-POWDER REINFORCEMENT

As is the case for larger particles, nanoparticles can be used to enhance a range of properties beyond the purely mechanical. Carbon nanotubes, for example, have been incorporated into polymer printed parts to achieve enhanced radar absorptivity [7.54]. Carbon nanotubes have also been shown to provide improvements in the toughness of polyimide 11 through the inhibition of crack propagation [7.55].

Nano-particles do also offer routes to the improving mechanical performance mechanical properties of printed parts and in innovative ways not seen with other fillers. An impressive example of this is work performed by Sweeney *et al*. Here the authors coated each material extrusion printed thermoplastic layer with carbon nanotubes. By using microwave heating it was then possible to locally heat the layer interfaces causing them to fuse to a greater extent, ultimately provided much higher fracture strengths [7.56].

However, when particle diameters drop below 1 micron attractive forces between particles have been shown to induce agglomeration [7.57], therefore increasing material viscosity. This effect may impose limits on usable particle volume fractions.

7.1.6.2 CHALLENGES ASSOCIATED WITH THE USE OF FILLERS

While the use of fillers has the potential to improve key AM part properties, there is also scope for these improvements to come at the cost of other types of performance. M. Rides of NPL has prepared an extensive review [7.58] on this topic.

This means that if adequate controls are not put in place, fillers can also become a source of scatter in part properties. Below is a list of examples of how fillers can introduced reduced performance and increased scatter in the value of key properties.

- Filler properties
    - If a filler is prone to moisture absorption and it is exposed to moisture, through high humidity for example, then subsequent swelling of the part may lead to reduced performance and reliability.
    - Large variability in filler characteristics such as particle size or fibre length and diameter may also be likely to introduce scatter. This may be a particular issue for natural fibres.
    - Poor wettability brought about by matching a hydrophobic filler with a hydrophilic polymers is likely to result in weak interfacial bonding, leading to poor and inconsistent mechanical properties.
    - Fillers with low degradation temperatures, such as many natural fibres, may also become problematic should the print temperature exceed the filler degradation temperature
- Material Mixing

  - Mix quality will be vital to ensuring consistent properties throughout the polymer-filler composite. The mixing process itself is likely to be performed by the feedstock manufacturer using a high temperature mixing process. In the case of material extrusion, filled polymer granules will then be converted to filament by high temperature extrusion.
  - Homogenous dispersion of a filler through a high viscosity polymer is likely to be difficult.
  - If long mixing times and high energy inputs are required to achieve a homogeneous mix then economic cost, thermal degradation of the polymer and mechanical degradation of filler may become increasingly problematic. This may limit the availability and quality of reinforced polymer feedstock for high viscosity polymers.
  - Quality control tests for key properties in a filled polymer include:
    - Glass transition temperature (ASTM D 3418)
    - Melting temperature (DIN EN ISO 11357)
    - Thermal expansion (DIN EN ISO 11359-1:2)
    - Moisture absorption (DIN EN ISO 62)
    - Melt flow index (DIN EN ISO 1133)
    - Tensile testing (DIN EN ISO 527-1)
    - Flexural testing (DIN EN ISO 178)
    - Impact testing (DIN EN ISO 179)
- Material Flow
  - Fillers are likely to have an impact on the rheological properties of polymers, with potentially differing effects on viscous and elastic behaviours. This will likely result in subsequent effects on material flow in material extrusion based AM.
  - A range of filler properties including particle: size, shape, stiffness, topology, density and interfacial energy are likely to impact phenomena such as particle: motion, agglomeration, mechanical degradation, migration, flow separation and electro static effects. These phenomena may all require consideration with regards to material flow.
  - Refer to guidance on build design for flow for information on optimising material flow during a build.

7.1.7 COMMON DEFECTS IN POLYMER COMPONENTS PRODUCED USING AM

For the purposes of this section, the term defects is used to group together unintended macroscopic, microscopic and chemical heterogeneities in the build that may cause it to be out of specification. Surface roughness is discussed separately in Section 7.5. Several defects types can be observed in parts made using AM processes. Some defects, such as porosity, are also observed in other non-AM manufacturing processes such as injection moulding, although to a lesser extent [7.59]. Other defects such as delamination are not observed in e.g. injection moulding since they are a direct consequence of the layer by layer deposition methods used in AM. Defects in polymer AM can be split into two main types:

- Geometric defects that affect the shape of the component;
- Chemical defects that affect the chemistry and microstructure of the polymer.

The nature of defects observed in a polymer can also be impacted by the polymer, blend or any additives included. For example, many defects are impacted by moisture levels in the polymer and polymers typically have different moisture uptake levels and the moisture can have a different effect on properties from cosmetic concerns e.g. ABS through to performance concerns e.g. PLA. [7.60]

7.1.7.1 GEOMETRIC DEFECTS

7.1.7.1.1 POROSITY

Voids have a significant detrimental effect on the mechanical properties of polymer components. Process-induced porosity is the most common source of voids within polymer AM components and is typically observed as more irregular/ elongated defects in the material. One source of such voids is lack of fusion, which occurs typically between build layers. In powder bed fusion (PBF) this is caused because of unsatisfactory melting of the powder in a region of the build. This can either be owing to the amount of energy supplied by the heat source or the insufficient application of powder to the powder bed [7.61].

In Material Extrusion the lack of fusion is typically the result of insufficient material being fed/applied to a region of the build. This generally occurs when the build parameters of the system are set with too wide a gap between build passes and consequently insufficient molten material infill. Further, in Material Extrusion environmental conditions such as moisture and recycling material can affect the melt properties of the material reducing the amount of material flowing through the print nozzle [7.61].

In PBF systems insufficient material feed/application could be a consequence of the following errors:

- Poor packing when the feedstock is in the build chamber [7.62].
- A change in the flow properties of the melted polymer so molten material does not fill the spaces between the powder particles [7.62].
- Too high or low energy density applied during melting e.g. high heating can cause powder particles to be expelled from the surface reducing the material available for melting [7.63].

Voids in polymer material in both Material Extrusion and PBF methods can also be caused by moisture uptake if the polymer is sensitive to moisture and is stored in a damp environment. On heating moisture becomes vapour, which can be trapped as voids in the solidifying material [7.64].

7.1.7.1.2 DISTORTION

As outlined in chapter 6 the repeated heating and cooling during additive manufacturing operations can lead to differential cooling within a component and consequently residual stresses that can distort the part. This is the main cause of distortion within polymer AM. In polymer AM, different polymers will have different volumetric changes during cooling leading to different levels of residual stress and distortion. Fillers e.g. carbon fibre although added to improve mechanical properties can also reduce distortion in the part [7.65]. In laser PBF the powder container is heated to just below the melting temperature of the polymer, which minimises differential heating rates and reduces distortion in the part. As with metal AM, support structure within the part can reduce distortion by aiding heat flow as well as supporting the part as it cools [7.62] [7.66].

In Material Extrusion the quantity of material deposited and lack of adhesion to the build plate means distortions can be significant leading to curling of the part. This can be partly mitigated by using a heated build plate and build chamber [7.67]. In Material Extrusion “over extrusion” during printing can also lead to distortion owing to excess material being present in the build. Typically, excess material is caused by incorrect selection of process parameters but it can also be due to changes in the melt properties of the material caused by e.g. moisture absorption. This typically presents as polymer overflowing or oozing onto the component. Excess material can also lead to “stringing” where a thin string of material is present where excess material is applied as the nozzle moves [7.68].

In some polymers moisture absorption, particularly at the surface of the part can also cause parts of the component to swell leading to residual stress and distortion [7.69]. Further, the relatively low melting temperatures of polymers mean that during thermal cycles polymers can soften and warp. This is especially prevalent in Material Extrusion near heated build beds where continuous contact with the bed can cause the polymer to distort [7.70].

7.1.7.1.3 STOPPAGE DEFECTS

Stoppages during polymer AM can be caused by equipment malfunction or power outages. Additionally for Material Extrusion a stoppage defect can occur when the machine runs out of filament. The main risk associated with such stoppages is misalignment of the next build layer once the process restarts, leading for example to steps in surfaces and even slumping because of insufficient or incorrect support structures. In Material Extrusion the part can also warp and come off the build plate on cooling which can make it difficult to realign the next layer to be built [7.71] [7.72].

The relatively low cost of polymer components means that when a stoppage occurs it is often best practice to re-start the build, especially if the part requires a high degree of dimensional accuracy. Some guidance suggests building the second (post stoppage) section of the part as a new build and then joining the two pieces together, however it should be recognised that this will add extra sources of variability to the process [7.71] [7.72].

7.1.7.2 CHEMICAL DEFECTS

The properties of polymers are related to the chemical composition of the polymer, the molecular characteristics of the long polymer chains and also the microstructure, i.e. how the polymer chains are arranged once solidified. Further, these factors interact with each other and the processing conditions in a complex way, to give the properties of the final part. As discussed in the melting and solidification section of this document polymers can be amorphous, semi crystalline or crystalline; the thermoplastics used for the polymer AM discussed here are typically amorphous or semi-crystalline.

The following four chemical changes can typically occur during polymer processing:

- Increased or decreased polymer chain length
- Removal of smaller molecules, for example through evaporation
- Decomposition of polymer chains into other molecules
- Absorption of moisture

7.1.7.2.1 INCREASED OR DECREASED CHAIN LENGTH

In PBF of semi-crystalline polymers repeated thermal cycles can change the chain length of the polymer, which is likely to cause a change in the degree of crystallinity, affecting the mechanical properties of the part [7.73]. The opposite effect is observed in Material Extrusion when print materials are recycled back into filament. Reprocessing shortens the polymer chains, which leads to a reduction in tensile strength of the material [7.74, 7.75].

Chain length can also be reduced through photo-oxidation of the polymer when it is exposed to sunlight over time. As with thermal degradation effects, this can lead to a reduction in tensile strength. This is particularly an issue for Material Extrusion filaments if they are not stored correctly. Additives are sometimes used to prevent photo-oxidation in applications where polymers are likely to be used outdoors [7.76].

7.1.7.2.2 REMOVAL OF SMALLER MOLECULES

In addition to the long chain molecules, a polymer may also include a small percentage of light components which can include shorter chain oligomers and monomer residues, solvent residues, catalysts, and additives. The temperatures applied during the polymer AM processes can be enough for these small molecules to desorb from the polymer. Depending on the additive type this can lead to a change in the properties of the component. In particular the removal of plasticisers could increase the crystallinity of the compounds, which can make them more brittle [7.77].

7.1.7.2.3 DECOMPOSITION

At higher temperatures, polymers can begin to decompose through pyrolysis. Pyrolysis products are typically characterised as carbon char, oils/waxes and gases. The pyrolysis products will have different percentages depending on the polymer but pyrolysis is detrimental to the performance of the component because all of these pyrolysis products have a negative impact on the mechanical properties of the polymer. In particular the pyrolysis products may fully or partially block the nozzle and reduce flow of the polymer [7.78]. For some polymers, e.g. polyvinyl acetate (PVA), pyrolysis can occur at or close to temperatures achieved during normal operation of the polymer AM machine. However for most polymers pyrolysis temperatures are typically observed when there is a malfunction of the heat source or when the formation of “hot spots” during the process increases the build temperature over the decomposition temperature. This has been observed particularly when there is a fault in the movement of the lasers in laser PBF and the heat is applied to a single zone continuously rather than the laser moving to build the part [7.77].

7.1.7.2.4 ABSORPTION OF MOISTURE

Many polymers used for polymer AM are hygroscopic and readily absorb water. As mentioned previously moisture absorbed in the polymer can lead to porosity and cause the polymer to expand and warp. As well as directly affecting the geometry of components [7.79] the presence of moisture can lead to changes in the degree of crystallinity of the polymer. At elevated temperatures, such as those seen during polymer AM, the presence of moisture can increase the crystallinity of the polymer. This in turn can change the glass transition temperature of the polymer, affecting its solidification and melting properties and causing it to become more brittle at room temperature.

7.1.8 SUMMARY

This discussion of melting and solidification processes in polymer additive manufacturing illustrates the fact that both phenomena highly influence the quality of a final printed part. It is also apparent that AM of polymers presents related but different challenges from those seen for additive manufacturing with metals.

The complex nature of polymers encompasses uncertainties in molecular weight, polymorphism, effects of materials ageing and the potential material decomposition and shrinkage. The knock on effects of these factors on physical and chemical properties therefore raises the need for careful control and fine-tuning of thermal process parameters.

It is also the case that a variety of the challenges that apply to metals carry over to polymer AM. Thermal gradients that exist between deposited layers will affect layer fusion and the potential for geometric distortions. The nature of the feedstock, be it the thickness of filaments or the particle size of powders, is also a major consideration with respect to how they interact with the primary heat source.

7.2 PART DESIGN

7.2.1 INTRODUCTION

This section describes the key factors in the design of additive manufactured parts, namely part geometry, attaining the desired physical and mechanical properties of the final printed part, and how to deal with anisotropy in a part as a consequence of the additive manufacture process. The section concludes with general design rules that may prove useful when discussing potential design choices.

The aim of the section is to inform the reader of basic part design principles and then expand on these in order to provide the depth of knowledge required to relate them to new designs. To aid in building a picture of what a potential additive manufactured part design process may look like the following points outline some key considerations:

- The first stage is likely to involve capturing the requirements for the part. The design basis will start by considering:
    - What is the intended use of the part?
    - How will the part function?
    - What kind of loads will the part be subjected to?
    - What kind of thermal and chemical environments will the part be subjected to?
- Based on these requirements a suitable polymer and potentially a filler will then be selected. The Modern Plastic Handbook is a useful reference for the polymer selection process [7.5].
- An initial design will then be generated and evaluated against the design criteria. This may be informed by standards that state maximum stresses and tolerances on materials properties**.** The design may then be improved until it meets the criteria.
- A detailed analysis of the part will then be done to evaluate the part across all load cases. It is likely that this process will require accurate data on materials properties and modelling software capable of simulating complex load cases and nonlinear materials properties.
- Modifications may then be made iteratively until the part meets the requirements.
- Small-scale parts and coupons will then be generated and subjected to loading conditions at the extreme of what may be expected when the part is in service. With the aid of standards this may become part of a qualification program.
- The result of the testing campaign will be verified against predictions.
- A full-scale prototype will then be manufactured and tested to destruction.
- Full-scale parts will then be manufactured and may be assessed using a non-destructive technique capable of detecting likely defects.
- Limited mechanical testing may also be considered for re-qualification when switching to a new material batch.

7.2.2 PART GEOMETRY

Part geometry is key in enabling a part to perform its desired function. It is therefore useful to be able to describe accurately the geometric elements within a design. For additive manufacture part design, the geometric elements used to compile a design can be categorised into three groups of “standard elements” [7.80]:

- *Basic elements* – elementary geometrical shapes such as cylinders and cubes that can be defined mathematically. These shapes are formed by moving a profile along a guidance curve giving rise to three sub-categories of basic elements: double curved elements (Figure 7-7A), single curved elements (Figure 7-7B) and non-curved elements (Figure 7-7C).
- *Element transitions* – areas in which basic elements are combined, such as joints. Element transitions can either come in the form of a transition between two bonded elements (Figure 7-8A) or two non-bonded elements (Figure 7-8B). Thus, element transitions are governed by attributes such as gap dimensions for non-bonded basic elements and transition thicknesses and angles for bonded basic elements.
- *Aggregated Structures* – the arrangement of two or more basic elements and their element transitions.

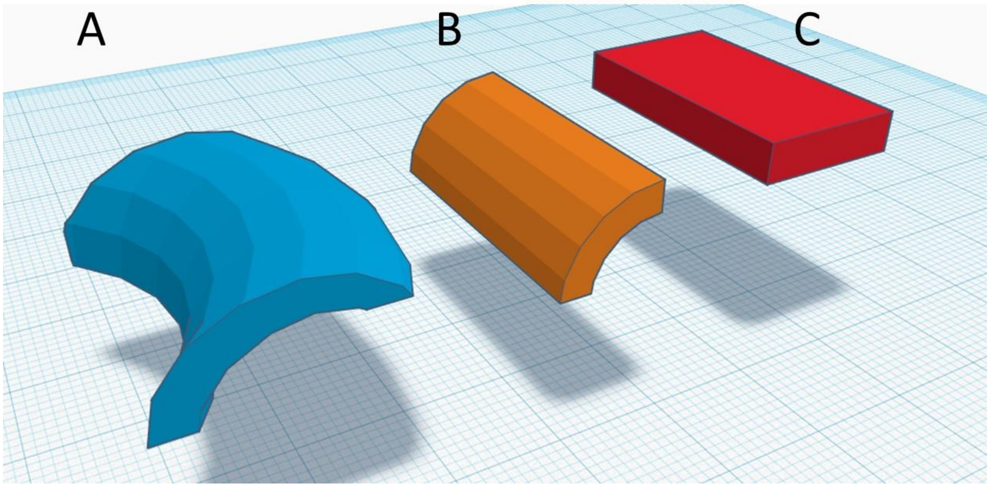

Figure 7-7 - Diagram showing examples of: A) a double-curved element, B) a single-curved element and C) a non-curved element.

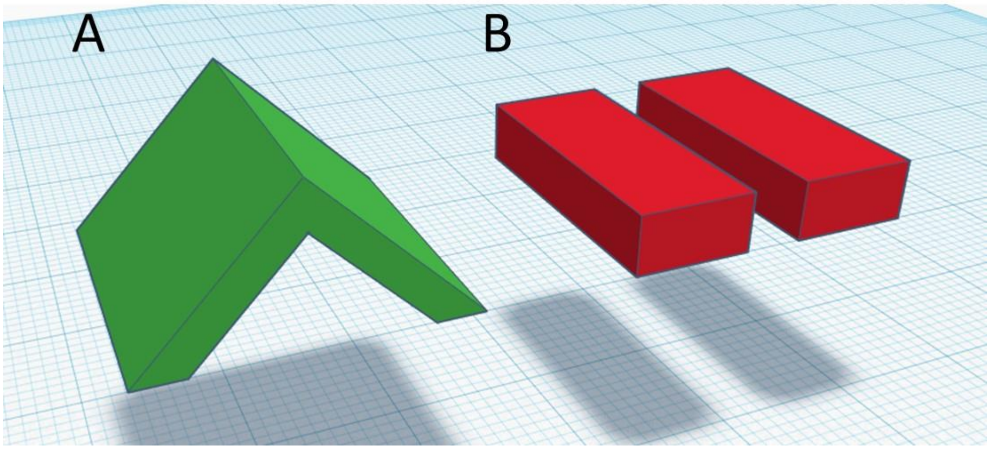

Figure 7-8 - Diagram showing example of: A) a transition between two bonded elements and B) a transition between two non-bonded elements.

Each set of standard elements can be defined by a set of attributes describing dimensions and angles, etc., and each set of attributes will have a range of values with which optimal part quality can be achieved. Thus, design rules can be developed that define suitable boundaries for these attribute ranges through the systematic manufacture and testing of printed parts with varying attribute values. G. Adam and D. Zimmer [7.81] have done just this for Laser Sintering (LS) (the same as L-PBF, which is the term used in this document) with PA2200 (nylon) on an Eosint P395 machine and Material Extrusion using Ultem (polyetherimide – PEI) on a Fortus 400mc machine. **Although guidance should be sought specific to the material and machine type, the following guidance <u>may</u> be used when designing for polymer AM (REC7.21):**

For both L-PBF and Material Extrusion:

- Element transition thicknesses did not influence element form accuracy.
- Element transition cross sections should remain the same or get smaller in the build direction.
- Sharp inner and outer edges in transitions between bonded elements cannot be formed completely defect-free. Rounding edges can improve accuracy in both techniques.
- The size of the melt pool radius imposes a limit on the dimensions of an edge.
- Edges that form extremes in the build direction should be blunted parallel to the build plane.
- Edges that form extremes in the horizontal direction should be blunted orthogonal to the build plane.
- Edges that form extremes in the horizontal direction should be blunted orthogonal to the build plane.
- Actual gap heights in both techniques were found to be smaller than their nominal heights

Specific to L-PBF:

- Sharp inner edges can increase the difficulty in removing passive supports, i.e. un-sintered powder. Rounded edges give the best results.
- Minimum attainable gap heights between non-bonded elements builds were found to be approximately 0.6 mm. Below these values powder particles were found to adhere to surfaces.
- Support free 90° overhangs were found to be failure free at lengths up to the maximum length tested (10 mm) in LS (L-PBF) builds. This was credited to the dispersed pseudo support structures provided by non-sintered powder.

Specific to Material Extrusion:

- The size of the polymer filament radius imposes a limit on the dimensions of an edge.
- Sharp inner edges can avoid the need for internal support structures.
- Minimum attainable gap heights between non-bonded elements builds were found to be approximately 0.4 mm. Below these values polymer filaments were found to agglutinate, sealing the gaps in both cases.
- Support free 90° overhangs were found to fail 1.8 mm in Material Extrusion builds owing to the inability of the low stiffness polymer to stabilise the structure in excess of this length.

7.2.3 PHYSICAL AND MECHANICAL PROPERTIES

When considering the physical and mechanical properties of a new AM part design the choices of build material and processing parameters are as important as the geometric elements of the design. It is also important to be able to validate a design using a regime of appropriate testing. This section examines these factors, as well as how a design can result in anisotropy in physical and mechanical properties.

7.2.3.1 CHOICE OF POLYMER

When designing a part the choice of polymer and even material supplier are some of the first key decisions that will affect the physical and mechanical properties of the final part. Not only are the intrinsic properties of the feedstock material important, but the layer by layer nature of AM also means that the degree of fusion of deposited layers is of the utmost importance. In Material Extrusion the molten filament beads being deposited transfer heat to the previously deposited, cooled beads, melting them. This allows for the diffusion of polymer chains across the interface between the beads and ultimately fusion at the interface upon cooling and solidification. Thus, when attempting to achieve high physical and mechanical properties it advantageous to select a polymer capable of a high degree of fusion under the available processing parameters.

Keys factors that can affect the fusion process include the polymers average molecular weight and the structure of any branching, as well as the nature of its functional groups. For example, highly branched polymer chains with large functional groups are likely to be less mobile. Likewise, the polarity of any functional groups is also likely to affect the mobility of a polymer in the molten state. These principles can also be extended to the choice of polymer in an L-PBF process where, even though the energy source is different, the principle of interlayer fusion is the same.

Therefore, as mentioned earlier in this document: **The interlayer fusion between deposited layers under the available processing parameters should be considered when selecting the feedstock polymer since this can have a significant impact on mechanical properties (REC7.22).**

Thought must also be given to recycled polymers, particularly the powder used in L-PBF processes which is likely to be reused between builds if mixed with a sufficient amount of virgin powder. When considering the use of recycled powder it is important to ensure key material properties have not degraded. For example, recycling polyamide powder that has been held above its T_g for an extended period of time leads to a deterioration in part quality and in particular a poor surface finish [7.27] [7.82]. **Recycling polymers may lead to a deterioration in part quality and it may be necessary to add a significant portion of virgin material to any recycled material for each build (REC7.23).** However, significant advances are being made in improving the recyclability of polymer powders [7.83].

7.2.3.2 STRUCTURAL DESIGN AND VALIDATION

Along with polymer choice, structural choices are likely to have a large impact on the physical and mechanical properties of a printed part. In order to understand how structural design can affect the physical and mechanical properties of a printed part, it is important to appreciate how the mesostructure of the part is affected by the process of AM. This is discussed further in the section 7.3 of this chapter; nevertheless it is good practice to consider challenges such as anisotropy during the part design phase as one of the limitations of the AM technique.

As alluded to in section 1.2.5 the incorporation of fillers, particularly in fibre form, will introduce anisotropy. Strength and stiffness of the part will be particularly affected, based on fibre alignment, which in turn will be affected by key build variables such as build direction.

The mechanical properties of a new part design are defined as the behaviour of the part under mechanical loading. This is usually characterised by moduli such as the stress divided by strain ratio, measured under different loading modes, including tension, compression, flexure shear or torsion [7.84]. In the case of polymeric materials, many of which are viscoeleastic (as described in section xxx), such moduli are usually functions of time and temperature and therefore it may be important to include these test parameters when reporting results.

The design must also consider the potential failure modes of a new part. Ordinarily, failure occurs in one of two ways: either plastic deformation (defined as a non-linear stress vs strain) or brittle fracture. These failure modes are characterised by evaluating the impact strength, strain rate, yield strength and ultimate strength under tension, compression, flexure, shear or torsion loading modes depending on the mechanical function of the part [7.84]. However, owing to the geometric and structural complexity of many part designs, it may be difficult to apply just one of these loading modes in isolation.

It is also important to consider crack propagation in a newly-designed part, in terms of fracture toughness / energy. This may be defined in one of three modes: crack opening, in plane shear and out of plane shear. While there are standards for testing crack opening and in plane shear modes as well as combinations of the two, a complex additive manufactured part design may also be subject to out of plane shear.

The incorporation of fillers is another important factor to consider with regards to crack propagation. Fibre composite parts manufactured by material extrusion are likely to be weaker in the direction transverse to the fibres than those in the direction of deposition. As is alluded to in section 1.2.5, when trying to predict interfacial bond strength it is also important to understand interactions at the fibre/matrix interface.

Finally, the durability of a new part design is likely to be important, depending on the intended function of the part. Durability relates mainly to creep and fatigue properties. Creep describes the ability of the part to withstand a prolonged static load. Fatigue, on the other hand, describes the ability of the part to withstand cyclic loading over a prolonged period of time. Again, standards exist for the testing of these properties. **It is therefore advisable that the mechanical properties and durability of a part should be assessed using recognised standards to ensure that these properties are appropriate for the parts intended use (REC7.24).**

7.2.4 DESIGN FOR ANISOTROPY

The layer by layer deposition of polymeric materials in AM means that not all of the material in the part is simultaneously melted and homogenised. This means that factors such as build direction and orientation, bead width, the size of any gap between beads and raster angle can all lead to varying degrees of anisotropy in a printed part. In Material Extrusion this tends to result in the printed polymer having inferior physical and mechanical properties compared to the feedstock material. Therefore, **if a part is designed and qualified to optimise properties in a particular direction under a given set of processing parameters then the build direction and processing parameters <u>should</u> not be altered without further qualification (REC7.25).**

7.2.5 SUMMARY

To summarise, when considering part design it is first useful to be familiar with terminology relating to geometric elements and the attributes used to describe them. Understanding the nature of these elements and how they combine in a proposed design can then allow for the application of design rules. Such rules offer the advantage of potentially avoiding critical design flaws at an early stage.

A significant consideration is the degree of anisotropy the manufacturing process produces in a part. The resulting anisotropy is likely to be reflected in its physical and mechanical properties and consequently should be considered against the design requirements. Any anisotropy will also be affected by the build design, in addition to polymer properties, and will be discussed in the following section. **Therefore, anisotropy resulting from the AM characteristics of the specific polymer and the features of the build design, <u>should</u> be accounted for when establishing mechanical and physical properties against the part design requirements. While published property databases will be valuable in guiding material choice, the final AM part properties may be anisotropic and therefore different in different directions (REC7.26).**

With a proposed design in place and the polymer selected, the design will then need to be validated through an iterative testing process. Any testing process will need to assess mechanical properties that reflect the part's proposed in-service application. Depending on the complexity of the part, this may require the testing of small coupons, followed by larger coupons encompassing multiple features (element tests), followed by the full scale part.

In conclusion, given the complexity of the part design process it is perhaps important to emphasise that once a part has been designed and qualified to perform under specific conditions, such as under load in a particular direction, any modifications to the design should be stringently tested and qualified.

7.3 BUILD DESIGN

7.3.1 OPERATOR COMPETENCE

In AM, as in other manufacturing processes, for example welding, the operator competence is important not only for safe operation of the machine but also because an inexperienced operator may cause differences in the control of the AM machine leading to variation in the final part. **Consequently all operators <u>should</u> be suitably qualified to use the AM machine approach to assess operator competence should be agreed between the manufacturer and Design Authority (DA) and should include the appropriate method and frequency of training and testing to ensure competency. Records of any competency certificates should be retained to provide the evidence of operator competence. If variation between operators is still considered a significant source of scatter, it may be necessary to specify named operators to build a critical part (REC7.27).** Much of the variation observed between AM operators is in the design of the build volume, discussed later on in this section, and so can be limited by recording aspects of the build layout in the process control document.

7.3.2 MACHINE CHOICE

As with metal components, machine choice is a crucial step in planning a polymer AM build and **the machine type and model should be recorded in the Process Control Document (REC7.28)**. In addition to typical considerations for manufacturing relating to the mechanical properties of the part, several factors should also be considered when deciding which machine to use:

- Size of part – Will it fit within the required build volume?
- Thermal properties of the polymer – many machines can only process low temperature polymers and some polymers need to be built in a heated build chamber.
- Surface finish – i.e. maximum un-machined surface roughness acceptable for the part.
- Build resolution – layer height, beam size and minimum feature size. Will the part be built to the specified level of detail? This is particularly important for small parts.

For polymers, as in metal AM, there can be significant machine to machine variation even if using the same machine type and therefore **if a part will be produced on different machines to those used for qualification and certification, all machines <u>should</u> undergo a pre-qualification process with calibration builds to show that any variation is within an acceptable range (REC7.29).**

7.3.3 FACILITIES ASPECTS

7.3.3.1 MACHINE LOCATION

In choosing the location for a polymer AM system, several factors should be considered. Most guidance on where to locate the printer will be set by the machine manufacturers and will consider the space it will need, power supply, controlled gas supply (if required) and internet access (if required for machine updates and data transfer). The role of the environmental conditions external to the machine is also important for some machines, particularly Material Extrusion which can build with a build chamber open to the air. As discussed previously, the role of moisture in developing defects in the material means that humidity in the build chamber and during feedstock storage should be within the range specified by the manufacturer. In addition, the temperature in the machine location can affect the melt properties of the polymer so the ambient temperature of the environment should be considered [7.85].

