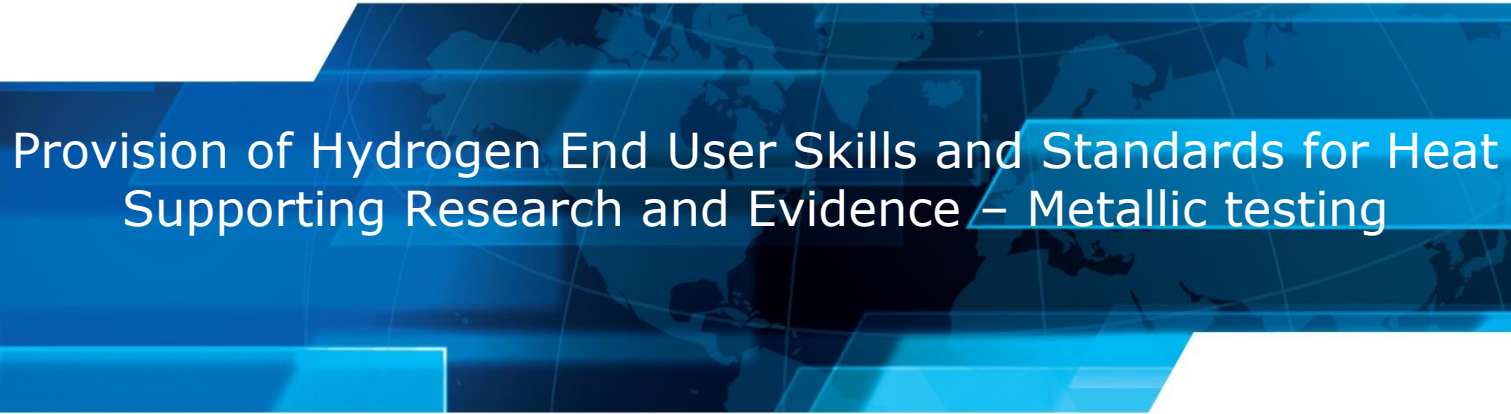




Report No: 34739/3v2/23

Date: July 2023

For: Department for Energy Security and Net Zero

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Provision of Hydrogen End User Skills and Standards for Heat Supporting Research and Evidence – Metallic testing

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Hydrogen Skills and Standards for Heat Programme (NZIP)

The Hydrogen Skills and Standards for Heat programme is working towards the development of technical standards for domestic and non-domestic hydrogen gas installations, and on associated competence frameworks and training specifications for installers. These will enable re-purposing of the existing natural gas system to be used with 100% hydrogen downstream of the emergency control valve (ECV). The standards developed should define the required criteria to safely repurpose existing natural gas equipment for hydrogen, to design and install new hydrogen safe pipework and appliances, and to train a workforce of competent hydrogen gas installers. This work will support future community trials of hydrogen heating and will contribute evidence to inform strategic decisions in 2026 on the role of hydrogen in heat decarbonisation. The programme forms part of the Department for Energy Security and Net Zero, Net Zero Innovation Portfolio, NZIP.

Under the programme, the British Standards Institution (BSI) will develop a series of Publicly Available Specification (PAS) standards. These should codify an agreed set of principles, requirements and guidance on the functionality, safety, installation, operating and servicing requirements for hydrogen meters, pipework, fittings, and ancillary devices. The Institution of Gas Engineers and Managers (IGEM) will develop two hydrogen enabling standards covering installation requirements for gas installers in domestic and non-domestic scenarios (up to light industrial sites). The standards should cover considerations for new hydrogen installations and re-purposing of existing gas infrastructure. Energy and Utility Skills (EUS) will codify both the IGEM domestic and non-domestic enabling standards into competency frameworks and training specifications to facilitate the training of a competent workforce for a village trial. Accredited Certification Scheme (ACS) assessment criteria and Approved Code of Practice (ACoP) assessment modules for both enabling standards should be developed, working with industry to ensure there is a clear path for existing competent engineers to train for hydrogen installations.

A number of contracts within the programme have been awarded to suppliers to undertake technical research and evidence gathering to support the development of the above standards. This document is the final project report for "Provision of Hydrogen End User Skills and Standards for Heat Supporting Research and Evidence – Metallic testing".

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Appendix B: Malleable iron composition and data
Appendix C: Lead composition and data

Executive Summary

Background

In order to introduce hydrogen as an alternative fuel for the UK, there is a need to determine whether existing gas transmission infrastructure can be operated with up to 100% hydrogen gas, and to review the potential for deploying new infrastructure to enable this. Research in this area, until recently, tended to focus on the high pressure transmission network, but the safety implications of this in the low pressure systems operating in domestic and small commercial buildings will also need to be assessed.

This report covers the metallic testing part of the scope of work in Lot 2 of Tender 'Provision of Hydrogen End User Skills and Standards for Heat Supporting Research and Evidence', Reference Number: 5045/04/2021. It follows on from the literature survey carried out by TWI and reported as 34739/2v2 where two materials identified for further testings, malleable iron and lead, were tested.

Objective

To further our understanding of the suitability of malleable iron and lead for low pressure systems downstream of the emergency control valve for 100% hydrogen service.

Work Carried Out

Slow strain rate tensile (SSRT) tests, were carried out on specimens of malleable iron and lead material in order to determine their relative susceptibility to hydrogen embrittlement. Tests were performed both in air and also in 2 bar 99.9999% purity hydrogen in order to allow a comparison of the material behaviour. To account for the material behaviour scatter, a larger number of tests was performed on the malleable iron than the lead. A strain rate of 10⁻⁵s⁻¹ was used.

After testing the fracture faces of a selection of specimens were examined using a scanning electron microscope (SEM) in order to establish the failure mechanisms in both air and hydrogen and whether hydrogen had influenced the failure mechanism in any way. The hydrogen content of both tested and untested material was also measured for comparison.

Conclusions

The following conclusions for malleable iron can be drawn from this study:

1. The SSRT test data are similar in air and hydrogen although it should be noted that elongation is reduced by the presence of hydrogen. Yield stress, UTS and reduction of area at failure were found to be similar in air and hydrogen.
2. There is an influence of hydrogen on the failure mechanism of malleable iron.

Further data would be required to change the status of cast iron from 'amber' to either 'red' or 'green'. This should include more specific test types which will be more representative of service stresses than SSRT testing. This could include further testing with consideration of other types of cast iron likely to be found in service.

The following conclusions for Lead can be drawn from this study:

1. The test methodology used for SSRT tests does not produce accurate stress-strain curves; therefore no conclusions have been drawn from this data.
2. Based on the ductility measurements and the post-test fractographic examination performed on the test specimens, there is no effect of hydrogen on the properties of this lead.

1 Introduction

In order to introduce hydrogen as an alternative fuel for the UK, there is a need to determine whether existing gas transmission infrastructure can be operated with up to 100% hydrogen gas, and to review the potential for deploying new infrastructure to enable this. Research in this area, until recently, tended to focus on the high pressure transmission network, but the safety implications of this in the low pressure systems operating in domestic and small commercial buildings will also need to be assessed.

This report covers the metallic testing part of the scope of work in Lot 2 of Tender 'Provision of Hydrogen End User Skills and Standards for Heat Supporting Research and Evidence', Reference Number: 5045/04/2021. It follows on from the literature survey carried out by TWI and reported as 34739/2v2 which is included as Appendix A of this report. As part of that review, open literature was surveyed to find evidence to either support or reject the use of a range of materials in domestic systems. Materials were rated according to a simple 'traffic light' classification system, according to whether the available data provided evidence on compatibility or lack thereof. Those materials, for which there were no data, were classified as amber; necessitating that environmental mechanical testing should take place, to allow for approval or rejection.

The literature review performed was for operation in 100% hydrogen, without contaminants, moisture, or the addition of odourants and colorants. It is understood that the additives could be either adverse or beneficial to the materials properties. Testing without odourants was selected for this study in order to optimise the number of tests which could be performed as part of this project. TWI has not been provided with any acceptance criteria for approval of materials for hydrogen service. Therefore, if any material shows any sign of hydrogen embrittlement, that material will be either kept as an amber rating pending further testing or moved to a red rating.

It should be noted that for service with odourants, all materials will need to start with an amber rating, due to the fact that the literature survey was carried out assuming pure hydrogen service.

This testing project uses slow strain rate tensile (SSRT) tests, which are ideal for screening a selection of materials, in order to determine their relative susceptibility to hydrogen embrittlement. Given the time dependency of the hydrogen embrittlement process, and the relatively slow diffusivity of hydrogen through many of the materials listed here, it is unlikely that a steady-state hydrogen concentration will have been achieved through many of the SSRT specimens, prior to the application of load. As such, these tests cannot necessarily be used to quantify the performance of in-service parts, which are exposed to hydrogen for far longer durations. Consequently, TWI does not suggest that the mechanical properties derived from such tests should be used to indicate absolute performance in hydrogen.

The intention of this testing programme is to provide environmental performance ratios which are taken to be the average properties, for specimens tested in the hydrogen-containing environment as a proportion of the equivalent properties from specimens tested in air. This is an approach that is commonly used to rank various materials against environmentally-assisted cracking, prior to making a down-selection of those materials which will be subjected to a full materials qualification programme. Such a qualification programme might ordinarily include fatigue and fracture testing, depending on the loading conditions of the components in question.

The decision to propose the SSRT test method was based on a balance between generating the largest amount of testing data possible, economically, and to schedule.

At present, TWI is not able provide a technical justification for testing without additives, as there is insufficient data to show how additives may affect materials properties in the presence of hydrogen. Furthermore, we have not conducted a review on this topic. However, DESNZ informed TWI testing without odorants (or other additives) was selected for this project following discussion between DESNZ and HSE. This decision was made using published data that indicated additives may inhibit the uptake of hydrogen. It is understood that the presence of additives was reported to reduce fatigue crack growth rate in certain steels and increase it in others, and the addition of some trace gases was shown to improve the performance of materials in hydrogen, making it harder to determine the impact of hydrogen on the test material. In addition, testing without additives increased the number of different materials which could be tested within the duration of the project.

The type of additives for hydrogen has not been finalised at present, but it is anticipated that the same odorant (mercaptan NB) as that for Natural Gas will be used in the initial trials.

For each alloy to be tested, it was agreed that SSRT tests be performed in air and 2bar hydrogen. The hydrogen level of 100% dry hydrogen with no additives, was agreed with Department for Energy Security and Net Zero (DESNZ).

Based on the previous literature review, there was a recommendation to test a cast iron and also lead for evidence of hydrogen environmental embrittlement (HEE). This document reports and discusses the results of these tests. The SSRT testing method selected was based on a balance between generating the largest amount of testing data possible, economically and to schedule. SSRT tests are an excellent screening methodology and the usual way this is reported is an HEE index which allows an easy comparison of ductility in hydrogen and in an inert environment.

$$\text{HEE Index} = \frac{\text{Ductility in hydrogen}}{\text{Ductility in inert environment}}$$

In this project, the inert environment is air at ambient pressure and the hydrogen environment is 2 bar. A HEE index of 0.7 or higher is generally considered an indication that HEE is not severe and a HEE index of 0.9 or higher indicates that the effect of HEE is small (Lee, 2016).

2 Objectives

To further our understanding of the suitability of malleable iron and lead for low pressure systems downstream of the emergency control valve for 100% hydrogen service.

3 Approach

3.1 Materials

Two materials were selected for this work-scope, based on the findings of the literature survey carried out by TWI, see Appendix A. This allows further understanding of their suitability to low pressure hydrogen service in the domestic setting. These were malleable iron and lead.

3.1.1 Malleable iron

New blackheart malleable iron tee-piece fittings were sourced, from which tensile specimens were extracted, (Figure 1). Whilst it is recognised that the size and thickness of the tee-pieces was greater than that of components typically present downstream of the safety valve, this was necessary in order to be able to extract mechanical test specimens.

Nevertheless, from a microstructural perspective, the malleable iron was thought to be representative of a typical cast iron component that may be encountered in the domestic setting.

The name cast iron refers to a wide range of alloys which contain 2-5% carbon. There are many different microstructures associated with cast irons, of which this blackheart malleable iron is one of them. The term blackheart comes from the fact that the fracture face of this cast iron has a black appearance due to all the carbon features on it.

Although this malleable iron will not be representative of all cast irons in service, it provides a good indication of the behaviour of some fittings of this type of material.

The chemical composition of the material was measured and also the hydrogen content on arrival. The diffusible hydrogen was measured by hot extraction at 400°C and the residual hydrogen was measured by melt extraction. A metallographic section was prepared using standard metallographic techniques to allow examination of the microstructure.

3.1.2 Lead

Lead was sourced in sheet form with a thickness of 3.55mm. The hydrogen content was measured on arrival.

3.2 SSRT testing

A series of SSRT tests were performed on both materials both in air and also in 2 bar hydrogen in order to allow a comparison of the material behaviour. In TWI's experience, a large amount of scatter can be experienced when performing mechanical tests with cast irons. To account for this, a larger number of tests was performed on the malleable iron than the lead.

A strain rate of 10^{-5}s^{-1} was used. The aim of the slow test is to allow hydrogen time to diffuse around in the material during test. Tests were based on those recommended in ASTM G142. The test gas used was 99.9999% purity hydrogen (see gas purity certificate in Appendix B). Prior to testing 10 purges with nitrogen followed by 10 purges with the test gas were used to ensure an explosive mixture was never present in the system and to maintain purity of the test environment. Prior to the testing in hydrogen, specimens were mounted in the test machine and exposed to 2 bar of hydrogen for at least 24 hours. The surface finish of the specimens were "as machined".

Six SSRT tests were performed on the malleable iron in air and six in 2 bar hydrogen. The specimen design selected is given in Figure 2.

Three SSRT tests were performed on the lead in air and three in 2 bar hydrogen. The specimen design is given in Figure 3.

A short gauge length was selected due to the high elongation expected during test and wide tabs were used in order to optimise gripping of the specimen during test. These flat tensile specimens were extracted using EDM in order to avoid contamination of the air with lead particles.

3.3 Post-test analysis

After test, a selection of the malleable iron fracture faces were examined using a scanning electron microscope (SEM) in order to establish the failure mechanisms of specimens tested in both air and hydrogen and whether hydrogen had influenced the failure mechanism in any way. The fracture surfaces of two lead specimens were examined using SEM; one specimen tested in air and one tested in hydrogen.

One specimen of each material was placed in a cryo-store post testing in hydrogen to minimise hydrogen losses. The hydrogen content was then measured. The cryo-store uses liquid nitrogen as a coolant meaning specimens are stored at or just above liquid nitrogen temperature. It is not anticipated that any hydrogen is lost from samples placed in the cryo-store. Samples were stored until TWI staff and equipment were available for the hydrogen measurement. In some cases this was a few weeks. Samples are cut if necessary whilst cold and then placed in the crucible used during the hydrogen analysis whilst still cold to ensure that no hydrogen is lost prior to measurement.

For the malleable iron samples, both diffusible and residual hydrogen contents were measured. Diffusible hydrogen is measured by vacuum hot extraction at 400°C and residual hydrogen is measured by melt extraction. Total hydrogen is the sum of diffusible and residual hydrogen. For the lead samples, only total hydrogen was measured as the low melting point of lead would mean that it released both the residual and diffusible hydrogen at 400°C. This was done by melt extraction. Diffusible hydrogen is the monatomic hydrogen that can diffuse in the sample. Residual hydrogen is that trapped at various sites within the microstructure which is not released below 400°C.

4 Results

4.1 Malleable iron

4.1.1 Composition and hydrogen content

The composition of the malleable iron is summarised in Table 1 and the test certificate is given in Appendix B.

Table 1 Composition of malleable iron (blackheart malleable iron)

Element	Composition (weight %)
C	3.44
Cr	0.06
Cu	0.06
Mn	0.42
Mo	<0.01
Ni	0.02
P	0.036
S	0.14
Si	1.23

The hydrogen content was found to be the same on arrival and post-test (specimen M01-10) within the accuracy of the measurements.

The levels were found to be less than 0.5ppm of diffusible hydrogen and residual hydrogen was measured to be 3ppm. The test certificate for this is given in Appendix B.

4.1.2 Microstructure

The microstructure was found to be a ferritic matrix with graphite rosettes at the centre of the material (Figure 4). Nearer the surface pearlite was also found (Figure 5). Note in these images that the ferrite is white, the graphite is black and the pearlite is grey. These microstructures are consistent with what would be expected for a blackheart malleable iron casting with high strength and ductility (for a cast iron). BS2789 (1985) suggests that such microstructures may have ductility in the range of 12-22% and ultimate tensile strengths of 350-420MPa when tested at conventional strain rates in air.

4.1.3 SSRT testing

Figures 6-9 summarise the results of the SSRT tests, full stress-strain curves are given in Figure 6 and Appendix B. From Figure 7, it is clear there is a slight reduction in the elongation in the presence of hydrogen. From Figure 8, the reduction in area data are similar in terms of both mean and range when comparing air and hydrogen tests. The yield stress data (Figure 9) shows that the air and hydrogen data are very close, with the exception of the second test in hydrogen which failed very early in test. This pattern is reflected in the ultimate tensile strength (UTS) data which are shown in Figure 10, although there is generally a slight reduction in UTS measured in hydrogen.

The mean and range of the data is given in Tables 2-3. The ranges in both air and hydrogen are large which is due to the nature of the malleable iron. As it is a cast material, casting defects and the proportion of carbon rosettes on the fracture surface will vary significantly.

Table 2 Mean and range of elongation and reduction in area in hydrogen and air for malleable iron specimens.

Property	Environment	Mean (%)	Range (%)	Standard deviation (%)
Elongation	Hydrogen	2.2	1.1 to 3.3	0.8
	Air	3.1	1.8 to 4.9	1.3
Reduction of area	Hydrogen	4.2	2.2 to 5.5	1.3
	Air	4.3	3.1 to 6.7	1.4

Table 3 Mean and range of yield and UTS in hydrogen and air for malleable iron specimens.

Property	Environment	Mean (MPa)	Range (MPa)	Standard deviation (MPa)
Yield strength	Hydrogen	162.9	105.4 to 183.0	28.8
	Air	173.3	160.0 to 183.8	8.9
UTS	Hydrogen	190.8	106.7 to 222.0	42.9
	Air	219.8	167.4 to 248.2	30.2

The HEE index has been calculated for each of the properties shown in Figure 6-9, based on the mean value in air and the mean value in hydrogen. It was also recalculated without the second hydrogen specimen which had a much lower stress at failure due to the presence of a large carbon-rich feature on the fracture face, which would have promoted brittle behaviour regardless of test environment. These HEE indexes are given in Table 4.

Table 4 HEE index calculated comparing SSRT data for malleable iron tested in hydrogen to those tested in air for malleable iron specimens.

Material property	Yield	UTS	Elongation	Reduction of area
All data	0.94	0.87	0.70	0.99
Excluding 2 nd hydrogen test	1.01	0.94	0.77	1.08

4.1.4 Fractography

A selection of the fracture faces of the malleable iron SSRT test specimens were examined. Figure 11 shows a montage of SEM backscatter electron images covering the whole fracture surface of specimen M01-01, which was tested in air. Typical details taken from this fracture surface are shown in Figures 12-13.

The dark regions are carbon rosettes which are typical of this material. As you can see these cover a large amount of the fracture surface but are not even in their distribution. In between the rosettes, ferrite can be seen. Figures 12-13 show details of the ferrite surface, the smooth regions which dominate the fracture surface are casting defects which are expected in this material type. The remaining regions failed by microvoid coalescence which is typical of ductile overload.

Figures 14-16 show a typical fracture surface for a malleable iron specimen tested in hydrogen (M01-11). The fracture surface for this specimen shows a more even distribution of smaller carbon rosettes, Figure 14, than seen on specimen M01-01. Again, this microstructural variability is typical of this type of product. Details of this fracture surface, which are typical of all the specimens examined which had been tested in hydrogen, are shown in Figures 15-16. Figure 15 shows a mixed mode failure in the ferrite region, a combination of micro-void coalescence due to ductile overload, and quasi-cleavage, seen nearer to the centre of this image. Figure 16 shows a region of quasi-cleavage at higher magnification. This is typical of fracture which has been influenced by hydrogen.

The second malleable iron specimen tested (M01-08), which had failed very early in the test at lower stress than the other specimens, was found to have a large carbon related (non-rosette) feature which covered a significant portion of the fracture surface. This feature is the dark region on the right hand side of the Figure 17. This feature is most likely associated with the manufacture of the component and is not unusual for this type of material. It is likely that this feature led to the lower result on the SSRT test.

4.2 Lead

4.2.1 Composition and hydrogen content

The composition of the 3.55mm lead sheet used in this project is given in Table 5 and the test certificate is in Appendix C. In table 5 it has been compared with two standards; BS 602:1085-1970 which is for lead pipes and BS EN 12588-2006 which is for lead sheet. The composition for the elements measured are within specification for both standards other than the copper levels are too high for BS 602:1085-1970 No.1.

Table 5 Composition of lead

Element	Composition (weight %)	BS 602:1085-1970			BS EN 12588-2006
	As measured	No.1	No.2	No.3	
Cu	0.0481	max 0.03	max 0.07	max 0.07	0.03-0.06
Sb	<0.0010	max 0.02	max 0.10	max 0.02	max 0.005
Bi	*	max 0.05		max 0.025	max 0.100
Ag	0.0029				max 0.005
Sn	<0.0010	max 0.075	max 0.50	max 0.005	max 0.05
Zn	<0.0010	max 0.005	max 0.005	max 0.005	max 0.001
Te	*			0.04-0.065	
O	0.0145				
Al	0.0539				
Si	0.0142				
C	0.0032				
Other		max 0.02	max 0.075	max 0.02	max 0.005
Lead	99.86	min 99.80	min 99.25	Balance	Balance

*Not measured

The hydrogen content was found to be 2ppm on arrival and 3ppm after test, the error on these measurements is ± 1 ppm. The test certificate for these measurements is given in Appendix C.

4.2.2 SSRT testing

Figure 18 gives the stress strain traces for four air tests and three hydrogen tests and results are summarised in Tables 6-7. The three hydrogen traces show significantly more noise than the air ones. This is likely to be due to the uneven slipping of the pull rods through the pressure vessel seals.

Table 6 gives the reduction of area and elongation measured on specimens post-test. There is not a significant change in these properties when comparing the air and hydrogen data. The HEE index in both cases is close to 1 (Table 8).

The tensile properties measured in hydrogen are slightly lower than those measured in air (Table 7). However the greatest decrease was seen in ultimate tensile strength, a HEE index of 0.82 (Table 8).

Table 6 Mean and range of elongation and reduction in area in hydrogen and air for lead specimens.

Property	Environment	Mean (%)	Range (%)	Standard deviation (%)
Elongation	Hydrogen	25.8	20.3 to 29.1	4.4
	Air	25.5	23.1 to 27.4	1.8
Reduction of area	Hydrogen	89.1	89.1 to 91.1	1.7
	Air	87.6	87.6 to 89.1	1.6

Table 7 Mean and range of yield and UTS in hydrogen and air for lead specimens.

Property	Environment	Mean (MPa)	Range (MPa)	Standard deviation (MPa)
Yield strength	Hydrogen	4.7	3.5 to 5.5	1.0
	Air	5.1	4.6 to 6.0	0.6
UTS	Hydrogen	6.2	5.9 to 6.7	0.5
	Air	6.6	5.9 to 7.1	0.5

Table 8 HEE index calculated comparing SSRT data for malleable iron tested in hydrogen to those tested in air for lead specimens.

Material property	Yield	UTS	Elongation	Reduction of area
HEE index	0.92	0.82	0.96	1.02

4.3 Fractography

Figures 19-20 show fracture faces of one lead specimen tested in air and one in hydrogen, respectively. The actual region which can be described as a fracture surface is very small thanks to the large amount of ductile deformation which occurred during test. The sides of these specimens were examined to look for any signs of secondary cracking (Figures 21-22), which would be an indication of embrittlement. (Secondary cracking is a mechanism by which a network of cracking can occur on the smooth surface of the specimen, usually there is a circumferential nature to these cracks due to the loading direction of the specimen.) No secondary cracking was found on either specimen. It can therefore be concluded that both the specimen tested in air and in hydrogen behaved in a fully ductile manner during the test.

5 Discussion

5.1 Malleable iron

The fracture surfaces all show that there is a high proportion of carbon rosettes and cast defects. In air, the remaining ferrite failed by a ductile overload mechanism whereas in hydrogen the ferrite failed in a mixed mode which also includes quasi-cleavage. Quasi-cleavage is typical of a fracture which has been influenced by hydrogen.

However, although the failure mechanism is clearly affected by the presence of hydrogen, the mechanical data is not vastly different especially if the data for M01-08 is excluded. It is important to remember though that features such as that found on this fracture surface are not unusual in cast iron products. For this reason, there will always be a lot of scatter in any mechanical data from cast iron products.

This data is for a typical cast iron found in service but may not be representative of all cast irons found in service.

The hydrogen measured in as-received material and material post-test were the same. Both values were low. This suggests that there was little/no uptake of hydrogen during test.

5.2 Lead

The data measured during hydrogen test exhibited a lot of noise. Normally this is an effect that is insignificant when compared with the test loads, however for these extremely low load tests it is significant. Another point of significance is that the ductility measured on the specimens post-test (Table 6) does not match the elongation data seen in the traces.

The post-test ductility measurements on specimens showed that there was no reduction in ductility between specimens tested in air and hydrogen. As these are measurements made on the specimens themselves, they are accurate assessments of the ductility of the specimen. These measures do not show any difference in behaviour between the specimens tested in air and hydrogen. This is reflected in the HEE index calculated for these two metrics (Table 8) which are both close to 1.

Although there is some reduction in tensile properties (yield and ultimate tensile strength) in hydrogen, the lowest HEE index calculated is 0.82 (Table 8). This value does not show a large decrease in behaviour.

It is unusual for materials to have reduced yield and UTS in hydrogen; ductility is usually the property which is most effected (Lee, 2016), however it should be noted that no previous SSRT data for lead was found. Given the uncertainty from this test data in terms of the ductility measured during the test, it is possible that the errors in measurement are greater than the differences found in the data.

Based on the ductility measurements performed on the test specimens and the fractographic examination, there is no effect of hydrogen on the properties of this material.

The total hydrogen measured on as-received material and post-test were 2ppm and 3ppm respectively. These values are within experimental error one another. This would suggest that little/no hydrogen is gained during the test.

6 Conclusions and Recommendations

6.1 Malleable iron

The following conclusions can be drawn from this study:

1. The SSRT test data are similar in air and hydrogen although it should be noted that elongation is reduced by the presence of hydrogen. Yield stress, UTS and reduction of area at failure were found to be similar in air and hydrogen.
2. There is an influence of hydrogen on the failure mechanism of malleable iron.

Further data would be required to change the status of cast iron from 'amber' to either 'red' or 'green'. This should include more specific test types which will be more representative of service stresses than SSRT testing. This could include further testing with consideration of other types of cast iron likely to be found in service.

6.2 Lead

The following conclusions can be drawn from this study:

1. The test methodology used for SSRT tests does not produce accurate stress-strain curves; therefore no conclusions have be drawn from this data.
2. Based on the ductility measurements and the post-test fractographic examination performed on the test specimens, there is no effect of hydrogen on the properties of this lead.

7 References

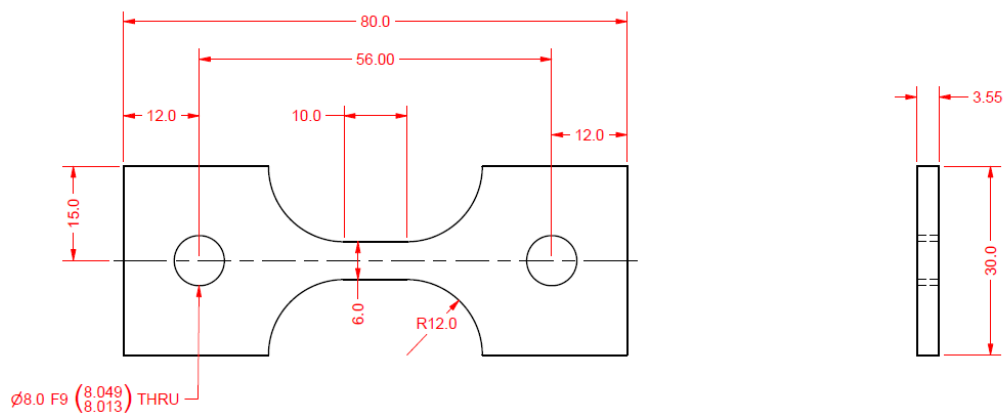
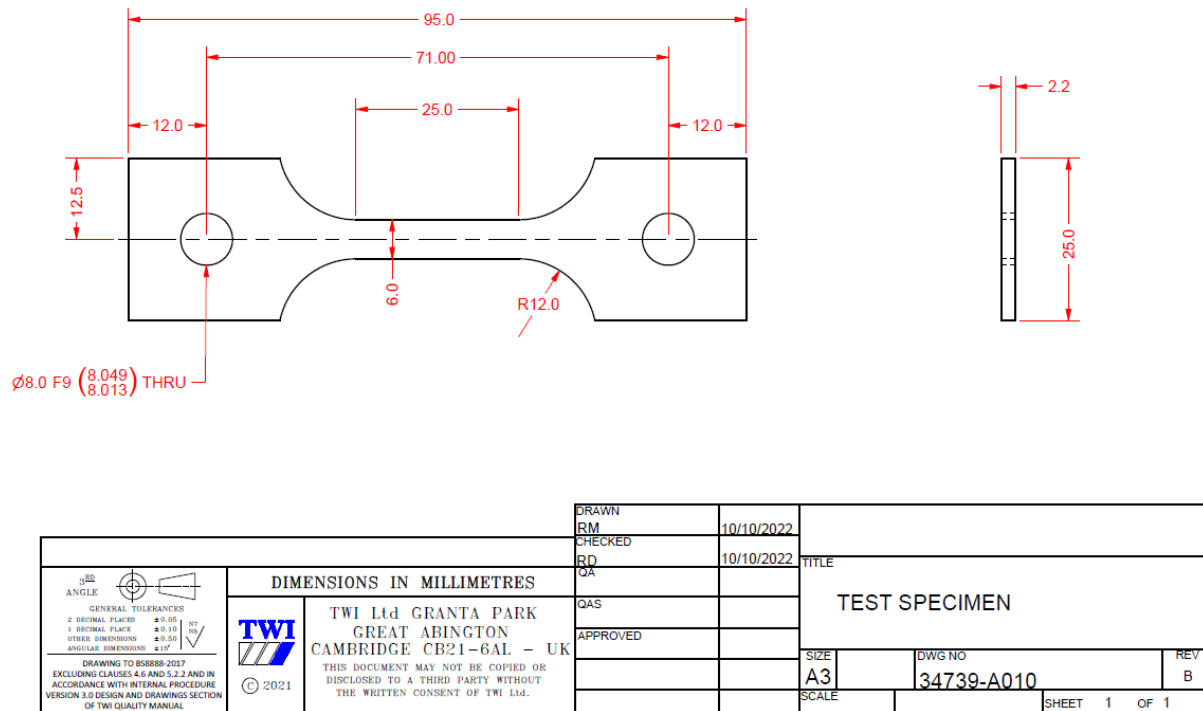
ASTM G142-98 (Reapproved 2022) 'Standard Test Method for Determination of Susceptibility of Metals to Embrittlement in Hydrogen Containing Environments at High Pressure, High Temperature, or Both'

BS2789 (1985) 'Spheroidal graphite or nodular graphite cast iron'

Lee J.A., 'Hydrogen Embrittlement' NASA/TM-2016-218602 (2016)



Figure 1 Photograph of malleable iron tee piece on arrival at TWI, note scale indicated by cm ruler.



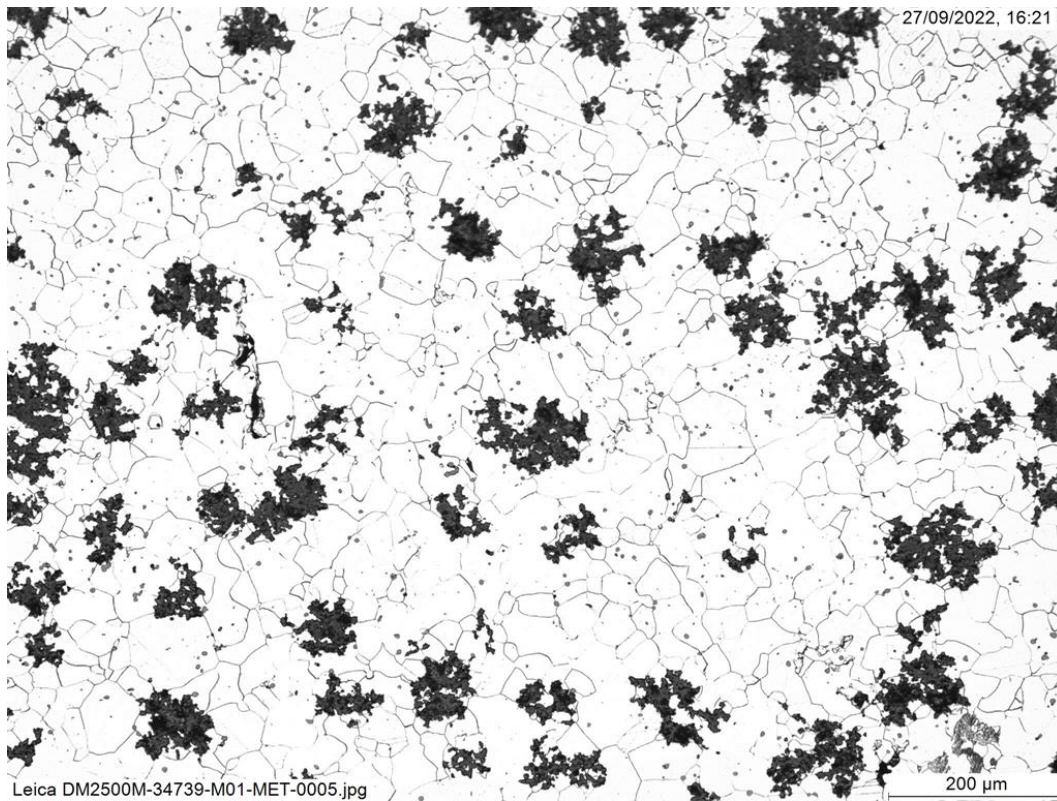


Figure 4 Photomicrograph of ferrite and graphite rosettes found in malleable iron. Etched in Nital. Magnification indicated by micron marker.

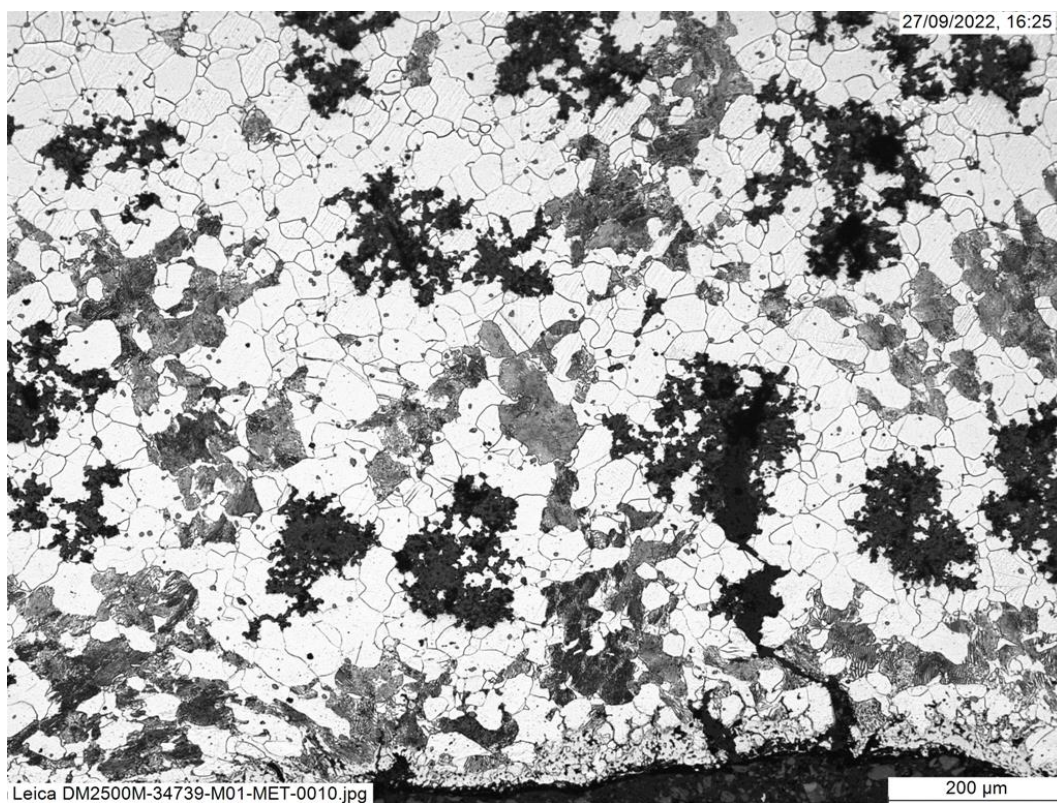


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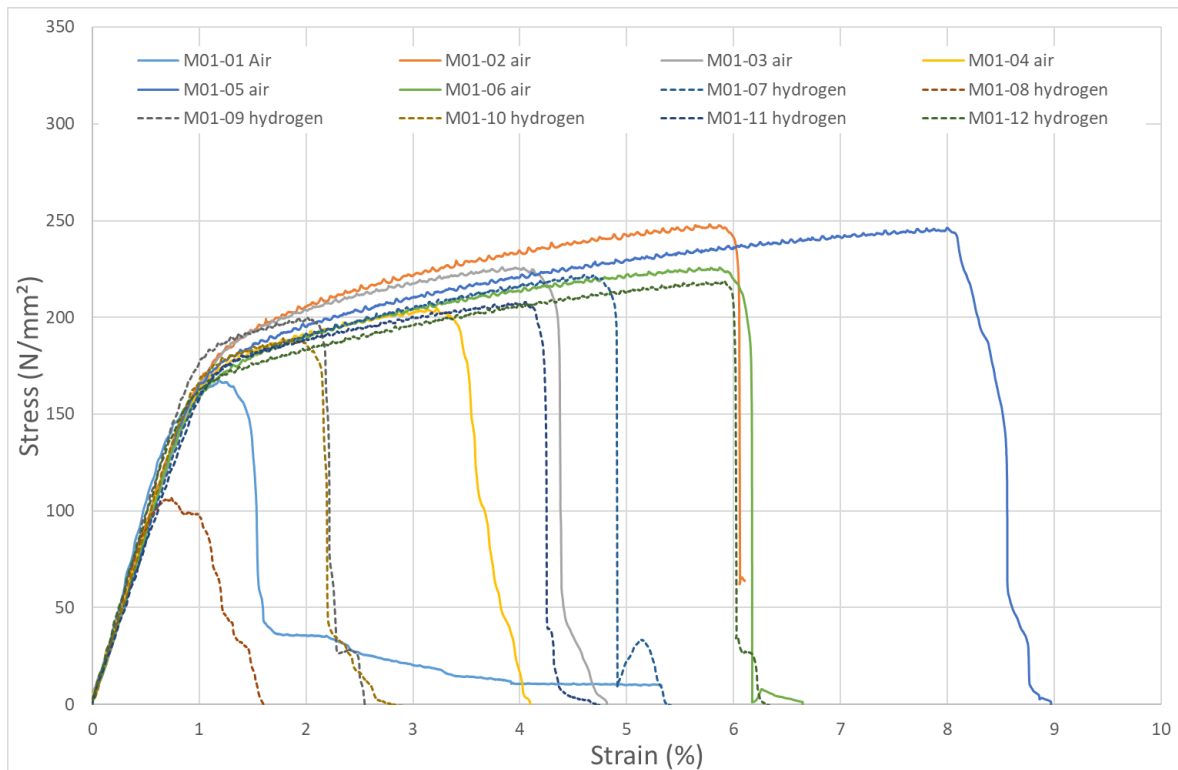


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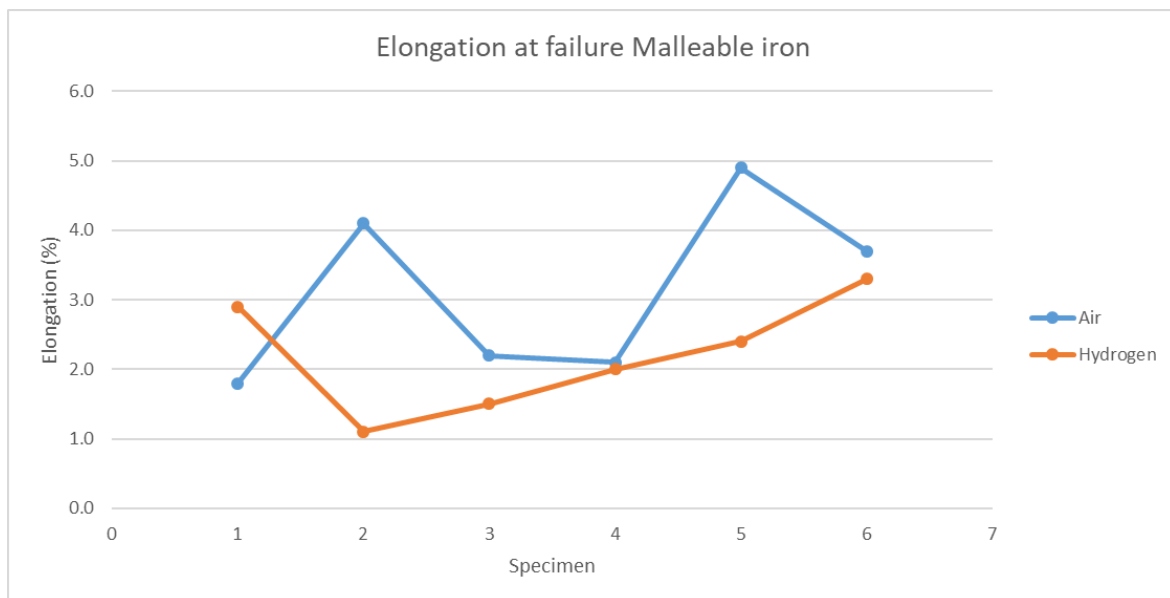


Figure 7 Elongation at failure measured after SSRT tests on malleable iron, both in air and hydrogen. Note that the second hydrogen result is from a sample which had a large non-rosette carbon feature on its fracture surface which will have contributed to its reduced ductility.

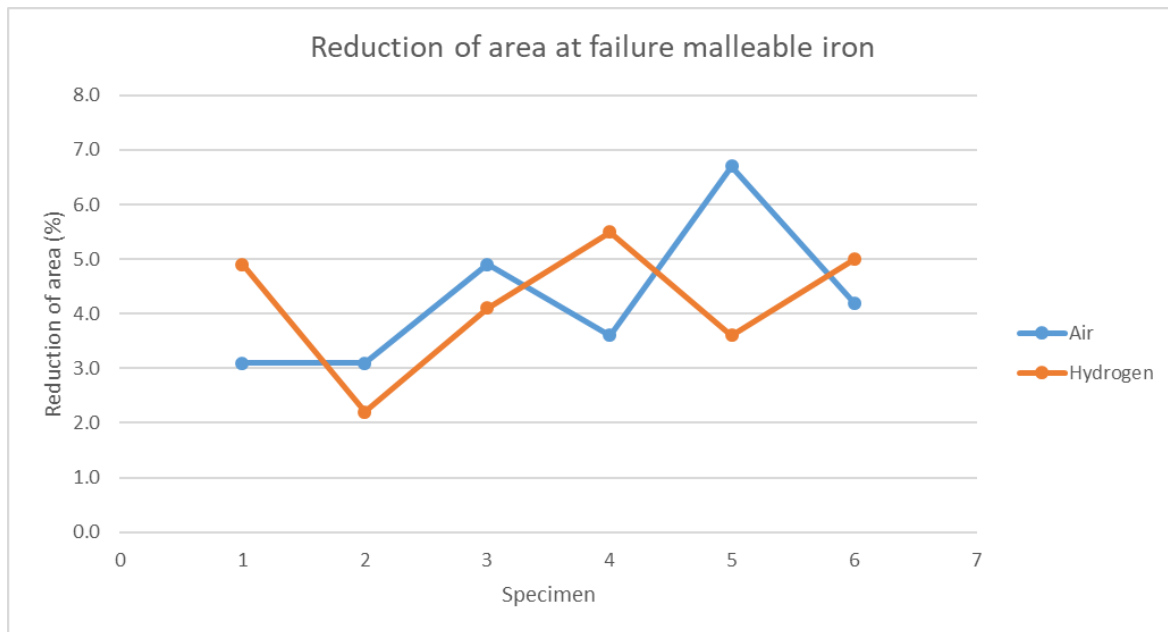


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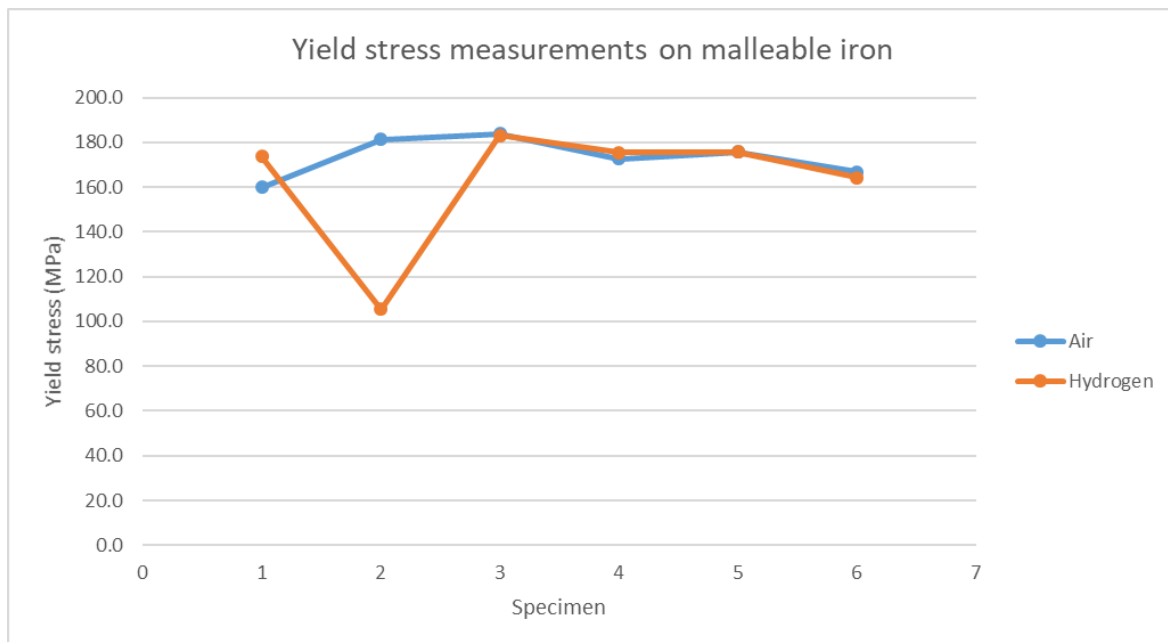


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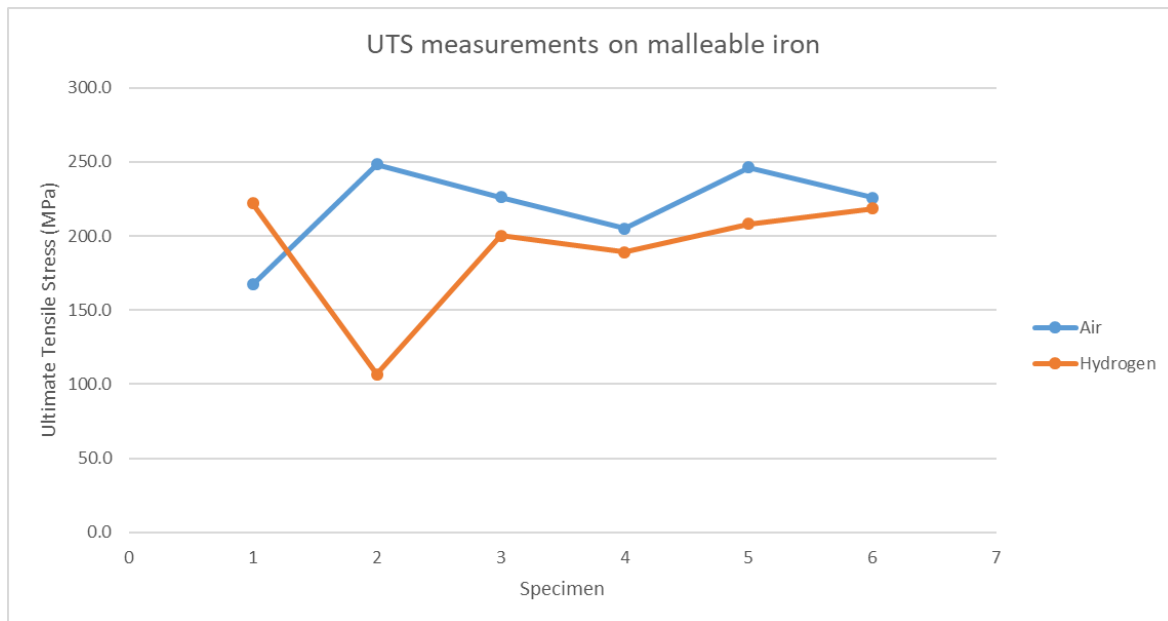


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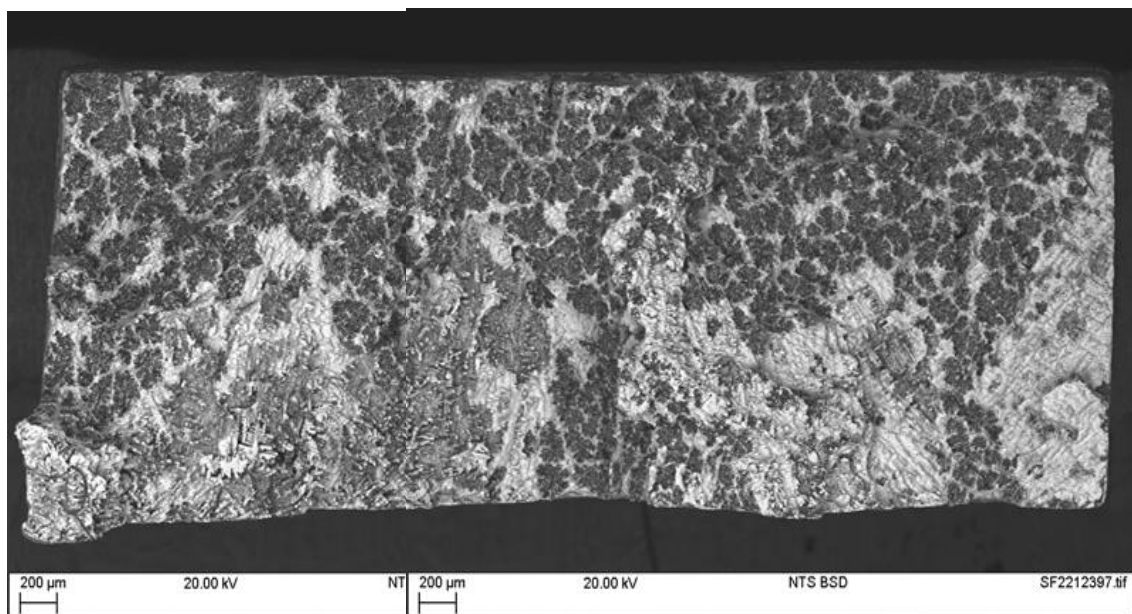


Figure 11 SEM images showing fracture surface of specimen M01-01 which was tested in air. Magnification indicated by micron marker.