This means that in addition to health and safety considerations, discussed later on in this section, machines will have a preferred operating temperature and humidity. Consequently, **the environment in which the build is performed should be controlled to keep humidity and temperature within the range specified by the manufacturer or in-house process control specifications. This is applicable for either a sealed build environment or the room the machine is placed in if builds are performed exposed to the atmosphere (REC7.30).**

Before use feedstocks, e.g. filaments or powder, should be stored in an environment that does not lead to a significant deterioration in properties through moisture uptake and / or significant fluctuations in temperature (REC7.31).

7.3.4 HEALTH AND SAFETY CONSIDERATIONS

7.3.4.1 HEAT SOURCES

The heat sources associated with the production of the part may pose a risk to the AM machine user and any surrounding equipment or facilities. For polymer AM the following heat sources pose a risk during operation:

- Heated build plate or build area
- Polymer melting – heated nozzles
- Polymer melting – lasers

As well as posing a risk during the build, these can also lead to latent heat sources that may remain when the machine is no longer running.

The main approach to mitigating the risks posed by heat sources is to limit access to the heat source itself. This is mainly achieved through engineering controls of AM systems. Restricted access facilities and Personal Protection Equipment (PPE) may be required where engineering controls are not practical.

Lasers used in laser powder bed AM would be identified as class 4 lasers if used on an open bench top meaning they are “capable of causing injury to both the eye and skin and will also present a fire hazard if sufficiently high output powers are used” [7.86]. The safety procedures and engineering systems that have been put in place by manufacturers mean that during conventional operation polymer AM machines can be considered as class 1 laser systems [7.87]. Such procedures could include an automated shut off when a build chamber door is open and interlocks that mean the laser can only be accessed directly during calibration and maintenance. It is the responsibility of the machine manufacturer to determine the laser safety classification of the equipment but users should be vigilant to any change in laser-based systems through malfunction or modification [7.88].

7.3.4.2 ATMOSPHERIC RISKS

7.3.4.2.1 EMISSIONS

The use of Material Extrusion printers in open office environments has led to several studies to understand further the emissions from the machines during use. A recent report by the Health and Safety Executive (HSE) identified the following key emissions:

1. Gaseous emissions from volatile organic compounds
2. Solid particulate emissions [7.77, 7.89]

Different polymers will have different emissions based on their original composition and also the temperature at which they pyrolyse or thermally degrade to form char.

Acrylonitrile butadiene styrene (ABS), in particular, has been shown to emit toxic volatile organic compounds (VOCs) such as styrene and formaldehyde, both of which also have the potential to be carcinogenic. Other polymers such as Polylactic acid (PLA) emits fewer VOC products and are currently used in medical applications because of their high biocompatibility [7.90]. Filament producers have made polymers available with lower emissions.

The HSE report also identifies that even low emission polymers such as PLA may emit large quantities of particulate during use.

HSE makes the following observations during their experiments to reduce the emissions from polymer Material Extrusion printers:

- Placing an enclosing hood over the 3D printer reduced particle emissions released to the room by 97% when exhausting air from the enclosing hood and by 99% in the recirculating air mode.
- Particulate and VOC emissions accumulate inside the enclosing hood during printing; the clearance time of the enclosing hood was approximately 20 minutes, therefore removing the hood before this time could result in personal exposure [7.89].

7.3.4.2.2 INERT GASES

Most polymer powder bed and some Material Extrusion processes are undertaken in an inert atmosphere such as nitrogen; these gases may pose a risk to operators if they escape from the build chamber because they can exclude the oxygen from the room resulting in suffocation. For most polymer systems the main risk is through accidental release. As with metals the following mitigations are often used to ensure safety when working with asphyxiant gases for polymers:

- Care should be taken when purging systems and connecting gas cylinders to ensure the gases are not released to the environment.
- Gas cylinder changeover procedures may be performed outside or in a large space so any released gases do not accumulate in confined spaces.
- Oxygen sensors may be placed at different points around the room where the AM build takes place to protect against the risks of asphyxiant gas accumulation.

For powder bed systems the risk is through accidental release and, as set out above, care must be taken when purging systems and connecting gas cylinders to ensure the gases are not released to the environment [7.91].

7.3.4.3 FEEDSTOCK

Many of the feedstock materials used in AM have chemical safety risks and as with any manufacturing process these risks should be assessed as per local guidelines and through Control of Substances Hazardous to Health (COSHH) guidelines. Further information on these guidelines can be found at [7.38]. A Materials Safety Data Sheet (MSDS) should be provided from the manufacturer with any feedstock material and risk and safety guidance on the MSDS should be followed, including appropriate PPE [7.38].

The use of polymer powders in powder bed AM poses additional risks to any chemical hazards outlined in the COSHH assessment. The small size of powder particles (<50 µm diameter) means they can pose an inhalation risk and PPE e.g. face masks may be required when handling polymer powder feedstock. Although less likely to cause sparks than metal powders, the fine powder feedstock are small enough to be categorised as combustible dusts and care should be taken to reduce the build up of static during powder handling, further guidance can be found in [7.92]. To mitigate these risks as many operations as possible – sieving, loading, storage, etc. - should be undertaken in sealed vessels since it significantly reduces the risk of powder as a feedstock material for the user [7.93, 7.94].

7.3.4.4 ROBOTIC SYSTEMS

Polymer AM systems rely on a significant level of robotics in the control and manipulation of the material. For enclosed systems such as powder bed systems the interlocks in the system should limit access during operation, and any maintenance and calibration of the machine should also check any safety systems associated with the machine. Material Extrusion polymer systems, although sometimes operating in an open environment, pose a lesser risk than e.g. robotic metallic welding operations, which may look superficially similar. This is for two reasons; firstly they exert much less force than robotic metallic welding systems and in the case of collision can be manually stopped by the user. Secondly, the Material Extrusion heated nozzle and molten plastic, whilst posing a risk of causing burns, are at a much lower temperature than typical robotic metallic welding operations. Despite this, good practices are recommended for polymer AM such as ensuring emergency stops for the system, enclosing the system or operating it in a separate area and marking any possible hazards [7.95, 7.96].

7.3.5 PART CONFIGURATION

Part configuration is the process of converting the computer aided design (CAD) file into instructions and parameters to run the AM machine. This can be done using either computer aided manufacturing (CAM) software or directly by the AM machine. For some machines part configuration can be done automatically and software exists to perform this process 797]. As outlined in section 7.1.4 of this chapter, the properties of the built polymer are influenced by its thermal history due to repeated cycles of heating and cooling as the part is built. This means the configuration of the part in the AM machine is important to the properties of the final part.

The significant differences between part configuration for powder bed and Material Extrusion processes means that for some parts of this section the guidance will be split between the two types of polymer AM process.

7.3.5.1 FILE CONVERSION

Polymer AM systems also typically run on the .STL (abbreviated from stereolithography) file input which exchanges pure geometric coordinates from the CAD file to the AM machine. As discussed in chapter 6 of this guidance the file conversion works by converting boundary surfaces of the CAD file into triangles or facets and describing these as vectors. If the file conversion is not performed correctly it can introduce errors to the part that will need to be corrected before the build can proceed. Further guidance on the effects of file type can be found in chapter 6 of this document and BS ISO 17296-4:2014 which covers general principles relating to data processing for AM [7.98].

If the file conversion from CAD to STL or similar has a significant effect on the required properties of the final part the AM producer should ensure that the converted file used to build the qualified part is the same as the file used for production builds (REC7.32).

7.3.5.2 TEST SPECIMENS

The sources of scatter that apply to manufactured parts will also apply to test specimens for qualification and certification of AM. Careful consideration should be given to build orientation because there may be significant reduction in properties in the z direction. Any post build processes performed on the part should also be performed on test specimens used in qualification and certification.

As with AM parts, build location and orientation should be considered for witness and test specimens so that they reflect, as accurately as possible, this source of scatter during the qualification process. Witness and test specimens should also undergo the same post-processes as the AM part (REC7.33).

7.3.5.3 POWDER BED POLYMER AM

7.3.5.3.1 PART ORIENTATION

Unlike other AM techniques polymer PBF does not need supports for overhangs as the polymer powder and heated build bed provide adequate support and thermal management to the part. This means that orientation of the part is not required to reduce overhangs but can be used to minimise the build volume used [7.99]. The thermal layer by layer nature of polymer AM means that anisotropy is observed in polymer PBF. This is particularly prevalent in the z direction and means that during build design it may be necessary to orientate the part to achieve the best mechanical properties [7.99, 7.100].

Some polymer PBF machines use a re-coater arm to apply the next powder layer to the build. If the part is parallel to the re-coater arm, the arm can strike the part. This is an issue for thin vertical walls, which have a lower rigidity and can be damaged during the build process. As such it is good practice to orientate these features so they are not parallel to the re-coater [7.100].

Another issue during build is islands, where islands are features that connect to the part at a later stage in the build process. This means that during build this section of the part can be unstable before joining to the rest of the part. By orientating the part so that islands are avoided, the risk of a failed build owing to an island collapsing is removed [7.100].

If the variation due to orientation of the part leads to a scatter of properties greater than those allowed by the Design Authority then it may be necessary to record and maintain the orientation of the part used during qualification and certification throughout all part manufacture (REC7.34).

7.3.5.3.2 PART LOCATION AND NESTING

Unlike other AM processes, polymer laser powder bed fusion components are sintered. This means the build chamber is held at a temperature just below the melting temperature of the material. This reduces the need for support structure but during normal operation there can be temperature variations across the build chamber, particularly on the edges of the build. This can detrimentally effect melting and solidification in the part and ultimately lead to variation in the mechanical properties. BS EN ISO ASTM 52911 states that “If a particularly high level of accuracy or material properties is required for a part, it is best to position it near the centre of the build chamber.”[7.100]

Since polymer powder bed systems can build parts without support structure the whole build bed in x,y and z directions can be used to build components. In addition, for efficiency, multiple parts can be built within the build chamber leading to the concept of “nesting” parts to save on the cost of feedstock. Nesting fills the volume of space with parts, including spaces within larger parts. For all components, particularly those used in critical applications nesting and the spacing between adjacent parts should be devised to minimise the thermal effects on the surrounding parts. Materialise recommends polymer laser PBF parts are more than 0.6 mm apart [7.101].

If the variation due to location and number of parts leads to a scatter of properties greater than those allowed by the Design Authority then it may be necessary to record and maintain the build plan used during qualification and certification throughout all part manufacture (REC7.35).

7.3.5.3.3 SCAN STRATEGY

As shown in Figure 7-9 scan strategies for laser PBF of polymers consist of two distinct regions: (1) the contour scan around the edges of the part, and (2) the hatching pattern to fill the main area of the part. Some parameters for each of these regions are shown below:

- Contour scan around the edges of the part
    - Number of contour lines
    - Machine parameters for contour lines

    - Order of contour lines and fill – e.g. some materials are best to contour first (e.g. PA2200) [7.99]
- Hatching to fill the main area of the part
    - Pattern and direction of hatching
    - Machine parameters for contour lines
    - Order of hatching being applied e.g. random / checkerboard

The interactions between layers are also accounted for in the scan strategy to allow subsequent layers to fully cool before building the next layer. This can be done by shifting the build pattern by a known amount for each subsequent layer. The effects of build order are also a consideration when building multiple parts because there may be more/less time to cool between layers, which will impact the melting and solidification and ultimately the mechanical properties of the part. For some materials multiple scans can be used to reduce the distortion caused by rapid cooling [7.102] [7.99].

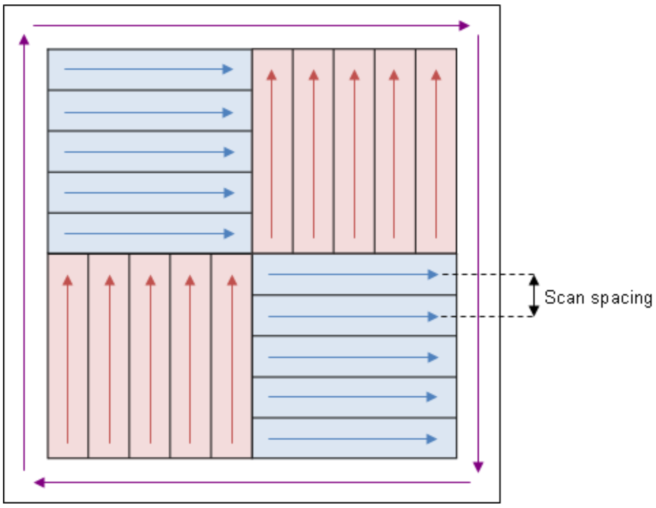

Figure 7-9 - Schematic representation of a checkerboard scan strategy typically used in powder bed systems. The arrows represent the scan vectors with the distance between these vectors defined as the scan spacing. The purple arrow demonstrates a single contour scan around the part.

If the effect of scan strategy is observed to be significant it may be necessary to record and maintain the scan strategy used in qualified builds in all subsequent part manufacture (REC X.XX) (REC7.36).

7.3.5.4 MATERIAL EXTRUSION POLYMER AM

7.3.5.4.1 PART ORIENTATION

As with other AM techniques the layer by layer deposition of Material Extrusion means that orientation is important in optimising the final part properties. Orientation of the part should be chosen based on the following parameters:

- Anisotropic mechanical properties – anisotropy, which is often manifested as lower mechanical properties in the z direction means that it may be necessary to orientate the part so that its strongest orientations are in the direction of load paths.

- Build time – parts with fewer layers will take less time to build.
- Minimising support structure – supports will typically be needed for overhanging structure of an angle greater than 45^{o} from the build plate. Consideration of part orientation is required to minimise the amount of support structure.
- Geometric effects – The layer-wise deposition means that Material Extrusion can lead to a stepped surface on the part. Further, certain shapes (e.g. holes) are easier to print accurately in the x-y direction than in a z direction. Consideration of part orientation is required to minimise part surface roughness and optimise shape characteristics [7.103].

A design engineer should therefore consider the orientation of filament beads and the intended load direction when deciding on the build direction (REC7.37). This should also be coupled with considerations such as the strength of bead fusion, the strength of the bead itself, the type and degree of porosity and the micromechanics of any porous structures. In 2015 NIST published a set of materials testing standards for additive manufacturing of polymer materials which provides in depth detail on this topic [7.104].

7.3.5.4.2 SUPPORT STRUCTURE

As discussed previously Material Extrusion enables support structure to be made using a different polymer to the polymer used in the final part. In many cases this second material is a PVA support material which can then be dissolved using water. This means that the surface roughness problems observed with mechanical removal of supports may be reduced. In selecting material for support structure, the removal of the support structure should be considered as well as reducing the mismatch in thermal properties of the two polymers used.

In Material Extrusion the material and pattern of support structure can influence the properties of the final part. **If the effect on the final part of the pattern, location and material of the support structure is observed to be significant then it may be necessary to record the support strategy used during qualification and ensure that the pattern, location and material of any support structure generated are the same when building the final part (REC7.38).**

7.3.5.4.3 PART LOCATION

The use of support structure in Material Extrusion limits the capability to nest many parts as seen in polymer PBF. Nevertheless, larger Material Extrusion machines can allow multiple parts to be built at the same time. Most Material Extrusion machine manufacturers include guidance for optimal distance between parts and software may be used to ensure that support structures for the parts do not overlap [7.97].

Many Material Extrusion machines work on a gantry system where the build head is held perpendicular to the build plane and the gantry moves the head in the x, y and z directions. This means that wherever the part is built on the build plate the melt conditions should be similar. For polymers that are built with heated build plates or build chambers there may be variation in temperature at different points in the build.

If the variation due to location and number of parts leads to a scatter of properties greater than those allowed by the Design Authority then it may be necessary to record and maintain the build plan used during qualification and certification throughout all part manufacture (REC7.39).

7.3.5.4.4 SCAN STRATEGY

Several parameters relating to scan strategy for Material Extrusion parts are highlighted in the diagram shown below. As for other AM techniques the scan strategy consists of two regions, a contour region and a filler region. Figure 7-10 also demonstrates the different parameters associated with each region. The effect of these parameters on the melting and solidification properties of the part and ultimately porosity means that scan strategy design is an important parameter for optimising the mechanical properties of the part. [7.105] gives further guidance on scan strategy and suggests techniques to improve strength such as aligning the filling pattern to the principal direction of the mechanical loads and increasing the number of contours.

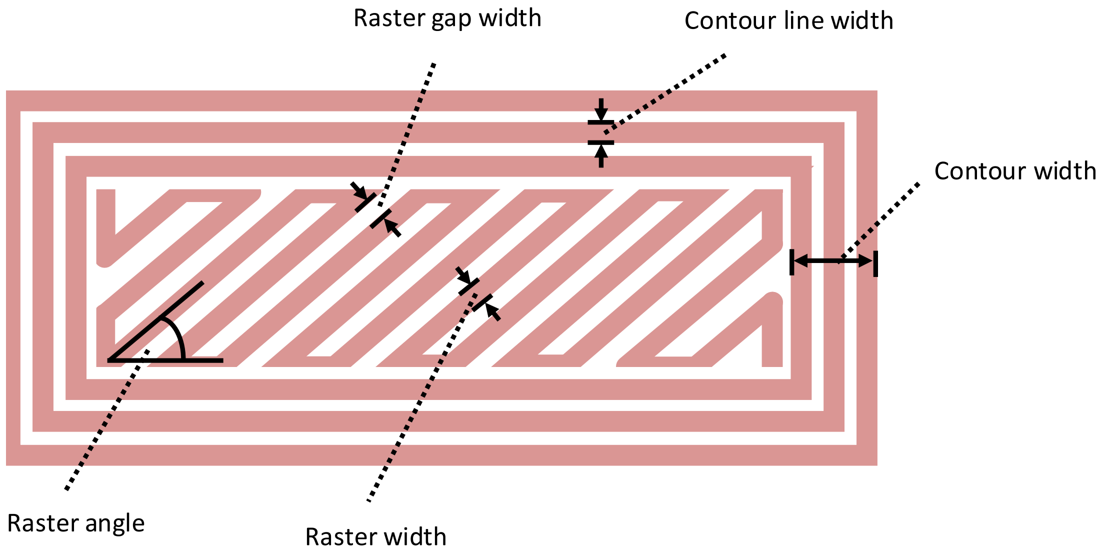

Figure 7-10 - Key parameters to describe scan strategy for Material Extrusion printers [7.106]

The deposition nature of Material Extrusion means that there are start and end points for each layer where the build head first drops to start the feature and then is removed to end the feature. These start and end points can lead to a small gap or an overlap in the polymer filament. For Material Extrusion, consideration must also be given to these toolpath start and end points, often the start/end points are moved for each subsequent layer of the build to ensure that the multiple layers do not amplify these effects.

If the effect of scan strategy is observed to be significant it may be necessary to record and maintain the scan strategy used in qualified builds in all subsequent part manufacture (REC7.40).

7.3.6 BUILD PARAMETERS / PARAMETER SET

The techniques discussed here are melt processes and consequently for both technologies the most important parameters for determining the quality of the part are the amount of heat applied and the speed at which the heat source moves. This can be quantified as the energy density of the part as outlined in section 7.1.4 of this chapter. Different polymers will have different energy density requirements. In addition to the heat applied to melt the material, polymer AM is typically undertaken in a heated build environment and/or using a heated build plate. In determining the amount of material deposited the layer height is also important for both techniques.

For both Material Extrusion and polymer PBF these parameters are input at the machine stage, either using a series of user defined values based on experience with the material or through a build parameter set provided by the machine manufacturer. Developing the build parameters for a quality part is often an iterative process where a user may start from a provided parameter set and alter that for their specific part. It is important that, however the build parameter set is developed, on qualification they are fixed and recorded in the process control document for the part to minimise variation in the build.

The build parameters or parameter set used (e.g. heat source power, build speed) should be recorded and maintained for any qualified build since any change in these parameters defined by the AM process may affect the mechanical properties, geometry and defects, and their scatter in the final part (REC7.41).

7.3.7 SUMMARY

This section has highlighted for AM the importance in planning the build both from a quality and safety perspective. In particular the effects of part configuration, scan strategy and build parameters on the anisotropy and thermal history of the part could lead to a significant scatter in relevant part properties. Consequently, for critical components these variables should be fixed to those optimised in the design phase of the build and then qualified for the part.

7.4 BUILD KEY PERFORMANCE VARIABLES

7.4.1 FEEDSTOCK

7.4.1.1 POWDER BED FUSION (PBF)

7.4.1.1.1 COMMONLY USED POLYMERS

Polymers with a polyamide backbone represent a well-established feedstock used in PBF processes. Going by the generic name of nylon, polyamide-11 and polyamide-12 are two of the most common [7.107]. Adding to this are the Poly(acrylonitrile-co-butadiene-co-styrene) (ABS), polystyrene (PS), polycarbonate (PC) and thermoplastic polyurethane (TPU) families of polymers [7.107] [7.108]. However, as PBF technology has started to advance from use as a prototyping technology to a manufacturing process capable of producing high performance parts, research has started to focus on the use of polymers associated with higher performance properties. Such polymers include: poly(ether ether ketone) (PEEK) [7.109], ultra-high molecular weight polyethylene (UHMWPE) [7.110], polyether ketone (PEK) [7.109] polyphenylene sulphide (PPS) [7.111] , poly(butylene terephthalate (PBT) [7.112], polypropylene (PP) [7.113] and polyethylene (PE) [7.114]. To improve processing or add extra functionality or environmental resistance the polymers used in AM may be a blend of different polymers with chemical additives and fillers. As the blend can impact the mechanical properties and scatter in properties of the final part **the polymer type used during qualification should be recorded and used for any subsequent builds. This should include any additives or mixes of polymers. It may be necessary to use the same manufacturer for all subsequent runs if information about the polymer blend is not available (REC7.42).**

7.4.1.1.2 POWDER RECOATING

In a typical PBF process, after each layer is formed via the selective heating process, powder recoating is performed to form a fresh layer of virgin material. This fresh layer of polymer is selectively heated to form the next part layer. Powder recoating is therefore a fundamental step in the PBF manufacturing process.

Typically, the polymer powder is spread from the feed piston across the build piston during the powder recoating stage using a counter rotating roller. Although some systems employ a blade, a counter rotating roller has been shown preferentially to induce a flow and tumble of powder particles as opposed to the dragging action of a blade. This results in a better distribution of polymer, i.e. a higher density and reduced bed surface roughness [7.115]. Likewise, the bed surface quality is also improved when employing finer particles, that is, until a diameter of 25 µm is reached. At <25 µm particle diameters, surface energy effects can induce particle aggregation which inhibits flow thereby reducing particle density [7.58].

Particle packing efficiency is also key to achieving high particle densities, making spherical morphologies preferable. The reason particle density is considered such an important characteristic is that a high density of feedstock particles is key to avoiding the formation of voids in the final printed part.

Powder recoating can impact the polymer L-PBF process and ultimately the mechanical properties of the final part, as such the powder and L-PBF system may need to be monitored to ensure accurate recoating. Example characteristics include: sphericity of particles for flowability, surface area to volume ratio for packing efficiency, average particle size and the ratio between tap density and bulk density of less than [7.116] (REC7.43).

7.4.1.1.3 POWDER MANUFACTURE

The primary powder manufacture methods employed for PBF feedstocks are grinding and milling processes, spray drying and solvent precipitation [7.117].

For polymer grinding processes, it is common to employ cryogenic temperature to first induce a brittle glass like state in the polymer. This helps to avoid the viscous process of energy dissipation as heat. Unfortunately, a major drawback with grinding is that it rarely results in spherical particles meaning it is difficult to produce a PBF quality powder feedstock in this way.

Precipitation from solvents and spray drying (which is form of precipitation from a solvent in its own right), are widely used for producing quality PBF powders. These techniques are better suited to the production of spherical particles with controlled diameters. However, it is the specific pairing of polymers and solvents required and the amount of research and testing the goes into the pairings that impose limits on development of new quality powders. There is also the consideration of the amount and environmental toxicity of solvent waste produced.

7.4.1.1.4 POWDER AGEING AND REUSE

A key parameter in the recoating process is known as the refresh rate. This relates to the ratio of '***new*** : ***cake*** (compacted powder from the build bed) : ***overflow*** (excess powder from previous recoating cycles)' powder comprising the feed powder, commonly set to approximately ***1***:***1***:***1***. Issues can arise through the "ageing" of powder as it is cycled through the process multiple times. This cycling is likely to have resulted in the powder having been held above its T_g for extended periods of time and having undergone multiple thermal cycles. For Nylon-12 in particular, the intrinsic properties as well as particle size and morphology have been shown to change on recycling [7.118]. These effects are likely to be most pronounced for recycled cake powder. A cake is likely to have been held at a high temperature for longer than overflow powder.

For critical components, the powder quality should be tracked through regular sampling and testing to ensure the powder does not fall outside of specification. The method and frequency of powder testing should be agreed between the manufacturer and Design Authority (DA). Example powder specification measurements should be determined by the component manufacturer but could include measurements of chemical composition, particle size distribution and flow and packing properties (REC7.44).

7.4.1.2 MATERIAL EXTRUSION

7.4.1.2.1 COMMONLY USED POLYMERS

Two of the most well established Material Extrusion polymers in use are Poly(acrylonitrile-co-butadiene-co-styrene) (ABS) and polylactic acid (PLA). It can be argued that ABS offers the most robust physical properties of the two polymers however PLA offers biodegradable characteristics [7.119] as well as a host of other desirable characteristics such as biocompatibility, low cost and non-toxicity. This has resulted in a rapid growth in the use of PLA in recent years.

As the engineering demands on polymer additive manufactured parts have increased, higher performance polymers have also started to become more widely used. Polycarbonate (PC) and high impact polystyrene (HI-PS) are two such materials.

The recycling of polymer feedstock is also becoming more prevalent as design focus shifts further towards sustainable manufacturing. **Since recycling can lead to thermal ageing, decomposition and a reduction in mechanical properties of polymers it should be proven that the properties of the feedstock material are adequate for the intended use, especially when utilising recycled material (REC7.45).**

As with the previous section, polymers used in Material Extrusion AM may be a blend of different polymers with chemical additives and fillers and as such the following guidance applies to both polymer AM techniques **the polymer type used during qualification should be recorded and used for any subsequent builds. This should include any additives or mixes of polymers. It may be necessary to use the same manufacturer for all subsequent runs if information about the polymer blend is not available (REC7.42).**

7.4.1.2.2 FILAMENT PRODUCTION

For polymers to be utilised in a Material Extrusion process they need to be processed into either a pellet form or, far more commonly, a filament.

Production of the deposition filament within a Material Extrusion machine usually involves the extrusion of the polymer in question through a single or twin-screw extruder, with the diameter tolerances of the filament determined by the extruder nozzle design. It is therefore important to have a good understanding of the tolerances required for the planned build and to ensure that feedstock properties, such as the filament diameter, meet these. An example would be to take regular measurement of filament diameter along the length of a roll to ensure it falls within the required tolerances.

The feedstock must also have: a low enough melt viscosity that does not have a high resistance to extrusion; good wettability, which helps improve bonding performance; and a favourable isoelectric point (pI), which is a measure of the pH at which the polymer has a net neutral charge. For example, an acidic polymer will have a high pI and a basic polymer will have a low pI. These values will play an important role in the interaction of the polymer with surfaces encountered during processing.

Finally, print quality will be largely reliant on the viscosity and flow properties of the polymer. The T_g/T_m of the polymer being paired with suitable processing temperatures will be vital in this regard. **Rheology techniques may be used to monitor feedstock viscosity, Differential Scanning Calorimetry (DSC) may be used to measure T_g and T_m and Thermogravimetric Analysis (TGA) may be used for monitoring decomposition behaviour (REC7.46).**

For thermoplastic polymers, an amorphous nature is also beneficial with crystallinity potentially resulting in sharper changes in viscosity as a function of temperature, owing to more discrete phase transitions.

It is also worth mentioning that filament recycling is starting to gain a lot of interest in research. The industry is aiming for a recycled filament that can be produced to a high level of quality in a reliable way.

7.4.2 HEAT SOURCE

While machine types, heat sources and feedstocks in polymer AM differ, it is helpful to consider just four parameters that are commonly used by the machine to control the melting and solidification in polymer AM:

- Build plate or build chamber heating - builds are often performed in a heated environment so the temperature difference between the build area and its surroundings is minimised.
- Heat source power and focus - the energy input to the system through the primary heat source e.g. laser.
- Build speed – the speed at which the primary heat source moves to develop the geometry required.
- Layer thickness – the amount of material in each layer of the build.

As with any mechanised manufacturing method, confidence in key performance variable (KPV) control and measurement methods (and their variability) is by scheduled calibration. **The calibration approach should be agreed between the manufacturer and Design Authority (DA) and should include those parameters/systems requiring calibration and the appropriate method and frequency of calibration. Records of any calibrations should be retained to provide the evidence that important KPV influencing parameters are as defined and inputted, and their variability is within acceptable limits (REC7.47).**

The Calibration frequency should be agreed between the manufacturer and Design Authority (DA), welding calibration standards such as BS EN ISO 17662:2005 offer good practise for the frequency of calibration of polymer AM equipment. They suggest a calibration frequency of at least annually with more frequent calibration applied in some circumstances e.g. whenever the equipment has been rebuilt or repaired. Standards also exist on the competence of testing and calibration laboratories [7.120].