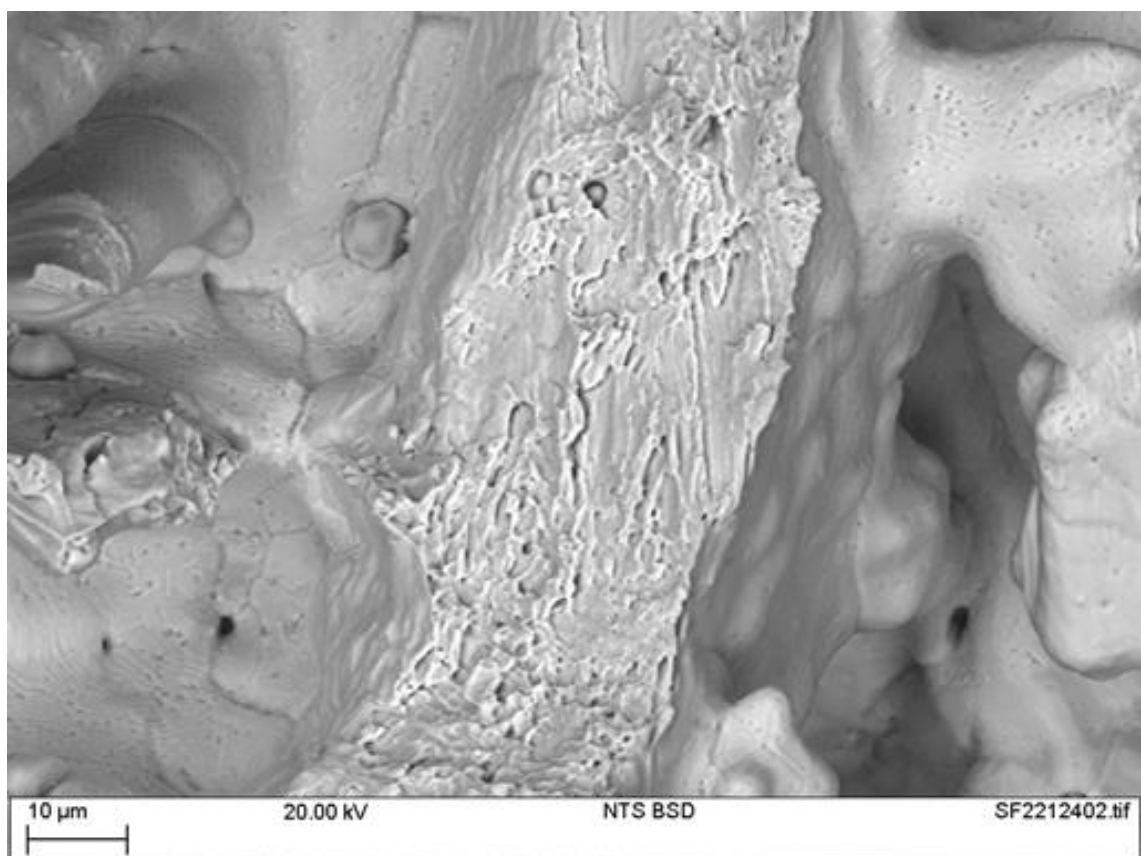


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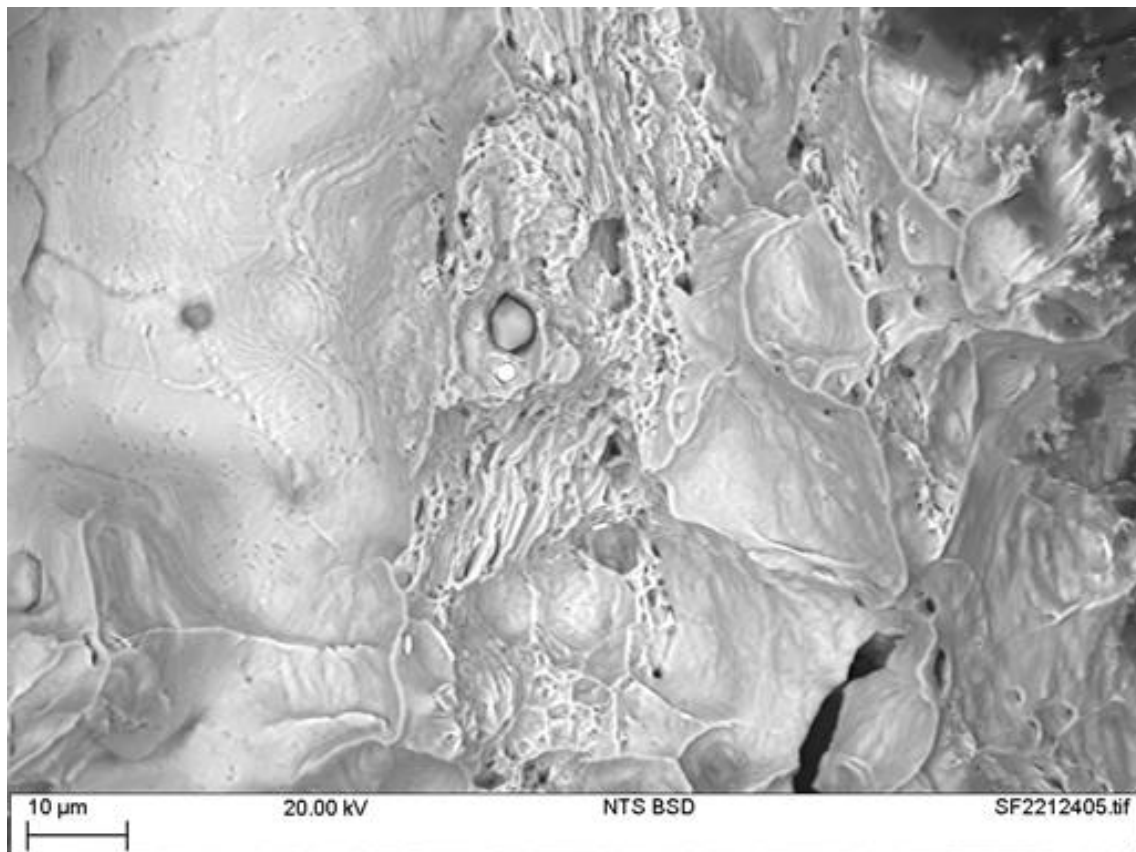


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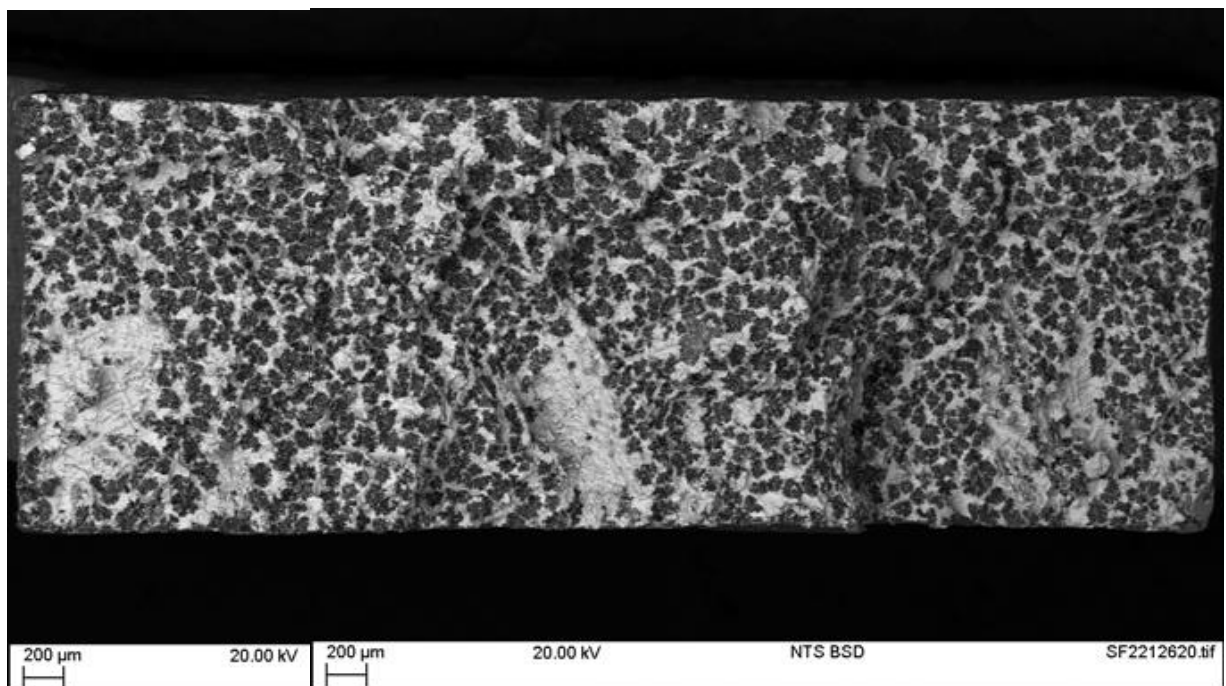


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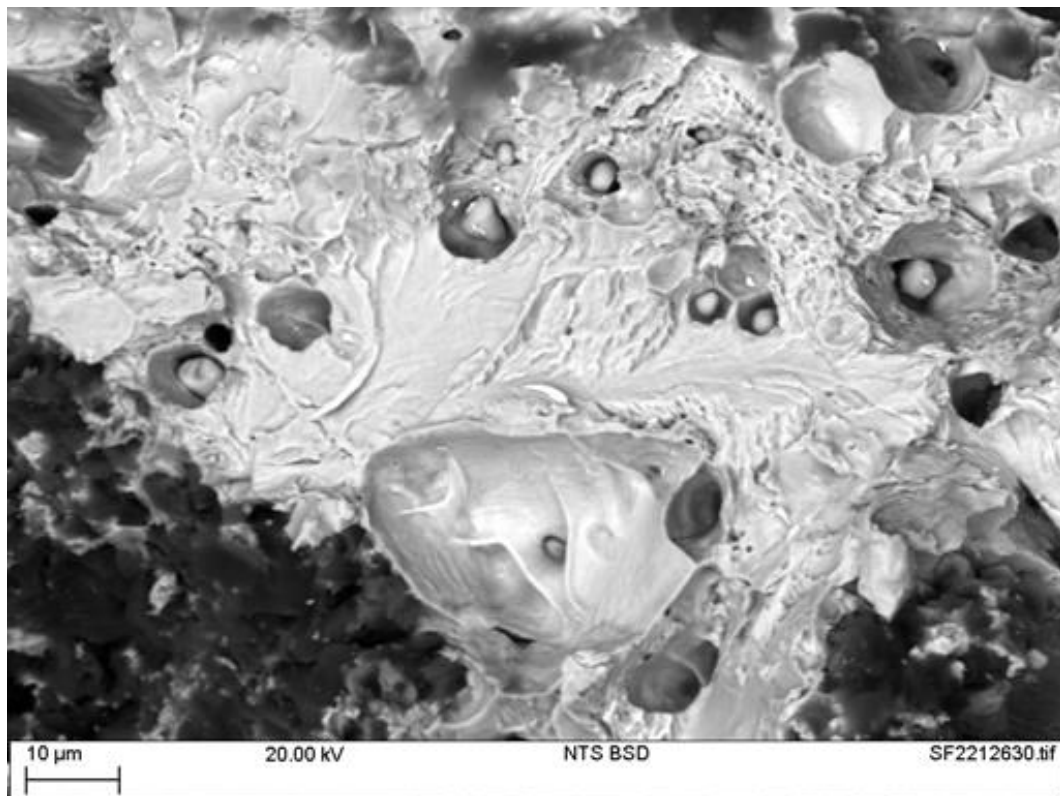


Figure 15 SEM image of typical detail on fracture surface of specimen M01-11 which was tested in hydrogen. Magnification indicated by micron marker.

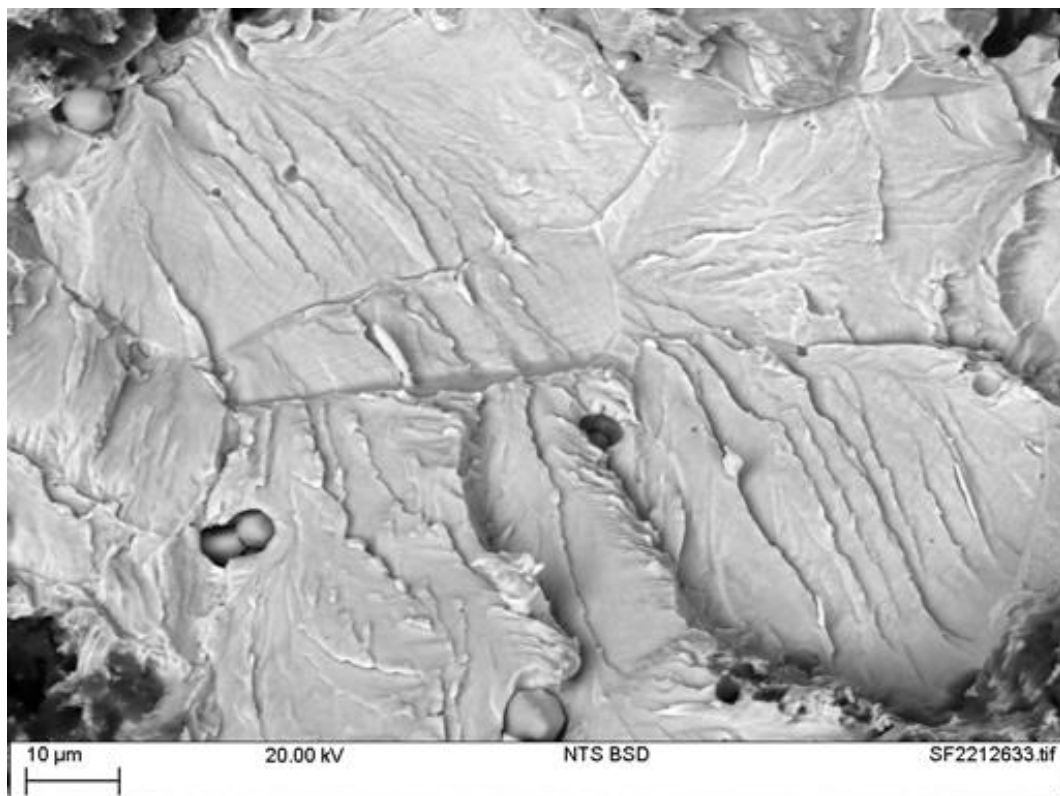


Figure 16 SEM image of typical detail on fracture surface of specimen M01-11 which was tested in hydrogen. Magnification indicated by micron marker.

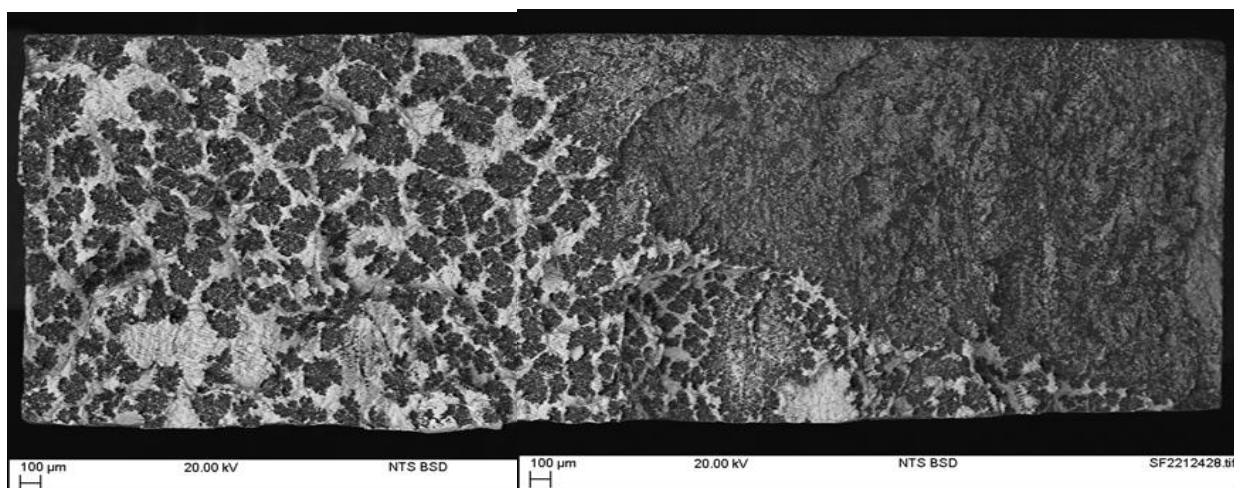


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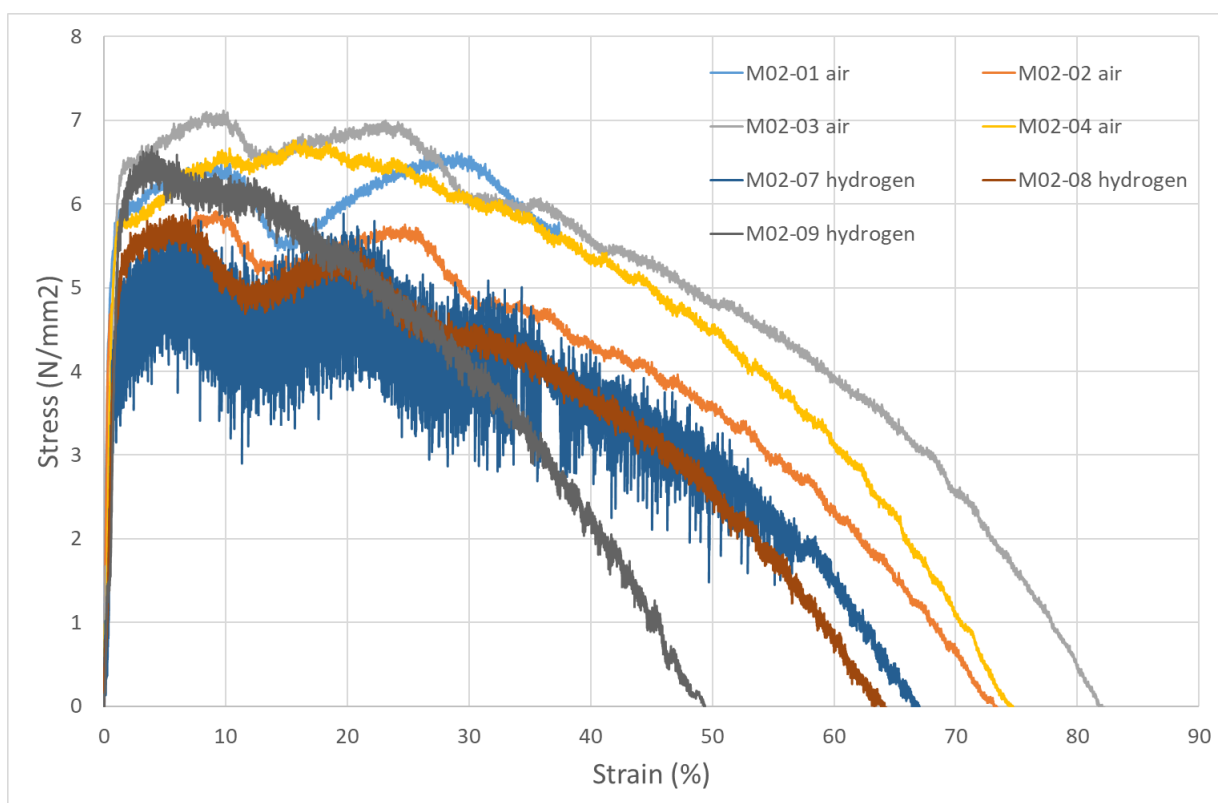


Figure 18 Summary of stress strain curves from SSRT tests on lead, both in air and hydrogen.

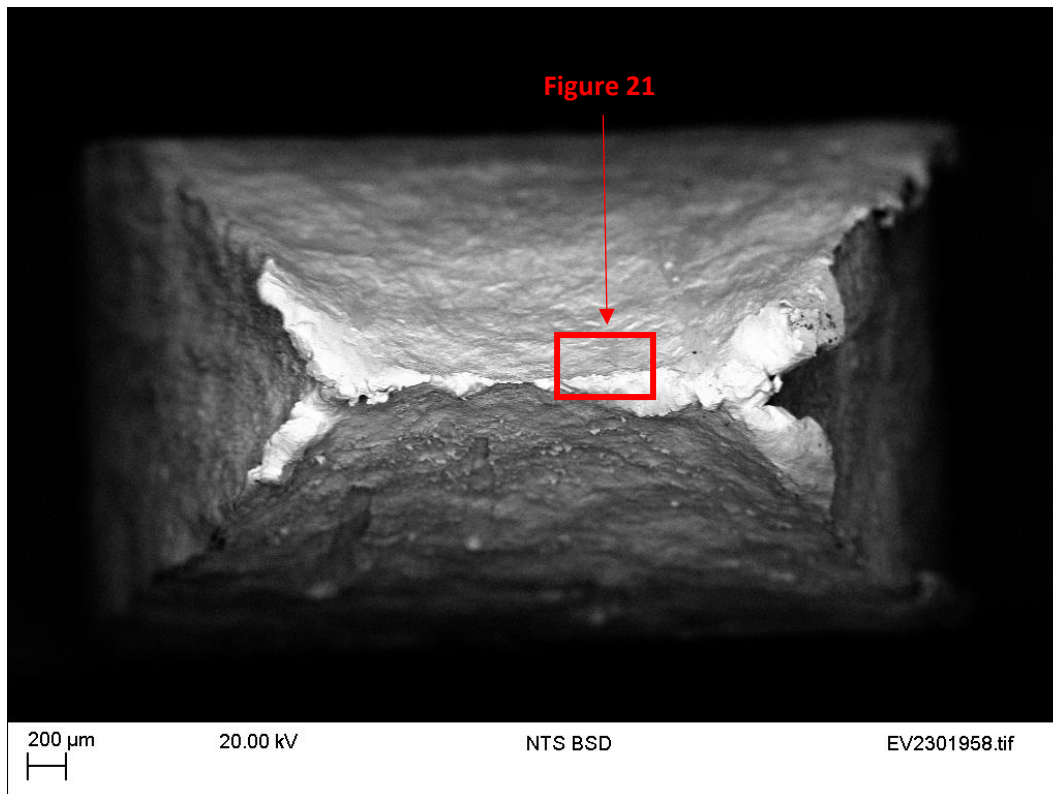


Figure 19 Scanning Electron Micrograph of fracture surface of lead specimen tested in air (M02-01). Magnification indicated by micron marker.

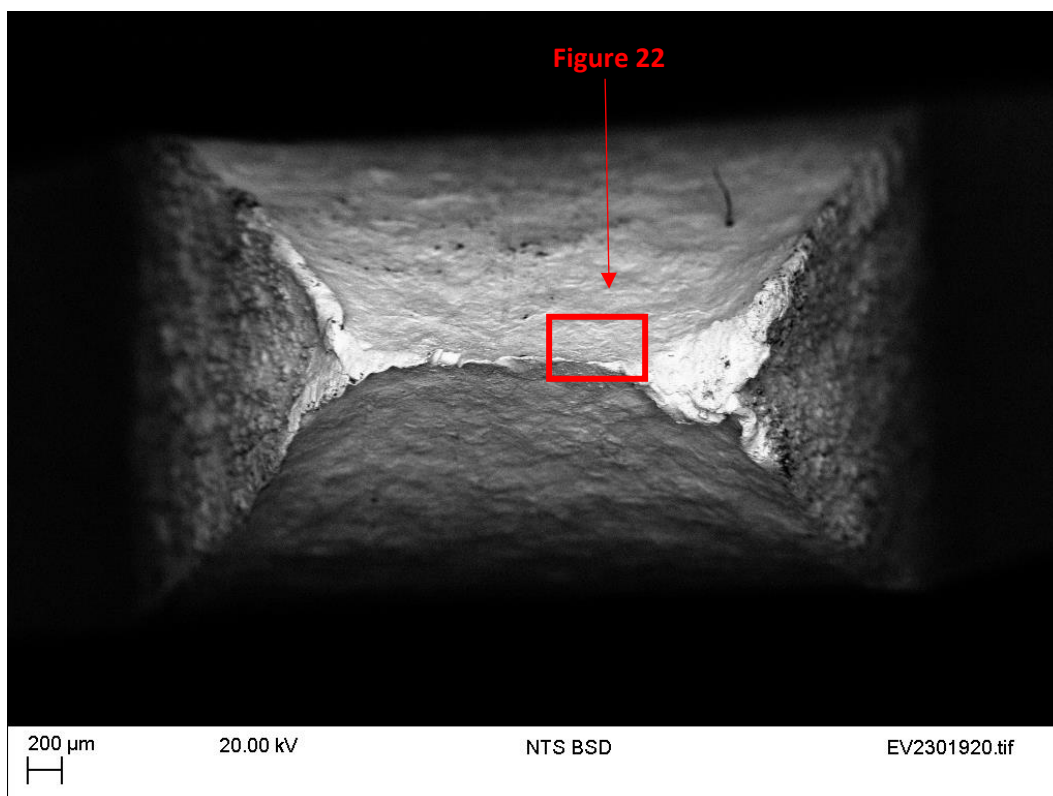


Figure 20 Scanning Electron Micrograph of fracture surface of lead specimen tested in hydrogen (M02-07). Magnification indicated by micron marker.

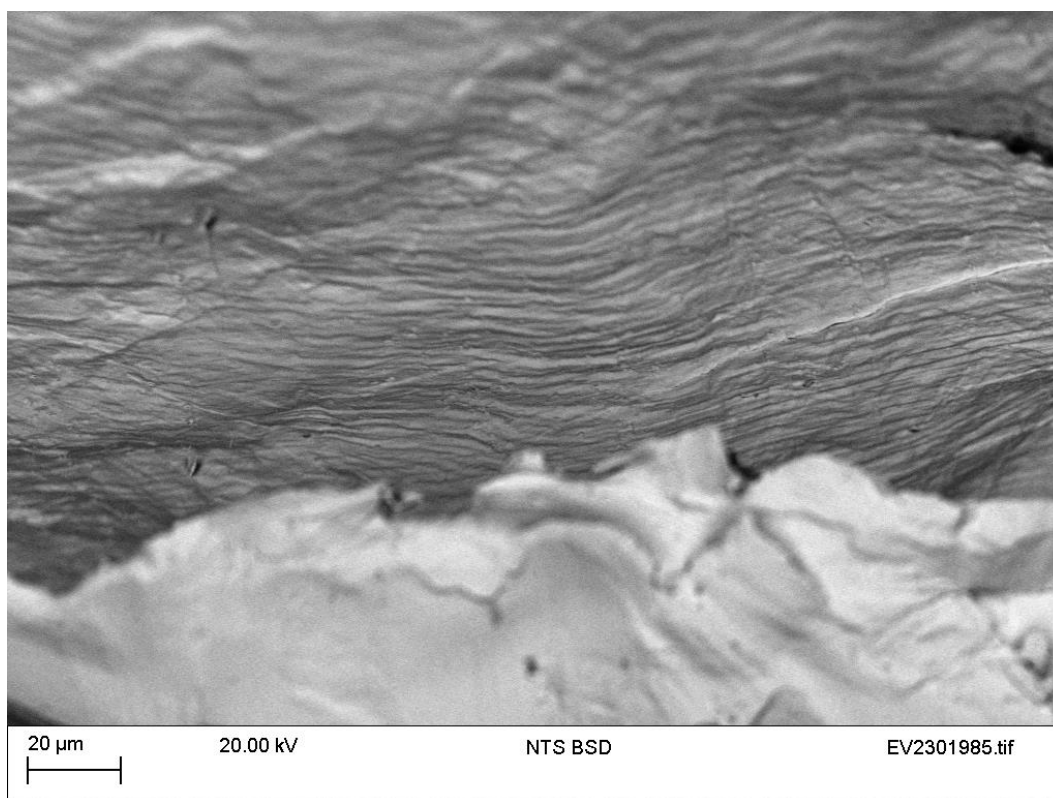


Figure 21 Scanning Electron Micrograph of side of specimen adjacent to fracture surface of lead specimen tested in air (M02-01). Magnification indicated by micron marker.

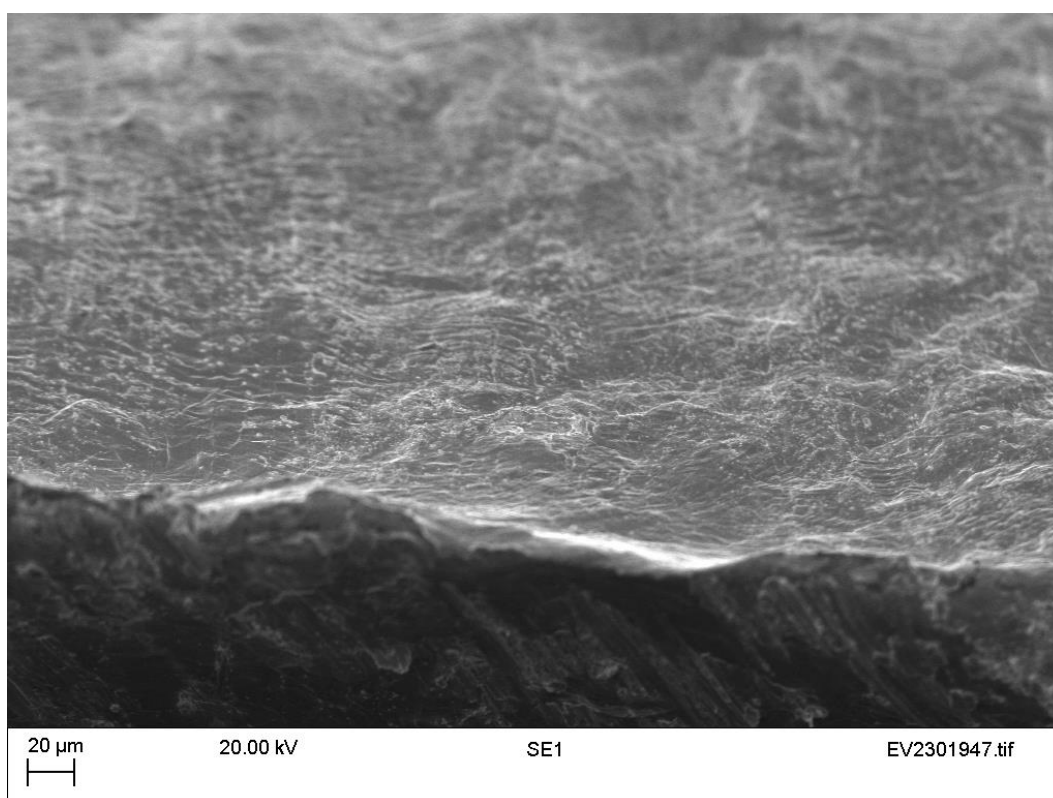


Figure 22 Scanning Electron Micrograph of side of specimen adjacent to fracture surface of lead specimen tested in hydrogen (M02-07). Magnification indicated by micron marker.

Appendix A

TWI Report 34739/2v2: Provision of Hydrogen End User Skills and Standards for Heat Supporting Research and Evidence – Literature Review



Report No: 34739/2v2/23

August 2023

For: Department for Business, Energy & Industrial Strategy

A large blue abstract graphic featuring a faint world map and geometric shapes. The title text is overlaid on this graphic.

Provision of Hydrogen End User Skills and Standards for Heat Supporting Research and Evidence – Literature Review

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Hydrogen Skills and Standards for Heat Programme (NZIP)

The Hydrogen Skills and Standards for Heat programme is working towards the development of technical standards for domestic and non-domestic hydrogen gas installations, and on associated competence frameworks and training specifications for installers. These will enable re-purposing of the existing natural gas system to be used with 100% hydrogen downstream of the emergency control valve (ECV). The standards developed should define the required criteria to safely repurpose existing natural gas equipment for hydrogen, to design and install new hydrogen safe pipework and appliances, and to train a workforce of competent hydrogen gas installers. This work will support future community trials of hydrogen heating and will contribute evidence to inform strategic decisions in 2026 on the role of hydrogen in heat decarbonisation. The programme forms part of the Department for Energy Security and Net Zero, Net Zero Innovation Portfolio, NZIP.

Under the programme, the British Standards Institution (BSI) will develop a series of Publicly Available Specification (PAS) standards. These should codify an agreed set of principles, requirements and guidance on the functionality, safety, installation, operating and servicing requirements for hydrogen meters, pipework, fittings, and ancillary devices. The Institution of Gas Engineers and Managers (IGEM) will develop two hydrogen enabling standards covering installation requirements for gas installers in domestic and non-domestic scenarios (up to light industrial sites). The standards should cover considerations for new hydrogen installations and re-purposing of existing gas infrastructure. Energy and Utility Skills (EUS) will codify both the IGEM domestic and non-domestic enabling standards into competency frameworks and training specifications to facilitate the training of a competent workforce for a village trial. Accredited Certification Scheme (ACS) assessment criteria and Approved Code of Practice (ACoP) assessment modules for both enabling standards should be developed, working with industry to ensure there is a clear path for existing competent engineers to train for hydrogen installations.

A number of contracts within the programme have been awarded to suppliers to undertake technical research and evidence gathering to support the development of the above standards. This document is the final project report for "Provision of Hydrogen End User Skills and Standards for Heat Supporting Research and Evidence – Literature Review".

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Executive Summary

Background

In order to introduce hydrogen as an alternative fuel for the UK, there is a need to determine whether existing gas transmission infrastructure can be operated with up to 100% hydrogen gas, and to review the potential for deploying new infrastructure to enable this. Research in this area, until recently, tended to focus on the high pressure transmission network, but the safety implications of this in the low pressure systems operating in domestic and small commercial buildings will also need to be assessed.

This report covers the literature review of the scope of work in Lot 2 of Tender 'Provision of Hydrogen End User Skills and Standards for Heat Supporting Research and Evidence', Reference Number: 5045/04/2021.

Objectives

- To further our understanding of the suitability of materials, both new and also, currently in service, for low pressure systems downstream of the ECV for 100% hydrogen service.
- To gather evidence to support the findings of the IGEM/H/1 reference Standard.

Work Carried Out

A list of relevant materials was derived from published data, Standards and current domestic gas supplier data sheets, covering the majority of current materials and key historic materials.

A search of publically available was made in order to find any data to help determine the suitability of each of these materials for this service. A classification methodology was developed to allow materials to be allocated a 'Red', 'Amber' or 'Green' rating. Material classes which would need further testing before being considered to be suitable are identified. A proposed test plan will be issued as a separate document.

Conclusions

Information and data on the suitability have been gathered for a number of metallic and non-metallic materials considered to be most likely to be present in existing service. A review of the information was conducted and the materials were classified as to their suitability for low pressure hydrogen service.

The results show that metallic materials generally fall into the 'Green' or 'Amber' categories. Those which fall into the 'Green' categories do not need testing prior to service in pure hydrogen, these are carbon steels, austenitic steels and aluminium alloys.

There was very little or no information on lead, cast iron, solders and brazing materials in hydrogen service. For most metallic material placed in the 'Amber' category, more information from limited testing on their performance may be sufficient to place them in the 'Green' category. For lead, cast iron, solders and brazing consumables, the recommendation is for a more comprehensive testing programme to generate evidence for their suitability of use.

For non-metallic materials there are a range of materials that could be present. To date many of the studies recorded in the open literature are for exposure to high pressure hydrogen gas during which swelling and rapid gas decompression damage are a concern. The published studies where low pressure hydrogen gas was present are a first guide suggesting that for most polymeric materials there will not be a substantial alteration on first saturation unless there is the potential for chemical alteration or additive elution. The absence of long-term exposure data means that one cannot definitively say that a non-metallic material will behave appropriately for the duration of the product.

To this end, the materials have been given an 'Amber' classification until such time as there is a relevant data set.

One major point that has been highlighted in this review during the assessment and classification process is the lack of guidance on acceptance criteria for low pressure hydrogen service. This has placed an emphasis on expert opinion in the assessment for some materials. Going forward, more clarity on acceptance criteria for materials in hydrogen service would be beneficial in the development of Standards and guidelines, not only for existing material but also for new materials.

In addition, testing to generate evidence to support the case of whether a particular material is suitable for hydrogen service would also benefit from clarity of an acceptance criteria. If testing is required, with a clear set of acceptance criteria, stakeholders would be able to define the type of testing and test conditions to generate the appropriate data required to make the assessment. This may also lead testing to become more standardised so that data, generated by different laboratories test-houses, can be directly compared and consistent data on the performance of materials be added in the future.

1 Introduction

In order to introduce hydrogen as an alternative fuel for the UK, there is a need to determine whether existing gas infrastructure can be operated with up to 100% hydrogen gas, and to review the potential for deploying new infrastructure to enable this. Research in this area, until recently, tended to focus on the high pressure transmission network, but the safety implications of this in the low pressure systems operating in domestic and small commercial buildings will also need to be assessed.

This report covers the literature review of the scope of work in Lot 2 of Tender 'Provision of Hydrogen End User Skills and Standards for Heat Supporting Research and Evidence', Reference Number: 5045/04/2021.

2 Objectives

- To further our understanding of the suitability of materials, both new and also, currently in service, for low pressure systems downstream of the ECV for 100% hydrogen service.
- To gather evidence to support the development of Standards by organisations such as IGEM and BSI.

3 Definitions and Scope of Literature Review

3.1 General

The following paragraphs detail the definitions and assumptions which were made to define the boundaries for carrying out this literature review.

3.2 Service environment

The following conditions were based on the scope of work defined by BEIS:

- Product: 100% hydrogen gas;
- Pressures: up to 75mbarg (1.075bara);
- Temperatures: -30°C to +50°C;
- Service life: undefined.

3.3 List of materials

A list of relevant materials was derived from published data, Standards and current domestic gas supplier data sheets, covering the majority of current materials and key historic materials. Table 1 gives a list of materials which were considered in this literature review, broken down into components categories. This list is not exhaustive but it covers the majority of materials commonly found in existing, or new, gas systems in domestic and commercial buildings in the UK.

The list of materials and the literature review are divided into two groups of materials, metallic materials, which includes; ferritic alloys, corrosion resistant alloys, solders, brazes and non-metallic materials, comprising thermoplastics and elastomers.

3.4 Assessment criteria

The assessment criteria for whether a certain material is suitable for low pressure hydrogen service, as defined by BEIS, are as follows:

- Fully relevant (Green) – the material can be regarded as being acceptable for use in a 100% hydrogen gas system operating within the service environment criteria. No further testing required;
- Partially relevant (Amber) – focussed testing is required to address specific aspects, before the material can be classified as acceptable or not acceptable;
- No relevant evidence (Red) – full testing required to provide new evidence to allow classification as acceptable or not acceptable.

For ease of understanding, the traffic light system has been adopted by the authors in this literature review, to represent the results of the assessment.

3.5 Classification methodology

The classification methodology adopted in this literature review to determine whether a material is suitable for 100% hydrogen service is summarised in the flowchart shown in Figure 1. The process firstly considers whether there is sufficient relevant data and information available, relating to each group of materials, to support the classification process. Depending on the availability of sufficient relevant data, the classification is either 'suitable' (Green) or 'not suitable' (Red). If there are few relevant data, doubts in the quality of the data or missing data, then the material is classified as 'uncertain' (Amber).

Materials can also be classified as being suitable (Green), based on expertise and inferred from supporting data. For example, if a material has been tested in a 100bar hydrogen environment and there are minimal or no effects on its properties, even if data for testing at 0.75mbar are not available, it can be inferred that the material is also likely to perform similarly or better at lower pressures. Where appropriate, data from higher temperature service have been used, this is justified in the relevant section of this report.

Materials in the 'Amber' category can be re-assessed, if relevant data and information become available. One route to obtain more supporting data is via testing of the material either in a partial testing programme or a more comprehensive testing programme. Material with some information may only require partial testing, but material without any data may require a more comprehensive test programme.

As might be expected from a review of this kind, the quality of referenced source materials plays a key role in the ability to classify a material as either acceptable or unacceptable (i.e. green or red, respectively). Whether or not source materials are deemed to be of sufficiently high enough quality to make a judgement on compatibility is determined by expert assessment, with justification provided under the appropriate subsections of this report. Where data are questionable and/or primary information has not been made available, a material will have been classified as amber.

4 Compatibility of Metallic Materials for Low Pressure Hydrogen Service

4.1 General

The information in this section of the report is considered to be baseline knowledge and is provided as a background to the later parts of this review document.

4.2 Interaction of hydrogen with metallic materials

The entry of atomic hydrogen into metallic systems can reduce mechanical properties such as tensile strength, toughness and ductility. Macroscopically this phenomenon is known as 'hydrogen embrittlement' (HE). Unfortunately, the micro-mechanisms and factors influencing susceptibility to HE are not yet fully understood, which can make it difficult to confidently select materials that are not susceptible. However, it is generally accepted that for hydrogen embrittlement to occur, three critical components need to be present:

- A susceptible microstructure;
- Tensile stress;
- A source of hydrogen.

If threshold conditions of high hydrogen concentration and stress are exceeded at the location of a sensitive microstructure, then cracks will initiate. Likewise, reduction or complete eradication of one of these variables can reduce or prevent cracking altogether.

4.3 Adsorption on the surface and absorption of hydrogen into the material

Hydrogen can enter a metal alloy during manufacture and processing (e.g., casting, welding, chemical pickling, electrochemical machining, electroplating and heat treatment), or through environmental exposure during operation (e.g. gaseous hydrogen exposure at elevated temperatures).

Developing an understanding of the key factors that control sorption processes of hydrogen on metallic and non-metallic materials is vital in order to develop a fundamental understanding of the behaviour of engineering materials in service. Sorption is the general term given for all modes of uptake of species at a surface. Adsorption refers to the series of events by which species (atoms, ions or molecules) bind to the surface of a material (the adsorbent). By contrast, absorption is the process of uptake of species within the bulk of a material, i.e. the adsorbate is dissolved in the host adsorbent.

Adsorption is the precursor to all modes of hydrogen uptake by materials, i.e. diffusion, sub-surface state population, bulk absorption, permeation and/or hydride formation, and hence a fundamental phase in the development of all forms of hydrogen damage.

The surface condition of a material will affect the amount of hydrogen which can enter a metallic material. An atomically clean surface will allow sorption and dissociation of hydrogen molecules much more readily than an oxidised surface. For example, an aluminium surface will typically have a tenacious oxide layer which will mean very little hydrogen can enter the material. Oxide layers found on materials including carbon steels and austenitic materials will also provide a greater barrier to hydrogen than a recently polished surface.

It should be noted that if material is strained in the presence of hydrogen, it will be forming new atomically clean surface. This means that materials tested in the presence of hydrogen can potentially suffer more embrittlement than those pre-charged in hydrogen and tested in other environments. Therefore, for some materials it will be appropriate to test in hydrogen and not pre-charge if hydrogen can move relatively easily through the crystallographic structure. However, for other materials, charging with hydrogen will be important in order to replicate the hydrogen levels present in service.

Where diffusion of hydrogen is fast, performing tests in air would give an opportunity for the hydrogen to escape, prior to fracture, meaning that hydrogen embrittlement effects may not be observed.

4.4 Significance of sub-surface concentration of hydrogen in metals

Following surface adsorption, further penetration of hydrogen from the sub-surface plane of the lattice into the bulk is controlled by diffusion, whose boundary condition is the sub-surface concentration of hydrogen. For any given metallic substrate (composition, microstructure, defect type (hydrogen trapping site) and concentration, etc.), the equilibrium solubility of hydrogen is governed by the temperature and hydrogen partial pressure, irrespective of the surface and/or subsurface conditions.

The driver for ingress of hydrogen into a microstructure is the total chemical potential, which indicates the direction and magnitude of diffusion gradients based on compositional gradients, stress gradients (related to the presence of secondary particles, dislocations, partial distribution of H, etc.) and electrical potential gradients and temperature. In essence, the diffusive flux of hydrogen is proportional to the gradient of the chemical potential of the dissolved hydrogen.

4.5 Trends for different metals and alloys

Hydrogen is characterised by a high mobility in metals and alloys. In face-centred cubic (FCC) lattices, such as those typically found in austenitic stainless steels, interstitial hydrogen generally prefers octahedral sites, while in body-centred cubic (BCC) and hexagonal close-packed (HCP) metals, interstitial hydrogen is located on tetrahedral sites at room temperature. The distance between the two nearest octahedral sites for FCC metals is around 0.2nm, which is almost twice that for the two nearest tetrahedral sites in BCC lattices. As a result, the diffusivity of hydrogen is generally lower in FCC metals compared to BCC metals.

The small size of the hydrogen atoms can facilitate permeation through the topmost atomic surface layers to the second, third etc. layers and diffusion via interstitial sites leading to the well-known solubility of hydrogen in the bulk of a number of metals. The large differences in hydrogen diffusivity between BCC and FCC crystal structures can be understood by calculating and comparing the distance of the nearest neighbouring interstitial sites in each unit cell.

4.6 Diffusion and solubility of hydrogen

The previous section of this document was concerned with the mechanisms of atomic hydrogen generation at the metallic surface (adsorption) and its entry into the material (absorption), which has been shown to depend strongly on interactions at the metal surface. However, whilst the subsurface concentration of hydrogen is related to the nature of the external environment, its behaviour, once dissolved within the bulk material (i.e. significantly subsurface), is nominally the same, irrespective of hydrogen source (i.e. whether gas phase entry, liquid phase entry etc.).

In simplistic terms, the rate of hydrogen diffusion is dictated by the potential for hydrogen atoms to migrate across the lattice of a material. Solubility is the relationship between the hydrogen content in a material and pressure and temperature.

The tendency of a metal to absorb hydrogen is first determined by its crystallographic structure. Indeed, hydrogen within the metal lattice is firstly located at interstitial sites and so their size and density are determinant.

Despite a substantial body of experimental work, and a number of theories being proposed to explain the interaction between hydrogen and metallic structures, the fundamental mechanisms of HE remain a controversial subject. What we do know is that dissociated and mobile ("diffusible") hydrogen will tend to migrate to regions of high stress, thus focussing its embrittling effect at crack-tips. The amount of hydrogen present, the crystallographic structure and the stress/strain levels will all have a significant effect on how much, if any, hydrogen embrittlement will occur in a given scenario.

In terms of the presence of hydrogen, it is important to consider how the continuous supply of hydrogen could potentially alter in-service mechanical properties versus materials that have previously been exposed but which are later operated in air. These two different hydrogen sources are often termed "external" and "internal" hydrogen embrittlement, respectively.

There are generally two approaches for generating testing data to assess whether a material is susceptible to hydrogen embrittlement, which are relevant to internal and external hydrogen. Special care should be taken when deciding which approach to take, to ensure the test is representative of the components and operating conditions in question.

- Approach 1: The first approach would be to attempt to pre-charge specimens with hydrogen offline, before testing them separately, without the continuous supply of hydrogen during the test itself. If specimens are to be pre-charged offline then it is necessary to estimate the through-thickness hydrogen concentration prior to testing. In cases where it is not possible to achieve a steady-state hydrogen concentration due to slow hydrogen diffusivity, it is necessary to consider the validity of the results, which might not be representative of long-term hydrogen exposure.

Specimens are sometimes pre-charged offline, in an accelerated manner, to rapidly achieve a steady-state, through-thickness hydrogen profile. This is normally achieved by increasing the temperature of the specimen during pre-charging (termed "thermal hydrogen charging"). When doing so, it is important to ensure that raising the temperature does not alter the material in a way that would not be experienced during service.

When materials are pre-charged offline and tested in air, it is particularly important to ensure that hydrogen losses do not occur during handling. Many materials, particularly carbon steels, will actively de-gas if the source of hydrogen is removed. To some extent hydrogen egress can be prevented by maintaining low temperatures, however, this can be difficult to achieve whilst the specimen is being instrumented, prior to conducting a mechanical test.

- Approach 2: The second approach is for specimens to be tested within a hydrogen-containing environment, with or without prior hydrogen pre-charging, so that hydrogen gas is continually in contact with the tips of any propagating cracks. The latter approach is experimentally more complex, as it requires a sealed pressure vessel to be used and for components of the load train and strain-monitoring equipment to be compatible with hydrogen gas.

4.7 Hydrogen traps

The presence of defects in the microstructure often increases the solubility, as they can potentially act as 'traps' for hydrogen. Examples of traps include:

- Grain boundaries;
- Phase boundaries;
- Dislocations;
- Interfaces between the matrix and inclusions;
- Vacancies.