When considering the heat source for polymer AM there are differences between heat sources – feedstock interactions. Consequently, it is necessary to split the guidance into two categories:

- Powder bed systems where the material is deposited first before being melted/sintered directly by the beam e.g. L-PBF.
- Material Extrusion systems where the material is melted and flows through a nozzle to be deposited in the required shape.

This distinction is also necessary because the control and measurement methods for each are significantly different.

7.4.2.1 POWDER BED FUSION (PBF)

7.4.2.1.1 HEATED BUILD CHAMBER

Polymer L-PBF can be considered a sintering process where the polymer powder bed is held at a temperature just below the melting point of the polymer and then the laser is used to raise the temperature and melt the powder at that point. There are several techniques used to pre-heat the powder in the build chamber and/or the powder hopper. Most common is the use of a band heater within the powder storage systems to heat the metal container and pre-heat the powder. Some systems also use radiative heating between layers or fan/convection heaters to pre-heat the powder [7.102]. **Since the melting and solidification is directly linked to the pre-heat and directly affects part properties, the pre-heating system used should be calibrated to ensure that it is consistently heating the material. Appropriate calibration methods should be agreed between the manufacturer and Design Authority (DA) but could include calibration builds from different locations across the build chamber to identify variations in pre-heating and the subsequent effect on the properties of the final part (REC7.48).**

7.4.2.1.2 LASER POWER AND SHAPE

The laser beam in polymer powder bed fusion is critical to the melting and solidification of the polymers used which in turn will influence the properties of the final part. The laser is used to produce a melt pool, the size and shape of which is important in reducing defects in the part. As well as the power of the laser, its motion can also influence the properties through the geometric accuracy and speed of travel.

As with metals, the lasers for polymer powder bed fusion machines rely on the laser power, the beam diameter and the laser spot location in the xy plane of the build plate [7.121]. A brief outline of calibration techniques is included below but further information on the calibration techniques for these parameters is outlined in the chapter 6 and in NIST publication 250-77 [7.122]:

- Laser beam power- This is calibrated based on requested versus actual power measured by a laser power meter. The shape of intensity across the beam is also measured and used to calibrate the system.
- Laser beam diameter – This is calibrated using the focus offset of the laser. By moving the laser focal point up and down the required spot size can be achieved.

- Laser spot location in the xy plane - This can be calibrated by using the laser to remove a thin layer of material, the deviation in the subsequent pattern can be used to calibrate the dimensional accuracy.

The laser beam for laser powder bed systems should be calibrated to ensure that its characteristics do not change through time to reduce scatter in the properties of the final part. The frequency of calibration should be agreed between the DA and the manufacturer based on the machine requirements. Characteristics to be calibrated should be agreed between the DA and the manufacturer based on the machine requirements but could include:

- **Laser beam power**
- **Laser beam diameter**
- **Laser spot location in the xy plane (REC7.49)**

7.4.2.1.3 LAYER HEIGHT

Also of importance to the properties of the final part is the layer height of the material before it is melted/sintered by the laser. Deviations in the layer height can influence the geometric properties of the part such as surface roughness. They can also lead to defects such as lack of fusion of the powder which can have a significant detrimental impact on the mechanical properties of the part. As outlined in chapter 6 in addition to feedstock properties the layer height for polymer powder bed systems is determined by the amount the build plate lowers during the deposition of each layer of powder. **Routine calibration for polymer laser powder bed fusion should also measure the correct and consistent drop of the build plate over time and at positions across the build plane (REC7.50)**.

7.4.2.1.4 BUILD SPEED

The speed of movement in laser powder bed fusion techniques is important since, along with the laser power, it determines the amount of energy provided to the melt pool over time. This in turn effects the melting and solidification of the part. If the laser moves too fast it can lead to insufficient melting and if it moves to slowly it can lead to keyhole porosity where enough energy has been input by the laser to remove material from the sample. **Beam speed is usually included in the build parameter set for a known material but can be confirmed by producing a series of small samples at different speeds and using their quality to determine the correct speed. This technique could also be used to calibrate the beam speed if required (REC7.51).**

7.4.2.2 MATERIAL EXTRUSION

7.4.2.2.1 HEATED BUILD PLATE AND CHAMBER

Almost all industrial standard Material Extrusion printers use either a heated build chamber, a heated build plate or both. In addition to the nozzle temperature the heated build bed/chamber are used to control the temperature throughout the part during the build. In both cases the heating reduces the presence of defects such as warping and increase the fusion between layers in the printer. **Consequently the temperature profile throughout the build chamber can have an impact**

on the properties of the final part, should be calibrated regularly and may be monitored during the build in addition to direct heating. The method and frequency of the temperature profile monitoring should be agreed between the manufacturer and Design Authority (DA). The movement of gases within the build chamber, by fans for example, can affect the temperature profile and lead to hot and cold spots in the build chamber, which can affect the properties of the final part. The effect of the movement of gases should also be considered when monitoring and calibrating the temperature across the build chamber (REC7.52) [7.123, 7.124].

7.4.2.2.2 NOZZLE TEMPERATURE

As mentioned in section 7.1.4 of this chapter, polymer properties are influenced by the melting and solidification conditions during the build. For Material Extrusion in particular the nozzle temperature determines how the material melts and then subsequently flows to produce the part. This means that the temperature of the nozzle is very important in determining the mechanical and geometric properties of the part and in particular reducing the instances of defects during the build. For many machines, a close control of properties is maintained through the use of approved filaments that come with a defined thermal parameter set. **The nozzle temperatures or parameter set used during qualification and certification should be maintained for subsequent builds (REC7.53).**

Typically, temperature control in the nozzle is achieved through microprocessor control of a feedback loop with the heater using a temperature sensor. Research has been undertaken to improve this through the use of better sensors and logic techniques to enhance the feedback loop [7.125]. Further, studies on melt flow have also been done to develop material extrusion control systems where the temperature of the nozzle is altered based on the flow properties of the polymer through the nozzle [7.126].

The nozzle temperature can drift with use so **the nozzle temperature should be calibrated to ensure consistent melt properties for subsequent builds. Some machine manufacturers offer set calibration instructions and builds which should be used where available (REC7.54).**

7.4.2.2.3 XYZ MOTION

Instead of considering build speed, layer thickness and motion of the heat source separately as in laser powder bed fusion, in Material Extrusion these three parameters are determined by the motion of the nozzle in relation to the build plate in the x, y and z planes. This is important in determining the geometry and surface properties of the part.

This motion in the x y and z plane is typically monitored through two key methods:

- Automated sensors that are used to determine tip location in relation to the build plane.
- xyz offset parameters developed based on calibration builds.

At the start of a build it is common for the printer to undergo a calibration to return the build plate to a “home” location in the x,y and z planes. The sensor data can then be used to zero the build plate and calibrate the location of the nozzle for each build [7.127].

It is good practice for Material Extrusion machines to undertake a xyz tip offset calibration regularly. For x and y characteristics this calibration can be performed by building a standard calibration build geometry e.g. a square and then modifying the tip offset parameters where the build deviates from the expected parameters. For the z offset this calibration can be performed by measuring the layer height of the standard build and inputting the z offset [7.127].

The accuracy of the x, y and z tip offset for Material Extrusion machines should be calibrated regularly to ensure geometric accuracy. The calibration schedule and process should be agreed between the DA and manufacture but could include calibration builds and xyz offset determination (REC7.55).

7.4.2.2.4 BUILD SPEED

As well as motion in the xyz plane, the speed of movement can also affect the properties of the final part since it determines how much material flows at each location and the layer height. If the build speed is too fast, not enough material will flow causing porosity in the part. If the build speed is too slow, too much material flows at each point which can cause the part to be misshapen through slumping of the excess material. Although build speed is usually pre-determined as part of a material parameter set, it can be confirmed using a ruler and a stop watch to measure the time taken to deposit a known length of material.

7.4.3 ENVIRONMENT

Metals have a propensity for forming oxides, nitrides and other phases depending on the mixture of gases present in the build chamber atmosphere. In the case of polymers, atmospheric composition is generally less critical. Key environmental factors relating to the additive manufacture of polymers relate more to the build chamber temperature and relative humidity. Airborne particulates generated during polymer AM can become problematic, especially if they become entrapped in the build. This is generally alleviated through the use of HEPA filters on controlled extraction systems.

However, atmosphere control systems are incorporated into some polymer AM machines and builds. For example, the Stratasys Fortus AM system commonly employs nitrogen build atmospheres.

For processes that involve the motion of a polymer powder, relative humidity is particularly important. For example, during the PBF recoating process, contact resulting from the relative motion of particles will result in an electrostatic charge and thus charge separation. The insulating nature of polymers will mean that charge equalisation cannot take place between the particles and instead takes place across moisture both at the particle surface and in the atmosphere. If electrostatic charge is allowed to build then the powder may become very difficult to handle and powder bed surface roughness can become too high, with detrimental implications towards part quality.

Conversely, in situations where humidity is found to be too high the increased moisture content of the feedstock polymer can result in the formation of voids and defects in the printed part, as discussed in section 7.3.3.1. Control over humidity during builds is therefore important, as is paying attention to the recommended storage conditions stated by the feedstock manufacturer.

Humidity in the build chamber or feedstock may affect the quality of the final part so <u>may</u> require both controlled feedstock storage conditions and in situ monitoring of the build chamber. For guidance on monitoring the relative humidity of polymers for selective laser sintering see standard BS EN ISO/ASTM DIS 52925 (REC7.56) [7.128].

7.4.4 IN-LINE MEASUREMENT AND CONTROL

In-line measurement for laser powder bed systems typically consist of the following:

- Powder bed monitoring – for example using standard cameras and image processing software to identify uneven distribution of the feedstock powder to reduce gaps in the feedstock that could cause lack of fusion defects.
- Melt pool / thermal monitoring – for example using an IR camera to identify where the laser has insufficiently melted or sintered the feedstock material.
- Geometric monitoring – for example using standard cameras and image processing software to identify geometric defects e.g. pores during build.

Currently systems are limited to tracking and identifying these defects but it is expected that in the future systems will be able to identify defects and reprocess the layer to ensure the part is built correctly every time. In-line monitoring is used in some polymer AM systems such as the EOS P 500 [7.129] and EOS have announced that their LaserProFusion system will enable the user to observe the characteristics of every pixel that has been printed by the system [7.130].

For Material Extrusion it is common to incorporate cameras into the build volume to monitor the build remotely. This can be used to pick up major geometric defects such as the strings from molten material observed when the nozzle deposits in free space. These cameras do not typically identify minor geometric defects such as warping and porosity [7.131]. In line monitoring for Material Extrusion has also been used to identify issues with the feedstock filament being used up or getting jammed in the system [7.132]. Thermal monitoring of the melt properties has predominantly been in the research domain and has included measuring the rheological properties of the feedstock during melt [7.126].

In-line monitoring may be used to reduce variability in the polymer AM machine. If in-line monitoring is used the in-line monitoring should be calibrated along with the AM machine as part of a regular maintenance schedule. The method and frequency of calibration of in-line testing should be agreed between the manufacturer and Design Authority (DA) (REC7.57).

7.4.5 SUMMARY

In polymer AM the variation of parameters during the AM build is an important source of scatter in the properties of the AM part and can be divided into three key categories:

- Feedstock
- Heat source
- Environment

The computer control applied in polymer AM means that many sources of variation are managed through a robust schedule of calibration and maintenance. The application of additional test coupons to track any potential degradation may also be used to monitor parameters and ensure a consistent heat source. For polymer feedstock materials the hygroscopic nature of some polymers means they require careful storage and environmental controls to control moisture pick up since it can affect part properties and ease of processing.

7.5 POST-PROCESSING

Simple AM parts may only require basic post-processing, for example removal from the build plate. In the majority of cases, additional post-processing activities are required for the part to meet its specification. The relieving of internal stresses and the optimisation of the surface finish are two good examples of this. As such, there is a wide range of post-processing techniques that can be employed, each with its own technical considerations. This section will therefore provide an insight into the post-processing techniques that may be used for polymer AM parts, along with some guidance on their use.

7.5.1 PART REMOVAL FROM THE BUILD PLATE

For many additive manufactured part designs, the build platform is not integrated into the part. Consideration should be given to the method that will be employed to remove the part from the build plate prior to any further finishing [7.133]. It may also be necessary to remove the part from support structures at this stage. Potential strategies can range from simply snapping the part away from the plate and support structures, to using cutting methods such as sawing. When selecting a strategy, thought must be given to any potentially detrimental effects on the part. For example, when snapping supports it is likely that residual features will be left on the surface of the part. Features such as those left behind when snapping support structure may need to be removed using surface finishing techniques. Cutting methods may also have detrimental effects on surface roughness, as well as introducing a source of heat that may lead to melting and even polymer decomposition, especially when cutting thermoplastic polymers. In situations such as this, cutting fluids may be required to help remove heat.

Initial design choices can also be made to aid in this part of the manufacture process. For example, the part-build platform and part-support interfaces should be designed with ease of separation in mind. Consideration should be given to the location of part-support interfaces during the design phase such that they are not placed in positions that are likely to cause damage to delicate, critical design features when they are removed. Furthermore, depending on the design of the AM machine employed, it may also be possible to remove the build plate with the part attached. This can make it easier to perform part separation techniques.

For AM techniques that employ powder feedstock, removal of excess powder is also likely to be important at this stage. Loose powder may be removed using compressed gas, brushing and vacuum lines. Consideration should also be given during the design phase towards the possibility of entrapping powder inside the part and whether this powder will need to be removed. This can involve incorporating features for powder removal into the design, or post-process machining to allow for powder removal. Any powder removed at this stage may be considered waste owing to the difficulty in defining its thermal history. It will also be necessary to consider the requirements for powder containment and extraction using appropriate ventilation systems to protect operators.

Consideration should be given to the method that will be employed to remove the part from the build plate prior to any further finishing, consideration could include:

- **Residual features left on the surface of the part when support structures have been removed**
- **The location of part-support interfaces during the design phase such that they are not placed in positions that are likely to cause damage to delicate, critical design features when they are removed**.
- **The possibility of entrapping powder inside the part and whether this powder will need to be removed (REC7.58).**

7.5.2 THERMAL POST-PROCESSING

The expansion and contraction forces that are exerted on a part resulting from repeatedly depositing hot polymer onto cooled polymer can lock residual stress into a printed part. These residual stresses superimpose on applied stresses in service and consequently may lead to unanticipated failure of the part. Residual stresses may also result in geometric distortions such as warping. Thermal post-processing can be employed to help relieve and minimise these residual stresses [7.133]. Thermal post-processing typically involves placing the part in an oven and gradually elevating the temperature to a point below the glass transition temperature of the polymer. The temperature is held for a period of time to allow stresses in the polymer chains to distribute evenly. The cooling process is controlled to prevent additional residual stress being introduced. It may be necessary to secure the part to a metallic fixture/jig whilst inside the oven to maintain dimensional stability. The thermal post-processing procedure may take time to develop and optimise for a particular polymer/process/part configuration.

Related to the formation of residual stresses, the small size of melt pools relative to the size of parts as a whole, coupled with the rapid cooling and resultant rapid polymer solidification, mean that non-uniform microstructures can be formed, resulting in anisotropy. Thermal post-processing may then be employed to normalise the part and such microstructures. There may also be specific mechanical property requirements that can only be achieved by specific microstructural conditions that require thermal post-processing. **If thermal post-processing is employed during qualification, the details of the process used during qualification and certification should be recorded and maintained for subsequent builds (REC7.59).**

7.5.3 SURFACE FINISHING

Surface quality can represent a particular challenge in additive manufacturing. A major contributing factor to the increased surface roughness in additive manufactured parts is the “stair casing effect”. The “stair casing effect” manifests as a kind of aliasing at the surface of a printed part resulting from the stacking of 2D layers to form the initial 3D model. While processing parameters such as build orientation and layer thickness can affect the degree of aliasing, post-processing techniques provide additional tools to reduce its severity.

Table 7-3 shows values for minimum layer thicknesses and surface roughness for some specific additive manufacture machines. Alongside Material Extrusion and L-PBF the table shows data for two other AM techniques not covered in this document. This data should help give an appreciation for the effect that various additive manufacture techniques and machines can have on surface finish

Table 7-3 - Surface roughness data for various additive manufacture machines [7.134].

Technique	Machine	Polymer	Minimum Layer Thickness (mm)	Surface Roughness µm R_a
Stereolithography	SLA 350	Epoxy 5190	0.100	2-40
Selective Laser Sintering	Actua 2100	Thermojet 45	0.125	5-35
Material Extrusion	FDM 1650	Acrylonitrile butadiene styrene (ABS)	0.253	9-40
Laminated Object Manufacturing	LOM 1015	Micronized rubber powder	0.114	6-27

Physical machining is one approach for smoothing a surface and reducing the stair case effect. For example, Hot Cutter Machining (HCM), in which a heated cutting tool is attached to a milling machine can significantly reduce surface roughness [7.135]. However, techniques such as this can prove difficult to apply to geometrically complex parts, meaning they are mostly found to be useful for smoothing flat surfaces. They do however offer the advantage of requiring a vastly reduced cutting force, as the heated tool softens the polymer. Care should be taken not to redeposit molten polymer with each pass of the tool.

Abrasive methods, such as the use of a vibratory bowl, can also be employed. The vibratory bowl approach involves placing the component to be finished inside a u-shaped bowl with abrasive media. The advantage to this technique is that it is able to abrade convex and concave surfaces, something that can be difficult with HCM. However, it is also prone to localised over-abrasion at corners and edges [7.136].

Abrasive methods that employ abrasive blasting with glass/plastic and even CO_2 ice can also be used for de-powdering a part. De-powdering is done to remove excess material, such as un-sintered residual polymer from an L-PBF process, while leaving the sintered polymer unaffected. Shot peening is also commonly used to smooth a surface with minimal material loss.

Another option available for improving surface finish is chemical etching. A popular solvent choice is dimethyl ketone (acetone), which has been shown to lead to a significant reduction in the surface roughness of ABS Material Extrusion manufactured parts, without coming at the cost of a significant reduction in the size of the part [7.137]. Acetone also offers the added benefits of low cost, low toxicity and a high diffusion rate. In the case of parts manufactured from ABS, submersion for 300 sec in a 90% dimethyl ketone, 10% water solvent bath has been shown to produce impressive results [7.91].

Laser polishing, also referred to as laser micro machining, is another commonly used surface finishing technique. A key advantage to laser polishing is the versatility offered in the types of material on which it can be used. Suitable materials range from silicon, ceramics and metals to polymers. The contactless nature of the method also gives it a degree of flexibility which lends itself well to automation. The process of laser micro machining generally involves the formation of a trail of removed material termed a "kerf". How the material is removed is related mainly to the nature of the polymer and the energy of the laser beam. For example, as laser wavelengths get shorter heat transfer can become great enough to melt and vaporise material. A disadvantage of this is that a high energy laser beam is likely to ionise vaporised material which can result in a plasma plume that can occlude the beam.

The various phase transitions that occur during laser micro machining result in three key zones being commonly identified around the incident beam. The first is the heat-affected zone (HAZ), the second is the melt zone and the third is the vaporisation zone. Of course, some polymers may sublime meaning there is no melt zone. Rather than purely thermal effects, it is also possible for chemical processes such as bond scission to occur if the beam energy reaches the bond energies found within the substrate polymer. In fact, short wavelength lasers can be used to efficiently convert energy into bond scission thereby reducing the overall heating effect, in a "photo ablation" process. The advantage to this kind of "cold laser machining" is that warping and delamination as well as edge melting effects are much diminished [7.138].

7.5.4 SUMMARY

There are numerous potential post-processing activities to consider and this chapter covered some of those that are most common across polymer AM. Each part will ultimately have its own set of post-processing activities to go through: some surfaces may be prepared for bonding, some areas may need precision machining/reaming for a close fit interface to another part or shaft, some threads may need tapping, etc.

7.6 COMPONENT VALIDATION

A full description of different component testing techniques is included in the Section 6.6 of this document. This section of the polymers chapter will instead seek to outline any significant differences in validation of polymer components manufactured using AM and highlight any relevant standards. Some polymer-specific AM standards exist (e.g. BS ISO/ASTM 52903-1:2020 [7.139]) nevertheless there is limited information specific to polymer additive manufacturing with regards to mechanical testing and test specimens in particular. In some cases, for example polymer powder bed fusion, it is possible to apply some of the guidance for metal AM mechanical testing to polymer AM mechanical testing.

As with metal AM samples the pyramid of tests (Figure 3-4) should be used to limit the number of whole parts that need to be cut up and used for testing (REC7.60).

BS EN ISO 17296-3:2016 gives an outline of appropriate testing standards for additive manufacturing based on the material and an assessment of different levels of component criticality:

- H (high): tests for highly engineered parts;
- M (medium): tests for functional parts that are not safety critical;
- L (low): tests for design or prototype parts [7.140].

BS EN ISO 17296-3:2016 may be used to identify appropriate tests for component validation in combination with discussion with the DA (REC7.61).

7.6.1 MANUFACTURE OF SPECIMENS FOR VALIDATION

In polymer AM the shape of each layer being built can impact the melting and solidification of that layer and subsequent/previous layers. This means the design geometry of a part or test specimen can affect the thermal history and subsequently the properties of that component. In particular, **anisotropy means that test specimens should be carefully orientated and located within the build chamber to ensure their properties are representative of the final part.** In some cases witness specimens with features similar to the final part can be used.

The guidance outlined in draft standard ISO/ASTM FDIS 52903-2 for Material Extrusion specimens includes the recommendations with respect to test specimens. **Although written for Material Extrusion techniques these recommendations in ISO/ASTM FDIS 52903-2 may be applied to both Material Extrusion and polymer powder bed fusion since both can exhibit anisotropy (REC7.62):**

- All test specimens used for qualification and certification of additive manufactured items should be manufactured using the same technique as the final part

- Test specimens should undergo the same post processing techniques as the final part

- Properties can be divided into as three categories with respect to direction dependence and test specimens should be built with the following guidance:
    - Direction independent properties - test specimens can be built anywhere on the build plane and in any orientation

  - Non-mechanical direction dependent properties – test specimens should be built in the least favourable direction within the build volume for that property.
  - Mechanical direction dependent properties (except tension – see below) – test specimens should be built in the least favourable direction within the build volume for that property.

- Tension specimens should be built as follows depending on class of part (see ISO/ASTM FDIS 52903-2 for class definitions):
  - Class 1 - A minimum of three XY or YX tension specimens, and a minimum of three ZX or ZY tension specimens
  - Class 2 - A minimum of three XY or YX tension specimens
  - Class 3 - No tension specimens needed unless requested by customer [7.139]

A standard on mechanical testing of polymer AM parts is currently under development by the ASTM/ISO F42 committee and although not yet ready for inclusion in this guidance, its progress should be monitored and may be considered in future for qualification and certification of polymer AM components (REC7.63) [7.141]. However, general guidelines on the manufacture of moulded polymer tensile test specimens, provided in BS ISO 527-2, include:

- All surfaces of the test specimens shall be free from visible flaws, scratches or other imperfections.
- Test specimens taken from finished goods shall be taken from flat areas or zones having minimum curvature.
- For reinforced plastics, test specimens should not be machined to reduced their thickness unless absolutely necessary.
- Test specimens with machined surfaces will not give results comparable to specimens having non-machined surfaces.

The following tips from Curbell Plastics may also aid in the machining of high quality polymer test specimens:

- When selecting tool tips, high speed steel is a good choice for unreinforced polymers. For reinforced polymers, carbide tipped tools may be necessary.
- Due to the low T_m and low thermal conductivity of polymers, water cooling and a clean air stream may be necessary to achieve a high quality finish.
- If a part contains large amount of residual stress, machining may result in the warping of specimens.
- Polymers with high moisture content may need to be conditioned prior to machining
- When turning a sample:
  - Fine, C-2 grade inserts are recommended.
  - If top surfaces are polished then material build-up can be reduced, ultimately producing a better surface finish.
  - Generous relief angle and negative back rake on cutting edges can help minimise rubbing actions.
- When milling a sample:

    - High spindle speeds are possible if the part is adequately clamped. However, care must be taken not to deform the part when clamping.
    - For good quality surface finishes, finish cuts should be performed with either 2 flute or 4 flute mills depending on the material.
    - To avoid sharp inside corners that may act as areas of stress concentration it is recommended that mills with rounded corners be used.
- When drilling a sample:
    - Heat reduction is critical.
    - The back side of the part should be supported to prevent chipping and drilling into unsupported areas should be avoided.
    - Feed rate should be reduced as the drill gets close to exiting the material.
    - Drills must be sharp.
    - Proper chip ejection is vital in preventing the excessive build-up of heat.
- When sawing a sample:
    - To avoid excessive heat build-up from friction thick walled parts should be sawed with a thin blade.
    - Blade manufacturers may provide specially optimised blades for given polymers.[7.142]

Further applicable standards to polymer AM test specimens are found in BS ISO 27547-1:2010 [7.143] and BS EN ISO 20753:2018 [7.144]. BS ISO 27547-1:2010 is a guide on preparing laser sintering specimens for accurate mechanical property and design allowable determination. BS EN ISO 20753:2018 is an outline of tensile test specimen preparation in polymers in general.

7.6.2 VISUAL INSPECTION

The first stage in the validation of a newly printed additive manufactured component is likely to be a visual inspection. At this stage it may be possible to identify geometric distortions such as warping, excessive shrinkage and general errors in deposition as well as gross surface defects such as excessive roughness and cracking. Depending on the severity of any detected issues and the requirements of the part it may be decided that post processing be employed to improve the quality of the part, or it may be decided that the part be scrapped. A good visual inspection process will provide a checklist of features to look out for and describe how to quantify the effect so that pass/fail criteria can be established.

7.6.3 DIMENSIONAL INSPECTION

When manufacturing a polymer AM part the geometric requirements and dimensional tolerances will have been specified during the design phase. Once the manufacturing and post processing phases have been completed the printed part will require measurement to ensure these features fall within the design specification. **When performing these measurements the measuring instrument <u>should</u> be agreed between the DA and manufacturer and accurate to a level that is appropriate to the tolerances stated in the drawings, for example within ±0.1 mm for dimensions of > 10 mm. At least three measurements <u>should</u> be collected if statistical analysis is to be performed using the data, as per BS EN ISO 16012:2015 (REC7.64) [7.145].**

In general, manual measurements will be carried out using callipers, micrometers and gauges. Automated technology can also be employed in the form of laser scanners, coordinate measuring machines, laser trackers and X-ray computer tomography. In order to obtain consistent measurements, care should be taken during the pre-measurement cleaning stage. If residual polymer from the printing process such as the remnants of support structures have not been fully removed then significant statistical variations are likely to be introduced.

It may also be necessary to produce test coupons in order to ascertain dimensional accuracy. **In this case it is recommended that a bar with a known cross section, for example 5 mm x 10 mm should be manufactured with lengths that fall within the ranges set by BS EN ISO 20457:2018 [7.146] with values adjusted to an integer multiple of the coupon thickness (REC7.65).**

For a full description of the qualification and classification principles that may be employed in the additive manufactured polymer parts see ISO/ASTM DIS 52924:2020(E) (REC7.66) [7.147]

7.6.4 SURFACE FINISH

Surface roughness measurements are generally carried out using profilometry techniques such as those described in the metals section of this report (see Section 6.5.3). **When obtaining surface roughness measurements it is important to note that the orientation of the surface relative to the build direction is likely to have a large impact on the measured surface roughness and as such this should be accounted for during validation (REC7.67).**

Surfaces parallel to the build plane should have the lowest surface roughness whereas surfaces that are perpendicular or offset at an angle relative to the build plane are likely to have a higher surface roughness owing to the “stair casing” effect. This effect is likely to become even more pronounced if large layer thicknesses are employed in the design. There is also likely to be a material specific element to this relationship.

7.6.5 DESTRUCTIVE TESTING

7.6.5.1 MECHANICAL TESTING

Many of the mechanical testing techniques outlined in Chapter 5, section 6 are also applicable to polymer AM but the differences in properties mean there are specific standards for polymers. In addition to the guidance outlined in this document, **the appropriate mechanical tests required to qualify the part should be agreed between the DA and the manufacturer based on several factors including the loading environment, external factors (e.g. heat) and the criticality of the part (REC7.68).**

7.6.5.1.1 APPLICATION OF POLYMER TESTING STANDARDS TO AM COMPONENTS

In 2015 NIST performed an assessment of polymer mechanical testing standards to determine their suitability for application to polymer additive manufacturing [7.148]. The assessment covered standards for both polymer and reinforced polymer materials using the following mechanical tests:

tensile, torsion, flexure, compression, shear, creep, fatigue, fracture toughness, impact, bearing strength and open hole compression. In all cases at least one published standard could be applied; however, guidance for applying the standard is required.

NIST gave further clarification on the issues that may be encountered when applying the standards to polymer AM:

- Geometrical limits on test specimens e.g. test sample sizes may be too large to fit in the AM machine.
- Required post-processing such that specimens built via additive manufacturing meet the requirements of the standard; this typically includes surface finish, dimensional requirements, or pre-crack requirements.
- Material isotropy requirements. AM specimens often have inherent anisotropy. The measurement methods that specify applicability for isotropic materials may still work, but the measured results may have larger uncertainties. This includes quantifying any differences in mechanical properties established between coupons and the final part.
- Application specific considerations, such as elevated testing temperatures or immersion environments [7.148].