Hydrogen traps are usually divided into two categories: deep or irreversible, and reversible. Categorisation is normally made on a case-by-case basis, depending on trap binding energy, operating conditions (e.g. temperature), and material.

Whether diffusing hydrogen becomes 'trapped' within the microstructure, or is able to diffuse easily from one interstitial site to another, is dependent on the potential energy well of the trap site. If the energy barrier of the trap site is significantly larger than that of the interstitial sites, diffusing hydrogen will sit within the site for longer than at the interstitial locations. In the extreme case, if the energy barrier for diffusion is sufficiently large, hydrogen is said to have become irreversibly trapped (given a constant temperature). For some material systems irreversible trapping is thought to be advantageous, as hydrogen is no longer free to diffuse towards the crack-tips, where it can participate in the fracture process.

An illustration of the energy wells that need to be overcome, so that hydrogen can move between sites, is presented in Figure 2. The activation energy of an interstitial diffusion site, E_a , is represented as a small energy well, and hence a low barrier for hydrogen diffusion from one site to another. Conversely, the reversible trap sites have larger energy wells and have an activation energy of E_t and binding energy of E_b . Provided thermal energy is sufficiently high, E_t can be overcome, and hydrogen is then able to jump out of the trap site and move to an adjacent energy well. As the binding energy becomes larger, there is a lower probability that hydrogen will be able to jump from the site in which it currently lies to the adjacent site. When the probability of hydrogen jumping from site-to-site becomes sufficiently low, the trap is said to be 'irreversible', although, as previously mentioned, there is no strict cut-off limit to this definition.

To confirm whether 'irreversibly' trapped hydrogen is able to participate in the fracture process, hydrogen pre-charged, slow strain rate specimens can be tested, without an active source of hydrogen charging during the test, provided any diffusible hydrogen has been removed, prior to testing. The ability for irreversible traps to prevent hydrogen from participating in the fracture process has led to the development of alloys, which have been tailored to include lattice defects to 'soak up' diffusing hydrogen. Alloys designed intentionally to include hydrogen traps represent an emerging area of research, for which further study is ongoing.

For simplicity, it has been assumed that all forms of lattice defects can influence hydrogen diffusion and can act as hydrogen traps. However, this is not always the case: for example, some defects within the metallic lattice, such as grain boundaries, can act also as 'highways', for fast transport of hydrogen through the material.

It should also be noted that trapping sites are not always beneficial.

For example, the oil and gas industry, in particular, is familiar with the problem of hydrogen pressure induced cracking (known as HIC or HPIC), in which hydrogen accumulates at inclusions, such as manganese sulphide in pipeline steels, causing blistering. Such voids between the inclusions and carbon steel matrix can also be classed as 'traps' albeit with the distinction that these do not become saturated by hydrogen. Rather, atomic hydrogen that reaches these interfaces with inclusions recombines to its molecular form ($H + H \rightarrow H_2$) and, in doing so, exerts a force on the neighbouring material. As hydrogen gas pressure increases within the void, the 'blister' grows larger. Consequently, such features are, perhaps, better classified as 'dynamic sinks' for molecular hydrogen, as they increase in size as the blister grows.

5 Literature Review Results for Metallic Materials

5.1 General

For this project, several different literature searches were conducted which generated multiple lists of published papers for review. Two primary databases were used for these searches - Scopus, an abstract database of peer-reviewed published papers; and Weldasearch, TWI's in-house abstract database of welding and joining technologies. Searches were also conducted for International Standards relevant to the project using BSOL Online (British, European and ISO Standards), as well as ASTM. In addition, individual authors drew on further information specific to their spheres of expertise. No literature was rejected but comments have been made with regards to relevant interpretation of data from various sources.

For the purposes of this section of the review, it is assumed that the ferrous and non-ferrous metals listed within the following sections are intended to be utilised for gaseous hydrogen service downstream of the gas safety valve. The lists of materials, provided in Table 1, have been compiled from a review of materials currently in use in UK domestic natural gas systems. However, it is not known whether these lists are exhaustive. For these reasons, the importance of on site material identification cannot be understated, details of which are provided in Section 7. If any metals expected to be in contact with gaseous hydrogen have been excluded from this document, this should be brought to the attention of the authors.

It should be noted that acceptance criteria, based on neither the mechanical properties of the materials in question, nor a description of the likely loading scenarios and magnitude of stresses on each component, have been provided by BEIS. Thus, for the purposes of this part of the review, the following is assumed:

- Stresses placed on any of the components in question are low. Loading on the component does not generate plastic strains within the component, including at the roots of any stress concentrators;
- Cyclic loading is an unlikely scenario, and thus evaluation of the resistance of the materials to fatigue and environmentally-assisted fatigue is not required;
- The operating environment is assumed to comprise 100% dry hydrogen only. In essence, this means the assessment is made without consideration for the effects of moisture or the addition of odourants, including organic or sulphurous components, mercaptans, etc. Where comments regarding operation under these conditions have been made, these are for information purposes only.

5.2 Carbon steels

5.2.1 Review

During a search of the available literature concerning carbon steels in hydrogen, a number of papers was found which considered the degradation of properties of carbon steels, at pressures of around 700bar. In all cases, properties were found to be detrimentally affected. Much of this work is summarised on the Sandia website. Although, this data would make it difficult to justify the use of a wide range of steels in such high pressure service, this does not mean that the significantly lower pressures, considered in this review (1.075bara), will be a problem.

A number of studies considering the re-use of national distribution networks for methane/hydrogen mixes has shown that, for the levels of partial pressure of hydrogen (up to 20% of 50bar) they anticipate, many pipe-line materials, such as API 5L Grades A and B, X42 and X46, which have relatively low yield strength, would be unlikely to experience problems. For example, Melaina et al. (2013), conclude: "They are not the type of steels that are susceptible to hydrogen induced brittle cracking. In addition, at the stress level generated in natural gas distribution system, hydrogen induced failures are not major integrity concerns for the steel pipes in distribution system."

TWI has experience of materials that are considered acceptable in terms of high temperature hydrogen attack. Many materials have been considered acceptable in such service, since the 1950's, when API-RP941 was first issued. Although there have been several editions, the empirical evidence remains valid that the carbon steels covered by API-RP941 will be acceptable in the service.

Although API-RP941 'Steels for hydrogen service at elevated temperatures and pressures in petroleum refineries and petrochemical plants' 8th Edition (2016) with FEBRUARY 2016 ERRATA 1, JUNE 2016 ERRATA 2, JANUARY 2018 ADDENDUM 1, AUGUST 2020 (API-RP941) is intended to cover high temperature, high pressure hydrogen attack of a range of ferritic materials, it is of significant relevance to this review. Whilst the Standard does explicitly state that it does not cover ambient temperature, at which atomic hydrogen is entering as a result of electrochemical mechanisms such as corrosion or cathodic protection, the inclusion of materials in this Standard implies suitability for hydrogen service. If a material used in such service were susceptible to embrittlement during the time the equipment is not at high temperature, this could lead to difficulties during service. Carbon steels are considered to be suitable for operating conditions below 204°C across a wide range of pressures that are well in excess of those considered in this study, as detailed in Annex F of API-RP941. The only failures of this class of material in hydrogen service were noted to be at 'exceptionally high stress' which, again, is not anticipated in the low pressure service considered for this study.

It is therefore reasonable to assume that all carbon steels can be seen to be suitable for hydrogen service at 75mbar (1.075bara), given the evidence-based acceptance criteria developed in API-RP941. For the purposes of this review, a carbon steel is assumed to include alloys with carbon contents of less than 2%. The addition of manganese is expected to improve the properties of steel with respect to this service. For this reason, it is considered reasonable to use any of the carbon steels specified in the proposed service conditions, provided that the conditions are dry.

5.2.2 Conclusions and further work for carbon steels

Provided the stresses and strains seen in service are not high (e.g. above yield strength), it is not expected that significant hydrogen embrittlement will be encountered in these service conditions. Therefore, the materials have been graded as either 'Green' or 'Amber', depending on the details of the data, as shown in Table 2. Thus, at this stage, no further work is recommended.

5.3 Cast irons

5.3.1 Review

Cast irons are assumed to be iron alloys whose carbon content is greater than 2%. There are a number of classes of cast iron under consideration in this review and the main difference is the morphology of the carbon within the structure. Malleable iron will have rosettes of carbon, whereas, ductile iron will contain spheroidal graphite. Whiteheart cast iron has a decarburised layer and the remainder of the alloy is ferritic with graphite rosettes.

Both rosettes and spheroidal graphite are potentially traps for hydrogen diffusing through the material and may present possible recombination sites for atomic hydrogen. However, as these materials are generally loaded in compression the likelihood of Hydrogen Pressure Induced Cracking (HPIC) from this recombined hydrogen is low.

Cast irons are considered, generally, to have very low ductility and an upper shelf Charpy value of around 20J is typical. Thus, a small reduction in ductility due to the presence of hydrogen might not be readily apparent. There may be more information to be gleaned from careful examination of fracture faces rather than the numbers generated by the mechanical tests.

In terms of literature dealing with the properties of cast iron when exposed to hydrogen, there are a few papers concerning cast iron inserts used inside copper casks for storage of spent nuclear fuel. These cast irons are classed as ductile cast iron. Forsstrom (2019) found that there was significant degradation of mechanical properties, although the properties were suggested to be sufficient for the application. The graphite sphere size here was 20 and 45 microns on average in the two cast irons considered. Sahiluoma et al. (2021), who assessed a ductile cast iron with spheroidal graphite diameter of 45 microns, found very similar results, again, for inserts in which to store spent nuclear fuel. Yoshimoto et al. (2019) carried out work looking at different sizes of spheroidal graphite and found that below 13 microns average diameter, the hydrogen content after charging (at 100MPa, 85°C, 452 hours) was around 10ppm and that the relative reduction in area was 77%. Thus, the loss of ductility was not large. However, as soon as the diameter of the graphite exceeded 13 microns, the hydrogen content after charging was much greater, circa 60ppm and the relative reduction-in-area was nearer 40%. Therefore, Yoshimoto suggested that the degree of embrittlement has a lot to do with the size of the spheroidal graphite and its ability to trap hydrogen. This hydrogen is then released during straining of the material and is able to diffuse readily to the crack-tip, where it can have an embrittling effect.

One paper which discussed results in which minimal hydrogen embrittlement was observed was Rajnovic et al. (2015). Here, two austempered ductile irons (ADI 300 and ADI 400) and as-cast ductile iron were exposed to hydrogen. Hydrogen embrittlement was observed for the as-cast material and the ADI 400 but not the ADI 300.

No pressure was given for the hydrogen exposure so ambient pressure is assumed. This is, of course, a pressure which would be more relevant to this study than other papers already discussed. et al.

Two further relevant papers on ductile cast iron were found: Matsunaga et al. (2016 and 2011). The earlier paper covers chemically-charged material and shows a significant degradation of properties whilst the more recent paper describes increased fatigue crack growth rates, for material tested in 7bar hydrogen and material pre-charged to saturation.

One study, which does consider relevant hydrogen pressures, summarises some of the results of Melainia et al. (2013). Here, the authors assert "For the other metallic pipes including ductile iron, cast and wrought iron, and copper pipes, there is no concern of hydrogen damage under general operating conditions in natural gas distribution systems." However, TWI has a concern that there is not enough data available to justify this statement.

5.3.2 Conclusion for cast irons

There are not many data available and the majority of what is available is more relevant to higher pressure hydrogen environments than the lower pressure environments, considered here. It might be that the morphology of carbon, within the microstructures of different types of cast iron, is important with respect to embrittlement characteristics, because it determines the ability to trap hydrogen and release it, subsequently, directly into the plastic zone at a crack-tip. All grades of cast iron have been graded as 'Amber' in the summary presented in Table 2.

5.3.3 Future work for cast irons

An assessment of the potential hydrogen content of the material in service would be useful. This could be through measurements of heritage assets or using diffusion calculations.

Performing slow strain rate testing (SSRT), comparing results and examination of the fracture faces could yield useful information. It is important to remember that there is a lot of scatter in data concerning cast irons because of the varied morphology of the carbon and the non-homogeneity, both chemically and in terms of mechanical properties, associated with this class of material. For this reason, a statistically significant number of specimens should be used and fracture faces should be examined in order to determine whether or not there has been a change in behaviour, as a result of the presence of hydrogen.

Also, as hydrogen will diffuse quickly through the material, it is recommended that some mechanical tests be performed in the presence of hydrogen in order that any hydrogen contained in the specimen is not lost during testing. This is especially significant as it is important that testing is performed slowly to allow hydrogen to have its maximum effect on the properties of the material. At present, however, TWI does not have any equipment which can perform tests at such low pressures of hydrogen. Equipment cannot be built in the timescale of the testing proposed for this project.

At this stage, a testing programme has not been drawn up, as it will most likely be beyond the scope of this project. If testing is not performed, it will not be possible to be sure that this class of materials is suitable for this service.

5.4 Lead

Lead is a very malleable material and its ductility has been used to great advantage by plumbers since Roman times. Despite extensive searching, no data have been found regarding its use in environments containing hydrogen. Given its ductility, even a large degradation of properties due to the presence of hydrogen could, potentially, leave it with sufficient mechanical properties for this low pressure hydrogen service. However, with no data to back this up, no certainty can be placed on its suitability.

The absence of data means that lead has been graded as 'Amber' in Table 2, despite the inherent ductility which the material typically displays. It is suggested that if lead is to be used in hydrogen service, there needs to be mechanical testing on both charged and un-charged material. Examination of fracture faces after testing will allow for an increased understanding of whether any embrittlement is occurring, even if there is scatter in the mechanical test data. It is understood that there is no particular Standard to which these heritage assets conform, so perhaps there may be significant variation in properties. This may mean it is not possible to qualify all lead assets, unless a large study were carried out.

5.5 Ferritic and martensitic stainless steels

5.5.1 Review

Fe-Cr-Ni precipitation hardenable martensitic stainless steels are a family of alloys that can be heat treated to achieve a range of different mechanical properties. Like most stainless steels, the main alloying addition is chromium, which is typically present at levels of between 11.5 to 18 wt%. Whilst these alloys contain nickel, this element is present in far lower levels than in austenitic stainless steels, and consequently, these materials will still undergo a ductile-to-brittle transition at low (sub-zero) temperatures. Precipitation hardenable martensitic stainless steels are often referred to by their composition and degree of ageing. For example, "17-4PH H900" means the material contains nominally 17wt% Cr and 4wt% Ni and has been precipitation hardened at 900 Fahrenheit (482°C).

The other class of martensitic stainless steels is the Fe-Cr type, which is generally cheaper to produce than Fe-Cr-Ni types, owing to the lower nickel content. These materials are often known by their AISI designations, with the most common types being 410, 420, 430 and 440.

Jewett et al. (1973) have summarised the results of various investigations into the tensile properties of different alloys in gaseous hydrogen environments, including martensitic stainless steels operating at 10,000psig (69MPa). Their programme included subjecting smooth and notched specimens to tensile testing with in-situ hydrogen charging. Under these conditions, the authors classified 400-series steels as among the most 'hydrogen-environment-embrittled' steels tested, with AISI 410 and 440C being placed in the 'extremely embrittled' category and 430F being placed in the 'severely embrittled' category. It is acknowledged that testing conditions have a pronounced influence on the testing results, and whilst the data provide some useful information on the suitability of different martensitic stainless steels to hydrogen environment embrittlement, the test pressures are orders of magnitude greater than would be experienced in domestic systems.

Murray et al. (1987) conducted a programme of tensile testing of 17-4PH stainless steel, following exposure to hydrogen gas at 202°C at a pressure of 13.8MPa.

These tests demonstrated a significant drop in ductility, as measured by reduction-in-area, for both solution-annealed material and specimens that had been aged to the H900 condition.

Ding et al. (2009) used notched tensile specimens to investigate the degree of embrittlement in gaseous hydrogen at a pressure of 0.2MPa. This included investigation of type 13-8 in various temper conditions (H800, H900, H1000, H1100, and H1200). Fracture stresses were determined by testing at slow extension rates in hydrogen, and by calculating environmental performance ratios versus equivalent specimens tested in air. The solution treated, H1100 and H1200 conditions showed minor reductions as a result of testing in hydrogen, whereas, the decrease in fracture stress was 35, 55 and 34% for the H800, H900 and H1000 conditions, respectively. This was accompanied by greater proportions of quasi-cleavage observed on the fracture faces, which is an indicator of embrittlement.

Tsay et al. (2002) used notched tensile specimens to investigate the degree to which gaseous hydrogen (2bar) would reduce the ductility of 17-4PH in the solution treated, H900 and H1025 conditions, as well as samples which had been subjected to laser surface annealing. Fracture stress was determined in air and hydrogen gas at slow strain rates. Gaseous hydrogen reduced the fracture stress by less than 6% for the three specimen types. All specimens failed by ductile rupture, except for the H900 condition tested in hydrogen, which exhibited quasi-cleavage at the notch root. These results suggest a small reduction in mechanical properties at low hydrogen pressures.

Perng and Altstetter (1987) have tested smooth and notched 29Cr-4Mo-2Ni (P87) tensile specimens in air and in 0.11MPa hydrogen gas between 298 and 573K. Tests in hydrogen gas revealed 17% reduction of notched tensile strength and a 50% loss of ductility. Effects were most severe at room temperature and gradually disappeared as the temperature increased above 373K.

5.5.2 Conclusions and future work for ferritic and martensitic stainless steels

As demonstrated by this review, data are scarce on the susceptibility to hydrogen embrittlement of martensitic stainless steel in hydrogen gas in the temperature and pressure range of interest, although there is a wealth of information on material performance under high-pressure or electrolytic hydrogen-charging conditions. Consequently, it is difficult to make a judgement on suitability for service. This conclusion is also shared by IGEM, who have previously arrived at the same conclusions.

Within ASME B31.12, which is the ASME code for Hydrogen Piping and Pipelines, and has been developed for piping in gaseous and liquid hydrogen service, ferritic and martensitic stainless steels are classed as "highly alloyed steels" which contain less than 90wt% iron. The high strength of these materials is said to promote severe hydrogen embrittlement, and based on testing data, alloys such as 410, 430, 440, and 17-4PH stainless steel are considered incompatible with hydrogen gas. In simplified terms, threshold conditions for hydrogen embrittlement are only met once high levels of strain and hydrogen concentration are met in the presence of a susceptible microstructure. Consequently, it is indeed possible that these materials are acceptable for use, depending on loading conditions, particularly in domestic situations where hydrogen concentrations generated within the material are likely to be very low. In general, we agree with the statement in the ASME code that states "comprehensive testing data are necessary before highly alloyed steels are considered for hydrogen gas service". Therefore, the materials have been graded as 'Amber' in Table 3.

It is notable that ferritic and martensitic stainless steels are commonly used as spring materials in valves and gauges, owing to their high strength and elastic modulus. It is unclear to what extent these materials will suffer from environmentally-assisted fatigue in the presence of hydrogen at the pressure and temperatures present within domestic systems (if at all).

5.6 Austenitic stainless steels

5.6.1 Review

Under high load, the face-centred cubic (FCC) matrix of austenitic stainless steels can undergo a phase transformation to body-centred tetragonal (BCT) martensite via a phenomenon known as 'strain-induced martensite formation'. This often occurs during aggressive machining operations, cold working of the material, or during operation under high loads, particularly when stress concentrators are present.

Although the regions transforming to martensite are generally localised, these areas also tend to be those under the highest tensile load. It is widely recognised that hydrogen favours areas of high tensile strain, and because hydrogen diffuses through the BCT lattice comparatively quickly, hydrogen is able to accumulate within transformed regions more readily than the neighbouring bulk material. The unfavourable combination of a martensitic structures alongside locally higher hydrogen concentrations and high stress can increase the tendency for hydrogen cracks to initiate. Delta-ferrite, if present within the material, can exacerbate the problem, providing a fast diffusion pathway for hydrogen. For these reasons, it is important to ensure that highly stressed austenitic components, designed for operation in hydrogen-containing environments, do not contain unnecessary stress concentrators so that austenite is stable at those locations, Omura et al. (2012).

A reasonable amount of work has been undertaken into the relationship between hydrogen environment embrittlement and strain-induced martensite in 300-series austenitic stainless steels, including assessing the effect of temperature. For example, Ogata (2015) conducted experiments from ambient temperature down to -253°C and has found that embrittlement is most severe in the temperature range of -70 to -20°C.

Testing has also been conducted to evaluate how cold working could alter the behaviour of austenitic stainless steel in hydrogen atmospheres. For example, Michler et al. (2015) found that the increased dislocation density caused by cold working would increase susceptibility of alloys such as type 316 to hydrogen environment embrittlement. The authors also found that materials that had intentionally been deformed at higher temperatures were less susceptible to hydrogen environment embrittlement, due to the lower degree of cold work in the material. Chen et al. (2019) have also discovered that type 304 stainless steel is less susceptible to hydrogen environment embrittlement if it has not been cold worked.

It has been found that certain austenitic stainless steels are less prone to form strain-induced martensite than others, and therefore less likely to suffer from HEE. For example, it has been demonstrated that alloys such as type 304 are at a greater risk of HEE as a consequence of strain-induced martensite than alloys such as type 316, Michler et al. (2009). For these reasons, authors such as Michler et al. (2015) have begun to categorise austenitic stainless steels as stable or metastable, depending on their propensity to form strain-induced martensite.

Some grades of material, such as type 310 stainless steel, have even shown almost complete resistance to transformation whatever the work-hardening conditions, and hence would be less prone to HEE.

Austenitic stainless steels are generally considered highly resistant to hydrogen embrittlement under gaseous hydrogen-charging conditions. As ASME B31.12 points out, these materials have been successfully deployed in high-pressure hydrogen gas service within pressure vessels and piping, including as cladding material. Indeed, TWI currently operates type 316L lined autoclaves in high-pressure hydrogen up to 1000bar and up to 80°C. When hydrogen embrittlement has been observed, generally this manifests as a slight reduction in ultimate tensile strength and reduced ductility, with little apparent impact on the proof strength of the material. Consequently, it has been suggested that the most relevant indicators of hydrogen embrittlement are reduction-in-area and elongation. San Marchi et al. (2014) have even suggested that provided the material is not operated outside of the elastic stress range, there is little likelihood of embrittlement occurring.

Jewitt et al. (1976) have demonstrated that annealed type 304 can be susceptible to hydrogen embrittlement in tension, with reduction-in-area of smooth tensile specimens as low as 30% compared with 75-80% without hydrogen. The authors also observed a significant loss of ductility and strength when undertaking notched tensile tests, with 50% ductility and 25% strength losses reported. However, these tests were conducted with a hydrogen pressure of 69MPa, which is far beyond the pressure range experienced in domestic systems.

Caskey (1983) conducted tests on smooth tensile specimens at temperatures between 78 and 380K, after thermal hydrogen pre-charging, and found that a local minimum was present at a temperature near to 220-280K. At 77 and 380K, the ductility was not significantly different to specimens that had not been hydrogen charged. In contrast, impact testing of type 304L showed a greater effect at 77 than 298K.

Han et al, (1998) have shown that temperature has a significant impact on fracture resistance of type 316. Samples showed relatively modest changes in ductility due to thermal hydrogen pre-charging. Testing in 10bar hydrogen gas showed a significant reduction in ductility at 150K and 220K; however, no ductility loss was experienced at 80K.

In some grades of austenitic stainless steel, sustained exposure to high temperature can result in the precipitation of grain boundary (GB) chromium carbide, which can compromise the corrosion resistance and mechanical properties of the material. This general phenomenon is known as sensitisation. To overcome this problem, stabilised austenitic alloys containing alternative carbide-forming elements have been produced, such that GB chromium carbide is not produced. Titanium and niobium are added to types 321 and 347 stainless steels, respectively, in order to produce coarse, stable carbides which inhibit sensitisation.

San Marchi et al. (2012) have undertaken a review on susceptibility of stabilised stainless steel to hydrogen cracking and found that limited data were available. The information, which was available, considered high pressure conditions, only, at 34.5MPa and 69MPa hydrogen pressures. Furthermore, there were discrepancies in the testing data, making interpretation of results difficult. Inconsistent results were attributed to differences in material testing variables, such as strain rate and method of hydrogen-charging.

Uniaxial tensile test data from type 347 stainless steel specimens, tested in hydrogen gas at 69MPa, showed a reduction in ductility, as manifested by differences in reduction-in-area of 50%, compared with specimens tested in helium. Notched tensile test results from the type 347 material showed almost no hydrogen effect at room temperature at a pressure of 34.5MPa, although it is notable that the displacement rate was faster than typically used for hydrogen embrittlement testing.

For type 321 stainless steel, tested in hydrogen at a pressure of 34.5MPa, the ductility, as measured by reduction-in-area, was only about 10% lower than the specimens tested in an inert environment. For notched specimens, ductility, as measured by the reduction-in-area, was 60% worse than the specimens tested in air; however, the strength was reduced by less than 10%. It is expected that with further reductions in pressure, to the levels experienced in domestic systems, the differences in strength between as-received and hydrogen-charged material would be negligible.

5.6.2 Conclusions for austenitic stainless steels

Although data are missing for the operating conditions in question, these materials are routinely used in hydrogen service and elevated temperatures and pressures. Extrapolation to the temperature and pressure relevant to domestic systems can be made safely. The results are summarised in Table 3, in which the materials have been classified as 'Green'.

5.7 Copper and copper alloys

5.7.1 Copper

Documents such as ASME B31.12-2019 correctly note that copper can, under certain conditions, become embrittled in hydrogen gas due to a reaction between dissolved hydrogen and oxygen (either in solution or within oxides) to form steam, resulting in "pores" (voids) at the grain boundaries that promote failure. This mode of failure is described by Caskey et al. (1976). Because of this mode of failure, oxygen-bearing copper is considered inappropriate for hydrogen service under certain operating conditions, e.g. during high temperature brazing in reducing atmospheres.

IGEM/H/1, the *Reference Standard for Low Pressure Hydrogen Utilisation*, IGEM (2021), contains a table of materials suitability for use in 100% hydrogen at less than 2bar pressure, which suggests that copper is suitable for use. However, the document also states, "...copper appears to be suitable for hydrogen utilisation, as long as it contains low levels of oxygen. There is a risk of embrittlement if low oxygen copper is not used", before suggesting that work should be conducted to determine the optimum oxygen content levels within copper. These statements appear to have been made based on extrapolation from high temperature data, outside of the temperature range likely to be experienced in domestic systems.

As previously mentioned in this review, there are generally two approaches for generating testing data to assess whether a material is susceptible to hydrogen embrittlement. The first is to attempt to saturate specimens with hydrogen offline, before testing them separately, without the continuous supply of hydrogen during the test itself. The second approach is for specimens to be tested within a hydrogen-containing environment, with or without prior hydrogen pre-charging, so that hydrogen gas is continually in contact with the tips of any propagating cracks. Unfortunately, the majority of testing data for copper have been generated by using pre-charged specimens which are subsequently tested in air.

The permeability of hydrogen through copper is very low, even more so than austenitic stainless steel. Consequently, when hydrogen pre-charging of copper has been conducted prior to testing, it is often performed at elevated temperatures, as this is the only practicable way to produce mechanical test specimens containing hydrogen. So-called “thermal pre-charging” is not necessarily representative of long-term exposure to hydrogen gas at ambient temperatures, and exposure at high temperatures might have activated degradation mechanisms, that might not be experienced under ambient conditions.

In copper, water formation due to the combination of hydrogen and oxygen at flaws within the material has been known to result in a form of embrittlement known as ‘steam embrittlement’, or ‘gassing of copper’, however TWI has reservations over the temperature range over which this mechanism is operative. Indeed, void formation and subsequent cracking is most pronounced above the critical point of water in copper, 647K (374°C) where the reaction between cuprous oxide and hydrogen forms steam. Given that recombination of hydrogen and oxygen is driven by diffusion processes, it is expected that the process of embrittlement near to ambient temperature would be incredibly slow.

Birkitt et al. (2021) have tested copper in 23vol%H₂ in CH₄ (UK Standard G222). Specimens were soaked at a pressure of 2barg for 6 weeks and immediately transferred for tensile testing. Although some differences were observed between the proof stress values for the control sample when compared with the gas-soaked specimens, overall it was suggested that gas soaking had no detrimental effect on the mechanical properties of the copper. Unfortunately, it was not clear whether the copper used in the study was oxygen-free or not.

A European collaborative project entitled GRHYD, Blanchard and Briottet (2020b), examined the resistance of pure copper to hydrogen embrittlement in three hydrogen/natural gas mixtures, with hydrogen concentrations of 6, 20 and 50% (assumed to be up to 5bar based on parallel tests undertaken on brass). Conventional smooth tensile specimens were tested alongside notched samples. For both types of test, no influence of hydrogen was observed.

In a US National Renewable Energy Laboratory report, Melaina et al. (2013) stated that “there is no concern of hydrogen damage under general operating conditions in natural gas distribution systems”.

During a review of hydrogen embrittlement of copper, San Marchi and Somerday (2012) identified inconsistencies in the literature amongst tests conducted on oxygen-free high conductivity (OFHC) copper. Walter and Chandler (1973) suggest no effect of hydrogen on cold-drawn, OFHC copper, whilst Vennet and Ansell (2022) report as much as 16% loss in ultimate tensile strength when tested in 69MPa hydrogen gas. Further ambiguities in testing data from experts, such as Louthan et al., 1972, suggest more research on the topic is warranted.

5.7.2 Brass

Whilst there are data available on the susceptibility of brass to hydrogen-assisted cracking during cathodic hydrogen charging experiments, there is very little information on susceptibility in dry hydrogen gas. However, a summary of the European collaborative project “GRHYD” is provided in the aforementioned THyGA literature review, Blanchard and Briottet (2020b).

During the GRHYD project, smooth and notched tensile specimens of CW617N and CW614N material were exposed to various natural gas and hydrogen mixes, including hydrogen concentrations of 6, 20 and 50% at 5bar (i.e. covering the partial pressure of hydrogen of between 0.3 to 2.5bar). CW617N is a leaded brass that is nominally Cu-Zn39-Pb2 (wt%) and CW614N is an alpha/beta brass (Cu-Zn39-Pb3). The results show little difference in results for the smooth specimens and mild differences in results for the notched specimens. The authors suggested that 20% H₂ was acceptable for the CW617N alloy whilst 6% H₂ was acceptable for the CW614N alloys. The reasons for this suggestion are not clear.

It is noted that in ASME B31.12 Appendix A, copper and copper alloys, including brass, bronze, and copper-nickel, are considered compatible with hydrogen under gaseous and liquid conditions.

5.7.3 Conclusions and future work for copper and brass

The Sandia review suggests copper containing oxides/oxygen is at risk of embrittlement and that these materials should not be used in hydrogen-environments. However, this is only relevant to high temperature operation where permeating hydrogen can combine with oxygen to form water vapour within the material. This degradation mechanism is unlikely to occur under normal operating conditions in domestic gas systems. Although the GRHYD (Blanchard and Briottet (2020b)) project considered natural gas and hydrogen mixes, we would tend to agree with its suggestion that there is no concern of hydrogen damage in the distribution system under normal conditions.

There are few data for brasses but no clear HE problem has been established or, indeed, is anticipated. Therefore, coppers and brasses have been graded as 'Amber' in Table 3 and a limited testing programme is recommended.

5.8 Aluminium

5.8.1 Review

With the exception of noble materials, such as gold, most metals will naturally react with the air to form a thin layer of oxidation, making the material "passive" and inhibiting further oxidation. In simplified terms, this native oxide acts as a barrier, minimising contact between the oxidising air and the substrate, and cutting down the rate of reaction between the two. In pure aluminium, a tenacious Al₂O₃ oxide layer forms relatively rapidly in air, and provided environmental and loading conditions do not change significantly, this layer will remain intact, protecting the reactive metal beneath.

As previously discussed in Section 4.1.1, a necessary precursor to gaseous hydrogen embrittlement of metals is dissociation of hydrogen molecules via adsorptive processes at the surface of the metal that is in contact with the hydrogen-containing environment. Provided the energy barrier for hydrogen dissociation is not overcome, atomic hydrogen ingress cannot occur, and the subsurface lattice hydrogen concentration will remain constant. In aluminium alloys, the oxide layer that forms at the surface acts as a kinetic barrier for hydrogen uptake, and thus ingress does not normally occur under dry conditions. In fact, despite an incomplete understanding of the mechanisms of entry, all of the data available suggest that gaseous hydrogen embrittlement does not occur if moisture is absent (San Marchi and Somerday, 2012; Speidel, 1984; Ordin, 1997).

This is not true when aluminium alloys are operating under electrolytic hydrogen-charging conditions, or under wet corrosive conditions.

Under such circumstances, the entry barrier for ingress is lowered and atomic hydrogen can be readily produced in large quantities, which raises the possibility of embrittlement, provided threshold strain levels are exceeded. Under wet conditions, some high strength aluminium alloys are prone to stress corrosion cracking (SCC). This is a particularly insidious failure mechanism whereby cracks grow steadily under a constant stress intensity that is below the critical stress intensity of the material operating under inert conditions. SCC is mentioned here only because hydrogen embrittlement is one mechanistic interpretation of this failure mode, once atomic hydrogen has entered the material's lattice. Embrittlement due to aqueous hydrogen charging or SCC are not considered part of this review, as the conditions required for these failure mechanisms to be operative have not been met in this instance.

Commercially-pure aluminium (Al 1100) has been studied by Walter and Chandler (1969), who found that the tensile properties of the material were unaffected by testing in high-pressure dry hydrogen gas at up to 52MPa. The authors also tested notched tensile specimens and also found no influence of the environment on the material.

Louthan and Caskey (1976) have conducted a large body of research on the permeability of hydrogen through various alloys. This has included determination of tensile properties in air at ambient pressure, and in helium and hydrogen at 69MPa. The aluminium alloys studied included 2011, 2024, 5086, 6061, 6063 and 7039. The results of this work have been plotted in Figure 3. Interestingly, the reduction-in-area is greater for the alloys tested in hydrogen and helium than those tested in air. This is likely to be due to the presence of moisture in the air, which will have resulted in localised oxidation of surfaces opening up during the test (Speidel, 1984; Ordin, 1997).

In a NASA report on the influence of gaseous hydrogen on metals, Walter and Chandler (1973) determined the fracture toughness, K_{IC} and threshold stress intensity factor K_{TH} of 2219-T87 in helium and hydrogen at room temperature and 144K (-129°C). Testing was undertaken using specimens extracted from 1.25 inch thick plate with approximately 8% cold work. The specimens were exposed to gaseous hydrogen at 5000psi (34.5MPa). Testing in the hydrogen-charging environment did not reveal any differences compared with tests undertaken in air. The average K_{IC} fracture toughness at ambient temperature was 33MPa.m^{0.5} in helium and 29MPa.m^{0.5} in hydrogen gas. At -129°C the average K_{IC} values were 41MPa.m^{0.5} in helium and 37MPa.m^{0.5} in hydrogen. The specimens were also loaded to pop-in, held in place, and the cracks allowed to arrest. The stress intensities at crack arrest were found to be roughly the same in both helium and hydrogen. On average, they were also equal to the K_{IC} of the material when tested in helium. It was therefore concluded that there is no effect of pure hydrogen on crack growth in this material.

Appendix A of ASME B31.12-2019 contains non-mandatory precautionary considerations for the use of various alloys, including aluminium. On this topic, the ASME document states: "Aluminum has very low solubility for hydrogen, but when exposed to wet hydrogen gas, aluminum is susceptible to hydrogen environment embrittlement, while in dry hydrogen gas, aluminum is resistant to hydrogen environment embrittlement... aluminum alloys should be used judiciously for hydrogen gas service if water vapor is present; however, all available data indicate that the susceptibility of aluminum to hydrogen embrittlement is very low in dry hydrogen gas."

5.8.2 Conclusions for aluminium

Although SCC is a known issue with some 2xxx, 5xxx and 7xxx series aluminium and hydrogen might play a role in the mechanism, this is more of a general risk and only relevant to wet operation and materials which are susceptible to SCC. These materials resist dry hydrogen gas and the alloys used for general engineering, which generally come from 5xxx and 6xxx series, are considered to be suitable for use under the conditions in question and are graded as 'Green' in Table 3.

5.9 Zinc alloys

Zamak is a zinc-based alloy commonly used for die-cast parts, the composition of which includes additions of aluminium, magnesium and copper. The most commonly used alloy is Zamak 3, although types 5 and 7 are also used.

Following a review of the literature, there appears to be very little information on the compatibility of Zamak in environments containing gaseous hydrogen. In an EU-funded Horizon 2020 project entitled "Testing Hydrogen admixture for Gas Applications (THyGA)" various alloys were tested in hydrogen/natural gas blends, Blanchard and Briottet, 2020b. In a presentation it was concluded that Zamak demonstrates "no hydrogen susceptibility", Blanchard and Briottet (2020a). Data in support of this conclusion have not yet been provided.

Although these presentation slides indicate that Zamak is not susceptible to hydrogen embrittlement, However, this conclusion is not supported by any publically-available data so the material has been graded 'Amber' (Table 3) and so a testing programme is recommended.

5.10 Solders and brazes

5.10.1 Background

Brazing and soldering are liquid phase joining processes in which a filler metal with a lower melting point than those of the materials being joined is employed. Typically, the distinction between soldering and brazing is the melting point of the filler alloy. Alloys used for soldering tend to have melting points lower than 450°C, whilst brazing alloys have melting points above this. During these processes, the parent materials remain in the solid phase but diffusion between the alloys and substrates is expected to occur, creating metallurgically-bonded joints.

Brazing and soldering alloys are commonly used for the joining of copper/copper alloy pipes, particularly for the transport of gas. The typical alloys used for forming such joints are:

- Lead-free solders
e.g. 95Sn-5Sb;
- Lead-based solder (employed, historically, but now banned for general use)
e.g. 60Sn-40Pb, 63Sn-37Pb;
- Copper-phosphorous brazing alloys
e.g. Cu-15Ag-5P;
- Silver brazing alloys
e.g. 30Ag-38Cu-32Zn.

5.10.2 Literature review

The literature search found no damage mechanism data for the identified braze and solder alloys within a hydrogen service environment. TWI has not carried out hydrogen exposure testing for these solder/braze alloys, therefore cannot report any known damage mechanisms.

When carrying out a literature review related to soldering and brazing, it is worth noting that there are many variables associated with the processes, which are typically undefined in academic literature. These variables could be, but not limited to: flux composition, braze/solder alloy composition, cleaning process, temperature, heat source and joint gap. All of these can have a large impact on the quality and microstructure of the resultant joint, which could in-turn influence their behaviour when exposed to hydrogen.

There is a wide range of Standards which govern the quality and control of brazed joints, encompassing filler metals, qualification of operators, brazing procedure approval (BPS) and subsequent examination. Some of the key British standards are summarised below:

BS EN 12797: 2000. Brazing. Destructive tests of brazed joints;
BS EN 12799: 2000. Brazing. Non-destructive examination of brazed joints;
BS EN 13134: 2000. Brazing. Procedure approval;
BS EN 14324: 2004. Brazing. Guidance on the application of brazed joints;
BS EN ISO 13585: 2012. Qualification test of brazers and brazing operators;
BS EN ISO 17672: 2016. Filler metals;
BS EN ISO 18279: 2003. Brazing imperfection in brazed joints;
BS EN ISO 18496: 2021. Brazing. Fluxes for brazing. Classification and technical delivery conditions.

Despite the wide range of Standards, in comparison with welded joints for example, responsibility for the control and testing of joints is more dependent on the relationship between the supplier and the customer, owing to the vast range of possible joint geometries, materials and filler metals, as well as processing variables. In common with many qualification Standards, the Standards listed do not address the issue of hydrogen service. However, they do provide strong frameworks for controlling joint quality, e.g. those for operator qualification (BS EN ISO 13585:2012) and brazing procedure specification (BS EN 13134:2000). It is understood that a large proportion of the Standards summarised are currently under consideration for their applicability to hydrogen service, so they may need to be re-evaluated, when they are updated.

In any case, the literature review found that there was limited information regarding testing of brazed or soldered joints for service in a hydrogen environment. Birkitt et al. (2021) confirmed, prior to their study, that no literature could be found on tin-copper and lead-based solders. Birkett et al. (2021) tested joints, mechanically, that had been soldered using tin-copper and lead-based solders. The testing studied the effects of 100% hydrogen, G222 natural gas/hydrogen blend or methane, after 6 weeks of soaking at 2 barg operating pressure and 20°C. It was concluded that, when comparing the control joint with a hydrogen-soaked joint, the ultimate tensile strengths for joints made with tin-copper were similar at 240 and 238MPa, respectively. For joints made with the lead-based solder, the lap shear strengths of the control joint and hydrogen-soaked joint were 10.4 and 8.4MPa, respectively. The authors believed the difference could be due to bonding defects, as opposed to effects of hydrogen, which is consistent with our earlier statement concerning parameters and their control.

The conditions in this study used a higher, yet similar hydrogen pressure to the current interest, so the results are useful, although details of the specific alloys used were not given.

The Hy4Heat project (BEIS, 2020, BEIS 2021) produced several documents that referenced the use of lead-free and leaded solder for a hydrogen service environment. IGEM (2021a) states that leaded and lead-free solders can be used for hydrogen service, provided the joint is leak-tight and that it is suitably made and tested. This paper does not reference specific solder alloys that are acceptable.

IGEM (2020) studied the flow of hydrogen and methane through joints with different conditions such as solder and flux, solder and no flux and no solder and no flux. This paper did not state the composition of solder that was tested. It did not state the difference between each test. Therefore, it is not possible to attribute the different variables to leak rates. The results showed that there was a difference in leak rates related to the process variables.

IGEM (2021b) tested poorly soldered joints for hydrogen and methane leak rates. The pressure range was similar to the service environment considered in this scope of work, as it was 20-75mbarg. It was found that the hydrogen leak rate was 0.11m³/h. As per previous IGEM reports, this one did not mention the solder alloy that was used to create the joint.

5.10.3 Conclusions for brazes and soldered joints

The literature review found very limited data for the performance of soldering and brazing alloys which are used for hydrogen service and are commonly employed for the joining of copper/copper alloy pipes, particularly for the transport of gas. However, the limited extent of information on soldered joints for various hydrogen service conditions, highlighted the need for mechanical property data. In comparison, no papers were found for brazes, despite IGEM documents referring to the use of brazing to join piping and tubing. As a result, testing is required to generate useful data for solders and brazing alloys and hence the alloys have been graded as 'Amber' in Table 4, as they do not exist, currently.

5.10.4 Future work for brazes and soldered joints

Currently, the data available fail to detail the specific compositions of the filler metals used and hence it is difficult to use this data. In addition, the quality and composition of soldered and brazed joints is sensitive to a wide range of variables, such as surface preparation, temperature, joint gap etc. Such details are not described in the studies and so an objective assessment cannot be made. In order to carry out a scientific study on how soldering and brazing alloys behave in contact with gaseous hydrogen, the first stage of such an investigation will need to focus on eliminating as many soldering/brazing variables as possible, and on producing a reliable and repeatable set of soldered/brazed joints for hydrogen exposure testing.

Such a study would begin with feasibility trials with the various filler metals within the series, listed in Table 4. The variables will be identified, and as many of these be fixed as is possible, to enable a test matrix to be developed with a view to creating comparable joints. Once variables have been fixed, the trials should aim to develop a set of parameters that allow the manufacture of representative soldered/brazed joints, aiming to eliminate features that may influence hydrogen testing results, such as incomplete fill, cracking, porosity, trapped flux etc.

Following development of the soldering/brazing parameters, they will be used to produce test samples for hydrogen exposure testing. The hydrogen exposure testing itself will be similar to the work conducted by Birkett et al. (2021), whilst extensively covering the braze metals and solders listed within, and using the experimental conditions of interest for this project.

6 Compatibility of Non-metallic Materials for Low Pressure Hydrogen Service

6.1 Background

Polymeric materials in the classes of thermoplastic, elastomeric and composite type polymeric materials are often found in various components of district and domestic supply lines. Their confirmed performance, or fitness-for-purpose, over a 30 year life span is required.

In the following sections the damage mechanisms for polymers in the presence of hydrogen will be summarised with attention to data found in the literature. In Table 5 this information is used to support the classification process as outlined in Section 3.4. This classification has been repeated in the subsequent paragraph for ease of reference for the reader.

The process firstly considers whether there are sufficient relevant data and information available relating to each group of materials to support the classification process. If there are sufficient relevant data, then the material classification is either 'suitable', i.e. 'Green', or 'not suitable' i.e. 'Red'. If there are insufficient relevant data, doubts in the quality of the data or missing data, then the material is classified as 'uncertain', i.e. 'Amber'.

In the future, if pressure in the supply lines increase, there may be a need for further reinforcement with fibres made from glass, carbon or aramid. These materials would need to be assessed for hydrogen exposure as the polymeric encasement will never provide an absolute barrier to hydrogen.

6.2 Damage mechanisms

6.2.1 General

Hydrogen gas can permeate into the amorphous region of an organic polymeric material. The process is one of solution and diffusion and the concentration and time dependency is specific to the chain chemistry and morphology. The effects of high pressure hydrogen gas on the material properties are summarised in Figure 4.

6.2.2 Physical ageing

Physical ageing of polymers can be caused by an alteration in the morphology due to ingress of most gases or liquid vapours. These processes can cause an increase or decrease in the glass transition temperature, in the first instance. Depending on the temperature of application, then this may alter the mechanical properties, such as creep under load and Young's modulus. The ingress of gases or vapours can lead to matrix swelling and, in some cases, depletion of additives such as stabilisers and antioxidants. These aspects have been studied extensively for carbon dioxide, as an example, but less is known for situations in which polymeric materials are exposed to low pressure hydrogen gas at near ambient conditions.

6.2.3 Permeation and location in polymer matrix

Studies on hydrogen uptake by nitrile butadiene rubber (NBR), using nuclear magnetic resonance spectroscopy, have confirmed that the hydrogen molecules were bound in the matrix and also present in the free volume, (Nishimura, 2012). Similar studies on the state of molecular hydrogen present in bisphenol A polycarbonate, using infrared spectroscopy, have confirmed the presence of molecular hydrogen trapped in the polymer matrix after exposure to 700bar at 30°C, (Ono H. F., 2020).

The relative permeability of materials to hydrogen can, in principle, assist with the selection process. However, it does not give confirmation of the suitability of a material as a barrier to hydrogen in conveyancing, through a specific external environment. There is the option to make comparison between the relative rate of permeability of hydrogen with natural gas components, but allowance must be made for the safety implications of gas build up in the external environment. To this end, attention is drawn to the broad concentration range over which hydrogen remains flammable compared with methane, as shown in Table 6.

Rate and concentration studies have been carried out on the transport of hydrogen into polymeric materials and values for the permeability, diffusion and solubility coefficients can be found in (Maxwell, 2008), (Kane, 2008) (Klopffer M. H., 2010), (Klopffer M. B., 2012), (Fujiwara H. O., 2021), (Jung, 2021), (Simmons K. K., 2020), (Melaina, 2013), (Menon N. C., 2016), (Yamabe, Crack growth behavior of sealing rubber under static strain in high-pressure hydrogen gas, 2011) and (Zheng, 2020), e.g. Table 7. It is evident from these data that the volume flow rate or permeability of hydrogen at 25°C through silicone > polytetrafluoroethylene > high density polyethylene > polychlorofluoroethylene, (Maxwell, 2008).

Also that one would expect the permeability of NBR to be of the same order as that of a fluoroelastomer but a factor higher, (Zheng, 2020). The permeability of polyethylene (PE100) to hydrogen is approximately 3 times that of polyamide 11 (PA 11) at 20°C and 5bar and was not found to vary after an exposure period of one year, (Klopffer M. H., 2010), (Klopffer M. B., 2012), (Schultheiß, 2007). A limited number of diffusion coefficients available in the open literature has been summarised in Table 8. An extensive listing of hydrogen gas permeability and diffusion coefficients, as measured at room temperature, is provided elsewhere (Barth, 2013). The expected time required for hydrogen to saturate 0.6cm into LDPE would be of the order of 7.64 days at 50°C and 900bar.

6.2.4 Thermal transitions

On exposure of filled ethylene propylene diene monomer (EPDM) and acrylonitrile butadiene rubber (NBR) specimens to hydrogen gas, there was no significant change in T_g caused by exposure to H_2 for one week at 860bar and 21°C, (Menon N. C., 2020). For Viton A there seems to be a shift in T_g from -2°C to -3°C with hydrogen exposure for a period of approximately 1 week under conditions of 1000bar at room temperature, (Menon N. C., 2016). This could be the result of reduced crystallinity, due to rearrangement of molecular chains in Viton. Similarly, only a slight reduction in T_g was observed for HDPE from -110°C to -111°C. A table of glass transition alteration, on exposure to argon or helium gases containing hydrogen, is summarised in (San Marchi, 2017) for Buna N, Viton A, EPDM, PTFE, HDPE, POM, Nylon 11 and the impression is that the data have been collected on materials after exposure to high pressure hydrogen.

The alterations, in all cases, fall in the range of an increase of 7°C or a reduction of 5°C. Heats of Fusion (ΔH), melting point (T_m), glass transition temperatures (T_g) and lamellae thickness are markers to confirm grades of materials within a polymer class. The heat of fusion can be used to determine the degree of crystallinity. Alteration in any of these data points can also be an indicator of ageing. These alterations may or may not have implications for the material in its final application.

6.2.5 Degree of swelling

The free swelling of polymers and elastomers in all gases occurs as a consequence of the gas solubility in the matrix. The swelling can have a detrimental effect on the mechanical and barrier properties. In most literature, the swelling is determined by physical measurements some time after decompression, (Zheng, 2020), (Castagnet S. O., 2017), (Ono H. F., 2018), (Fujiwara H. , 2017). As an example, NBR has been shown to have swollen by 3.1% in the absence of filler, after out gassing for 35 minutes having previously been exposed to 100barg hydrogen (Zheng, 2020).