A list of the types of mechanical testing that were assessed is shown below along with the associated standards marked “yes with guidance”:

- Tension - ASTM D3039/DM [7.149], ISO 527-2 [7.150], ASTM D638 2010 [7.151], ISO EN 527-4 [7.152]
- Flexure - ISO 178[7.153], ASTM D6272–10 [7.154], ASTM D790-10 [7.155]
- Compression - ASTM D695-10[7.156], ISO 604[7.157],
- Shear - ISO 15310: 1999 [7.158]
- Creep - ASTM D2990-09 [7.159], ISO 899-1:2003 [7.160], ISO 899-2:2003[7.161]
- Fatigue - ASTM D7791-12 [7.162], ASTM D7774-12[7.163], ISO 13003[7.164]
- Fracture toughness - ISO 13586: 2000 [7.165], ASTM D6068–10 [7.166]
- Impact - ISO 180: 2000[7.167], ASTM D6110-10 [7.168], ASTM D256-10 [7.169], ISO 179–1: 2010[7.170], ISO 179-2:1997 [7.171],
- Bearing Strength and Open Hole Compression - ISO 12815:2013 [7.172], ASTM D5961 / D5961M - 17 [7.173], ASTM D953 - 10 [7.174],

NIST included additional comments on the effectiveness of standards. For example a stress concentration where the filaments ended was thought to cause failure in the sample, highlighting the importance of path planning in test specimens as well as the final part. They also discussed that further studies should be undertaken to understand the effect of machined vs. as-built notches in polymer fracture toughness specimens.

A significant challenge in applying polymer test standards to polymer AM components is the anisotropy of AM components. Anisotropy in general is not typically referenced in polymer standards but it is referenced in standards for fibre-reinforced polymers. Such standards are not always appropriate for polymer AM due to the significant difference in properties of the fibre and the matrix. In their assessment of standard applicability for shear testing in particular, NIST noted the test methods may not be directly applicable to AM manufactured materials for two main reasons.

- In fibre-reinforced composites the fibre typically has a much higher modulus than the resin matrix, in AM parts there is typically only one material present and consequently the mechanics of load distribution and crack propagation will be different in an AM material.
- Failure in composites may show different behaviour to failure in polymers. For example sharp initiation cracks form in composites between the fibre layers. In polymer AM there is limited formation of a sharp initiation crack owing to the thermal processing between layers [7.148].

7.6.5.2 THERMAL ANALYSIS

In addition to mechanical testing techniques, the low melting point and glass transition temperature of polymers means that their thermal properties are important for characterising the chemical composition of the part. These properties will influence not only how the polymer behaves during manufacture but also its amorphous or semi-crystalline nature which in turn influences the mechanical properties of the polymer. Four main thermal analysis techniques are used for polymers. For AM samples these can be split into two main analysis categories: thermo-analytical and thermo-mechanical.

7.6.5.2.1 THERMO-ANALYTICAL ANALYSIS

The following tests are full melt tests and use small samples (3-8 mm widths) of material. The small sample size for these techniques means that, if the tests are required, it is good practice to take samples from a variety of locations in a part in case there are is any significant variability.

- Thermogravimetric analysis (TGA) – In TGA the mass of a sample is measured whilst the temperature of the sample is increased at a constant rate. At different points in heating the rate of mass loss will change giving a characteristic pattern. The gases released at different points in the heating can be determined by combining TGA with for example mass spectrometry [7.175].
- Differential scanning calorimetry (DSC) – in DSC the material is heated at a constant rate and the heat flow (either exothermic or endothermic) is measured. During events such as melting or glass transition the heat flow changes and the location of these peaks can be used to determine these properties as well as giving an indication of the crystallinity of the material [7.176-7.178].

7.6.5.2.2 THERMO-MECHANICAL ANALYSIS

The following tests use mechanical property testing along with thermal techniques so it is good practice to apply previous advice for mechanical test coupons to those for these techniques:

- Heat deflection under load – the sample is placed under a bending load in a heated oil bath. The temperature at which the material deforms under a load is recorded and used to determine the thermal response of the material [7.179].

- Dynamic mechanical analysis (DMA) – In DMA the material undergoes a sinusoidal force and the material displacement is measured. By heating the sample its glass transition temperature can be determined by observing the temperature at which there is reduction in stiffness indicating the glass transition temperature has been reached [7.177, 7.180].

7.6.5.3 MICROSTRUCTURAL ANALYSIS

Microstructural analysis in polymers is used in two key ways: to determine the porosity of the sample and to characterise its microstructure which can both can be observed using optical microscopy. Importantly, samples must be carefully sectioned and polished using techniques that avoid melting or smearing the surface to be inspected. To determine porosity, an image is taken using optical or scanning electron microscopy and then image processing software can be used to identify and quantify porosity in the images of the sample.

Although not typically used on final part's optical microscopy using polarised light can be used to determine the morphology and crystallinity of the polymer. In particular the identification and size of spherulites in polymer samples provides information about the thermal history of the polymer and ultimately its mechanical properties [7.181].

7.6.5.4 FIRE, SMOKE AND TOXICITY TESTING

Fire and flammability testing can be divided into two key categories:

- Developing fire – how the material reacts to fire: ignitability, flame spread, heat release
- Fully developed fire – The material's resistance to a fire: load-bearing, insulation and integrity capacity

The measurement techniques used to determine fire retardancy for standard polymers will apply to polymer AM [7.182].

In addition to the flammability, many polymers for aerospace applications are tested for their smoke and toxicity. This is done by analysing the gases or particulates produced during burning of the polymer. Although testing for smoke and toxicity for AM will be similar to conventional polymers there may be extra additives present in polymer AM blends that may affect the emissions.

Some typical flame, smoke and toxicity tests are shown below:

- 60s and 12s Vertical Burn
- 15s Horizontal Burn
- Toxic Gas Emission
- Smoke Density
- Heat Release Rate of Cabin Materials [7.183]

Polymers such as ULTEM 9085 and Poly Aryl Ether Ketone polymers (e.g. PEKK or PEEK) have good flame, smoke and toxicity characteristics and are available for use with polymer AM machines [7.183]. As with the use of any novel material in an aircraft its response to fire should be fully understood.

7.6.5.5 MOLECULAR WEIGHT DETERMINATION

As outlined in section 7.4 of this chapter, the chain length of the polymer can change during the AM process due to thermal cycles in the build chamber and polymer recycling, which can have a detrimental effect on the mechanical properties of the part. Although usually identified through changes in mechanical properties the chain length of the polymer may need to be measured through routine molecular weight measurements.

As outlined in BS ISO 16014-1:2019, molecular weight is typically measured using size-exclusion chromatography. In this technique the polymer is dissolved in a solvent and then passed through a column containing particles with different pore sizes. As the polymer passes through the column the polymer molecules are separated by their size. Larger molecules are unable to fit in the pores so wash through more quickly than smaller molecules. A detector then measures the polymer concentration in the solvent washed out which can then be used, along with a calibration curve, to determine the range of molecular weights present in the polymer. There should not be a difference in the accuracy of the molecular weight determination for an AM polymer in comparison to a conventionally manufactured polymer [7.184].

7.6.6 NON-DESTRUCTIVE EVALUATION

In their assessment of the applicability of non-destructive evaluations techniques to AM processes in [7.185], Lu et. al. found the following techniques would be applicable to both Materials Extrusion and L-PBF techniques:

- Ultrasonic testing
- Radiography e.g. X-ray computer tomography (CT)

In addition, they highlighted that liquid penetrant testing would be applicable to laser powder bed fusion. It should however be noted that the paper does not distinguish between metal powder bed fusion and polymer powder bed fusion and includes techniques such as eddy current testing and magnetic particle testing that are only applicable to metal samples. They also highlighted that techniques such as liquid penetrant and ultrasonic testing require a smooth surface and consequently polymer AM samples may require post processing to remove the typically rough as-built surface. Inspection techniques such as micro- X-ray CT are not generally affected by surface roughness [7.185].

A standard guide on NDE of AM parts is currently under development by the ASTM/ISO F42 committee and although not yet ready for inclusion in this guidance, its progress should be monitored and may be considered in future for qualification and certification of polymer AM components (REC7.69).

The application of CT measurement is discussed further in Section 6.6 of this document and covered in BS EN 16016 [7.186]. As with metals there are three main issues with the application of CT for qualification of polymer AM parts:

- AM design organisations generally have yet to define a minimum defect size for CT imaging so pores or defects too small to be imaged by the CT scanner could be missed and still affect the mechanical properties of the part.
- Noise and artefacts of the measurement in the image affecting results.
- Image conversion and the reliance on user input.

7.6.7 SUMMARY

This section has provided a summary of testing techniques applied to polymers, in addition to those for metals, including fire, smoke and toxicity testing and thermal analysis. Although limited guidance is currently available from standards authorities and in the literature, where available the applicability of polymer standards to AM have been discussed, particularly the challenges of anisotropy. Although at the time of writing this chapter there are few standards for polymer AM component validation it is hoped that in the coming years standards will be produced and published to extend the range of polymer standards to include AM.

7.7 COMPONENT HANDOVER

The guidance for release documentation and component validation is the same for metals and polymers but is repeated here to make this chapter as standalone as possible.

When designing any new component or replacing an existing component it is typical for the Design Authority to provide a process and part specification to a manufacturer for the manufacturer to make the component. The digital nature of additive manufacturing mean there are wide numbers of parameters that can be recorded and this may make it difficult to process and record all the associated data. What is important with AM components, as with any component is that the part producer and the Design Authority agree the appropriate data to collect and record to give confidence in the properties and scatter in properties of the final part.

Based on the guidance in this document it is clear that in comparison to conventional components additional data will be required for AM parts to give confidence in the properties of both the part and any test coupons. The Process Control Document should be agreed between the Design Authority and the manufacturer and should be used as the primary means to give evidence of the controls in place to reduce the scatter in properties during manufacture and to outline the testing required to confirm that properties are not deviating from those measured during part qualification.

In addition ISO/ASTM 52901 has a great deal of detail on how to outline the requirements for purchased AM parts and should be used as a further guide on the handover of purchased AM components (REC7.70). The required documentation is divided into three separate sections:

- Part ordering information – standard information that would be required to order a part such as the number and type of parts required, identification of the part (marking or tagging) and details of manufacturing and purchasing organisations.
- Definition of the part to be manufactured – details of the part to be built and process specifications to meet the required part properties. This should include part geometry and tolerances but could also include surface texture, build orientation, feedstock, acceptable imperfections or deviations, and process control information.
- Part characteristics, functionality and performance – the required properties of the part, depending on the part requirements but covering aspects such as dimensional accuracy, defects, mechanical properties, residual stress, or chemical composition [7.187].

Another useful standard is BSI ISO 17359:2011 which states that records of parameters for condition monitoring and diagnostics of machines should include, as a minimum, the following information:

- Essential data describing the machine.
- Essential data describing operating conditions.
- The measurement position.
- The measured quantity units and processing.
- Date and time information.

The quoted values should also outline details of the measuring systems used to obtain each value and the accuracy of the measuring system [7.188].

7.8 SUMMARY OF RECOMMENDATIONS

7.8.1 AM MACHINE

7.8.1.1 SUMMARY OF AMC-TYPE RECOMMENDATIONS

REC7.3: Temperature gradients between the feed and build pistons should be recorded and carefully controlled for polymer L-PBF to reduce the risk of geometric distortions in the printed part – Section 7.1.5

REC7.11: For Material Extrusion the impact of head degradation should be considered since head degradation can have a detrimental effect on the properties of the final part – Section 7.1.5

REC7.17: The energy delivered to the polymer during Laser Powder Bed Fusion should be sufficient to melt polymer particles fully – Section 7.1.5

REC7.27: All operators should be suitably qualified to use the AM machine. An approach to assess operator competence should be agreed between the manufacturer and Design Authority (DA) and should include the appropriate method and frequency of training and testing to ensure competency. Records of any competency certificates should be retained to provide the evidence of operator competence. If variation between operators is still considered a significant source of scatter, it may be necessary to specify named operators to build a critical part – Section 7.3.3
REC7.28: The machine type and model should be recorded in the Process Control Document – Section 7.3.3

REC7.29: If a part will be produced on different machines to those used for qualification and certification, all machines should undergo a pre-qualification process with calibration builds to show that any variation is within an acceptable range – Section 7.3.3

REC7.30: The environment in which the build is performed should be controlled to keep humidity and temperature within the range specified by the manufacturer or in-house process control specifications. This is applicable for either a sealed build environment or the room the machine is placed in if builds are performed exposed to the atmosphere – Section 7.3.4

REC7.32: If the file conversion from CAD to STL or similar has a significant effect on the required properties of the final part the AM producer should ensure that the converted file used to build the qualified part is the same as the file used for production builds – Section 7.3.5

REC7.41: The build parameters or parameter set used (e.g. heat source, power, build speed) should be recorded and maintained for any qualified build. Asince any change in these parameters defined by the AM process may affect the mechanical properties, geometry and defects, and their scatter in the final part – Section 7.3.7

REC7.47: The calibration approach should be agreed between the manufacturer and Design Authority (DA) and should include those parameters/systems requiring calibration and the appropriate method and frequency of calibration. Records of any calibrations should be retained

to provide the evidence that important KPV influencing parameters are as defined and inputted, and their variability is within acceptable limits – Section 7.4.2

REC7.48: Since the melting and solidification is directly linked to the pre-heat and directly affects part properties, the pre-heating system used should be calibrated to ensure that it is consistently heating the material. Appropriate calibration methods should be agreed between the manufacturer and Design Authority (DA). These but could include calibration builds from different locations across the build chamber to identify variations in pre-heating and the subsequent effect on the properties of the final part – Section 7.4.2

REC7.49: The laser beam for laser powder bed systems should be calibrated to ensure that its characteristics do not change through time to reduce scatter in the properties of the final part. The frequency of calibration should be agreed between the DA and the manufacturer based on the machine requirements. Characteristics to be calibrated should be agreed between the DA and the manufacturer based on the machine requirements but could include:

- **Laser beam power**
- **Laser beam diameter**
- **Laser spot location in the xy plane – Section 7.4.2**

REC7.50: Routine calibration for polymer laser powder bed fusion should also measure the correct and consistent drop of the build plate over time and at positions across the build plane – Section 7.4.2

REC7.52: The temperature profile throughout the build chamber can have an impact on the properties of the final part. It, should therefore be calibrated regularly and may be monitored during the build in addition to direct heating. The method and frequency of the temperature profile monitoring should be agreed between the manufacturer and Design Authority (DA). The movement of gases within the build chamber, by fans for example, can affect the temperature profile and lead to hot and cold spots in the build chamber, which can affect the properties of the final part. Therefore, the effect of the movement of gases should also be considered when monitoring and calibrating the temperature across the build chamber – Section 7.4.2

REC7.53: The nozzle temperatures or parameter set used during qualification and certification should be maintained for subsequent builds – Section 7.4.2

REC7.54: The nozzle temperature should be calibrated to ensure consistent melt properties for subsequent builds. Some machine manufacturers offer set calibration instructions and builds which should be used where available. The method and frequency of calibration of in-line testing should be agreed between the part manufacturer and Design Authority (DA) – Section 7.4.2

REC7.55: The accuracy of the x, y and z tip offset for Material Extrusion machines should be calibrated regularly to ensure geometric accuracy. The calibration schedule and process should be agreed between the DA and manufacture but could include calibration builds and xyz offset determination – Section 7.4.2

REC7.57: In-line monitoring may be used to reduce variability in the polymer AM machine. If in-line monitoring is used the in-line monitoring should be calibrated along with the AM machine as part of a regular maintenance schedule. The method and frequency of calibration of in-line testing should be agreed between the manufacturer and Design Authority (DA) – Section 7.4.5

7.8.1.2 GUIDANCE-TYPE RECOMMENDATIONS

REC7.5: The effective thermal conductivity will play a major role in determining temperature distribution during a selective heating process and thus may prove a valuable consideration when planning key process variables – Section 7.1.5

REC7.9: The lack of a distinct melting point in amorphous polymers means that for Material Extrusion melt liquefier temperatures and filament feed rates may require fine-tuning to give optimal results – Section 7.1.5

REC7.56: Humidity in the build chamber or feedstock may affect the quality of the final part so may require both controlled feedstock storage conditions and in situ monitoring of the build chamber. For guidance on monitoring the relative humidity of polymers for selective laser sintering see standard BS EN ISO/ASTM DIS 52925 – Section 7.4.4

7.8.2 BUILD STRATEGY

7.8.2.1 AMC-TYPE RECOMMENDATIONS

REC7.2: When planning a two material build, differences in the melting and solidification properties of both polymers should be considered as this can lead to localised differences in crystallinity and distortion if those properties are significantly different – Section 7.1.4

REC7.6: The extruder temperature and the build bed temperature should be matched to the specific polymer in use – Section 7.1.5

REC7.10: During Material Extrusion care should be taken not to induce thermal decomposition of the polymer. This may be particularly relevant when maximising melt temperature in order to achieve a high degree of interlayer fusion – Section 7.1.5

REC7.13: For Laser Powder Bed Fusion, when considering the beam speed parameter the compromise between build speed and part quality should be considered. For example a high beam speed will result in a faster build rate but will generally lead to a deterioration in build quality – Section 7.1.5

REC7.15: The effect of shrinkage on a build should be considered and accounted for prior to part manufacture – Section 7.1.5

REC7.16: The melt shear velocity should be considered for optimum Laser Powder Bed Fusion particle coalescence. For example. a sufficiently high shear storage modulus in the molten state and an associated low melt shear viscosity, 60 Pa s in the case of nylon-12 [7.31], may be desirable [7.16] – Section 7.1.5

REC7.18: The orientation and build packing of parts should be considered and, if necessary, established and fixed for a particular part, or part family, depending on part criticality – Section 7.1.6

REC7.19: For Material Extrusion the fusion between deposited layers should be considered since this can have a significant impact on mechanical properties. This may be achieved by reducing the overall cooling of material between layer depositions, which can be achieved by increasing the raster speed and/or layer thickness and decreasing the interlayer cooling time – Section 7.1.6

REC7.20: For Material Extrusion the direction in which the fibres are deposited relative to the intended mechanical loading direction should be a key consideration when planning a build, as should the material flow rate and size of the nozzle aperture – Section 7.1.6

REC7.25: If a part is designed and qualified to optimise properties in a particular direction under a given set of processing parameters then the build direction and processing parameters should not be altered without further qualification – Section 7.2.5

REC7.26: Anisotropy resulting from the AM characteristics of the specific polymer and the features of the build design, should be accounted for when establishing mechanical and physical properties against the part design requirements. While published property databases will be valuable in guiding material choice, the final AM part properties may be anisotropic and therefore different in different directions – Section 7.2.5

REC7.33: As with AM parts, build location and orientation should be considered for witness and test specimens so that they reflect, as accurately as possible, this source of scatter during the qualification process. Witness and test specimens should also undergo the same post-processes as the AM part – Section 7.3.5

REC7.37: For Material Extrusion a design engineer should consider the orientation of filament beads and the intended load direction when deciding on the build direction – Section 7.3.5

7.8.2.2 GUIDANCE-TYPE RECOMMENDATIONS

REC7.8: The following guidance may be considered when deciding on selective heating parameters for Laser Powder Bed Fusion:

- **Operating the process within the stable sintering region of the feedstock polymer;**
- **Optimising the wavelength of the incident radiation to the absorption coefficient of the feedstock polymer;**
- **Ensuring the incident beam radius is appropriate for the feedstock polymer particle size – Section 7.1.5**

REC7.12: The optimal ratio between energy supplied and energy required to the melt the polymer (EMR) may be used in order to maximise the mechanical properties of a printed part – Section 7.1.5

REC7.14: To fully understand the thermal properties of the feedstock polymer it may be necessary to consider the polymorphic state of the polymer at each stage of the manufacture process – Section 7.1.5

REC7.34: If the variation due to orientation of the part leads to a scatter of properties greater than those allowed by the Design Authority then it may be necessary to record and maintain the orientation of the part used during qualification and certification throughout all part manufacture – Section 7.3.5

REC7.35: If the variation due to location and number of parts leads to a scatter of properties greater than those allowed by the Design Authority then it may be necessary to record and maintain the build plan used during qualification and certification throughout all part manufacture – Section 7.3.5

REC7.36: If the effect of scan strategy is observed to be significant it may be necessary to record and maintain the scan strategy used in qualified builds in all subsequent part manufacture – Section 7.3.5

REC7.38: If the effect on the final part of the pattern, location and material of the support structure is observed to be significant then it may be necessary to record the support strategy used during qualification and ensure that the pattern, location and material of any support structure generated are the same when building the final part – Section 7.3.5

REC7.39: If the variation due to location and number of parts leads to a scatter of properties greater than those allowed by the Design Authority then it may be necessary to record and maintain the build plan used during qualification and certification throughout all part manufacture – Section 7.3.5

REC7.40: If the effect of scan strategy is observed to be significant it may be necessary to record and maintain the scan strategy used in qualified builds in all subsequent part manufacture – Section 7.3.6

REC7.51: Beam speed is usually included in the build parameter set for a known material but can be confirmed by producing a series of small samples at different speeds and using their quality to determine the correct speed. This technique could also be used to calibrate the beam speed if required – Section 7.4.2

7.8.3 PART DESIGN

7.8.3.1 AMC-TYPE RECOMMENDATIONS

REC7.21: Although guidance should be sought specific to the material and machine type, the guidance in section 1.2.2 may be used when designing for polymer AM – Section 7.2.2

REC7.24: The mechanical properties and durability of a part should be assessed using recognised standards to ensure that these properties are appropriate for the parts intended use – Section 7.2.5

7.8.4 FEEDSTOCK

7.8.4.1 AMC-TYPE RECOMMENDATIONS

REC7.4: A well-defined melt pool should be used to allow for good dimensional accuracy. This may be achieved by selecting a polymer with a high heat of fusion and a narrow melting point range – Section 7.1.5

REC7.7: For Laser Powder Bed fusion AM careful temperature control should be used to ensure that the powder bed does not fuse during preheating. In polyamide the glaze point could be used to identify the appropriate powder bed temperature and a temperature of 12 °C below the glaze point has been shown to limit this effect [7.10] – Section 7.1.5

REC7.22: The interlayer fusion between deposited layers under the available processing parameters should be considered when selecting the feedstock polymer since this can have a significant impact on mechanical properties – Section 7.2.3

REC7.31: Before use, feedstocks, e.g. filaments or powder, should be stored in an environment that does not lead to a significant deterioration in properties through moisture uptake and / or significant fluctuations in temperature – Section 7.3.4

REC7.42: The polymer type used during qualification should be recorded and used for any subsequent builds. This should include any additives or mixes of polymers. It may be necessary to use the same manufacturer for all subsequent runs if information about the polymer blend is not available – Section 7.4.1

REC7.44: For critical components formanufactured using Laser Powder Bed Fusion, the powder quality should be tracked through regular sampling and testing to ensure the powder does not fall outside of specification. The method and frequency of powder testing should be agreed between the manufacturer and Design Authority (DA). Example powder specification measurements should be determined by the component manufacturer but could include measurements of chemical composition, particle size distribution and flow and packing properties – Section 7.4.1

REC7.45: Since recycling can lead to thermal ageing, decomposition and a reduction in mechanical properties of polymers it should be proven that the properties of the feedstock material are adequate for the intended use, especially when utilising recycled material – Section 7.4.1

7.8.4.2 GUIDANCE-TYPE RECOMMENDATIONS

REC7.23: Recycling polymers in Laser Powder Bed Fusion may lead to a deterioration in part quality and it may be necessary to add a significant portion of virgin material to any recycled material for each build – Section 7.2.3

REC7.43: Powder recoating can impact the polymer Laser Powder Bed Fusion (L-PBF) process and ultimately the mechanical properties of the final part, as such the powder and L-PBF system may need to be monitored to ensure accurate recoating. Example characteristics include:

Sphericity of particles for flowability

- **Surface area to volume ratio for packing efficiency**
- **Average particle size**
- **The ratio between tap density and bulk density [7.116] – Section 7.4.1**

REC7.46: Rheology techniques may be used to monitor feedstock viscosity, Differential Scanning Calorimetry (DSC) may be used to measure Tg and Tm and Thermogravimetric Analysis (TGA) may be used for monitoring decomposition behaviour – Section 7.4.1

7.8.5 POST-PROCESSING

7.8.5.1 AMC-TYPE RECOMMENDATIONS

REC7.58: Consideration should be given to the method that will be employed to remove the part from the build plate prior to any further finishing, consideration could include:

- **Residual features left on the surface of the part when support structures have been removed.**
- **The location of part-support interfaces during the design phase such that they are not placed in positions that are likely to cause damage to delicate, critical design features when they are removed.**
- **The possibility of entrapping powder inside the part and whether this powder will need to be removed – Section 7.5.3**

REC7.59: If thermal post-processing is employed during qualification, the details of the process used during qualification and certification should be recorded and maintained for subsequent builds – Section 7.5.3

7.8.6 TESTING

7.8.6.1 AMC-TYPE RECOMMENDATIONS

REC7.1: Existing, recognised standards (e.g. ASTM, ISO, BSI) should be used where available to inform the qualification and certification of AM components – Section 7.1.2

REC7.60: As with metal AM samples the pyramid of tests (Figure 3-4) should be used to limit the number of whole parts that need to be cut up and used for testing – Section 7.6.1

REC7.63: A standard on mechanical testing of polymer AM parts is currently under development by the ASTM/ISO F42 committee and although not yet ready for inclusion in this guidance, its progress should be monitored and may be considered in future for qualification and certification of polymer AM components – Section 7.6.1

REC7.64: When manufacturing a polymer AM part the geometric requirements and dimensional tolerances will have been specified during the design phase. When performing these

measurements the measuring instrument should be agreed between the DA and manufacturer and be accurate to a level that is appropriate to the tolerances stated in the drawings, for example within ±0.1 mm for dimensions of > 10 mm. At least three measurements should be collected if statistical analysis is to be performed using the data, as per BS EN ISO 16012:2015 – Section 7.6.3

REC7.65: It may be necessary to produce test coupons in order to ascertain dimensional accuracy. In this case it is recommended that a bar with a known cross section, for example 5 mm x 10 mm should be manufactured with lengths that fall within the ranges set by BS EN ISO 20457:2018 [7.146] with values adjusted to an integer multiple of the coupon thickness – Section 7.6.5

REC7.67: When obtaining surface roughness measurements it is important to note that the orientation of the surface relative to the build direction is likely to have a large impact on the measured surface roughness and as such this should be accounted for during validation – Section 7.6.5

REC7.68: The appropriate mechanical tests required to qualify the part should be agreed between the DA and the manufacturer based on several factors including the loading environment, external factors (e.g. heat) and the criticality of the part – Section 7.6.5

REC7.69: A standard guide on NDE of AM parts is currently under development by the ASTM/ISO F42 committee and although not yet ready for inclusion in this guidance, its progress should be monitored and may be considered in future for qualification and certification of polymer AM components – Section 7.6.6

REC7.70: In addition ISO/ASTM 52901 has a great deal of detail on how to outline the requirements for purchased AM parts and should be used as a further guide on the handover of purchased AM components – Section 7.7

7.8.6.2 Guidance-type Recommendations

REC7.61: BS EN ISO 17296-3:2016 may be used to identify appropriate tests for component validation in combination with discussion with the DA – Section 7.6.1

REC7.62: Although written for Material Extrusion techniques these recommendations in ISO/ASTM FDIS 52903-2 may be applied to both Material Extrusion and polymer powder bed fusion since both can exhibit anisotropy – Section 7.6.1

7.9 CHAPTER 7 GLOSSARY OF ABBREVIATIONS

ABS - Acrylonitrile butadiene styrene
AM - Additive manufacturing
ASTM - American Society for Testing and Materials
BSI - British Standards Institution
CAD - Computer aided design
CAM - Computer aided manufacturing
COSHH - Control of Substances Hazardous to Health
CT - Computer tomography
CTE - Coefficients of thermal expansion
DA - Design Authority
DMA - Dynamic mechanical analysis
DO - Design Organisation
DP - Degree of polymerisation
DSC - Differential Scanning Calorimetry
ECS - Environmental Control System
ED - Energy density
EMR - Energy melt ratio
FDM - Fused Deposition Modelling
FFF - Fused Filament Fabrication
HSS - High Speed Sintering
ISO - International Organization for Standardization
KPV - Key Performance Variables
LS - Laser Sintering
MCRI - Military Certification Review Item
MSDS - Materials Safety Data Sheet
NDE - Non-destructive evaluation
NIST - National Institute of Standards and Technology
PAEK - Poly(aryl ether ketones)
PBF - Powder bed fusion
PBT - Poly(butylene terephthalate
PCD - Process Control Document
PDI - Polydispersity index
PE - Polyethylene
PEEK - Polyetherether ketone
PEI - Polyetherimide
PEKK - Polyetherketoneketone
PEKK - Polyether ketone
PETG - Polyethylene terephthalate
pI - Isoelectric point
PLA - Polyactic acid
PO - Production Organisation
PPS - Polyphenylene sulphide
PPS - Polypropylene
PVA - Polyvinyl alcohol
SSR - Stable sintering region
TAA - Type Airworthiness Authority
TGA - Thermogravimetric Analysis
UHMWPE - Ultra-high molecular weight polyethylene
VOC - Volatile organic compounds

7.10 CHAPTER 7 REFERENCES

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8.1 CONCLUSIONS

8.1.1 OVERVIEW

The aim of this document is to provide guidance on the qualification and certification of metallic and polymeric additive manufactured (AM) parts for use in military aviation. In this document the terms qualification and certification are used with the following meanings:

- Qualification – the demonstration that the product, process or service conforms to a specified requirement.
- Certification – a procedure by which a third party gives written assurance that a product, process or service conforms to a specified requirement.