6.2.6 Tensile properties

The tensile properties (modulus and yield stress) of polyethylene or polyamides were not affected by the presence of hydrogen at 100barg and room temperature, (Klopffer M. H., 2010), (Klopffer M. H., 2010). Young's modulus of PTFE was increased by 35% with an increase of 15% for HDPE under exposure of several 100bars, (Menon N. C., 2016). The explanation given was an internal restructuring of the polymeric chains in the crystalline region. Under a hydrogen gas pressure of 30bar, no alteration was detected in the Young's modulus and yield stress of polyamides and polyethylene, after exposure for 13 months, (Castagnet S. G., 2012), (Castagnet S. G., 2010), (Klopffer M. B., 2012), (Barth, 2013). The ultimate tensile strength of HDPE was found to reduce after exposure to hydrogen pressures above 280barg (Alvine, 2014). In one study, a polyethylene (PE80) pipe was exposed to hydrogen gas for 6 weeks at 2barg and 20°C without deterioration in mechanical properties (Birkitt, 2020).

6.2.7 Compressive stress relaxation

Compressive stress relaxation is used in studies in order to establish the likelihood of compression set occurring in elastomeric materials used in seals. It is also used as an input property for life-time prediction models, such as Williams Landel and Ferry (WLF), (Lehr, 2017).

Pressure surges or reductions can lead to an alteration in the dimensions of the seal housings and therefore compression. Compression set was studied on NBR and EPDM and was found to increase in the presence of high pressure hydrogen from approximately 20 to 40% in the absence of filler (Menon N. C., 2020), (Menon N. C., 2016), (Simmons K. K., 2020), (Yamabe, 2011).

6.2.8 Chemical ageing

Chemical ageing is considered to be a situation where bonds are broken and reformed. This process is not reversible. In consideration of the literature, it is tentatively proposed that the interaction of hydrogen with an organic matrix will only be in the form of a chemical reaction where atomic hydrogen is first formed. Atomic hydrogen can be produced from a gaseous supply, when additives or catalysts containing metals such as palladium are present.

In one example, the hydrogenation of 1,4-diphenylbutadiyne was achieved in the presence of a carbon supported palladium catalyst at temperatures of 36°C or higher, under a pressure of 6000pa (0.06bar) hydrogen, (Dinh, 2008). Other examples, where palladium was intentionally introduced into the matrix as a “getter” in a silicone polymer for the protection of metallic substrates, have been provided, (Dong, 2020) (Ortiz-Acosta, 2018). The artificial nature of the scavenging of hydrogen in these systems suggests that similar events will not occur in polymeric materials previously used in natural gas pipelines, unless palladium is present. It is documented that Ziegler-Natta catalysts are used in the presence of 8bar hydrogen gas at 75°C in the polymerisation of ethylene to form polyethylene (Niyomthai, 2018). Residual Ziegler-Natta catalysts and metallocenes were detected in field specimens of ethylene propylene diene monomer rubber (EPDM) and polyethylene, using specialist analytical equipment, (Bichinho, 2005).

The continued polymerisation or cross-linking of the polymeric matrix on the introduction of hydrogen gas is unlikely, however, the composition of each polymer and elastomer should be checked with the respective suppliers. Some formulations for elastomers, such as EPDM and NBR, can have as many as nine components (Menon, 2020) and thermoplastics commonly contain colorants, residual catalysts and antioxidants. Invariably, such reactions may result in cross-linking of unsaturated polymer chains leading to embrittlement. In discussions with the suppliers, it would be good to know first if information can be recovered on whether catalysts containing Fe, Co, Ni, Rh, Pt or Pd were used in the initial synthesis. Analytical methods, such as atomic absorption spectroscopy (AAS) or X-ray fluorescence spectroscopy (XRF), are specialised methods that have previously been used for this purpose (Bichinho, 2005). The concentrations of catalysts expected to be detected are of the order of mg per kg of polymer and typically a few grams of sample are used in the analytical methods. Ideally, thermoplastic and elastomeric materials would be sampled from materials previously exposed in the natural gas line, with a view to depth-profiling where possible. Examples of some catalysts are provided in Table 9.

6.3 Polyethylene

Polyethylene is the polymer most commonly used in low pressure gas pipe lines. Variations in molecular weights, chain branching and cross-linking produce such grades as PE-80, PE-100, high density polyethylene HDPE, raised temperature polyethylene (PE-RT) and cross-linked products (XLPE or PEx). Some grades contain fillers to alter the mechanical properties and also to limit the degradation that can occur, mainly through oxidation. As indicated in Section 6.2.1, hydrogen will permeate through polyethylene grades, albeit that the molecular weight and degree of cross-linking will alter the rate. Previous studies, in which HDPE was exposed to low pressure hydrogen gas for extended periods of a year, have been alluded to and no substantial alteration was detected in mechanical properties. The presence of residual catalysts and other fillers may result in the production of atomic hydrogen with the potential for hydrogenation of residual unsaturation. It is not clear if exposure to low pressure hydrogen gas will cause the displacement of stabilisers and antioxidants.

6.4 Elastomers

Elastomeric materials are used as seals where the O-ring groove fill is set by the design engineer. In previous sections, the permeation rates of hydrogen through elastomers compared with thermoplastics has been shown to be higher. The transport rates of gases depend on the presence of fillers and may result in compression set, leading to failure in sealing.

6.5 Conclusions for non-metallic materials

Many of the studies in the open literature are for exposure to high pressure hydrogen gas, during which swelling and rapid gas decompression damage are a concern. The published studies, using low pressure hydrogen gas, suggest that, for most polymeric materials, there will not be a substantial alteration on first saturation, unless there is the potential for chemical alteration or additive elution. In the absence of long-term exposure data, it is difficult to be sure that performance of non-metallic material will not be affected, eventually. In view of this, the materials have been given an 'Amber' classification in Table 5.

7 Materials Identification on Site

7.1 Background

It would be useful to be able to identify what material or grade of a particular component is made from whilst assessing an existing system to determine if the materials present were suitable for hydrogen service.

A range of methods can be used to identify an unknown material. These range from the basic methods, requiring few or no tools, to more sophisticated equipment and techniques carried out in laboratories. It is not the purpose of this report to list and cover all the methods or to provide a detailed explanation of each one but to provide an overview and to discuss some of the methods that could be used on site, in a non-destructive manner.

Laboratory techniques are used if materials can be sampled and collected for testing. These tests tend to provide more accurate information on a material composition, but will generally require destructive sampling of the material, time to carry out the tests in suitable equipped laboratory and trained personnel.

For metallic materials, these include techniques such as wet analytical chemistry, optical emission spectrometry (OES), X-ray diffraction (XRD), X-ray fluorescence (XRF) and mass spectrometry (MS). For non-metallic materials, Fourier transform infrared spectroscopy (FTIR) and differential scanning calorimetry (DSC) are commonly used.

Laboratory based methods will not be covered in this report, however, portable versions of some of these types of equipment designed for use on site will be.

7.2 Metallic materials

7.2.1 Basic methods

7.2.1.1 Label ID code

One method most people tend to overlook is to see whether the component has a label, identification markings or a code. If this is present, then it may be a simple case of searching and tracing this back to the manufacturer(s) which should provide details of the material of manufacture.

7.2.1.2 Appearance

The appearance of the metallic material can often give an indication of what type of metal it may be. The general colour and texture can give clues to the type of metal it is. An indicative guide is given in Table 10.

7.2.1.3 Magnetism

Magnetism is one property of metals that could be used to identify metallic material. Metallic materials can be classified simply as magnetic or non-magnetic, or more precisely; ferromagnetic, paramagnetic or diamagnetic. In general, a permanent magnet is attracted strongly to a ferromagnetic material, weakly to paramagnetic one and weakly repulsed by a diamagnetic material.

Thus, knowing the magnetic properties we may be able deduce what type of material an unknown metal may be. In general, the information given in Table 11 can be used to assist in identifying a metal.

7.2.1.4 Hardness

Hardness is also a property that can be used to help identify metals. The hardness of the material can be determined relatively against other materials or quantitatively using hardness measurement tools.

One common way of determining the relative hardness of a material is to try and scratch it with another, the softer material will be deformed relative to the harder material, for example carbon steel will generally scratch aluminium or copper. Another common method to determine relative hardness is to use a file on an unknown metal, depending on how easily the file cuts into the metal then its hardness can be inferred relative to the file material (usually made from case-hardened steel). Although these simple methods require little or no tools to perform, they only provide limited information on the hardness properties of the material, moreover they will damage the material being tested so they cannot be considered as non-destructive methods. Also from a safety prospective, it would not be recommended to damage any components that are either in service or to be put into service.

Hardness can also be quantified by laboratory hardness testing machines and tools. A number methods exists for carrying out these tests and they all follow the same general principle: a shaped indenter is pressed into a metal surface with a known load and the resultant indentation provides a quantitative measure of the hardness of the metal. Different methods (Vickers, Brinell, Rockwell) use different shaped indenters (diamond or ball-shaped) and hence the hardness values are given in different scales.

Portable hardness tools are available and can be use on site, however, they will generate a small degree of damage on the metal surface and the suitability and safety concerns should be assessed, prior to use. The three main principal portable hardness testing methods are: Ultrasonic Contact Impedance (UCI) (ASTM A1038-19), Rebound or Leeb methods (ASTM A956/A956M-17a) and Rockwell principle (ASTM E110 – 14). The principle of UCI is based on determining the shift in resonant ultrasonic frequency, arising from the contact of a diamond indenter on the end of the probe with the material under test. The Rebound method determines the indenter velocity as it rebounds from the workpiece and moves through a coil in the instrument. The Rockwell principle, is the same as the laboratory method.

7.2.2 Advanced methods

The basic methods for identifying a metallic material are often useful to provide an indication of the type of material an unknown metal could be. However, to positively identify the elements from which a metallic component is made, more advanced techniques need to be used.

Portable XRF and OES machines can be used to determine the approximate elemental composition of a metallic material. When compared with compositions of known metals and alloys as reference Standards, it can also provide a list of possible alloys that the unknown materials could be.

The XRF technique uses an X-ray source to excite electrons in the material. When electrons fill the gaps left by ones removed from the inner orbit, they release fluorescent X-rays and the X-ray energy is specific to a particular element and its intensity is indicative of the concentration.

In the OES method, an electric arc or laser is used to excite the materials tested and the light emitted is analysed spectrographically to obtain a spectrum. Similar to XRF, the energy and intensity of the peaks will provide details of the elemental constituents and composition of the unknown metal.

These two methods are commonly used to identify unknown metallic materials on site. They are often referred to as 'positive material identification' (PMI) techniques and a number Standards describe their use in this context and also highlight some of the advantages/disadvantages of each method (BS 7339:1990, ASTM E1916-11, API 578:2018).

7.3 Non-metallics (polymers)

7.3.1 Basic methods

7.3.1.1 Label ID code

As with metallic materials the presence of a label, identification markings, colour or a code (BS EN ISO 11469:2016) may provide clues as to the type of material from which the component may be made or enable it to be traced back to the manufacturers, who should provide details of the material of manufacture.

7.3.1.2 Appearance and general properties

The appearance, in the form of colour and translucence of the polymer, will provide some information to help identify unfilled grades. In some instances, where polymers vary in molecular weight within a class, then the supplier will add a dye to change the colour (older Aldyl A PE is tan, more modern MDPE is yellow and HDPE is black or black with yellow stripes). Polymers made from the same base material may come in many forms, with different additives and often in range of colours. Thus, using appearance as indicator will not be a reliable method, unless contact can be made with the original supplier.

The relative density of the polymer may be determined from a simple buoyancy test. Whether it floats or sinks, in range of liquids, can be used to provide an indication of the density of the material and this property can be used to help determine the type of polymer. For example, polyethylene (PE) and polypropylene (PP) will float, whereas, Polyvinyl Chloride and Unplasticised (uPVC) will sink in water. In practice, this test can be only be carried out if a sample of the unknown component can be safely removed, without compromising its safety and performance or on an identical spare component. In addition, the presence of filler and/or an additive may affect the density values. More sophisticated tests to measure the density are specified in Standards, such as ASTM D792-20 and BS EN ISO 1183-1:2019. However, these generally require laboratory equipment so they may not be suitable for site use.

In some cases, it may be possible to remove 10 to 20mg from the surface of a polymeric part and heat the specimen in a small portable calorimeter.

This would allow the melting point, cold crystallisation temperature and glass transition temperature to be determined in some instances. Portable infrared spectroscopy methods are available and currently used on site to identify materials such as coatings. These methods could be employed to establish the polymer group.

7.3.2 Advanced methods

FTIR is used for qualitatively and quantitatively for determining the presence of specific chemical groups, e.g. C=O, or C-H, or C-CH₃ in polymeric materials, (ASTM D5477-18, ASTM E1252-98(2021), ASTM E168-16, BS ISO 4650:2012). This is possible since each group has characteristic frequencies at which bond vibrations of infrared radiation occurs. The Fourier Transform method has enabled the response of the material to a single excitation to be transformed into a spectral scan. By reference to an established collection of infrared spectra, it is possible to assign specific absorptions to particular groups to confirm the type of polymer.

This test is usually carried out on a sample of the polymer or solvent extraction, in the case of rubber materials (BS EN 549:2019), in laboratory equipment. However, portable versions of FTIR equipment are commercially available and do not require sampling of the material and so this method can be used, non-destructively, on site. The portable method does not have the same sensitivity in the main, because of the short integration interval. The review highlights the currently unknown impacts of residual catalysts and additives, particularly plasticisers. These can be identified using pyrolysis - gas chromatography (Py-GC) and mass spectrometry (MS). Methods and critical values for this will be developed and identified through the testing phase of this study.

8 Summary

Information and data on the suitability have been gathered for a number of metallic and non-metallic materials considered to be most likely to be present in existing service. A review of the information was conducted and the materials were classified as to their suitability for low pressure hydrogen service, using the procedures outlined in Sections 3.3 and 3.4. The results of the assessment and classification are presented using a 'Red', 'Amber' and 'Green' system, for ease of understanding, and are summarised in Tables 2-5 for each set of materials.

The results show that metallic materials generally fall into the 'Green' or 'Amber' categories. There was very little or no information on lead, cast iron, solders and brazing materials in hydrogen service. For most metallic material placed in the 'Amber' category, more information from limited testing on their performance may be sufficient to place them in the 'Green' category. For lead, cast iron, solders and brazing consumables, the recommendation is for a more comprehensive testing programme to generate evidence for their suitability of use.

For non-metallic materials there are a range of materials that could be present. To date many of the studies recorded in the open literature are for exposure to high pressure hydrogen gas during which swelling and rapid gas decompression damage are a concern. The published studies where low pressure hydrogen gas was present are a first guide suggesting that for most polymeric materials there will not be a substantial alteration on first saturation unless there is the potential for chemical alteration or additive elution. The absence of long-term exposure data means that one cannot definitively say that a non-metallic material will behave appropriately for the duration of the product. To this end, the materials have been given an 'Amber' classification until such time as there is a relevant data set.

One major point that has been highlighted in this review during the assessment and classification process is the lack of guidance on acceptance criteria for low pressure hydrogen service.

This has placed an emphasis on expert opinion in the assessment for some materials. Going forward, more clarity on acceptance criteria for materials in hydrogen service would be beneficial in the development of Standards and guidelines, not only for existing material but also for new materials.

In addition, testing to generate evidence to support the case of whether a particular material is suitable for hydrogen service would also benefit from clarity of an acceptance criteria. If testing is required, with a clear set of acceptance criteria, stakeholders would be able to define the type of testing and test conditions to generate the appropriate data required to make the assessment. This may also lead testing to become more standardised so that data, generated by different laboratories test-houses, can be directly compared and consistent data on the performance of materials be added in the future.

The acceptance criteria will need to be material specific. For example for cast irons, it may be in terms of whether any features on the fracture faces exhibit any of the characteristics of hydrogen enhanced cracking mechanisms. In some industries, a hydrogen environmental embrittlement (HEE) index is used. This is a ratio of the elongation measured in a slow strain rate tensile test, measured in the environment and that measured in air or inert environment. For carbon steels which have been rated 'Green' in this review, this judgement is based on historical industrial data rather than measurements that are environment specific. It is therefore not possible to give one simple acceptance criteria that will be appropriate for all materials. Development of acceptance criteria for materials operating in low pressure hydrogen-containing environments represents an active area of research. In the absence of any standardised guidance on acceptance criteria for low pressure hydrogen utilisation, TWI has opted to measure the HEE index and also to examine the fracture surface for any sign that hydrogen has influenced the mechanism of fracture. If there is any sign that the fracture mechanism has been influenced or that the HEE index is statistically less than 1, TWI will be unable to give the material concerned a 'Green' rating for hydrogen service. At this stage, no fatigue, corrosion or fracture requirements are included in the test plan, the authors do not know whether these would be relevant to this service.

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Table 1 List of materials

Component	Materials	Grade	Standard	Notes
Metallic pipework	Carbon Steel	Black Steel pipe - BS3601/320, 3601/410, 3602/360, 3602/410. S360, S430. Max 1.7 % of carbon content with combination of 030-080 % of manganese	BS3601 Type F and 3602	BS3601 Type F longitudinally furnace butt welded or continuous welded (Grade A only), Type E - longitudinally electric resistance welded (Grades A and B), and 3602 seamless pipe
	Malleable Iron	Commonly W 40-05. Carbon 2.16-2.90, Silicon 0.90-1.90, Manganese 0.15-1.25, Sulphur 0.02-0.20, Phosphorus 0.02-0.15.		Whiteheart malleable cast iron -Small sections contain pearlite and temper carbon in ferritic substrate.
	Cast Iron	<0.9% P, <0.12% S		
	Ductile Iron	Medium Pressure Ductile Iron (MPDI)	EN 969	Iron-carbon-silicon alloy. 3-4%C, Si 2-3% + nickel.
		Galvanised Malleable Iron		Pre 1930 impure zinc
	Stainless Steel	316L		
	Copper	Phosphorous-Deoxidized, High Residual Phosphorous Copper (99%Cu, 0.015% to 0.04%P)	BS EN 1976 + BS EN 1173	Finishing could be chrome plated or plastic coated. Phosphorus de-oxidised copper; Cu-DHP or CW024A
		R220		Annealed
		R250		half-hard
		R290		hard
	Corrugated Stainless Steel Tube (CSST)	300 series SS - normally 316L or 304L		
	Lead	99.7% pig lead		Not legal from 1991
	Aluminium	6063?, 1000, 2000 series.		flexible cooker pipe

Table 1 (continued) List of materials

Component	Materials	Grade	Standard	Notes
Polymer pipe	Polyethylene	MDPE - medium density polyethylene pipe PE80 +CBB, PE100, PE2406, PE2708	BS EN 1555-1:2021	Note: polybutylene not approved for gas
		HDPE - PE100		
		PEX		
		Dupont Aldyl "A"		limited crack resistance (1965-1980)
	Polyamides	PA11, and PA12		
	Polyvinyl-chloride	PVC-HI grade (ISO 6993-1) K-value: 65. IM>7%.		Note: possible H ₂ induced phase separation of plasticiser
Flexible piping	Multi-material	Stainless steel convoluted walled hose covered with a protective UV stabilised PVC outer sleeve		
		ALUPEX - electron beam cross-linked polyethylene (PE-Xc) + aluminium middle layer + outer layer of chemically cross-linked polyethylene (PE-Xb)		
		NBR (nitrile butyl rubber) inner material + EPDM outer		
		302 SS single braid layer reinforcement		
FRP	Fibre reinforced multi-material	HDPE, Polyphenylene sulphide (PPS) inner + glass or aramid-fiber reinforced thermoset (e.g., epoxy)outers.		

Table 1 (continued) List of materials

Component	Materials	Grade	Standard	Notes
Meters and Fittings	Carbon Steel	Low carbon steel: BS1501-224-490A/B, BS 970, BS3602/360, BS3602/410		
	Chrome Plated Carbon Steel			
	Stainless Steel	316 & 316L, 321, 304		
	Brass	Yellow brass, also known as 272 brass, C272 brass, or C27200, consists of 62-65% copper and approximately 37% zinc, as well as small percentages of lead, nickel, tin, and iron.	BS-00746-2014	
	Brass for hot pressing	Grade CW602N or CW617N		
	Brass rod	Grade CW602N, CW614N or CW617N		
	Brass sheet and strip	Grade CW508L		
	Copper	Grade CR004A		
	Malleable cast iron	Commonly W 40-05. Carbon 2.16-2.90, Silicon 0.90-1.90, Manganese 0.15-1.25, Sulphur 0.02-0.20, Phosphorus 0.02-0.15.		
	Austenitic stainless steel	Grades 1.4404 and 1.4541		
	Bronze / Gun Metal	Gunmetal Casting Alloy – LG2 (CC491K/B62/C83600)	ASTM B62-93	84-86%Cu, 4-6% Z, Pb, Sn
	Cast Iron	Malleable cast iron EN-GJMW-400-5 or EN-GJMW-350-4 EN-GJMB-350-10 or EN-GJMB-300-6		
	Zinc	Zamac,		
	Aluminium	A360/As80/A356		

Table 1 (continued) List of materials

Component	Materials	Grade	Standard	Notes
Joining	Solder	(ASTM B32 Alloy Sn50), 95-5 tin-antimony solder		
		(ASTM B32 Alloy Sn50), 95-5 tin-antimony solder		
		conventional 60/40 and 63/37 Sn-Pb solder		
	Brazing rod	BCuP series alloys containing phosphorus -copper-phosphorous brazing alloy that may contain from 0%-30% Silver (Ag).		
		BAg series alloys - silver content of anywhere between 24% and 93%.		
Hoses	Polymeric	PVC, Stainless steel, Nitrile rubber, Polyester, Natural rubber		
	Polymeric	Black NBR Synthetic Rubber Inner - High Tensile polyester Reinforcement - Orange Synthetic Rubber Outer		
	Strip wound flexible hose	Carbon steel		
Spring materials in valves and gauges	Ferritic and martensitic stainless steels	Typical precipitation hardening martensitic stainless steels, eg, 13Cr, 15-5PH, 17-4PH.		
Valves	Copper alloy excluding aluminium bronze		BS EN 15069:2008	EN 1503-4
	Ductile cast iron excluding laminar cast iron			EN 1503-3
	Forged steel and cast iron			EN 10222

Table 1 (continued) List of materials

Component	Materials	Grade	Standard	Notes
Seals	Elastomer	Nitrile O-Ring (NBR rubber and Buna-N)	BS EN 549	
		Nylon-11		
		Viton-A		
		Ethylene Propylene Diene Monomer (EPDM)		
		Fluoroelastomer FKM (dipolymer)		
		Polyoxymethylene (POM)		
		Neoprene		
		Vulcanised rubber + Carbon Black + sulphur + zinc oxide or stearic acid	BS EN 549	
	Hemp	Hemp (thread seal)	BS-06891:2015	Hemp shall not be used a threaded joint except in conjunction with jointing compounds for existing long screen back nut seals

Table 1 (continued) List of materials

Component	Materials	Grade	BS Standard	Notes
Jointing Compound/Anaerobic Sealants/Tape	Compound	Boss white, Hawk white, jet lube, all jointing compounds to BS EN 751-2 Class A	BS EN 751-2 Class A	
	PTFE Tape	PTFE tape		
Washers	Fibre washers	Non asbestos fibre – (can include nitrile or PTFE)		
	Rubber washers	Vulcanised fibre (cellulose)		
	Gaskets	316 stainless steel gaskets		
Soft body parts	Rubber	Ethylene Propylene Rubber (EPR / EPDM)		
Ball valves	Seating material	PEEK seats and PTFE-coated stainless steel		