The document has examined the Military Aviation Authority's (MAA) existing regulatory framework and certification standards for airworthiness assurance of manufactured parts for: (a) aircraft structures; (b) aircraft engines; and (c) aircraft systems. From these the regulations, acceptable means of compliance (AMC) and guidance that are especially relevant to AM parts are explained and highlighted. The document also contains a review of standards and literature on the design, build, characterisation and documentation of parts using AM, e.g. sources of scatter, methods for monitoring and control, etc., again making and highlighting recommendations. From this the document provides information that may be used to set out a qualification plan for the AM components under consideration.

AM has been considered as simply another manufacturing process, which will produce scatter in materials properties that need to be accurately represented in the properties of the final part. For Grade A aircraft structures the key properties are the materials design allowables (static strength and deformation) and fatigue. For aircraft engines the key property for a Critical Part is the Critical Part Life.

8.1.2 DOCUMENTARY EVIDENCE

The military regulatory publications and certification standards that have been examined with respect to AM parts are mainly the Regulatory Articles (RAs) in the 5000 series (Type Airworthiness Engineering (TAE) regulations) and the applicable parts of Def Stan 00-970. For aircraft structures Def Stan 00-970 Part 1 Fixed Wing Aircraft has been used, and within this Section 3 Structure and Section 4 Design and Construction – and relevant Leaflets. For aircraft engines Def Stan 00-970 Part 11 Engines is the appropriate part and within this Section 3 General Requirements for Aircraft Engines and Annex A Lifing Procedure for Critical Parts.

The UK develops and procures aircraft and their engines in collaboration with other nations who have their own regulations and certification specifications, which may be used for their qualification and certification. In these cases the alternative qualification evidence is still assessed against Def Stan 00-970 to determine compliance.

When considering the design and build aspects of AM the document refers to existing standards and peer-reviewed technical literature. In some cases published advice from recognised authorities has been used to consider the applicability of existing standards to AM, for example reports published by the US National Institute of Standards and Technology (NIST) on mechanical testing. The painstaking process of standard development means that AM-specific recognised standards are constantly in development and will emerge gradually over time. Where appropriate and possible, emerging standards have also been examined to provide guidance – in fact in the course of developing this document some standards have gone from in-development to first issue.

8.1.3 GENERAL THEMES OF THE GUIDANCE

The Four Pillars of Airworthiness is an important principle introduced and described in Regulatory Article 1220, in summary the four pillars are that: (1) an effective Safety Management System (SMS) should be established and detailed; (2) Recognised standards should be used and their use detailed; (3) Arrangements for the use and management of competent persons and competent organisations should be detailed; and (4) Arrangements for ensuring independent assessment, technical evaluation and safety audit should be detailed. The four pillars underpin all the activities related to airworthiness of an aircraft and drive the requirements that have been discussed in the document.

Any manufacturing method will produce parts that have scatter in their properties, including AM. In fact features of AM mean the sources of scatter are numerous, and in many cases unfamiliar compared to conventional methods, for example because of the use of fine powders as a feedstock material. Sources of scatter include but are not limited to chemical inhomogeneity, microstructure (and microstructural homogeneity and texture across the part), voids, pores, residual stresses, surface roughness, etc. A crucial theme is that the properties established from coupons, test elements, etc. should accurately represent the scatter in properties, from all sources, in the final part. Scale and build location effects are features of AM and therefore the philosophy of the testing pyramid (see Figure 8-1), the use of which is customary in the design and manufacturing of aircraft structures, is a means to provide assurance in the properties, and scatter in properties, in the final part.

The properties from conventional manufacturing methods cannot be used for AM parts. Further, the properties for AM parts should be rationally derived rather than obtained through the use of arbitrary scatter factors. The scatter in a particular property from conventional manufacturing generally follows a statistical distribution, for example the Normal distribution for tensile yield strength in aircraft structures and log-Normal for life-to-first-crack (LTFC) in aircraft engine discs. It cannot be assumed that the scatter in the same property from an AM part follows the same distributional form that is customary from a conventional manufacturing method. It is therefore necessary to establish explicitly the statistics of the scatter using customary methods. It is also crucial that a single population of a property is defined with confidence – and that censoring or inadvertent omission of data is guarded against. The establishment of properties that are specific to the AM part is a fundamental theme of the guidance, including mechanical strength, fatigue properties (where necessary fatigue crack initiation and propagation), environmental resistance, and response to non-destructive evaluation techniques, amongst others.

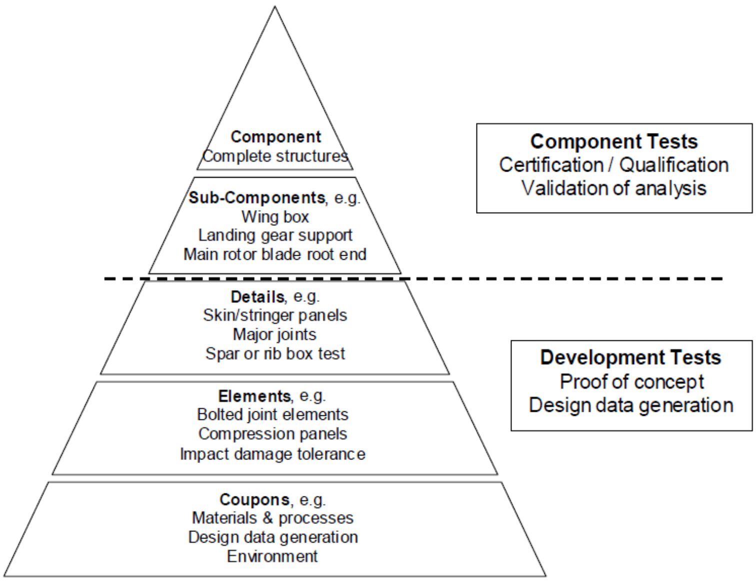

Figure 8-1 - the structural test 'pyramid'.

Existing guidance on the use of premium castings in aircraft structures has been examined since AM and casting processes share some characteristics (e.g. cast microstructures, propensity for voids / cracks, scale effects) and it is argued that the guidance is applicable to AM. Premium (high quality) castings are those that have a casting factor of 1.0 and can be used providing that: (i) it is demonstrated, in the form of process qualification, proof of product, and process monitoring that, for each casting design and part number, the castings produced by each foundry and process combination have coefficients of variation of the material properties that are equivalent to those of wrought alloy products of similar composition…; (ii) each casting receives inspection of 100 percent of its surface…, and inspection of structurally significant internal areas and areas where defects are likely to occur…; and (iii) one casting undergoes a static test and is shown to meet the strength and deformation requirements… It is required that for a particular process and foundry the following is done:

- Qualification of the process.
- Proof of the product.
- Monitoring of the process.

Of significant importance is the emphasis the guidance places on non-destructive inspection.

8.1.4 GUIDANCE SPECIFIC TO AIRCRAFT STRUCTURES

For aircraft structures the document focuses on the regulations, AMC and guidance for Grade A parts. A part shall be Grade A if the deformation or failure of the part would result in one or more of the following:

- Structural collapse at loads up to and including, the design ultimate load.
- Loss of control.
- Failure of motive power.
- Unintentional operation of, or inability to operate, any systems or equipment essential to the safety or operational function of the aeroplane.

- Incapacitating injury to any occupant.
- Unacceptable unserviceability or maintainability.

Guidance is given on the use of customary statistical techniques for the rational derivation of materials design allowables (static strength and deformation) of either A or B-basis (the definition of which is explained in the document).

Good fatigue design is based on the use of a robust, well understood and verifiable design philosophy, i.e. the Safe Life (based on the use of S-N curves) and Damage Tolerant approaches (based on fracture mechanics calculations and da/dN vs. ΔK fatigue crack growth curves). The Safe Life design philosophy is mandated for combat aircraft and rotorcraft. Whichever design philosophy is adopted it will be necessary to instigate a comprehensive test programme to establish the necessary fatigue design data. Sufficient S-N or da/dN data must be derived for design purposes using coupons of the material and manufacturing parameters under consideration at constant stress amplitude and at appropriate R ratios; the bottom part of the testing pyramid in Figure 8-1. Eventually fatigue testing of whole components will be required using realistic spectrum loading conditions to verify the actual design with that manufactured component. The Safe Life design philosophy uses factors on S-N curves to allow for scatter in fatigue performance and assumes that this scatter is normally distributed. Using this distribution the safe life is estimated from the mean, giving a life at which less than 1 in 1000 items will fail.

8.1.5 GUIDANCE SPECIFIC TO AIRCRAFT ENGINES

A Safety Analysis is used to classify aircraft engine parts according to the consequences of their failure. Parts whose failure could result in a Hazardous Engine Effect are Engine Critical Parts, and must have a risk of failure not exceeding 10^{-7} per engine flying hour. Critical parts are grouped into: (a) rotating parts; (b) static, pressure loaded parts; and (c) other parts. Influencing parts that could affect Engine Critical Parts must also be considered. This is an important detail when considering the consequences of failure of an AM part, even if it does not fit into either (a), (b) or (c) categories.

Engine Critical Parts must have an Engineering Plan, Manufacturing Plan and Service Management Plan as part of their assurance right through life from design through to disposal, which will include details of any manufacturing processes and controls (e.g. in-service inspections). Their life must be established using an appropriate method that provides an adequate factor of safety, for Def Stan 00-970 Part 11 using a Safe Life approach established from experience or test. Safe Life methodologies (LTFC and 2/3 Dysfunction) depend for their validity that material failures follow a log-normal distribution. The understanding of risk in the 2/3 Dysfunction is also based on an understanding of the values and spread associated with fatigue crack initiation and propagation lives. Damage Tolerance, and 2/3 Dysfunction beyond 0.38 mm crack depth, require the fatigue crack propagation rates and their scatter to be rationally derived. Further, the exchange rates applied to major and minor cycles during fatigue crack initiation and propagation should be appropriate for how the two elements of fatigue life are affected by those cycles.

8.1.6 GUIDANCE SPECIFIC TO AIRCRAFT SYSTEMS

For aircraft systems much of the guidance and regulation for aircraft structures is duplicated in the structural components of aircraft systems e.g. fuel systems and so there is limited guidance specific to aircraft systems.

Although there is an emphasis in this document on determining the mechanical properties and controlling variability of components, for aircraft systems in particular it is also important to consider the certification and qualification of other component characteristics that are not necessarily explicitly required by Def Stan 00-970. Depending on the function and criticality of the component, additional testing such as vibration, pressure, shock or testing, environmental (temperature range, corrosion) testing should be considered.

8.1.7 GUIDANCE SPECIFIC TO DESIGN AND BUILD PROCESSES

The design and build sections have focussed on where, for the purposes of qualification and certification, additive manufacturing is different to other manufacturing techniques. It is clear from this chapter that the sources of scatter for additive manufacturing are numerous. An important distinction must be made between those variables that can be recorded and controlled (machine type, post-processing requirements) and those in-build variables that should be monitored through calibration of the machine and through controlling feedstocks and other consumables. The design and build process section has sought to cover the full timeline of the additive manufacturing process from part design through to post-processing.

Taking guidance from high performance castings, the recording of details of the process of additive manufacturing is a key recommendation of these sections through the Process Control Document and this document should be provided as part of any airworthiness documents. Another key theme of this section is the requirement for test samples to be proven to be representative of the final AM component. Although required for all manufacturing techniques, the different thermal histories observed by different geometric shapes mean that test coupons may not be representative. Another new area of consideration for qualification and certification is the importance of feedstock in the properties of the final part. In particular, how the feedstock properties may deteriorate as it is stored and, in powders, re-used.

A key challenge of qualification and certification of additive manufacturing is that it is not one single process and is instead a collection of processes that use computer control to build up material to make components. By keeping the guidance process agnostic, where possible and distinguishing between the different types of processes, where required, the document has been able to make sure that the guidance is relevant and applicable to a range of AM processes. In the future, as new AM processes are inevitably developed it is expected that new sources of variation will appear as well as new ways to control the AM process. An example of this is in-line measurement of properties which has been applied to machines in the past couple of years and will provide an additional source of documentation to confirm the quality of the build.

8.2 SUGGESTIONS FOR FURTHER WORK

At the time of writing AM is developing very rapidly, as are many technologies associated with it. The expert community of airworthiness regulators, aerospace manufacturing engineers, scientists and standards organisations are continuously developing and publishing guidance and standards specific to AM. Further the UK MOD is in the process of transforming Def Stan 00-970 the better to reflect the EASA Certification Specifications. As a consequence it is likely that elements of this Guidance Note will become out of date, potentially fairly quickly. Given the importance placed on the use of recognised standards as one of the four pillars of airworthiness it is therefore suggested that the Guidance Note is regularly reviewed for currency and updated where necessary.

As stated, the document provides information that may be used to set out a qualification plan for the AM components under consideration. Is it suggested that ideally the advice in the document should be tested by using it to take a real AM part through the qualification process. This will allow the usability of the guidance to be tested and potentially reveal any unintended errors, omissions or ambiguities that have slipped through the various reviews.

9.1 OVERVIEW

The recommendations made in Chapters 3, 4 and 5 on airworthiness assurance of manufactured parts – aircraft structures (Chapter 3), aircraft engines (Chapter 4) and aircraft systems (Chapter 5) – and Part Design and Build, Metals (Chapter 6) and Polymers (Chapter 7) have been collected together and presented here. The document is for guidance only and does not contain authorised regulations or acceptable means of compliance. Nevertheless the guidance does make specific recommendations that use regulation-type and AMC-type language, namely containing “shall” and “should” respectively. These recommendations are thus classified as either regulation-type or AMC-type. Other recommendations are guidance-type. They are then further arranged in order from high level to more specific rather than the order in which they appear in the chapters.

They are presented as tables below:

Table 9-1 - Summary of Regulation-type Recommendations for Chapter 3 - Airworthiness Assurance of Manufactured Parts (Aircraft Structures)

Table 9-2 - Summary of AMC-type Recommendations for Chapter 3 - Airworthiness Assurance of Manufactured Parts (Aircraft Structures)

Table 9-3 - Summary of Guidance-type Recommendations for Chapter 3 - Airworthiness Assurance of Manufactured Parts (Aircraft Structures)

Table 9-4 - Summary of Regulation-type Recommendations for Chapter 4 - Airworthiness Assurance of Manufactured Parts (Aircraft Engines)

Table 9-5 - Summary of AMC-type Recommendations for Chapter 4 - Airworthiness Assurance of Manufactured Parts (Aircraft Engines)

Table 9-6 - Summary of Guidance-type Recommendations for Chapter 4 - Airworthiness Assurance of Manufactured Parts (Aircraft Engines)

Table 9-7 - Summary of Regulation-type Recommendations for Chapter 3 - Airworthiness Assurance of Manufactured Parts (Aircraft Systems)

Table 9-8 - Summary of AMC-type Recommendations for Chapter 3 - Airworthiness Assurance of Manufactured Parts (Aircraft Structures)

Table 9-9 - Summary of Guidance-type Recommendations for Chapter 4 - Airworthiness Assurance of Manufactured Parts (Aircraft Systems)

Table 9-10 - Summary of Regulation-type Recommendations for Chapter 6– Part Design and Build - Metals

Table 9-11 - Summary of AMC-type Recommendations for Chapter 6 - Part Design and Build - Metals: AM Machine

Table 9-12 - Summary of AMC-type Recommendations for Chapter 6 - Part Design and Build - Metals: Build Strategy

9.2 AIRWORTHINESS ASSURANCE OF MANUFACTURED PARTS (AIRCRAFT STRUCTURES) – CHAPTER 3

Table 9-1 - Summary of Regulation-type Recommendations for Chapter 3 - Airworthiness Assurance of Manufactured Parts (Aircraft Structures)

REC No	Recommendation Description (Regulation-type recommendations – containing "shall")	Doc section number
3.8	The relevant sections in the requirements in Def Stan 00 970 Part 1 shall be used to set out a qualification plan for the Additive Manufactured (AM) components under consideration. The information in Chapter 3 of this document (Airworthiness Assurance of Manufactured Components - Aircraft Structures) and Appendix A (Additive Manufacturing and the Military Aviation Authority's (MAA's) Regulatory Framework) may be used as a guide to those requirements.	3.10
3.1	It is recommended that a Grade A Additive Manufactured (AM) part, whether for a new or existing aircraft, shall be subject to the Military Certification Review Item (MCRI) process until the technology is sufficiently mature to maintain variability in a predictable and repeatable manner.	3.2
3.3	For Grade A aircraft structures it is recommended that both the Additive Manufactured (AM) process AND the part shall be qualified and certified to establish, and provide confidence and assurance in, the variability in their properties.	3.81
3.4	For the Safe-Life approach scatter factors for Safe S-N curves for Additive Manufactured (AM) parts shall be rationally derived, i.e. they shall be determined from tests of elements that are representative of individual structural features and with the application of customary statistical techniques to give the required probability of failure.	3.82

Table 9-2 - Summary of AMC-type Recommendations for Chapter 3 - Airworthiness Assurance of Manufactured Parts (Aircraft Structures)

REC No	Recommendation Description (AMC-type recommendations – containing “should”)	Doc section number
3.6	The philosophy of the testing pyramid, with its increasing level of size and feature complexity as specimens and elements become more representative of the final part, should be adopted to provide a level of assurance that the sources of scatter have been captured in the design allowables and fatigue properties.	3.10
3.2	It is possible that AM parts may have microstructures that have a different susceptibility to environmental degradation when compared to conventional forms and it is recommended that their particular susceptibility should be established.	3.2
3.7	Each Grade A AM part should receive inspection of 100 percent of its surface, and inspection of structurally significant internal areas and areas where defects are likely to occur, using approved non-destructive inspection methods.	3.8.1
3.5	Since AM-produced microstructures can be very different from those from established processes it is recommended that non-destructive evaluation (NDE) probability of detection (POD) characteristics should be established specifically for the part and microstructures of interest.	3.8.2

Table 9-3 - Summary of Guidance-type Recommendations for Chapter 3 - Airworthiness Assurance of Manufactured Parts (Aircraft Structures)

REC No	Recommendation Description (Guidance-type recommendations)	Doc section number
3.9	The information in this document may be used as a guide to set out an appropriate qualification plan for the non-critical AM components under consideration.	3.10

9.3 AIRWORTHINESS ASSURANCE OF MANUFACTURED PARTS (AIRCRAFT ENGINES) – CHAPTER 4

Table 9-4 - Summary of Regulation-type Recommendations for Chapter 4 - Airworthiness Assurance of Manufactured Parts (Aircraft Engines)

REC No	Recommendation Description (Regulation-type recommendations – containing "shall")	Doc section number
4.13	The relevant sections in the requirements in Def Stan 00 970 Part 11 shall be used to set out a qualification plan for the Additive Manufactured (AM) components under consideration. The information in this Chapter 4 of this document and Appendix A may be used as a guide to those requirements.	4.8
4.1	A Critical Additive Manufactured (AM) part, whether for a new or existing aircraft engine, shall be subject to the MCRI process until the technology is sufficiently mature to maintain variability in a predictable and repeatable manner.	4.2
4.7	For aircraft engine parts that could result in a hazardous engine effect it is recommended that both the Additive Manufactured (AM) process AND the part shall be qualified and certified to establish, and provide confidence and assurance in, the variability in their properties.	4.7.2.2
4.6	The properties and scatter in properties of an Additive Manufactured (AM) part (i.e. that design / material / application combination) shall be measured and rationally derived rather than assumed from previous experience.	4.7.2.2
4.2	In the absence of Additive Manufactured (AM)-specific acceptable means of compliance (AMC) and guidance material in CS E, and in any case, the Design Organisation (DO) (engine manufacturer) shall prove to the Type Airworthiness Authority (TAA), using appropriate and agreed methods, that any AM parts have suitable structural integrity assurance for their Class / Group, or similar classification of effect on failure.	4.5.1.4

Table 9-5 - Summary of AMC-type Recommendations for Chapter 4 - Airworthiness Assurance of Manufactured Parts (Aircraft Engines)

REC No	Recommendation Description (AMC-type recommendations – containing “should”)	Doc section number
4.12	Even though the UK standard specifies a Safe Life approach, e.g. 2/3 Dysfunction, it is nevertheless recommended that the fatigue crack initiation and propagation characteristics of critical AM parts should be rationally derived to provide a level of assurance in the inherent safety of different lifing approaches.	4.7.2.2
4.3	It is recommended that the environmental properties of AM parts should be established specifically rather than based on experience of parts from established manufacturing methods.	4.5.1.5
4.8	It is recommended that each Class 1/Group 1-type AM part should receive inspection of 100 percent of its surface, and inspection of structurally significant internal areas and areas where defects are likely to occur, using approved non-destructive inspection methods.	4.7.2.2
4.10	Since AM-produced microstructures can be very different from those from established processes it is recommended that non-destructive evaluation (NDE) probability of detection (POD) characteristics should be established specifically for the part and microstructures of interest.	4.7.2.2

Table 9-6 - Summary of Guidance-type Recommendations for Chapter 4 - Airworthiness Assurance of Manufactured Parts (Aircraft Engines)

REC No	Recommendation Description (Regulation-type recommendations – containing “shall”)	Doc section number
4.4	it is recommended that EASA Certification Memorandum CM–PIFS-013, Issue 01 may be used to help those involved in qualification and certification of critical AM aero engine parts to set out an appropriate plan for the establishment of safe cyclic life	4.6.1
4.9	The philosophy of the testing pyramid, with its increasing level of size and feature complexity as specimens and elements become more representative of the final part, may be adopted to provide a level of assurance that sources of scatter have been captured in the design values and fatigue properties.	4.7.2.2
4.5	It is anticipated and recommended that AM will require unique AMC and guidance material, with its own Class / Group classification (based on the Safety Analysis), to be included in the standard.	4.2.2.1
4.11	It is recommended that consideration is given to the choice of appropriate exchange rates for fatigue crack initiation and propagation in AM critical parts.	4.7.2.2
4.14	The information in this document may be used as a guide to set out an appropriate qualification plan for the non-critical AM components under consideration.	4.8

9.4 AIRWORTHINESS ASSURANCE OF MANUFACTURED PARTS (AIRCRAFT SYSTEMS) – CHAPTER 5

Table 9-7 - Summary of Regulation-type Recommendations for Chapter 3 - Airworthiness Assurance of Manufactured Parts (Aircraft Systems)

REC No	Recommendation Description (Regulation-type recommendations – containing “shall”)	Doc section number
5.7	The relevant sections in the requirements in Def Stan 00-970 Part 1 shall be used to set out a qualification plan for the Additive Manufactured (AM) components under consideration. The information in this chapter (Airworthiness Assurance of Manufactured Components - Aircraft Systems) and Appendix A (Additive Manufacturing and the Military Aviation Authority’s (MAA’s) Regulatory Framework) may be used as a guide to those requirements	5.9
5.1	It is recommended that an Additive Manufactured (AM) part, whether for a new or existing aircraft, shall be subject to the Military Certification Review Item (MCRI) process until the technology is sufficiently mature to maintain variability in a predictable and repeatable manner	5.2
5.3	For Grade A (critical) parts it is recommended that both the Additive Manufactured (AM) process AND the part shall be qualified and certified to establish, and provide confidence and assurance in, the variability in their performance	5.7.1
REC 5.4	it is recommended that the properties and scatter in properties of an AM part (i.e. that design / material / application combination) shall be measured and rationally derived rather than assumed from previous experience	5.7.2

9.4.1 RECOMMENDATIONS FOR ACCEPTABLE MEANS OF COMPLIANCE

Table 9-8 - Summary of AMC-type Recommendations for Chapter 3 - Airworthiness Assurance of Manufactured Parts (Aircraft Structures)

REC No	Recommendation Description (AMC-type recommendations – containing “should”)	Doc section number
5.5	The philosophy of the testing pyramid, with its increasing level of size and feature complexity as specimens and elements become more representative of the final part, should be adopted for critical parts to provide a level of assurance that the sources of scatter have been captured in the design allowables	5.7.2
5.2	It is possible that AM parts may have microstructures that have a different susceptibility to environmental degradation when compared to conventional forms and it is recommended that their particular susceptibility should be established	5.5

9.4.2 GUIDANCE-TYPE RECOMMENDATIONS

Table 9-9 - Summary of Guidance-type Recommendations for Chapter 4 - Airworthiness Assurance of Manufactured Parts (Aircraft Systems)

REC No	Recommendation Description (Regulation-type recommendations – containing “shall”)	Doc section number
5.7	The information in this document may be used as a guide to set out an appropriate qualification plan for the non-critical AM components under consideration	5.9

9.5 PART DESIGN AND BUILD, METALS – CHAPTER 6

Table 9-10 - Summary of Regulation-type Recommendations for Chapter 6– Part Design and Build - Metals

REC No	Recommendation Description (Regulation-type recommendations – containing "shall")	Doc section number
6.1	For critical AM components a Process Control Document shall be supplied as part of the airworthiness documentation. Any changes to the process control document shall be subject to the Military Certification Review Item (MCRI) process. The contents of the Process control document should be written based on the recommendations outlined within this document. The Process control document could include but not be limited to details of the control of: - AM machine. - Build strategy. - Feedstock. - Post-processing. Testing.	6.1.1

Table 9-11 - Summary of AMC-type Recommendations for Chapter 6 - Part Design and Build - Metals: AM Machine

REC No	Recommendation Description (AMC-type recommendations – containing "should")	Doc section number
6.3	If the AM machine is unattended during a build time, procedures should be put in place to detect unplanned stoppages and report them.	6.1.1.3
6.4	Stoppages during the build should be avoided; if stoppages are unavoidable they should be demonstrated not to be detrimental to the properties and scatter in properties of the final part.	6.1.1.3
6.6	All AM machine operators should be shown to be suitably qualified to use the additive manufacturing machine. If variation between operators is deemed a significant source of scatter, it may be necessary to specify named operators to build a critical part.	6.2.3
6.8	If a part will be produced on different machines to those used for qualification and certification, all machines used should undergo a pre-qualification process with calibration builds to show that any variation is within an acceptable range.	6.3.1
6.18	As with any system the calibration routine should show control over all aspects that are critical to the final part. The frequency of re-calibration should be sufficient to provide confidence that unacceptable changes have not occurred between calibrations.	6.4
6.19	The software version used to print qualified AM builds should be recorded and any change in software should be shown not to be detrimental to the properties and scatter of the final part.	6.4

REC No	Recommendation Description (AMC-type recommendations – containing "should")	Doc section number
6.29	The laser beam for laser powder bed systems should be calibrated at least annually to ensure that its characteristics do not change through time to reduce scatter in the properties of the final part.	6.4.2.1.2
6.30	Electron beam powder bed systems should be calibrated at least annually to ensure that parameters such as electron beam power, speed and motion are within acceptable limits as part of the assurance that the part has the specified properties.	6.4.2.1.3
6.31	Available standards should be applied to calibration of Direct Energy Deposition techniques. Arc welding AM systems such as WAAM should be calibrated with standards such as BS EN ISO 15609-1:2004 and BS EN 50504:2008 as a guide. Blown powder systems which are similar to laser cladding should use standards such as BS EN ISO 15609-4:2009 to guide in calibration.	6.4.2.2
6.32	Calibration builds should be used to determine the geometric accuracy of robotic movement systems for direct energy deposition techniques.	6.4.2.2.1
6.33	If certification is based on a pre-heated build plane, the pre-heating temperature of the build plane should be calibrated to ensure it is at the correct temperature and does not varying to a point where the scatter in material properties could be affected.	6.4.2.3
6.34	If certification is based on a pre-heated build plane, the pre-heating temperature of the build plane should be calibrated to ensure it is at the correct temperature and does not varying to a point where the scatter in material properties could be affected.	6.4.3
6.35	Any oxygen sensors used to confirm oxygen content should be calibrated regularly to ensure continuing compliance of AM builds, further guidance on oxygen sensor systems can be found in BS EN 50104:2010	6.4.3
6.36	For direct energy systems the flow rate of the gas should be controlled and calibrated to ensure it is constant.	6.4.3
6.37	The device filtration system should be qualified to an approved standard such as the British standard for HEPA filters and should have a regular maintenance and calibration regime to ensure that the filter does not become clogged with powder and ineffective. Filters should be monitored and handled so as not to introduce additional contamination and variability into the machine and ultimately the part.	6.4.3
6.38	It is recommended that calibration builds should be used to calibrate all types of additive manufacturing machines used to build critical parts. The frequency and format of these builds should be determined based on the part requirements and the change in properties over the lifetime of the machine. Example properties that could be measured from calibration builds include geometric, mechanical and microstructural properties.	6.4.4

Table 9-12 - Summary of AMC-type Recommendations for Chapter 6 - Part Design and Build - Metals: Build Strategy

REC No	Recommendation Description (AMC-type recommendations – containing “should”)	Doc section number
6.7	If a part is designed and qualified to optimise properties in a particular direction then any change in orientation or build methodology for the part (discussed later on in this chapter) will particularly affect the properties of the final part and should not be altered from the optimised orientation.	6.3
6.9	If the file conversion from CAD to STL or similar has a significant effect on the required properties of the final part the AM producer should record the file and not reconvert from CAD data once the part has been qualified.	6.3.3.1
6.11	If supports are used, their structure and shape should be recorded along with any CAD models of the part to ensure that the support structure used in qualification and certification is repeated for each part built.	6.3.3.2
6.14	Build location and orientation should be considered for test specimens so that they more fairly reflect this source of scatter during the qualification process.	6.3.3.4
6.16	The effects of surface roughness on fatigue in particular means that this edge contouring could have a significant effect on the scatter in mechanical properties. If this is the case, the method of edge contouring used should be recorded and the same technique used for all qualified builds.	6.3.3.5
6.17	The build parameters used (e.g. heat source power, build speed) should be recorded and maintained for any qualified build since any change in these parameters defined by the AM process may affect the mechanical properties, geometry and defects, and their scatter in the final part.	6.3.4

Table 9-13 - Summary of Guidance-type Recommendations for Chapter 6 - Part Design and Build - Metals: Build Strategy

REC No	Recommendation Description (Guidance-type recommendations)	Doc section number
6.12	If the variation due to location and number of parts leads to a scatter of properties greater than those allowed by the design authority then it may be necessary to record and maintain the build plan used during qualification and certification throughout all part manufacture.	6.3.3.3
6.15	If the effect of scan strategy is observed to be significant it may be necessary to record and maintain the scan strategy used for all part manufacture.	6.3.3.5

Table 9-14 - Summary of AMC-type Recommendations for Chapter 6 - Part Design and Build - Metals: Feedstock

REC No	Recommendation Description (AMC-type recommendations – containing "should")	Doc section number
6.2	Evidence that properties have not deteriorated during storage should be provided when undertaking any project using AM as well as information about the storage conditions and timings in which the feedstock properties remain within a specification. Storage conditions should take into account storage at the powder manufacturer/provider, during transport and at the part manufacturing facility.	6.1.1
6.21	Powders of some alloys such as titanium alloys should be stored and handle under inert gas e.g. argon.	6.4.1.2
6.22	If the feedstock (e.g. titanium) or process (e.g. PBF) are moisture sensitive, evidence should be provided that moisture levels in the powder environment or powder are below a value that will affect the properties and scatter of the final part.	6.4.1.2
6.23	For critical components, the powder quality should be tracked through regular sampling and testing to ensure the powder does not fall outside of specification. Example powder specification measurements should be determined by the component manufacturer but could include measurements of chemical composition, particle size distribution and flow and packing properties.	6.4.1.3.4
6.24	Powder samples for testing should be representative of the powder used in the final part.	6.4.1.3.4
6.25	Where different powder batches, whether virgin or used are mixed, both powders should be confirmed as within specification or the new mixture of powders should be re-tested to confirm the powder properties are within.	6.4.1.3.4
6.26	For the AM of aerospace parts using highly controlled and repeatable robotic welding systems the characteristics of the wire should be controlled to a much higher level of consistency along the length than is typical for welding. This could include properties such as diameter, composition, surface quality (kinks and nicks), surface contamination, etc.	6.4.1.4
6.27	Wire feed rate should be recorded for each build as one of a number of parameters that demonstrate that the part is being built in accordance with its certification.	6.4.1.4.1
6.28	The wire manufacturer, diameter measuring system and specification agreed and followed for each numbered batch should be recorded for each batch used for the manufacture of AM activity components.	6.4.1.4.3

Table 9-15 - Summary of AMC-type Recommendations for Chapter 6 - Part Design and Build - Metals: Post-Processing

REC No	Recommendation Description (AMC-type recommendations – containing "should")	Doc section number
6.39	Any such stress relieving step performed before removing the part from the build plane should be recorded in the manufacturing plan and monitored to ensure repeatability Surface finishing techniques may be required on surfaces where support structure has been removed.	6.5.1
6.4	The effect of any EDM artefacts on final properties should be considered, recording and monitoring where required.	6.1.1.3
6.42	Post processing techniques should be recorded and carefully calibrated to ensure there is consistency in their application. In addition, any test specimens should have the same post-processing treatments as the final part. Details of the parameters of post-processing techniques should be recorded and the technique used should be calibrated to ensure repeatability. Post processing techniques include but are not limited to: - Thermal techniques – e.g. Solution treatments and aging, homogenisation and normalisation. - Hot Isostatic Pressing (HIP). - Surface finishing. - Cold working	6.5.4

Table 9-16 - Summary of Guidance-type Recommendations for Chapter 6 - Part Design and Build - Metals: Post-Processing

REC No	Recommendation Description (Guidance-type recommendations)	Doc section number
6.41	Surface finishing techniques may be required on surfaces where support structure has been removed to maintain consistency.	6.5.1

Table 9-17 - Summary of AMC-type Recommendations for Chapter 6 - Part Design and Build, Metals: Testing

REC No	Recommendation Description (AMC-type recommendations – containing “should”)	Doc section number
6.5	For critical components, calibration builds should be performed on AM powder bed machines if there is a changeover of metal alloy types.	6.1.3.4
6.13	If witness specimens are used to reduce the number of whole-part cut ups, evidence should be produced to demonstrate that the witness specimens are representative of the final part.	6.3.3.4
6.43	For powder bed systems it is recommended that test specimens should be built with each build to track variability between builds. The test specimens should be representative of the final part with microstructure and mechanical properties used to confirm this.	6.6.1
6.45	If parts are to be built in different orientations, the microstructure should be determined in different build orientations to make sure there is a true picture of its three-dimensional nature, e.g. grain structures, cracks and delaminations.	6.6.5.3
6.46	Surface finishing should be applied to any region of an AM component where NDT techniques requirie contact with the surface, e.g. ECT, UT, are undertaken.	6.6.4

Table 9-18 - Summary of Guidance-type Recommendations for Chapter 6 - Part Design and Build - Metals: Testing

REC No	Recommendation Description (Guidance-type recommendations)	Doc section number
6.44	Most mechanical test standards can be applied to AM specimens but with the following guidance: - Care must be taken in using flat plate or thin specimens since these samples may be difficult to build using AM and consequently test coupons may not be representative of the AM parts. - Test reports should include the location and orientation of parts within the build volume of the AM system used, as outlined in ISO/ASTM 52921. - Test methods with strict requirements for isotropy such as ASTM E1875 (Dynamic Young’s modulus) may be difficult to apply if the AM process produces samples that are anisotropic. - Post processing of specimens may be required for some test methods such as ASTM E0399 (Linear-Elastic Plane-Strain Fracture Toughness) and ASTM E0384 (Knoop and Vickers hardness) to achieve the required surface roughness for some tests.	6.6.5.1

Table 9-19 - Summary of AMC-type Recommendations for Chapter 6 - Part Design and Build - Metals: Component Handover

REC No	Recommendation Description (AMC-type recommendations)	Doc section number
6.47	ISO/ASTM 52901 has a great deal of detail on how to outline the requirements for purchased AM parts and <u>should</u> be used as a further guide on the handover of purchased AM components.	6.7.1

9.6 PART DESIGN AND BUILD, POLYMERS – CHAPTER 7

Table 9-20 - Summary of AMC-type Recommendations for Part Design and Build - Polymers, AM machine

REC No	Recommendation Description (AMC-type recommendations – containing “should”)	Doc section number
7.3	Temperature gradients between the feed and build pistons should be recorded and carefully controlled for polymer L-PBF to reduce the risk of geometric distortions in the printed part	7.1.5
7.11	For Material Extrusion the impact of head degradation should be considered since head degradation can have a detrimental effect on the properties of the final part	7.1.5
7.17	The energy delivered to the polymer during Laser Powder Bed Fusion should be sufficient to melt polymer particles fully	7.1.5
7.27	All operators should be suitably qualified to use the AM machine. An approach to assess operator competence should be agreed between the manufacturer and Design Authority (DA) and should include the appropriate method and frequency of training and testing to ensure competency. Records of any competency certificates should be retained to provide the evidence of operator competence. If variation between operators is still considered a significant source of scatter, it may be necessary to specify named operators to build a critical part	7.3.3
7.28	The machine type and model should be recorded in the Process Control Document	7.3.3
7.29	If a part will be produced on different machines to those used for qualification and certification, all machines should undergo a pre-qualification process with calibration builds to show that any variation is within an acceptable range	7.3.3
7.30	The environment in which the build is performed should be controlled to keep humidity and temperature within the range specified by the manufacturer or in-house process control specifications. This is applicable for either a sealed build environment or the room the machine is placed in if builds are performed exposed to the atmosphere	7.3.4
7.32	If the file conversion from CAD to STL or similar has a significant effect on the required properties of the final part the AM producer should ensure that the converted file used to build the qualified part is the same as the file used for production builds	7.3.5
7.41	The build parameters or parameter set used (e.g. heat source, power, build speed) should be recorded and maintained for any qualified build. Any change in these parameters defined by the AM process may affect mechanical properties, geometry and defects, and their scatter in the final part	7.3.7
7.47	The calibration approach should be agreed between the manufacturer and Design Authority (DA) and should include those parameters/systems requiring calibration and the appropriate method and frequency of calibration. Records of any calibrations should be retained to provide the evidence that important KPV influencing parameters are as defined and inputted, and their variability is within acceptable limits	7.4.2

REC No	Recommendation Description (AMC-type recommendations – containing “should”)	Doc section number
7.48	Since melting and solidification is directly linked to the pre-heat and directly affects part properties, the pre-heating system used should be calibrated to ensure that it is consistently heating the material. Appropriate calibration methods should be agreed between the manufacturer and Design Authority (DA). These could include calibration builds from different locations across the build chamber to identify variations in pre-heating and the subsequent effect on the properties of the final part	7.4.2
7.49	The laser beam for laser powder bed systems should be calibrated to ensure that its characteristics do not change through time to reduce scatter in the properties of the final part. The frequency of calibration should be agreed between the DA and the manufacturer based on the machine requirements. Characteristics to be calibrated should be agreed between the DA and the manufacturer based on the machine requirements but could include: • Laser beam power • Laser beam diameter • Laser spot location in the xy plane	7.4.2
7.50	Routine calibration for polymer laser powder bed fusion should also measure the correct and consistent drop of the build plate over time and at positions across the build plane	7.4.2
7.52	The temperature profile throughout the build chamber can have an impact on the properties of the final part. It should therefore be calibrated regularly and may be monitored during the build in addition to direct heating. The method and frequency of the temperature profile monitoring should be agreed between the manufacturer and Design Authority (DA). The movement of gases within the build chamber, by fans for example, can affect the temperature profile and lead to hot and cold spots in the build chamber, which can affect the properties of the final part. Therefore, the effect of the movement of gases should also be considered when monitoring and calibrating the temperature across the build chamber	7.4.2
7.53	The nozzle temperatures or parameter set used during qualification and certification should be maintained for subsequent builds	7.4.2
7.54	The nozzle temperature should be calibrated to ensure consistent melt properties for subsequent builds. Some machine manufacturers offer set calibration instructions and builds which should be used where available. The method and frequency of calibration of in-line testing should be agreed between the part manufacturer and Design Authority (DA)	7.4.2
7.55	The accuracy of the x, y and z tip offset for Material Extrusion machines should be calibrated regularly to ensure geometric accuracy. The calibration schedule and process should be agreed between the DA and manufacture but could include calibration builds and xyz offset determination	7.4.2
7.57	In-line monitoring may be used to reduce variability in the polymer AM machine. If in-line monitoring is used the in-line monitoring should be calibrated along with the AM machine as part of a regular maintenance	7.4.5

REC No	Recommendation Description (AMC-type recommendations – containing "should")	Doc section number
	schedule. The method and frequency of calibration of in-line testing should be agreed between the manufacturer and Design Authority (DA)	

Table 9-21 - Summary of guidance-type Recommendations for Part Design and Build - Polymers, AM machine

REC No	Recommendation Description	Doc section number
7.5	The effective thermal conductivity will play a major role in determining temperature distribution during a selective heating process and thus may prove a valuable consideration when planning key process variables	7.1.5
7.9	The lack of a distinct melting point in amorphous polymers means that for Material Extrusion melt liquefier temperatures and filament feed rates may require fine-tuning to give optimal results	7.1.5
7.56	Humidity in the build chamber or feedstock may affect the quality of the final part so may require both controlled feedstock storage conditions and in situ monitoring of the build chamber. For guidance on monitoring the relative humidity of polymers for selective laser sintering see standard BS EN ISO/ASTM DIS 52925	7.4.4

Table 9-22 - Summary of AMC-type Recommendations for Part Design and Build - Polymers, Build strategy

REC No	Recommendation Description (AMC-type recommendations – containing “should”)	Doc section number
7.2	When planning a two material build, differences in the melting and solidification properties of both polymers should be considered as this can lead to localised differences in crystallinity and distortion if those properties are significantly different	7.1.4
7.6	The extruder temperature and the build bed temperature should be matched to the specific polymer in use	7.1.5
7.10	During Material Extrusion care should be taken not to induce thermal decomposition of the polymer. This may be particularly relevant when maximising melt temperature in order to achieve a high degree of interlayer fusion	7.1.5
7.13	For Laser Powder Bed Fusion, when considering the beam speed parameter the compromise between build speed and part quality should be considered. For example a high beam speed will result in a faster build rate but will generally lead to a deterioration in build quality	7.1.5
7.15	The effect of shrinkage on a build should be considered and accounted for prior to part manufacture	7.1.5
7.16	The melt shear velocity should be considered for optimum Laser Powder Bed Fusion particle coalescence. For example. a sufficiently high shear storage modulus in the molten state and an associated low melt shear viscosity, 60 Pa s in the case of nylon-12 [7.31], may be desirable [7.16]	7.1.5
7.18	The orientation and build packing of parts should be considered and, if necessary, established and fixed for a particular part, or part family, depending on part criticality	7.1.6
7.19	For Material Extrusion the fusion between deposited layers should be considered since this can have a significant impact on mechanical properties. This may be achieved by reducing the overall cooling of material between layer depositions, which can be achieved by increasing the raster speed and/or layer thickness and decreasing the interlayer cooling time	7.1.6
7.20	For Material Extrusion the direction in which the fibres are deposited relative to the intended mechanical loading direction should be a key consideration when planning a build, as should the material flow rate and size of the nozzle aperture	7.1.6
7.25	If a part is designed and qualified to optimise properties in a particular direction under a given set of processing parameters then the build direction and processing parameters should not be altered without further qualification	7.2.5
7.26	Anisotropy resulting from the AM characteristics of the specific polymer and the features of the build design, should be accounted for when establishing mechanical and physical properties against the part design requirements. While published property databases will be valuable in guiding material choice, the final AM part properties may be anisotropic and therefore different in different directions	7.2.5
7.33	As with AM parts, build location and orientation should be considered for witness and test specimens so that they reflect, as accurately as possible, this source of scatter during the qualification process. Witness and test specimens should also undergo the same post-processes as the AM part	7.3.5

REC No	Recommendation Description (AMC-type recommendations – containing “should”)	Doc section number
7.37	For Material Extrusion a design engineer should consider the orientation of filament beads and the intended load direction when deciding on the build direction	7.3.5

Table 9-23 - Summary of Guidance-type Recommendations for Part Design and Build - Polymers, Build strategy

REC No	Recommendation Description (Guidance-type recommendations)	Doc section number
7.8	The following guidance may be considered when deciding on selective heating parameters for Laser Powder Bed Fusion: • Operating the process within the stable sintering region of the feedstock polymer; • Optimising the wavelength of the incident radiation to the absorption coefficient of the feedstock polymer; • Ensuring the incident beam radius is appropriate for the feedstock polymer particle size	7.1.5
7.12	The optimal ratio between energy supplied and energy required to the melt the polymer (EMR) may be used in order to maximise the mechanical properties of a printed part	7.1.5
7.14	To fully understand the thermal properties of the feedstock polymer it may be necessary to consider the polymorphic state of the polymer at each stage of the manufacture process	7.1.5
7.34	If the variation due to orientation of the part leads to a scatter of properties greater than those allowed by the Design Authority then it may be necessary to record and maintain the orientation of the part used during qualification and certification throughout all part manufacture	7.3.5
7.35	If the variation due to location and number of parts leads to a scatter of properties greater than those allowed by the Design Authority then it may be necessary to record and maintain the build plan used during qualification and certification throughout all part manufacture	7.3.5
7.36	If the effect of scan strategy is observed to be significant it may be necessary to record and maintain the scan strategy used in qualified builds in all subsequent part manufacture	7.3.5
7.38	If the effect on the final part of the pattern, location and material of the support structure is observed to be significant then it may be necessary to record the support strategy used during qualification and ensure that the pattern, location and material of any support structure generated are the same when building the final part	7.3.5
7.39	If the variation due to location and number of parts leads to a scatter of properties greater than those allowed by the Design Authority then it may be necessary to record and maintain the build plan used during qualification and certification throughout all part manufacture	7.3.5
7.40	If the effect of scan strategy is observed to be significant it may be necessary to record and maintain the scan strategy used in qualified builds in all subsequent part manufacture	7.3.6
7.51	Beam speed is usually included in the build parameter set for a known material but can be confirmed by producing a series of small samples at different speeds and using their quality to determine the correct speed. This technique could also be used to calibrate the beam speed if required	7.4.2

Table 9-24 - Summary of Guidance-type Recommendations for Part Design and Build - Polymers, Part Design

REC No	Recommendation Description (AMC-type recommendations – containing “should”)	Doc section number
7.21	Although guidance should be sought specific to the material and machine type, the guidance in section 7.2.2 may be used when designing for polymer AM	7.2.2
7.24	The mechanical properties and durability of a part should be assessed using recognised standards to ensure that these properties are appropriate for the parts intended use	7.2.5

Table 9-25 - Summary of AMC-type Recommendations for Part Design and Build - Polymers, Feedstock

REC No	Recommendation Description (AMC-type recommendations – containing "should")	Doc section number
7.4	A well-defined melt pool should be used to allow for good dimensional accuracy. This may be achieved by selecting a polymer with a high heat of fusion and a narrow melting point range	7.1.5
7.7	For Laser Powder Bed fusion AM careful temperature control should be used to ensure that the powder bed does not fuse during preheating. In polyamide the glaze point could be used to identify the appropriate powder bed temperature and a temperature of 12 °C below the glaze point has been shown to limit this effect [7.10]	7.1.5
7.22	The interlayer fusion between deposited layers under the available processing parameters should be considered when selecting the feedstock polymer since this can have a significant impact on mechanical properties	7.2.3
7.31	Before use, feedstocks, e.g. filaments or powder, should be stored in an environment that does not lead to a significant deterioration in properties through moisture uptake and / or significant fluctuations in temperature	7.3.4
7.42	The polymer type used during qualification should be recorded and used for any subsequent builds. This should include any additives or mixes of polymers. It may be necessary to use the same manufacturer for all subsequent runs if information about the polymer blend is not available	7.4.1
7.44	For critical components manufactured using Laser Powder Bed Fusion, the powder quality should be tracked through regular sampling and testing to ensure the powder does not fall outside of specification. The method and frequency of powder testing should be agreed between the manufacturer and Design Authority (DA). Example powder specification measurements should be determined by the component manufacturer but could include measurements of chemical composition, particle size distribution and flow and packing properties	7.4.1
7.45	Since recycling can lead to thermal ageing, decomposition and a reduction in mechanical properties of polymers it should be proven that the properties of the feedstock material are adequate for the intended use, especially when utilising recycled material	7.4.1

Table 9-26 - Summary of Guidance-type Recommendations for Part Design and Build - Polymers, Feedstock

REC No	Recommendation Description (Guidance-type recommendations)	Doc section number
7.23	Recycling polymers in Laser Powder Bed Fusion may lead to a deterioration in part quality and it may be necessary to add a significant portion of virgin material to any recycled material for each build	7.2.3
7.43	Powder recoating can impact the polymer Laser Powder Bed Fusion (L-PBF) process and ultimately the mechanical properties of the final part, as such the powder and L-PBF system may need to be monitored to ensure accurate recoating. Example characteristics include: • Sphericity of particles for flowability • Surface area to volume ratio for packing efficiency • Average particle size • The ratio between tap density and bulk density [7.116]	7.4.1
7.46	Rheology techniques may be used to monitor feedstock viscosity, Differential Scanning Calorimetry (DSC) may be used to measure Tg and Tm and Thermogravimetric Analysis (TGA) may be used for monitoring decomposition behaviour	7.4.1

Table 9-27 - Summary of AMC-type Recommendations for Part Design and Build - Polymers, Post Processing

REC No	Recommendation Description (AMC-type recommendations – containing “should”)	Doc section number
7.58	Consideration should be given to the method that will be employed to remove the part from the build plate prior to any further finishing, consideration could include: • Residual features left on the surface of the part when support structures have been removed. • The location of part-support interfaces during the design phase such that they are not placed in positions that are likely to cause damage to delicate, critical design features when they are removed. • The possibility of entrapping powder inside the part and whether this powder will need to be removed	7.5.3
7.59	If thermal post-processing is employed during qualification, the details of the process used during qualification and certification should be recorded and maintained for subsequent builds	7.5.3

Table 9-28 - Summary of AMC-type Recommendations for Part Design and Build - Polymers, Testing

REC No	Recommendation Description (AMC-type recommendations – containing "should")	Doc section number
7.1	Existing, recognised standards (e.g. ASTM, ISO, BSI) should be used where available to inform the qualification and certification of AM components	7.1.2
7.60	As with metal AM samples the pyramid of tests (Figure 3-4) should be used to limit the number of whole parts that need to be cut up and used for testing	7.6.1
7.63	A standard on mechanical testing of polymer AM parts is currently under development by the ASTM/ISO F42 committee and although not yet ready for inclusion in this guidance, its progress should be monitored and may be considered in future for qualification and certification of polymer AM components	7.6.1
7.64	When manufacturing a polymer AM part the geometric requirements and dimensional tolerances will have been specified during the design phase. When performing these measurements the measuring instrument should be agreed between the DA and manufacturer and be accurate to a level that is appropriate to the tolerances stated in the drawings, for example within ±0.1 mm for dimensions of > 10 mm. At least three measurements should be collected if statistical analysis is to be performed using the data, as per BS EN ISO 16012:2015	7.6.3
7.65	It may be necessary to produce test coupons in order to ascertain dimensional accuracy. In this case it is recommended that a bar with a known cross section, for example 5 mm x 10 mm should be manufactured with lengths that fall within the ranges set by BS EN ISO 20457:2018 [7.146] with values adjusted to an integer multiple of the coupon thickness	7.6.5
7.67	When obtaining surface roughness measurements it is important to note that the orientation of the surface relative to the build direction is likely to have a large impact on the measured surface roughness and as such this should be accounted for during validation	7.6.5
7.68	The appropriate mechanical tests required to qualify the part should be agreed between the DA and the manufacturer based on several factors including the loading environment, external factors (e.g. heat) and the criticality of the part	7.6.5
7.69	A standard guide on NDE of AM parts is currently under development by the ASTM/ISO F42 committee and although not yet ready for inclusion in this guidance, its progress should be monitored and may be considered in future for qualification and certification of polymer AM components	7.6.6
7.70	In addition ISO/ASTM 52901 has a great deal of detail on how to outline the requirements for purchased AM parts and should be used as a further guide on the handover of purchased AM components	7.7

Table 9-29 - Summary of Guidance-type Recommendations for Part Design and Build - Polymers, Testing

REC No	Recommendation Description (Guidance-type recommendations)	Doc section number
7.61	BS EN ISO 17296-3:2016 may be used to identify appropriate tests for component validation in combination with discussion with the DA	7.6.1
7.62	Although written for Material Extrusion techniques these recommendations in ISO/ASTM FDIS 52903-2 may be applied to both Material Extrusion and polymer powder bed fusion since both can exhibit anisotropy	7.6.1

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10 MASTER GLOSSARY

ABS - Acrylonitrile butadiene styrene
AAS - Atomic Adsorption Spectroscopy
ADCC - Approved Design Change Certificate
ADH – Aviation Duty Holder
AIA – Aerospace Industries Association
AM – Additive Manufactured/Manufacturing
AMC – Acceptable Means of Compliance
AMS - Aerospace Material Specification
Ar - Area Safe Cyclic Life
ASD-STAN - an association that establishes, develops and maintains standards on behalf of the European aerospace industry
ASMS – Air Safety Management System
ASTM - American Society for Testing and Materials
BCAR - British Civil Airworthiness Requirements
BS – British Standard
BSI – British Standards Institute
CAD - Computer Aided Design
CAM - Computer Aided Manufacturing
CCD -
CIP – Critical Impact Parameter
COSHH - Control of Substances Hazardous to Health
CS – Certification Specification
CS E - Certification Specification - Engines
CT - Computed Tomography
CTE - Coefficients of thermal expansion
DA - Design Authority
DAOS – Design Approved Organisation Scheme
DED - Direct Energy Deposition
Def Stan – Defence Standard
DMA - Dynamic mechanical analysis
DO - Design Organisation
DoD – Department of Defense
DP - Degree of polymerisation
DPI - Dye Penetrant Inspection
DSC - Differential Scanning Calorimetry
DTD – Directorate Technical Development
EA - European Co-operation for Accreditation
EASA – European Aircraft Safety Agency
EBM - Electron Beam Melting
EBSD - Electron Backscatter Diffraction
ECS - Environmental Control System
ECT - Eddy Current Testing
ED - Energy density
EDM - Electro-discharge Machining
EDS - Energy Dispersive Spectroscopy
EIFS – Effective Initial Flaw Size
EMR - Energy melt ratio
ENSIP – Engine Structural Integrity Program

ER – Exchange Rate
ESDU – Engineering Sciences Data Unit
FAA – Federal Aviation Administration
FAR – Federal Aviation Regulations
FDM - Fused Deposition Modelling
FFF - Fused Filament Fabrication
HEPA - High Efficiency Particulate Air
HIP - Hot Isostatic Pressing
HSE - Health and Safety Executive
HSS - High Speed Sintering
IAF - International Accreditation Forum
ICP-MS - Inductively coupled plasma mass spectrometry
IGF - Inert Gas Fusion
ILAC - International Laboratory Accreditation Co-operation
IM – Integrity Management
IP – Intellectual Property
ISO - International Organization for Standardization
JSSG – Joint Services Specification Guide
KPV - Key Performance Variable
LS - Laser Sintering
LTFC – Life to First Crack
MAA – Military Aviation Authority
MACP – Military Air System Certification Process
MAR – Military Aircraft Register
MCRI - Military Certification Review Item
MIG - Metal Inert Gas
MIL-HDBK – Military Handbook
MIL-STD – Military Standard
MMAC - Manual of Military Air System Certification
MMDH – Metallic Materials Data Handbook
MMPDS - Metallic Materials Properties Development and Standardization
MOD – Ministry of Defence
MRP – MAA's Regulatory Publications
MSDS - Materials Safety Data Sheet
MTC – Military Type Certificate
Nd:YAG - Neodymium: Yttrium Aluminium Garnet
NDE – Non-destructive evaluation
NDT - Non-destruction Inspection
Ni – Fatigue crack initiation life
NIST – National Institute of Standards and Technology
NP – Fatigue crack propagation life
NT – Total fatigue life
ODR – Operational Data Recording
OEI – One Engine Inoperative
OLM – Operational Loads Measurement
PAEK - Poly(aryl ether ketones)
PBF - Powder Bed Fusion
PBT - Poly(butylene terephthalate
PCD - Process Control Document
PDI - Polydispersity index
PE - Polyethylene

PEEK - Polyetherether ketone
PEI - Polyetherimide
PEKK - Polyetherketoneketone
PETG - Polyethylene terephthalate
pI - Isoelectric point
PI – Propulsion Integrity
PLA - Polyactic acid
PO - Production Organisation
POD – Probability of Detection
PPE - Personal Protective Equipment
PPS - Polyphenylene sulphide
PPS - Polypropylene
PR EN – Pre-Standard European Norms
PSCDTL – Predicted Safe Cyclic Damage Tolerant Life
PSCL – Predicted Safe Cyclic Life
PSIP – Propulsion Structural Integrity Program
PT – Project Team
PVA - Polyvinyl alcohol
RA – Regulatory Article
RTSA – Release to Service Authority
SAE – [formerly] Society of Automotive Engineers
SEM - Scanning Electron Microscopy
SI – Structural Integrity
SLM - Selective Laser Melting
SQEP – Suitably Qualified and Experienced Person(s)
SSR - Stable sintering region
ST - Solution Treat
TAA – Type Airworthiness Authority
TCB – Type Certification Basis
TCR – Type Certification Report
TGA - Thermogravimetric Analysis
UHMWPE - Ultra-high molecular weight polyethylene
UK – United Kingdom
UKAS – United Kingdom Accreditation Service
US – United States (of America)
USAF – United States Air Force
USN – United States Navy
UT - Ultrasound Testing
VOC - Volatile organic compounds
WAAM - Wire Arc Additive Manufacture
XPS - X-ray Photoelectron Spectroscopy
XRCT - X-Ray Computed Tomography
XRF - X-ray Fluorescence Analysis

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GKN Aerospace Personnel
Lloyd’s Register Personnel
Lockheed Martin UK personnel
Manufacturing Technology Centre (MTC) personnel
Members of the Military Aircraft Airworthiness Advisory Group
Members of the Propulsion Airworthiness Advisory Group
The Certification of Novel Technologies Project Steering Group
TWI Personnel

APPENDIX A ADDITIVE MANUFACTURING AND MAA'S REGULATORY FRAMEWORK

A.1. INTRODUCTION

All aspects of the safety of military aviation are underpinned by the Military Aviation Authority's (MAA) Regulatory Framework; the scope of the Regulatory Policy is laid out in MAA001 [A.1].

The MAA publishes its regulatory framework as a series of MAA Regulatory Publications (MRPs) in three layers: overarching documents, Regulatory Articles, and manuals [A.2]. An overview of the documents is shown in Table A-1 (*The Pocket Guide to MAA Regulation* is a concise explanatory guide [A.3]).

Unless specifically excluded, the MRPs apply to any personnel, be they civilian or military, involved in the certification, design, production, maintenance, handling, control or operation of Air Systems on the UK Military Aircraft Register (MAR) and associated equipment [A.1].

For the purposes of the design, manufacture and certification of AM parts, the regulations of primary concern are those associated with Type Airworthiness, which are found in the 5000 series (Type Airworthiness Engineering Regulations) – with some aspects also covered in the 4000 series (Continuing Airworthiness Engineering Regulations). These, and other regulations that need to be considered, are identified in this Appendix. These further considerations include, but are not necessarily limited to, standardisation, competence, record and configuration management, and approval of manufactured and repaired parts.

Readers are encouraged to refer to the most up to date versions of the MRPs by checking the MAA's website [A.2].

A.2. INTRODUCTION TO REGULATORY ARTICLES

The Regulatory Articles provide the information on the overarching mandatory activities (Regulations) that have to be followed without exception, and contain the word **shall** in bold. They state how MOD expects the mandatory requirements to be met with Acceptable Means of Compliance (AMC), which always use the word **should** in bold. Guidance material is provided for each regulation/AMC. While each RA is succinct, the RAs together form a large body of information, with RAs cross-referencing other RAs and standard procedures. Below is a summary of RAs that are worth drawing attention to here, highlighting in particular: standardisation; competence; record and configuration management; and approval of manufactured and repaired parts.

Text reproduced directly from the RAs is shown in italics. Non-italicised text is from the authors.

Table A-1 - Overview of MAA's Regulatory Framework

Overarching documents	
MAA01	MAA Regulatory Policy
MAA02	MAA Master Glossary
MAA03	MAA Regulatory Processes
Regulatory Articles	
1000 series	General Regulations (GEN)
2000 series	Flying Regulations (FLY)
3000 series	Air Traffic Management Regulations (ATM)
4000 series	Continuing Airworthiness Engineering Regulations (CAE)
5000 series	Type Airworthiness Engineering Regulations (TAE)
Manuals	
Manual of Air Safety	
Manual of Post-Crash Management	
Manual of Military Air Traffic Management	
Manual of Aerodrome Design and Safeguarding	
Display Flying Handbook	
Manual of Maintenance and Airworthiness Processes (MAP-01)	
Manual of Maintenance and Airworthiness Processes – MOD Form 700 Series of Forms (MAP-02)	
Defence Aerodrome Manual (DAM)	
Defence Aerodrome Manual (DAM) - word version	
MRP Part 145 Supplement - Requirements Document	
Aircraft Post Crash Management (APCM) Aide Memoire	

A.2.1. RA1220 PROJECT TEAM AIRWORTHINESS AND SAFETY

With regard to airworthiness the Type Airworthiness Authority (TAA) **shall** have an Airworthiness Strategy for each aircraft in order to set down the intended approach to the demonstration and sustainment of airworthiness through life. The Airworthiness Strategy for a particular aircraft (and military role) should describe how it will demonstrate the four pillars of airworthiness, which are described in detail in Regulatory Article 1220 [A.4] and are, in précis:

1. An effective Safety Management System (SMS) should be established and detailed.
2. Recognised standards should be used and their use detailed.

3. Competence – Arrangements for the use and management of competent persons and competent organisations should be detailed, for example issuance and management of Letters of Airworthiness Authority (LoAA).
4. Independence. The arrangements for ensuring independent assessment by the Project Team (PT), independent technical evaluation, and independent safety audit should be detailed.

A.2.2. RA4812

The 4000 series regulates continuing airworthiness engineering activity to sustain military in service aircraft. Worth highlighting here is RA4812 [A.5] which deals with Certification of Aircraft and Component Release.

The MAA also publishes manuals (summarised in Table A-1) that provide extensive information on all aspects of military aviation and its management. The 4000 series of RAs is supported by the Manual of Airworthiness and Processes (MAP)-01 [A.6] - a large document with guidance on the application of processes to manage airworthiness. Further, MAP-02 is a comprehensive list and description of military aviation engineering documentation processes used [A.7].

RA4812(1) - Regulation: *The Certification of Aircraft Release* ***shall*** *be endorsed by appropriately authorised certifying staff on behalf of the organisation when it has been verified that all maintenance has been properly carried out by the organisation in accordance with approved procedures, taking into account the availability and use of the Technical Information specified in RA4810 (MRP 145.A.45)* [A.8]*, and that there are no non-compliances that are known to endanger Air Safety*.

RA4812(2) - Regulation: *The Certification of Aircraft Release* ***shall*** *be endorsed before flight at the completion of any maintenance on aircraft* (see MAP-01 and MAP-02).

RA4812(4) - Regulation: *A document containing the Certification of Component Release* ***shall*** *be issued on the following occasions*:

- *a. At the completion of any maintenance on a component whilst off the aircraft.*
- b. *When a component is removed as serviceable from an aircraft or assembly for use on another aircraft or assembly, known as cannibalisation*.

A.2.3. RA5301 TO RA5320 CONTROL OF DESIGNS AND DESIGN RECORDS

This series of RAs deals with the control of designs, design records and any changes to designs (which could be a consequence of AM). They form an important part of the airworthiness assurance for manufactured components [A.10, A.11, A.12].

During the development and life of an Air System there are likely to be a number of changes in its design. Incoherence between the design and the design records could lead to unforeseen consequences. The design must be subject to configuration control and maintenance of design records including retention in order to ensure a smooth transition to the certification of design. With respect to additive manufactured parts, this could be either new/altered designs of parts (enabled by AM), parts of the same design but manufactured differently (i.e. by AM) or parts that have been repaired using AM processes. Some noteworthy regulations are reproduced in Table A-2.

Table A-2 – Highlighted RAs in the series RA5301 to RA5320 (Control of Designs and Design Records)

Control of Designs - Highlighted RAs		
5301 Control of Designs	Para.	Text
Regulation (1)		*The Design Organisation (DO)* ***shall*** *control the design of an Air System (and related products, parts, appliances, and air launched weapons) in accordance with an agreed Configuration Management Plan (CMP).*
Regulation (2)		*The DO* ***shall*** *retain adequate records of design and development and ensure they are maintained throughout the life of the project.*
5305 In-service design changes	Para.	Text
Regulation (1)		*The Type Airworthiness Authority (TAA) or Commodity Chief Engineer (CE)* ***shall*** *be responsible for managing the design change procedure.*
AMC	1	*In-Service changes to the Air System Type Design* ***should*** *be conducted in accordance with (iaw) the classification and approval process in RA 58203. In-Service design changes to individual Products, Parts, Appliances, Airborne Equipment and ALW* ***should*** *be conducted iaw this Regulation.*
AMC	2	*The TAA or Commodity CE* ***should*** *ensure that, when selecting an organization for any design change, the organization has been approved under the MAA Design Approved Organization Scheme (DAOS)*
AMC	3	*During the design change procedure, the TAA or Commodity CE* ***should*** *manage configuration iaw their respective Configuration Management Plan (CMP)*
Regulation (2)		*The TAA or Commodity CE* ***shall*** *ensure that In-Service design changes are conducted within an Air Safety Management System (ASMS).*
Regulation (3)		*The TAA or Commodity CE* ***shall*** *select the most appropriate Design Organization (DO) to develop the required Modification.*
5320 Aircraft Maintenance Programme – Design Guidelines	Para.	Text
Regulation (1)		*Each aircraft Type Airworthiness Authority (TAA)* ***shall*** *ensure the protocols of an aircraft maintenance programme are implemented throughout the life of the project.*

A.2.4. RA5602 PROPULSION SYSTEMS PART LIFING, CRITICAL AND COMMON POOL PARTS

This RA provides regulations that are specific to the propulsion system [A.13]:

When considering the use of AM parts in a propulsion system RA5602 can be highlighted since it emphasises the importance placed on manufacturing and repair processes for integrity of parts, especially those classed as Critical, and consequently the safety of the air system:

RA5602(3) – Control of Critical Parts. *The Propulsion System DO **shall** control the manufacture of critical parts and **shall** record the manufacturing history*.

A.2.5. RA5726 INTEGRITY MANAGEMENT

This RA replaces the three separate RAs for Structural, Systems and Propulsion Integrity Management (RA5720, RA5721 and RA5722 respectively) and should be read carefully since it incorporates substantial revisions. It is a large document with six regulations that must be complied with, in order to manage the integrity of the aircraft throughout its life. The regulations are supported by extensive AMC and GM information, which taken together describe the measures that would form a planned programme of integrity management. The six regulations are [2.1]:

- RA5726(1) – Structural Integrity Management.
- RA5726(2) – Establishing Structural Integrity.
- RA5726(3) – Sustaining Structural Integrity.
- RA5726(4) – Validating Structural Integrity.
- RA5726(5) – Recovering Structural Integrity.
- RA5726(6) – Exploiting Structural Integrity.

In essence the theme of the RA is about ensuring that the design of the aircraft, including any changes through life for whatever reason, is fit for its intended and actual use. AMC for RA5726(1) states that the Establish – Sustain – Validate – Recover – Exploit (ESVRE) management framework should be used to counter threats to Integrity throughout an aircraft's life. The TAA **should** consider the most effective and efficient strategy for managing IM activities. As a minimum, consideration **should** be given to the need for separate activities for the three most commonly used Integrity disciplines (Structural, Systems and Propulsion), including Integrity Working Groups (IWG). The overall approach **should** be recorded in the Air System Integrity Strategy Document (AISD).

A.2.6. RA5810 MILITARY TYPE CERTIFICATE

It is possible that AM parts are integrated into new military-operated aircraft. This RA provides the framework *to demonstrate that an Air System's Type Design meets appropriate safety requirements. A systematic, independent certification process is required for new types of UK military registered Air Systems. The award of a Military Type Certificate (MTC) demonstrates that the military Air System has met the Type Design safety requirements* [A.15]. It is an extensive document comprising 20 regulations (which will not be reproduced here). The overarching thrust of the RA is that rigorous and detailed processes and procedures must be followed to ensure that an aircraft's design complies with airworthiness codes and must be certified as such before Release To Service (RTS).

A.2.7. RA5820 CHANGES IN TYPE DESIGN

The main theme of this RA is about ensuring that any change to Type Design (i.e. ANY change from the original MTC) is managed and any implications for airworthiness are recognised and approved prior to implementation. The requirements, AMCs and GM in this RA have important consequences for AM since there may be a desire to introduce an AM part, as a substitute for an existing part, during the life of the aircraft. An important concept is the classification of a Type Design change as either major or minor. RA5820(1) *Any change in Type Design shall be classified as 'minor' or 'major' and the classification approved by the Type Airworthiness Authority (TAA) or Design Organization (DO) under privilege (see RA5820), to determine the route to approval* [A.16].

The document provides a useful chart that summarises the classification process (Figure A-1).

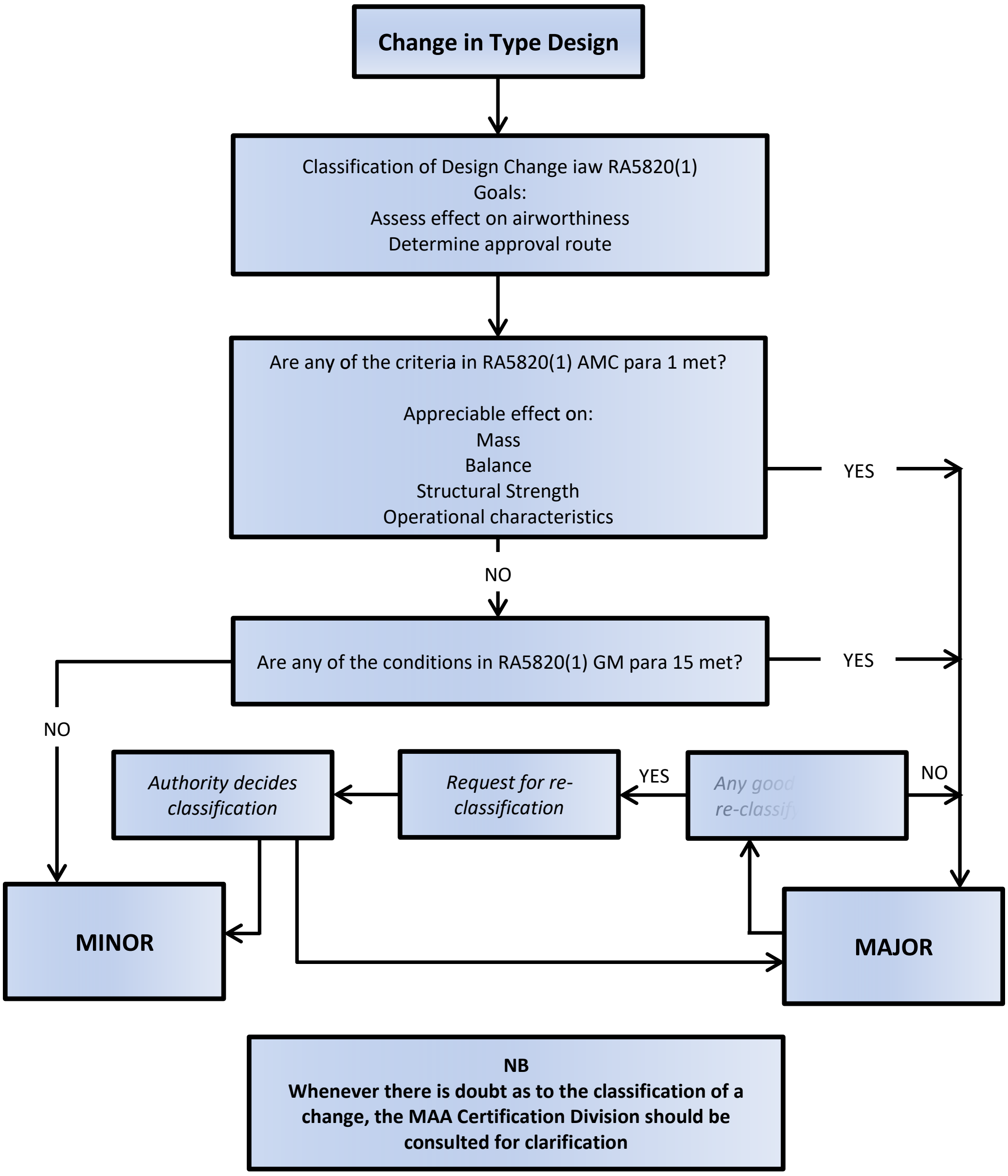

Figure A-1 - RA5820 classification process.

Annex A of RA5820 provides useful examples of major changes. An AM-relevant example of a major change is given in Paragraph 2. a. Structure (2) *Changes to materials, processes or methods of manufacture of primary structural elements, such as spars, frames and critical parts* [A.16].

A.2.8. RA5835 MILITARY PRODUCTION ORGANISATION

A production organisation (PO) for air systems (and related products, parts and appliances) ***shall*** *demonstrate to the TAA or Commodity PTL, as appropriate, that it complies with a recognised quality management system* [A.17].

A.2.9. RA5850 MILITARY DESIGN APPROVED ORGANISATION

One of the four pillars of airworthiness is the use of competent organisations. The Design Approved Organisation Scheme (DAOS) is a mechanism by which the competence of a DO can be assessed. Approval under DAOS is subject to adherence with the established procedures and rules governing the responsibilities and privileges for Military Design Approved Organisations. This article contains 13 regulations: (1) Responsibilities of a Design Organisation; (2) Scheme Inclusion and Approval Award; (3) Design Assurance System; (4) Design Organisation Exposition; (5) Approval Requirements; (6) Changes in Design Assurance System; (7) Investigations and Inspections; (8) Findings; (9) Validity of Approval; (10) Privileges; (11) Designs using Government Furnished Equipment; (12) Record Keeping; and (13) Instructions for Sustaining Type Airworthiness. Regulation 5850 (1) and 5850 (3) can be highlighted [A.18]:

- 5850(1) Responsibilities of a Design Organisation - *a DO or Co-ordinating Design Organisation (CDO)* ***shall*** *fulfil the defined design and development responsibilities under their Terms of Approval*. AMC Para. 1 *The DO* ***should***, *(d) Determine that the design of products, parts and appliances, or changes or repairs thereof, as applicable, comply with applicable airworthiness requirements and have no feature that may lead to an unsafe condition*.
- 5850(3) Design Assurance System - *the DO* ***shall*** *demonstrate that it has established and is able to maintain a design assurance system for the control and supervision of the design, and of design changes, of products, parts and appliances covered by the application*. AMC Para. 16 *The DO* ***should*** *specify and document the manner in which the design assurance system accounts for the acceptability of the parts or appliances designed or the tasks performed by partners or subcontractors*.

A.2.10. RA5855 PARTS AND APPLIANCES

This article provides the regulations (and AMCs and guidance material) necessary to ensure only approved parts and appliances are used in air systems. The use of non-approved parts and appliances can lead to unforeseen consequences. It is necessary to demonstrate the compliance of parts and appliances for use on an air system with applicable regulations and the Type Design criteria. Some noteworthy paragraphs [A.19]:

- RA5855(1) Compliance with Applicable Requirements - *the TAA* ***shall*** *ensure compliance with applicable requirements for parts and appliances to be installed in an Air System*. AMC Para. 3

Any non-standard part (standard *has a specific meaning in this context*) ***should*** *comply with the appropriate European Technical Standard Order (E)TSO or an appropriate requirement accepted by the MAA Certification Division*.

- RA5855(2*)* Release of Newly Produced Parts and Appliances for Installation… AMC Para. 6 *With respect to the authorised release certificate, only the following documents* ***should*** *be accepted as an equivalent to the MOD Form 731 for identifying a part or appliance as serviceable*: *(a) A European Aviation Safety Agency (EASA) Form 16; or (b) A release certificate following the template of European Military Airworthiness Requirements (EMAR) Form 1, when issued by an authority recognised by the MAA following the European Military Airworthiness Document Recognition process and specifically recognised in this area of competence*.

A.2.11. RA5865 REPAIRS

Some AM processes are being developed to effect repairs on air system parts. This article provides the regulatory framework to ensure only competent and approved organisations are allowed to design and carry out repairs. It has 11 regulations: (1) Demonstration of Capability; (2) Service Design Organisation Approval; (3) Repair Design; (4) Classification of Repairs; (5) Issue of a Repair Design Approval; (6) Production of Repair Parts; (7) Repair Embodiment; (8) Limitations; (9) Unrepaired Damage; (10) Record Keeping; and (11) Instructions for Sustaining Type Airworthiness. Quoting RA5865(6) Production of Repair Parts - *Parts and appliances to be used for the repair* ***shall*** *be manufactured in accordance with production data based upon all the necessary design data as provided by the DO: (a) By a Production Organisation (PO) appropriately recognised in accordance with RA 5835 [A.17]; or (b) By an Approved Maintenance Organisation (AMO) (in accordance with RA 4800 to 4821 [A.20 to A.21]) or a Military Maintenance Organisation (MMO) in accordance with (RA 4809 [A.22])*. AMC Para. 46 *Parts or appliances used for the repair* ***should*** *be appropriately marked in accordance with RA 5885 [A.23]* [A.24].

With respect to additively manufactured repairs (i.e. where material is added to the original part) the above wording could be interpreted to mean that the repair itself, taking into account any consequential effects on the original part/substrate, shall be manufactured in accordance with production data.

A.2.12. RA5885 IDENTIFICATION OF PRODUCTS, PARTS AND APPLIANCES

To comply with configuration control requirements each product, part or appliance to be fitted on an air system must be individually identified. There are important safety, operational and economic benefits if the possibility of recurrent failure of a product, part or appliance can be confined to identifiable material batches, components, equipment or aircraft. To achieve this, traceability and interchangeability are required for selected products, parts and appliances [A.23].

A.3. Appendix A Glossary of Abbreviations

ADS – Air System Document Set
AISD - Air System Integrity Strategy Document
ALARP – As Low As Reasonably Practicable
AM – Additive Manufactured/Manufacturing
AMC – Acceptable Means of Compliance
AMO – Approved Maintenance Organisation
APCM - Aircraft Post Crash Management
ASMS – Air Safety Management System
ATM – Air Traffic Management Regulations
CAE - Continuing Airworthiness Engineering Regulations
CDO - Co-ordinating Design Organisation
CE – commodity Chief Engineer
CMP – Configuration Management Plan
DAM - Defence Aerodrome Manual
DAOS - Design Approved Organisation Scheme
Def-Stan – Defence Standard
DM – Design Modifications
DO – Design Organisation
EASA – European Aircraft Safety Agency
ESVRE – Establish – Sustain – Validate – Recover – Exploit
FLY – Flying Regulations
GEN – General Regulations
GM – Guidance Material
IWG – Integrity Working Group
JAP(D) – Joint Air Publication
MAA – Military Aviation Authority
MAP – Maintenance and Airworthiness Processes
MMO – Military Maintenance Organisation
MOD – Ministry of Defence
MRP – Military Aviation Authority Regulatory Publications
MTC - Military Type Certificate
PI – Propulsion Integrity
PO – Production Organisation
PTL – Project Technical Lead
QVT – Quality Verification Test
RA - Regulatory Articles
TAA – Type Airworthiness Authority
TAE - Type Airworthiness Engineering Regulations
UK – United Kingdom

A.4. APPENDIX A REFERENCES

A.1. MAA01: Military Aviation Authority Regulatory Policy Issue 6, 16 December 2016.
A.2. https://www.gov.uk/government/collections/maa-regulatory-publications [23 May 2017].
A.3. MAA - The Pocket Guide to MAA Regulation https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/520718/pocket_guide_to_maa_regulation.pdf [23 May 2017].
A.4. RA1220 Project Team Airworthiness and Safety Issue 4, 26 October 2016.
A.5. RA4812 Certification of Aircraft and Component Release (MRP145.A.50) Issue 4, 26 July 2016.
A.6. MAA – Manual of Maintenance and Airworthiness 01 – Issue 7.1, 29 July 2015.
A.7. MAA – Manual of maintenance and airworthiness processes supplement - MOD form 700 series of forms (MAP-02) – Issue 9, 29 November 2016.
A.8. RA4810 Technical Information (MRP145.A.45) Issue 4, 8 July 2016.
A.9. Defence Standard 05-057 Configuration Management of Defence Materiel Issue 6, 7 March 2014.
A.10. RA5301 Control of Designs Issue 2, 29 August 2016.
A.11. RA5305 Modification Classification Issue 3, 25 August 2016.
A.12. RA5320 Aircraft Maintenance Programme – Design Guidelines Issue 3, 25 August 2016.
A.13. RA5602 Propulsion System Part Lifing and Critical Parts Issue 3, 30 November 2020.
A.14. RA5726 Integrity Management Issue 2, 30 November 2020.
A.15. RA5810 Military Type Certificate (MRP 21 Subpart B) Initial Issue, 25 August 2016.
A.16. RA5820 Changes in Type Design (MRP 21 Subpart D) Initial Issue, 25 August 2016.
A.17. RA5835 Military Production Organization (MRP 21 Subpart G) Initial Issue, 25 August 2016.
A.18. RA5850 Military Design Approved Organization (MRP 21 Subpart J) Initial Issue, 25 August 2016.
A.19. RA5855 Parts and Appliances (MRP 21 Subpart K) Initial Issue, 25 August 2016.
A.20. RA4800 General Requirements (MRP Part 145) Issue 8, 26 July 2016.
A.21. RA4821 Findings (MRP 145.A.95), approved maintenance organizations (AMOs) only Issue 3, 27 November 2014.
A.22. RA4809 Acceptance of Components (MRP 145.A.42) Issue 4, 26 July 2016.
A.23. RA5885 Identification of Products, Parts and Appliances (MRP 21 Subpart Q) Initial Issue, 25 August 2016.
A.24. RA5865 Repairs (MRP 21 Subpart M) Initial Issue, 25 August 2016.

APPENDIX B FACTORS AFFECTING FATIGUE IN AM COMPONENTS

B.1 INTRODUCTION

Components produced by Additive Manufacture (AM) are starting to be used in aerospace applications. Like the rest of the aircraft to which they are fitted they will be subjected to a fatigue environment however, because of the nature of the AM process, their response to fatigue will not necessarily be the same as that of their traditionally manufactured counterparts. This annex starts with a summary of the features and factors relating to fatigue. It then examines the key factors within the context of their effect on AM components before ending with some mitigation strategies for these effects.

B.2 FATIGUE SUMMARY

Fatigue is a major concern in all aerospace parts and can occur whenever a component is subjected to a varying or alternating stress. Fatigue can affect any component irrespective of its method of manufacture.

Fatigue conditions are generally classified as high or low cycle although there is no clear definition of the two states. High cycle fatigue occurs when the applied stress is within the elastic limit of the material and so very high cycle life is achieved. Low cycle fatigue involves higher stresses that generally cause an element of yielding within the material and consequently cycle life is shorter. The crossover between the two states is gradual but normally occurs at around 10,000 cycles when the applied stress drops well below the material yield stress. For lives of less than about 1000 cycles the material response has more in common with static strength [B-1].

Figure B-2 shows the general form of S-N curves for a typical steel and aluminium. In practice, Design Organisations (DO) will use a range of S-N curves for various alloys and also various features, for example lugs, high transfer load points, low-load transfer joints and notches / open holes - possibly with a range of K_t values.

For some materials there is an applied stress below which no appreciable damage will occur, this is referred to as the fatigue limit which can be found experimentally. This behaviour can be found predominantly in steels and titanium alloys. Other materials such as aluminium alloys display no fatigue limit and continue to accrue damage (however slight) even at very low applied stress. For the purposes of life calculation these materials are given a nominal fatigue limit equivalent to a life of 10 million cycles.

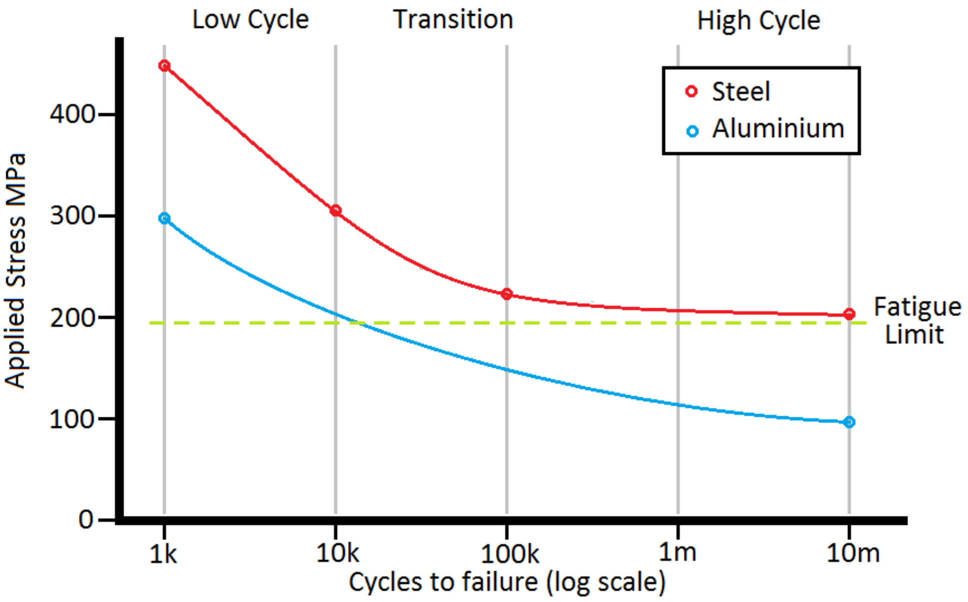

Figure B-2: Typical S-N curves for aluminium and steel

The progress of a fatigue failure has 3 distinct stages as shown in Figure B-3.

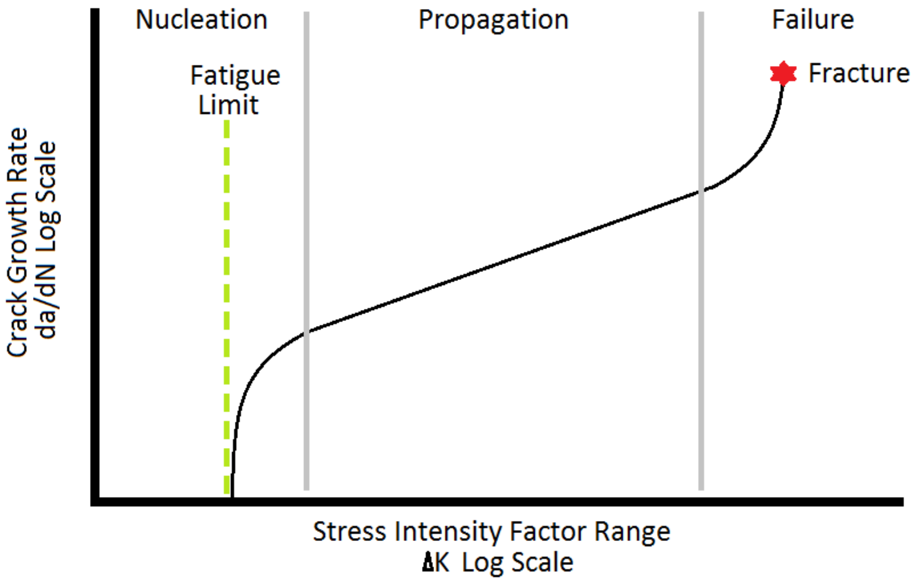

Figure B-3: Three stages of fatigue crack growth.

1. Nucleation: This is the initial formation of a crack in the component material. The crack usually initiates at a flaw in the component that acts as a stress raiser. Surface flaws tend to initiate cracks much faster than internal flaws. If no such flaws exist then the crack nucleation can be significantly delayed.
2. Propagation: This is a period of steady state growth in the crack that does not cause component failure. Both the crack extension per load cycle and the stress intensity factor range will steadily increase during this stage according to the Paris law.
3. Failure: The reduction in load bearing area and the stress concentration factor of the crack causes the stress in the remaining material to increase significantly which accelerates the

rate of propagation until failure occurs by overload. Depending upon the material and loading conditions there may also be a phase of unstable crack growth prior to the final overload.

The rate at which the failure progresses through these stages depends upon a number of factors including the material properties, the applied stress and the presence of defects.

Nucleation of a fatigue crack is affected by several factors. From the S-N curves above it is apparent that the applied stress has a major effect however stress concentrators such as surface roughness, voids, inclusions and deliberate design features such as sharp radii also have an effect which can result in an otherwise safe applied stress exceeding the fatigue limit and consequently initiating a crack.

In linear elastic fracture mechanics the Inglis equation [B-2] gives an estimation of the maximum stress (and hence the stress concentration factor) at a crack tip based upon the crack length (a), its tip radius (ρ) and the applied stress (σ).

$$\sigma_{max} = \sigma\left(1 + 2\sqrt{\frac{a}{\rho}}\right)$$

In this equation it is apparent that as the crack tip radius approaches zero the maximum stress will become infinite however this is not as unreasonable as it sounds. Ductile materials have a non-linear response to stress and fatigue because they yield which causes crack tip blunting so the crack tip radius will never be zero whilst very brittle materials such as glass and ceramics can actually fail completely because of very small scratches or internal flaws. This equation also holds for enclosed features such as holes, voids and inclusions in which case the ‘a’ term is half the major axis dimension of the feature.

When surface roughness acts as the initiator of a fatigue crack the failure may have multiple nucleation points as shown in Figure B-4.

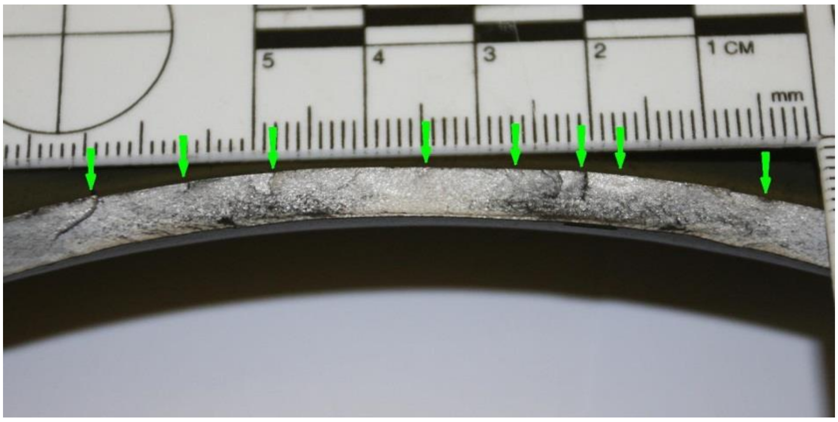

Figure B-4: Multiple fatigue crack nucleation points (arrowed) on an aluminium forging.

The cracks propagating from other nearby nucleation points will often coalesce to make a dominant larger crack. When these adjacent cracks merge a ratchet line will form as the material shears to accommodate the difference between the two crack planes as shown in Figure B-5.

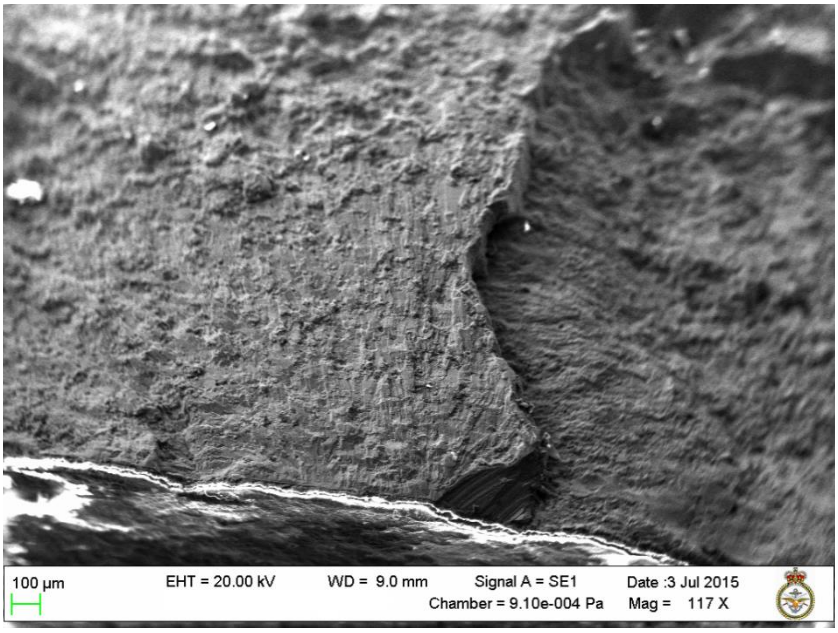

Figure B-5: Ratchet line formed where two crack planes merge.

Once a crack has established it will inhibit the nucleation of further cracks by relieving the stress on the surrounding material and start propagating along the path of highest stress. Crack propagation is achieved by repeated crack opening and closing as the material load changes. The rate of propagation is controlled by the applied stress, the size and position of the crack and the material's ability to blunt the crack tip.

Beach marks are left on the fracture surface after each period of crack growth such as a ground-air-ground cycle. They are often visible to the naked eye or with low power magnification as shown in Figure B-6.

Figure B-6: Beach marks in a steel component.

Striations are marks left behind on the fracture surface by the fatigue propagation. Each mark represents one crack opening cycle. The marks are generally very small and closely spaced, as shown in Figure B-7, (typically 20 nm to 200 nm) depending on the applied stress and material. Consequently striations cannot be seen without an electron microscope.

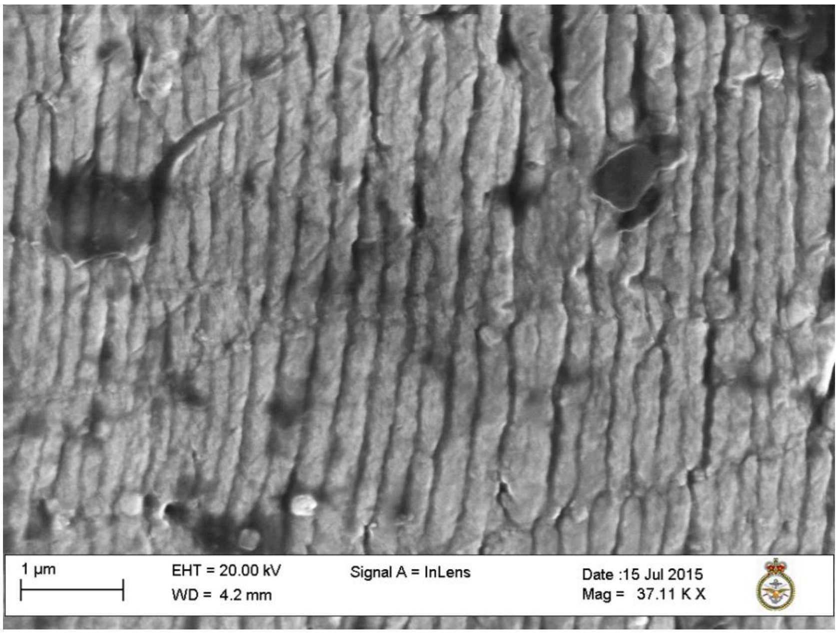

Figure B-7: Striations spaced at ~200 nm in an aluminium forging.

Fatigue testing is generally conducted using a constant load/unload cycle that allows the material response to be reliably characterised. The majority of real world applications will apply a spectrum of loads and frequencies to a component, some of which will be more damaging than others, so it is important to assess the combined effect of all of the loading elements in the spectrum. Miners rule achieves this by adding together the fraction of life consumed for each loading case in the spectrum.

When components have a mixed loading of static and alternating stress it can be difficult to determine whether the combined loads are within safe limits for the material. In these cases established criterion plots can provide an indication of whether the design is likely to be subject to fatigue failure [B-1] – examples of plots are Goodman, Modified Goodman, Soderberg, Gerber, Smith-Watson-Topper. Using Goodman as an example, the plot is constructed using the material UTS as the maximum mean stress and the material fatigue limit as the maximum alternating stress as shown in Figure B-8.

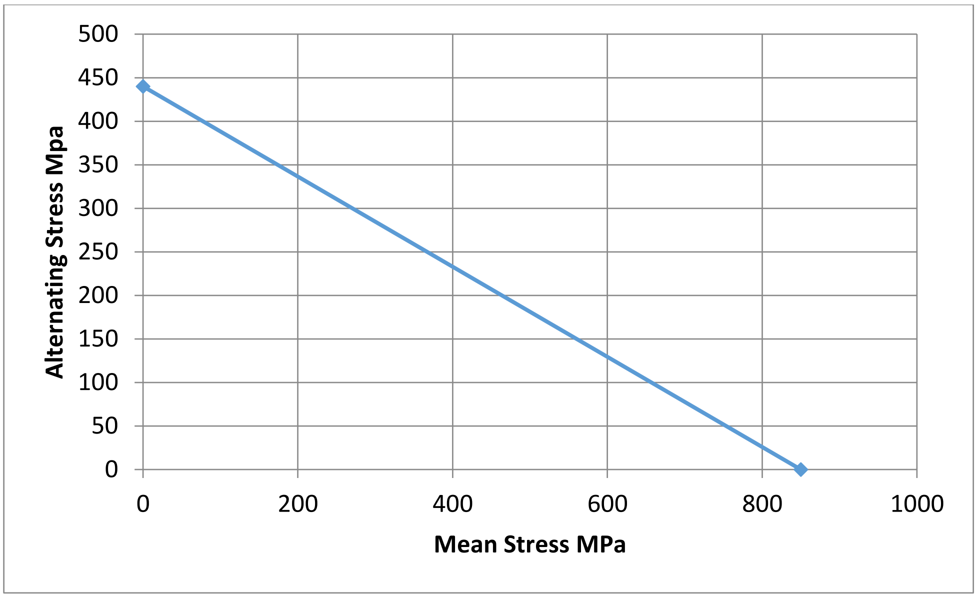

Figure B-8: Goodman criterion plot for a medium carbon steel.

Combinations of loading values can then be plotted on the graph (also taking into consideration any know stress concentration factors) and any points that lie above the line are likely to be susceptible to fatigue failure.

For initial design purposes a fatigue life scatter factor is applied [B-3]. This factor sets a conservative limit on the life that may be achieved by a population of components.

For aeroplanes, the cornerstone of safe-life substantiation is a full-scale test of a complete airframe to a factor of 5 times the service life. This factor consists of an allowance of 3 1/3 for scatter in fatigue performance and a further factor of 1.5 which is applied to those parts of the structure where the loads are not monitored on a continuous basis. Where only one side of a component has been tested, for example a port or starboard taileron, the scatter factor is increased to 4. *Exceptionally*, individual structural elements can be substantiated by calculation alone; here it must be shown that the calculations are based upon conservative assumptions and that the calculated safe life exceeds the service life by a factor of at least 2.0.

For helicopters, the emphasis is on the rotating (dynamic) components, where the stress levels are relatively low and compliance is demonstrated using a factor on stress. Several examples of each component are tested and in these circumstances a stress factor of about 1.5 is required to allow for scatter. An additional stress factor of 1.2 is applied unless the design loads are suitably conservative. A further stress factor may be used to accelerate the test. *Exceptionally*, individual dynamic components can be substantiated by calculation alone; here it must be shown that the calculations are based upon conservative assumptions and that the calculated safe fatigue strength exceeds that which would be required by test by a factor of at least 1.2.

B.3 FATIGUE AND AM OVERVIEW

There are a number of common factors that affect the fatigue life of a component some of which include AM specific elements. In the following section each factor will be discussed briefly in general and then in more detail where AM specific issues exist.

B.3.1. ALTERNATING STRESS

This is the cyclic loading that drives the propagation of a fatigue failure. It is common to all fatigue cases and no AM specific elements have been identified.

B.3.2. MEAN STRESS

Except in cases of pure completely reversed bending fatigue there will always be an element of mean stress present in a fatigue failure. From the Goodman plot (Figure B-8) it is apparent that mean stress can have a serious effect on fatigue life. Mean stress values can come from several sources.

B.3.2.1. STATIC LOADING

There will be a mean stress applied to any component that carries a static load such as engine mountings. The application of a mean stress to a component subject to cyclic loading increases the likelihood of a fatigue failure [B-4]. No AM specific elements to static loading have been identified.

B.3.2.2. EQUIVALENT MEAN STRESS

In cases where the cyclic loading is not fully reversed there will be an equivalent mean stress. In the case of unidirectional loading this is equal to half of the stress range plus half the minimum stress. No AM specific elements to equivalent mean stress have been identified.

B.3.2.3. RESIDUAL STRESS

Residual stresses are effectively a static load originating within the material itself and can be a significant factor in any fatigue situation. They arise from a variety of sources including cold working and welding. Controlled cold work to introduce a specific degree of residual stress can have a positive effect on some materials, either to improve precipitation in age hardening materials or to give a degree of work hardening to non-heat treatable materials. The residual stresses arising from welding operations can be considerable and in some cases can approach the yield stress of the material. Since AM materials are essentially a very long and intricate weld bead the residual stresses can be both large and complex if left untreated. Electron beam melting AM processes usually occur at temperatures close to the annealing temperature of the material which significantly reduces the level of residual stress in the finished component. In contrast laser selective melting processes are carried out at much lower temperatures so post processing should be considered to remove the resulting residual stress. For the majority of materials annealing should be considered as the minimum heat treatment. Hot Isostatic Pressing (HIP) is preferable but the equipment is complex, large and expensive so a balance must be sought between cost and the required properties. The use of HIP is unlikely in the context of containerised forward manufacturing facilities [B-5,B-6,B-7,B-8,B-9].

B.3.3. STRESS CONCENTRATION FACTORS

Stress concentrations factors are the result of any feature, accidental or intended, that disrupts the internal stress distribution of the material. Such disruption usually results in a localised increase in the stress field that can lead to failures ranging from immediate overload to increased susceptibility to fatigue damage.

B.3.3.1. MATERIAL VARIABILITY

Changes in composition due to feedstock variation will introduce inhomogeneity that can act as a stress concentrator. For AM parts there are several potential sources of such variability including inhomogeneous wire feedstock, inadequate cleaning of powder systems during change of material, batch mixing and contamination of the inerting gas. In the case of titanium alloys contamination of the argon supply with nitrogen or oxygen can lead to the formation of alpha casing which has a particularly damaging effect on fatigue life [B-6, B-10].

B.3.3.2. GEOMETRY

Sharp corners and sudden changes in section will cause a change in the local stress concentration [B-11] and consequently will need some attention in the design process. The flexibility of AM allows unusual design features and rapid wall thickness changes hence, as with conventionally manufactured items, consideration should be given to the use of gradual transitions and fillet radii between features to minimise stress concentrations.

B.3.3.3. SURFACE FINISH

The effect of surface finish on fatigue life is considerable. Although the subsequent propagation rate of a fatigue crack will be unchanged the time to initiate the crack is significantly shortened by increasing the roughness of a surface. With very rough surfaces there is also a danger of multiple crack nucleation points that will further shorten the time to failure. Figure B-9 shows the surface profile from the X plane of an additively manufactured item produced by selective laser melting (SLM).

The typical Ra value for the surface in Figure B-9 is 17 µm, about the same as a medium quality sand casting.

The roughness profile of an as manufactured surface has multiple components including weld pool solidification marks, successive beads, beam wander, weld beam power/melt pool size and dwell spots/end of line hot/cold spots some of which are visible in Figure B-10. The higher beam power of electron beam systems means that these components generally have a rougher surface than those manufactured by laser melting [B-8, B-12, B-13, B-14, B-15, B-16].

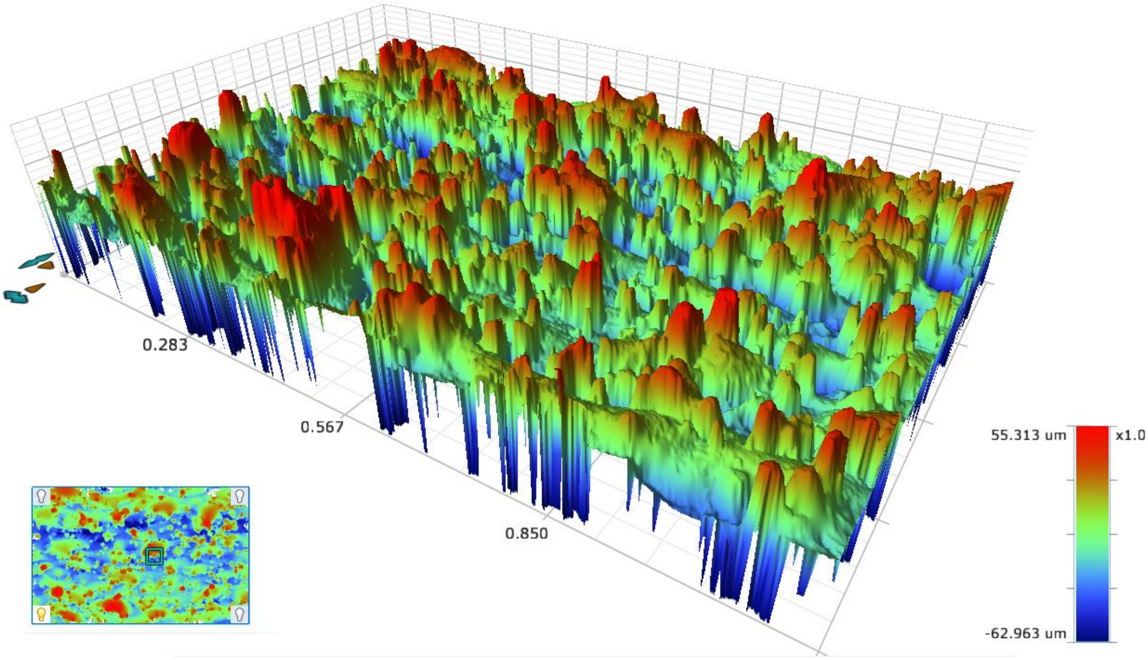

Figure B-9: Optical profilimetry plot for the ‘X’ plane of a 316L SLM component.

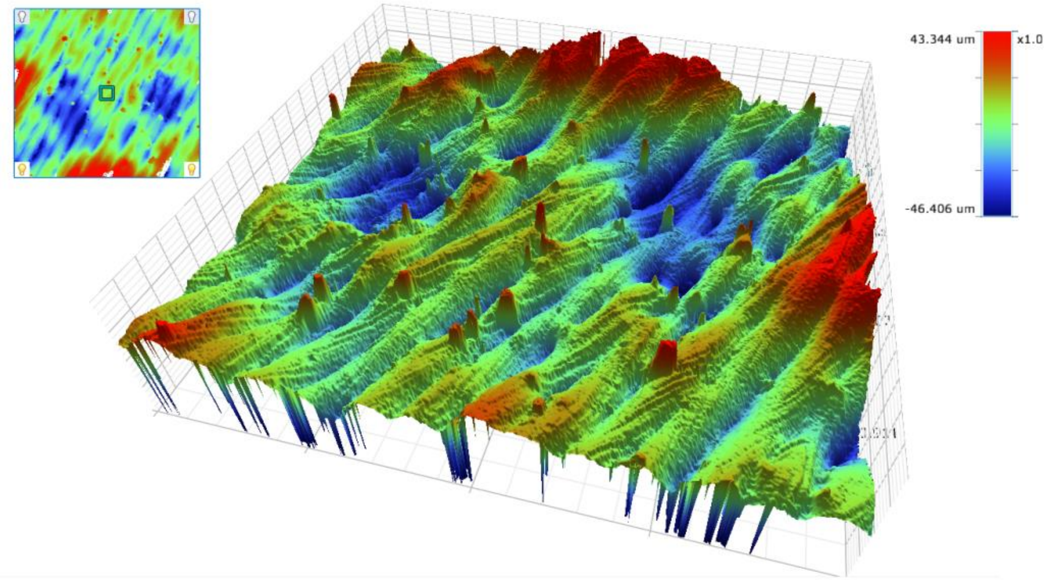

Figure B-10: Optical profilimetry plot for the ‘Z’ plane of a 316L SLM component

The fatigue performance of the surface can be improved by a number of processes discussed later. The processes that have the greatest beneficial effect on fatigue life are those that impart a residual compressive stress on the surface. Subtractive processes may cause parts to deform if adequate residual stress relief has not been carried out beforehand.

B.3.3.4. DEFECTS

In general defects will act as stress concentrators. Defects at the surface of a component can be particularly damaging because they act as a pre-existing crack, effectively removing much of the nucleation phase of a fatigue failure. If the surface of a component is defect free then fatigue cracks will often start at a defect in the core of the material since this is easier to achieve than creating a crack on a smooth surface.

The most likely defects within AM components include lack of fusion, gas porosity and foreign particle inclusions. Of these, lack of fusion defects are generally the most damaging because of their size and shape as shown in Figure B-11. The combination of comparatively long major axis and narrow extremities produces a much higher stress concentration factor than the typically spherical shape of porosity or inclusions [B-5, B-6, B-7, B-13, B-14, B-15, B-16, B-17, B-18, B-19, B-20, B-21, B-22, B-23, B-24].

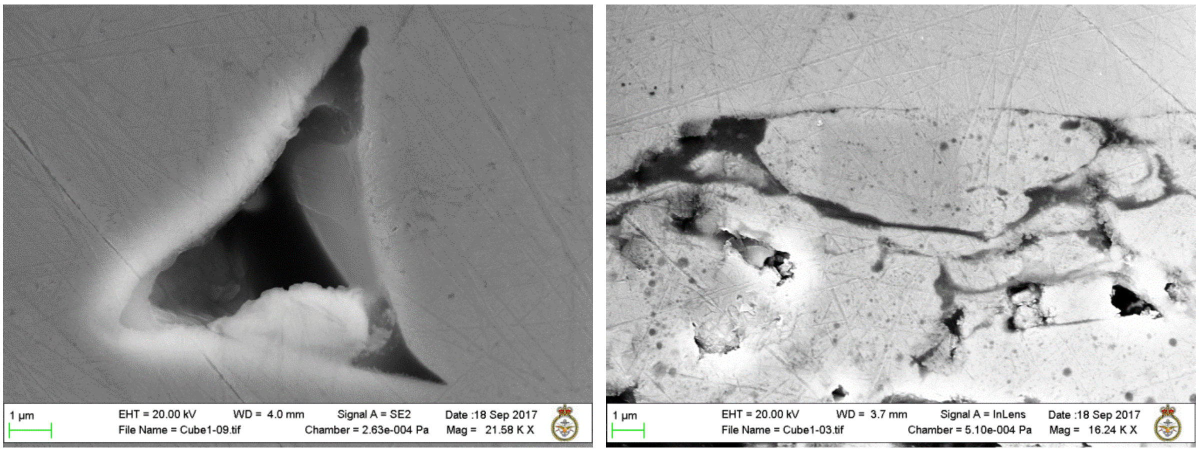

Figure B-11: Lack of fusion defects from the top (L) and base (R) of a 316L AM component.

It can also be seen in Figure B-11, the appearance of the defects can be location sensitive. The defect from the top of the build only involves 3 or 4 particles of powder lying on the previously built layer whilst that from the base (close to the base plate) extends across numerous particles and their interfaces. This extensive flawing can be due to the heat sink effect of the base plate interfering with the normal weld pool solidification making it important that sufficient support structure is used to prevent the occurrence of large defects in the start of a build.

B.3.4. TEXTURE

Texture is the alignment or lack of alignment in the crystal structure within a material. If a material displays no texture then the orientation of the crystal structure in each grain will be effectively random and the material properties should be isotropic. On the other hand if the crystal structures in the grains tend to align in a particular way then the properties will become increasingly anisotropic. Within AM components there is a tendency for the crystal structure to orient itself in a particular relationship to the build direction because of the directional nature of the solidification of the weld pool. This means that unless it is controlled or subsequently altered then the texture will have an effect on the properties and consequently on the fatigue behaviour of an AM component.

B.3.5. TOPOLOGY OPTIMISATION

One of the greatest benefits of AM is its ability to enable topology optimised designs that provide significant weight savings compared to non-optimised components. From a fatigue life perspective however topology optimisation is not without potential issues. The process of optimising a structural part effectively removes the majority of its redundant load path capacity. Significant care should be taken when selecting optimisation parameters for any component that will be subject to fatigue conditions [B-25, B-26].

B.3.6. MITIGATION STRATEGIES

There are many ways that the deleterious effects of the factors such as defects and surface finish can be mitigated, these include:

1. Heat treatment/Hot Isostatic Pressing.
2. Machining.
3. Chemical etching.
4. Abrasive flow machining.
5. Shot peening.
6. Laser Shock Peening.
7. High pressure rolling/burnishing.
8. Low plasticity burnishing
9. Scan strategy/parameter optimisation.

The following paragraphs examine these methods in more detail.

B.3.6.1. HEAT TREATMENT

Heat treatments can help prevent failure in AM parts by reducing the residual stress in the material. These treatments include stress relief, annealing, solution heat treatment (with or without subsequent precipitation) and recrystallization depending on the material and degree of reduction required. The reduction of the residual stress improves the fatigue life by effectively reducing the mean applied stress component of the Goodman criterion plot. These heat treatments can also be effective in reducing the amount of anisotropy introduced into the material by texture.

Hot isostatic pressing can be beneficial not just for the reduction in residual stress but also for reducing the size of internal voids. This achieved by heating the part to temperatures similar to those in the above treatments and simultaneously applying high pressure to the outer surface using a non-reactive gas such as argon. The reduction in void size makes it less likely that a fatigue failure will initiate at an internal defect however HIP has no effect on surface breaking defects or roughness and so should be used in conjunction with one of the surface treatments [B-6, B-8, B-14, B-15, B-18, B-19, B-23, B-24, B-27, B-28].

B.3.6.2. MACHINING

Many AM components will require subsequent finishing of functional surfaces and bores by traditional machining methods to ensure correct alignment, sealing or similar properties. Machining of the outer surfaces to remove roughness can also give significant benefits to the fatigue life of the component, particularly in the low cycle fatigue domain.

Depending upon the part design and expected stress distribution a stress relief heat treatment may be required prior to machining operations to reduce the likelihood of warping or cracking as material removal alters the balance of the internal stresses [B-8, B-13, B-14, B-15, B-16].

B.3.6.3. CHEMICAL ETCHING

Careful selection of etchants can reduce the component surface roughness by causing the preferential removal of minor protrusions. Chemical etch has the advantage of being effective on almost the whole surface a complex structure although care must be taken to avoid over etching or leaving etchant on the surface after cleaning [B-29].

B.3.6.4. ABRASIVE FLOW MACHINING

This process has many of the benefits of chemical etching with added advantage of using generally safer materials. The major drawback of this process is the heavy equipment required to force the thickened abrasive through the workpiece [B-30, B-31].

B.3.6.5. SHOT PEENING

Shot peening can improve fatigue performance by developing a compressive residual stress in the surface of the peened part and reducing the overall roughness of the surface. The shot material should be selected to avoid leaving damaging contamination on the finished surface [B-30].

B.3.6.6. LASER SHOCK PEENING

Laser shock peening uses a very intense laser pulse to ablate either original material or a sacrificial coating from the surface of the component. The resulting reaction force creates an intense compressive residual stress that can extend below the surface significantly further than other peening systems. Laser shock peening has the potential to be used during the build process to modify the component internal stress as it is manufactured [B-9].

B.3.6.7. LOW PLASTICITY BURNISHING

Low plasticity burnishing can be used to produce a compressive residual stress in the surface of a component with minimal change in dimensions. Systems are available that will burnish concurrently with post manufacture machining operations or standalone [B-32].

B.3.6.8. HIGH PRESSURE ROLLING/BURNISHING

The use of high pressure rolling or burnishing between build layers has been found to produce a useful modification to the generally columnar grain structure normally found in an as-manufactured component leading to a reduction in the anisotropy of the physical characteristics [B-33].

B.3.6.9. SCAN STRATEGY/PARAMETER OPTIMISATION

Careful selection of the build process parameters including build direction, scan strategy, cross hatch rotation, base plate heating, beam power, spot size, beam shape and scan speed can have a significant effect on the resulting as built microstructure. Unfortunately not all of these parameters are currently available to be adjusted in some commercially available additive manufacture machines [B-17, B-21, B-34, B-35].

B.4 CONCLUSIONS

For the purposes of Def Stan 00-970 part 11 [B-35] many of the items discussed above will count as anomalies i.e. surface damage or material process discontinuity. As such the avoidance or mitigation of these anomalies is important when it comes to calculating the predicted safe cyclic damage tolerance life. A failure to remove these anomalies will result in the use of excessive scatter factors that will have an adverse effect on the component life.

The anomalies will also have an effect on subsequent validation testing because all results, including those where the component failed early, must be used in the lifing calculation unless a thorough review of the failure can provide a justification to omit the result.

With proper consideration of all of the relevant factors, fatigue issues should not prevent AM components from become increasingly common in aerospace engineering.

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