Table 2 Ferritic materials assessment

Material family	Type	Grade	Nominal composition	Performance	Reference	Rating	Future work/Comment
Carbon steels	API 5L Grades A and B, X42, X46 and similar			"They are not the type of steels that are susceptible to hydrogen induced brittle cracking. In addition, at the stress level generated in natural gas distribution system, hydrogen induced failures are not major integrity concerns for the steel pipes in distribution system."	Results of NaturalHy https://www.nrel.gov/docs/fy13osti/51995.pdf		Note of caution: Acceptance criteria unknown
	API 5L Grade B			In 2 barg, 20% hydrogen ie 0.6bar partial pressure hydrogen, no detrimental effects on tensile properties.	K. Birkitt, M Loo-Morrey, C Sanchez, L O'Sullivan 'Materials aspects associated with the addition of up to 20 mol% hydrogen into an existing natural gas distribution network' Int. J Hydrogen Energy vol.46, p.12290-12299 (2021)		Not at full partial pressure, however material justified in other ways in this Table.
	All carbon steels - taken to mean all with less than 1% Mn and no purposeful additions. Also all steels with additions of Mo and Cr.			All carbon steels ok for less than 200°C. This standard also covers steels with deliberate additions of Mn,Mo and Cr	Nelson curves, Annex F, API-RP941 8th edition (2016)		Note of caution: Acceptance criteria unknown
	BS 3601 and BS3602 mentioned specifically			These were approved for use in town gas which was circa 50% hydrogen. However the likely impurities in town gas would have acted to inhibit HEE so this code of practice is not necessarily applicable to pure hydrogen.	BSI Code of Practice CP2010: 2 (1970) 'Design and construction of steel pipelines in land'		
	All carbon steels 'used in gas appliances and gas distribution networks' considered in THyGA			At pressures of 30-50mbar when mixed at up to 50% with methane, hydrogen embrittlement should not be a problem unless high stresses or strains are present. Careful monitoring of stress concentrating defects required.	L Blanchard and L Briottet 'Non-combustion related impact of hydrogen admixture - material compatibility' THyGA deliverable D2.4 (2020)		Green if no stress concentrating defects present
	Chrome-plated carbon steel			Assuming that the chrome layer is on the outside for aesthetic reasons, no additional problems are anticipated above and beyond the substrate material properties UNLESS there was significant hydrogen ingress during the plating process			
Ductile iron, cast and wrought iron				"For the other metallic pipes including ductile iron, cast and wrought iron, and copper pipes, there is no concern of hydrogen damage under general operating conditions in natural gas distribution systems"	Results of NaturalHy https://www.nrel.gov/docs/fy13osti/51995.pdf		This is a very broad statement which is based on a small amount of data.
Cast irons		EN 1561-GJL250		There is a lot of scatter in data, it is therefore hard to judge from this data whether the material will be acceptable in hydrogen. This scatter may be as specimens are taken from different locations in the casting.	K Birkitt, M Loomorrey, A Bannister, S Hawksworth, K Jeffrey, KO Kowen 'Materials aspects associated with the addition of up to 20mol% hydrogen into an existing natural gas distribution network' Paper ID129, ICHS 2019 and also K Birkitt, M Loo-Morrey, C Sanchez, L O'Sullivan "Materials aspects associated with the addition of up to 20 mol% hydrogen into an existing natural gas distribution network." Int.J.Hydrogen Energy 46(2021) 12290-12299		Determine hydrogen content in service. Perform SSRT testing on charged and uncharged material. Examine fracture faces to look for signs of embrittlement.
	Selected grades, ductile cast irons and one austempered	Various		There might be a threshold graphite diameter below which embrittlement isn't seen. Most data for much higher hydrogen content than anticipated in this service environment.	Six other papers found regarding ductile cast iron, see text.		Determine hydrogen content in service. Perform SSRT testing on charged and uncharged material. Examine fracture faces to look for signs of embrittlement.
Lead	Any, including pig lead 99.5% lead			No relevant data found			

Table 3 Corrosion resistant material assessment

Material family	Type	Grade	Nominal composition	Performance	Reference	Rating	Comments
Stainless steel	austenitic stainless steel	304 (UNS S30400) 304L (UNS S30403) 304LN (UNS 30453) 304N (UNS30451)	Fe-19Cr-10Ni	Susceptible to strain induced martensite transformation. Role of martensite on embrittlement has yet to be established. Sensitisation possible, but does not appear to affect HE resistance. Permeability appears almost independent of specific microstructure in ASS, with the exception of martensite formation, which increases permeability and diffusivity.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321		Although data are missing for the operating conditions in question, these materials are routinely used in hydrogen services and elevated temperatures and pressures. Extrapolation to the T and P relevant to domestic systems can be made safely.
				Annealed 304 is susceptible to HE in tension. RA can be as low as 30% compared to 75-80% without H. 69 Mpa H2.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321 Table 3.1.1.1 Page 135 RP Jewitt, RJ Walter, WT Chandler and RP Frohberg. Hydrogen Environment Embrittlement of Metals (NASA CR-2163). Rocketdyne for the National Aeronautics and Space Administration, Canoga Park CA (March 1973). RJ Walter, RP Jewitt and WT Chandler. On the Mechanism of Hydrogen-Environment Embrittlement of Iron- and Nickel-base Alloys. Mater Sci Eng 5 (1970) 99-110.		
				Caskey conducted tests on smooth tensile specimens at temperatures between after thermal hydrogen pre-charging and found that a local minimum was present at a temperature near to 200K. Between 77K and 380K the ductility was no significantly different specimens that had not been hydrogen charged.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321 Page 129 GR Caskey. Hydrogen Compatibility Handbook for Stainless Steels (DP-1643). El du Pont Nemours, Savannah River Laboratory, Aiken SC (June 1983).		
				Significant loss of ductility and strength of notched specimens exposed to internal or external hydrogen. Loss of 50% ductility and 25% strength reported. Greater losses in strength and ductility at higher pressures. Tensile testing of stainless steel in external hydrogen gas does not provide limiting behaviour for material that will be exposed for long periods of time.	RP Jewitt, RJ Walter, WT Chandler and RP Frohberg. Hydrogen Environment Embrittlement of Metals (NASA CR-2163). Rocketdyne for the National Aeronautics and Space Administration, Canoga Park CA (March 1973). CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321 Page 129		
				Impact energy of 304L is affected by H ₂ and moreso at 77K than 298K. This is contrary to the tensile results which show opposite temperature sensitivities.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321 GR Caskey. Hydrogen Compatibility Handbook for Stainless Steels (DP-1643). El du Pont Nemours, Savannah River Laboratory, Aiken SC (June 1983).		

Table 3 (Continued) Corrosion resistant material assessment

Material family	Type	Grade	Nominal composition	Performance	Reference	Rating	Comments
Stainless steel	austenitic stainless steel	316 (UNS 31600) 316L (UNS 31603) 316N (UNS 31651)	Fe-18Cr-12Ni + Mo	Room temperature tensile testing in H₂ generally shows little or no loss in ductility. Ductility loss of about 10% was noted in low nickel 316 alloy when tested in 1 Mpa hydrogen at RT. Strain-induced martensite thought to be responsible. Low temperatures shown to have a significant impact on fracture resistance of 316. Thermally pre-charged samples showed relatively modest changes in ductility due to thermal pre-charging. Testing in 10Bar H₂ gas shows a significant reduction in ductility at 150K and 220K. No ductility loss at 80K. Greatest losses in ductility near to 200K.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321 Page 147 CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321 Page 147 G Han, J He, S Fukuyama and K Yokogawa. Effect of strain-induced martensite on hydrogen environment embrittlement of sensitized austenitic stainless steels at low temperatures. Acta mater 46 (1998) 4559-4570. GR Caskey. Hydrogen Compatibility Handbook for Stainless Steels (DP-1643). El du Pont Nemours, Savannah River Laboratory, Aiken SC (June 1983).	Green	Although data are missing for the operating conditions in question, these materials are routinely used in hydrogen services and elevated temperatures and pressures. Extrapolation to the T and P relevant to domestic systems can be made safely.
	Stabilised austenitic stainless steel	321 (UNS S32100) 321H (UNS S32109) 347 (UNS S34700) 347H (UNS S34709) 347LN (UNS 34751)	Fe-10Cr-10Ni + Ti Fe-10Cr-10Ni + Nb	321 can be susceptible to hydrogen-assisted fracture but results are not consistent. Possible shortcomings in testing methodology (e.g. strain rate). RA measured in 34.5MPa H₂ was only about 10% less than the value measured in helium. Effect of H₂ on ductility similar at RT and 144K. Ductility 10-15% less than the value measured in helium. HAC more pronounced in notched materials. 321 in 34.5MPa H₂ at RT show RA loss of >60% and >10% loss in strength. Unaffected at 144K. 347 can be susceptible to hydrogen-assisted fracture but the results are not consistent. Possible shortcoming in testing methodology (e.g. strain rate). RA measured in 69MPa H₂ was less than 50% of the equivalent in helium.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321 Page 162		

Table 3 (Continued) Corrosion resistant material assessment

Material family	Type	Grade	Nominal composition	Performance	Reference	Rating	Comments
Stainless steel	martensitic stainless steel (precipitation hardening)	General	General	In general, very little data exist for these alloys in gaseous hydrogen. Based on the available data, this family of alloys is not recommended for service in hydrogen environments.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321		Although the IGEN document, Sandia review, and associated references seem to suggest martensitic stainless steels should not be used in hydrogen service, this appears to be based on high pressure and high temperature operation. Data from tests conducted at low pressure and temperature reveals only marginal reductions in mechanical performance. It does not seem reasonable to classify this material as unacceptable for operation at low pressure and near-ambient temperature without evidence. Limited testing programme suggested.
		17-4 PH	Fe-Cr-Ni	Hydrogen precharging of 17-4PH in 13.8 Mpa (138 Bar) hydrogen gas at 475K (202C) for 24 hours resulted in significant loss of reduction in area in smooth tensile specimens for both solution annealed and H900 conditions	GT Murray, JP Bouffard and D Briggs. "Retardation of hydrogen embrittlement of 17-4PH stainless steels by nonmetallic surface layers". Metall Trans 18A (1987) 1162-164		
		13-8 PH		Tsay et al., used notched tensile specimens to investigate the degree to which gaseous hydrogen (2 Bar) would reduce ductility of 17-4PH in the solution treated, H900 and H1025 conditions, as well as samples which had been subjected to laser surfac annealing. Fracture stress was determined in air and hydrogen gas at slow strain rates. Gaseous hydrogen reduced the fracture stress by less than 6% for the three specimen types. All specimens failed by ductile rupture, xcept for the H900 condition tested in hydrogen, which exhibited quasi-cleavage at the notch root. Ding et al., Used nothced tensile specimens to investigate the degree of embrittlement in gaseous hydrogen at a pressure of 0.2MPa. This included investigation of 13-8 in various precipitation conditions (H800, H900, H1000, H1100, and H1200). Fracture stresses were determined by testing at slow extension rates in hydrogen, and by calculating environmental performance ratios versus equivalent specimens tested in air. The solution treated, H1100 and H1200 conditions showed minor reductions as a result of testing in hydrogen, whereas the decrease in fracture stress was 35, 55 and 34% for the H800, H900 and H1000 conditions, respectively. This was accompanied by greater proportions of quasi-cleavage observed on the fracture faces.	L.W. Tsay, W.C. Lee, R.K. Shiue, J.K. Wu, "Notch tensile properties of laser-surface-annealed 17-4 PH stainless steel in hydrogen-related environments" Corrosion Science, Volume 44, Issue 9, 2002, Pages 2101-2118. Y.S. Ding, L.W. Tsay, M.F. Chiang, C. Chen, "Gaseous hydrogen embrittlement of PH 13-8 Mo steel". Journal of Nuclear Materials, Volume 385, Issue 3, 2009, Pages 538-544.		

Table 3 (Continued) Corrosion resistant material assessment

Material family	Type	Grade	Nominal composition	Performance	Reference	Rating	Comments
Stainless steel	Ferritic stainless steel	Fe-Cr (10-30%). Typically 12-18 wt% Cr.		General trends emerging from the literature are that ferritic stainless steels are at least as susceptible to hydrogen-assisted fracture as the unstable austenitic stainless steels (301, 304). NASA reports classify type 430F as severely embrittled by high pressure hydrogen gas	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321 Page 87		The results of Perng and Altstetter suggest a possible sensitivity to HE within the temperature and pressure range of interest. Whether or not this is an unacceptable level of embrittlement is dependent on provision of acceptance criteria. Testing programme recommended.
		430F		Jewett et al (1973) have summarised the results of various investigations into the tensile properties of different alloys in gaseous hydrogen environments, including martensitic stainless steels operating at 10,000 psig (69MPa). Testing included subjecting smooth and notched specimens to tensile testing with in-situ hydrogen charging. Under these conditions, the authors classified 400-series steels as among the most 'hydrogen-environment-embrittled' steels tested, with AISI 410 and 440C being placed in the 'extremely embrittled' category and 430F being placed in the 'severely embrittled' category. It is acknowledged that testing conditions have a pronounced influence on the testing results, and whilst the data provide some useful information on the suitability of different martensitic stainless steels to hydrogen environment embrittlement, the test pressures are orders of magnitude greater than would be experienced in domestic systems.	RP Jewett, RJ Walter, WT Chandler and RP Frohberg. Hydrogen Environment Embrittlement of Metals. Rocketdyne for the National Aeronautics and Space Administration, Canoga Park CA (March 1973).		
			29Cr-4Mo-2Ni (P87)	Tests in air and 0.11MPa hydrogen gas from 298 to 573K revealed 17% reduction of notched tensile strength and a 50% loss of ductility. Effects most severe at room temperature and gradually disappeared as the temperature increased above 373K.	T-P Perng and CJ Altstetter. Comparison of Hydrogen Gas Embrittlement of Austenitic and Ferritic Stainless Steels. Metall Trans 18A (1987) 123-134.		

Table 3 (Continued) Corrosion resistant material assessment

Material family	Type	Grade	Nominal composition	Performance	Reference	Rating	Comments
Copper and copper alloys	Commercially pure copper	4001	Cu (oxide free)	Nominally pure oxide-free copper appears to be relatively unaffected by high pressure hydrogen gas. However, effect of long term exposure at high pressure is not clear. Copper with oxygen inclusions is embrittled by hydrogen, forming water, but can also react with oxygen in solution. Process of embrittlement is slow at ambient temperatures as it requires diffusion of the active species, namely oxygen and hydrogen.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321. page 255.	Yellow	The Sandia review suggests Cu containing oxides/oxygen is at risk of embrittlement and that these materials should not be used in hydrogen-environments, however, this is only relevant to high temperature operation where permeating hydrogen can combine with oxygen to form water vapour within the material. This degradation mechanism is unlikely to occur under normal operating conditions in domestic gas systems. Although the MultiH project considered natural gas and hydrogen mixes, we would tend to agree with its suggestion that there is no concern of hydrogen damage in the distribution system under normal conditions. It is understood that the IGEM/H/1 Standard will be updated during 2023 to remove this suggestion that low oxygen copper is required. Assuming this is the case, TWI would suggest that no testing is required for copper and that it is changed to 'Green' status.
			Cu (unclear whether CP)	Birkitt et al, (2021) have tested copper in 23vol%H ₂ in CH ₄ (UK Standard G222). Specimens were soaked at a pressure of 2 barg for 6 weeks and immediately transferred for tensile testing. Although some differences were observed between the proof stress values for the control sample when compared to the gas-soaked specimens, overall it was suggested that gas soaking had no detrimental effect on the mechanical properties of the copper. It was not clear whether the copper used in the study was oxygen free or not.	K. Birkitt, M. Loo-Morrey, C. Sanchez, L. O'Sullivan, Materials aspects associated with the addition of up to 20 mol% hydrogen into an existing natural gas distribution network, International Journal of Hydrogen Energy, Volume 46, Issue 23, 2021, Pages 12290-12299,		
			Cu (containing oxides)	Available data combined with the observation that pure coppers are low strength suggests Cu is not strongly affected by hydrogen provided the copper is oxide-free. Oxygen-free high-conductivity copper generally used where oxygen inclusions cannot be tolerated. Hydrogen effects on alloys containing other trace elements (e.g. P) have not been reported with respect to hydrogen service.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321. page 255.		
				Tensile: Walter and Chandler suggests no effect of hydrogen on properties of cold drawn OFHC copper. Whilst Vennett and Ansell report as high as 16% loss of UTS in 69MPa hydrogen gas. This is perhaps attributed to oxides in the material.	RJ Walter and WT Chandler. Effects of High-Pressure Hydrogen on Metals at Ambient Temperature: Final Report (NASA CR-102425). Rocketdyne (report no. R-7780-1) for the National Aeronautics and Space Administration, Canoga Park CA (February 1969).		
				High pressure hydrogen reported to have no appreciable effect on notched tensile properties of OFHC copper. Testing at cryogenic temperatures (144K) showed no reduction in properties in 34.5 Mpa hydrogen.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321. page 256.		
				It appears that the conditions for hydrogen damage on iron or copper do not apply to natural gas distribution system, thus there should be no concern of hydrogen damage on iron and copper pipes in the distribution system	Melaina M W, Antonia O, Penev M (2013): "Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues" NREL Technical report NREL/TP-5600-51995.		
				A type of copper alloys is the OFHC (oxygen free high conductivity) in which the absence of oxygen is assessed using hydrogen gas at elevated temperature. If oxides are present in the microstructure, they are located at grain boundaries and they react with hydrogen, creating water vapour bubbles, which can lead to blistering. This type of embrittlement is similar to the recombination of hydrogen causing blistering in steels (San Marchi and Somerday, 2012), (Jewett et al., 1973; Nieh and Nix, 1980) but is only used as assessment for OFHC and this testing is far from operating conditions in which those alloys are used.	Blanchard L, Briottet L "Non-combustion related impact of hydrogen admixture - material compatibility" THyGa Project Deliverable D2.4.		

Table 3 (Continued) Corrosion resistant material assessment

Material family	Type	Grade	Nominal composition	Performance	Reference	Rating	Comments
Copper and copper alloys	Brass	Beta-brass	CuZn50	SCC is a general concern with these materials, although this is a general risk in domestic systems, not isolated to HE. Beta-brass is seldom used.	TWI comment		See previous comment
		Alpha/Beta-brass	CuZn40	SCC is a possibility with these materials, although this is a general risk in domestic systems, not isolated to HE.	TWI comment		
		Alpha/Beta-brass CW617N, CW6	CuZn40Pb2/CuZn40Pb3	In the context of GRHYD project, the susceptibility of two brass alloys (CW617N and CW614N) was evaluated in GN + H2 mixture up to 5 bar pressure under tensile loading on smooth and notched specimens (Briottet et al., 2016). It was found that for the CW617N 20%H2 was acceptable, Figure 18 and 6%H2 for the CW614N	Blanchard L, Briottet L "Non-combustion related impact of hydrogen admixture - material compatibility" THyGa Project Deliverable D2.4.		
		Alpha-brass	CuZn30	SCC unlikely.	TWI comment		
		Alpha/Beta-brass CW617N, CW6	CuZn40Pb2/CuZn40Pb3	No significant susceptibility when tested in natural gas with 6 and 20% hydrogen	CEA THyGA Project https://thyga-project.eu/wp-content/uploads/20201026-Webinar-Materials_THY_WP2_020_Presentation-Webinar-Materials.pdf THyGA		

Table 3 (Continued) Corrosion resistant material assessment

Material family	Type	Grade	Nominal composition	Performance	Reference	Rating	Comments
Aluminium	1XXX series		Al	Considerable scatter in the data in terms of hydrogen solubility, varying by six orders of magnitude when extrapolated to room temperature. Care should be taken when extrapolating, as hot extraction techniques do not necessarily take into consideration trapping within the material. Reported diffusivity values vary by two orders of magnitude at high temp and many orders of magnitude at ambient temperature, when extrapolating. Al often considered as a barrier to hydrogen permeation, due to the formation of Al oxide on the surface.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321. page 242.		Although SCC is a known issue with 2xxx and 7xxx series aluminium, and sometimes other grades, this is more of a general risk and only relevant to wet operation. These materials generally thought to be suitable for use under the conditions in question.
		1100		The tensile properties of CP Al (Al 1100) were unaffected by testing in high-pressure hydrogen gas. Similarly high purity Al annealed bar 99.99%Al was found to be unaffected by hydrogen up to 52MPa.	RJ Walter and WT Chandler. Effects of High-Pressure Hydrogen on Metals at Ambient Temperature: Final Report (NASA CR-102425). Rocketdyne (report no. R-7780-1) for the National Aeronautics and Space Administration, Canoga Park CA (February 1969). RP Jewitt, RJ Walter, WT Chandler and RP Frohberg. Hydrogen Environment Embrittlement of Metals (NASA CR-2163). Rocketdyne for the National Aeronautics and Space Administration, Canoga Park CA (March 1973).		
		Commercially pure		Notched tensile properties of CP Al were not degraded by testing in high-pressure gaseous hydrogen.	RJ Walter and WT Chandler. Effects of High-Pressure Hydrogen on Metals at Ambient Temperature: Final Report (NASA CR-102425). Rocketdyne (report no. R-7780-1) for the National Aeronautics and Space Administration, Canoga Park CA (February 1969). RP Jewitt, RJ Walter, WT Chandler and RP Frohberg. Hydrogen Environment Embrittlement of Metals (NASA CR-2163). Rocketdyne for the National Aeronautics and Space Administration, Canoga Park CA (March 1973).		
				No known data on fracture properties of pure Al in hydrogen gas.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321. page 243.		

Table 3 (Continued) Corrosion resistant material assessment

Material family	Type	Grade	Nominal composition	Performance	Reference	Rating	Comments
Aluminium	2XXX series	General	Al-Cu	Few data on 2XXX-series Al in gaseous hydrogen. Data that is available shows a slight increase in ductility when testing in high pressure H ₂ gas, probably because of removal of atmospheric moisture during testing.	MR Louthan and G Caskey. Hydrogen Transport and Embrittlement in Structural Metals. Int J Hydrogen Energy 1 (1976) 291-305.		Although SCC is a known issue with 2xxx and 7xxx series aluminium, and sometimes other grades, this is more of a general risk and only relevant to wet operation. These materials generally thought to be suitable for use under the conditions in question.
				No known or published data on notched tensile properties	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321. page 248.		
		2219-T87	Al-Cu	Fracture performance of 2219-T87 found to be similar in helium and hydrogen gas at room temperature.	RJ Walter and WT Chandler. Influence of Gaseous Hydrogen on Metals: Final Report. Rocketdyne for the National Aeronautics and Space Administration, Canoga Park CA (Oct 1973).		
	7XXX series	7039 (likely not heat treated)	Al-Zn-Mg-Cu	Tensile: Limited data for 7XXX aluminium, however the information that is available suggests that the tensile properties of these alloys are not affected by gaseous hydrogen.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321. page 252.		
				Despite an incomplete understanding of the fundamental thermodynamics and kinetics of hydrogen gas-aluminum interactions, all of the available data suggest that the mechanical properties of aluminum alloys are not degraded in dry gaseous hydrogen	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321. page 251.		
					M.O. Speidel: in Hydrogen Embrittlement and Stress Corrosion Cracking, R. Gibala and R. F. Hehemann, eds., American Society for Metals, Metals Park OH, 1984, pp. 271-296.		
					P.M. Ordin, "Safety Standard for Hydrogen and Hydrogen Systems: Guidelines for Hydrogen System Design, Materials Selection, Operations, Storage, and Transportation," Office of Safety and Mission Assurance, National Aeronautics and Space Administration, Washington DC 1997.		
		7475	Al-Zn-Mg-Cu	No known information on notched tensile properties of 7XXX alloys.	CS San Marchi, BP Somerday: "Technical reference for hydrogen compatibility of materials" Sandia Report SAND2012-7321. page 252.		
				Fracture: sustained-load testing on 7XXX series in high pressure hydrogen did not reveal any hydrogen-assisted crack extension. Testing conducted using WOL specimens tested for 5000 hours in 207 MPa hydrogen gas. Note that this is dependent on specific stress intensities selected for testing.	R.E. Stoltz and A.J. West: in Hydrogen Effects in Metals, I. M. Bernstein and A. W. Thompson, eds., The Metallurgical Society of AIME, New York, 1981, pp. 541-553.		
Zinc	Zamac/Zamak		Zn	Zamak, copper and brass CW617N: no hydrogen susceptibility.	Blanchard L and Briottet L : "Testing Hydrogen admixture for Gas Applications" 2nd ThyGa Workshop, May 2020.		Although these presentation slides indicate that Zamak is not susceptible to hydrogen embrittlement, this conclusion is not supported by any publicly-available data. Testing programme is recommended

Table 4 Solders and brazes assessment

Material	Type	Grade	Nominal composition	Performance	Reference	Rating	Comments
Solder	ASTM B32 Alloy Sn50) - 95-5 tin-antimony solder		95Sn-5Sb	Authors tested tin-copper (lead free) solders and studied the effects of 100% hydrogen, G222 natural gas/hydrogen blend or methane after 6 weeks of soaking at 2barg operating pressure and 20°C. Authors found that tensile test results were comparable and hydrogen did not affect the joint.	K. Birkitt, M Loo-Morrey, C Sanchez, L O'Sullivan 'Materials aspects associated with the addition of up to 20 mol% hydrogen into an existing natural gas distribution network' Int. J Hydrogen Energy vol.46, p.12290-12299 (2021)		Little or no information available, where data was obtained the compositions of materials was not specified, testing programme recommended
Solder	Lead solder		60Sn-40Pb and 63Sn-37Pb	The test studied the effects of 100% hydrogen, G222 natural gas/hydrogen blend or methane after 6 weeks of soaking at 2barg operating pressure and 20°C. Authors did not think hydrogen effected the tensile properties of the joint	K. Birkitt, M Loo-Morrey, C Sanchez, L O'Sullivan 'Materials aspects associated with the addition of up to 20 mol% hydrogen into an existing natural gas distribution network' Int. J Hydrogen Energy vol.46, p.12290-12299 (2021)		
Braze	BCuP series alloys containing phosphorus -copper-phosphorous brazing alloy that may contain from 0%-30% Silver (Ag).		Cu-15Ag-5P	No information found in literature			
Braze	BAG series alloys - silver content of anywhere between 24% and 93%.		30Ag-38Cu-32Zn	No information found in literature			

Table 5 Non-metallic materials assessment

Material family	Type	Grade	Nominal composition	Performance	Reference	Rating	Comments
Elastomers	Nitrile O-Ring (NBR rubber and Buna-N)	NBR NF	NBR Nipol 1042 (100), stearic acid (1), zinc oxide (5), sulfur (1.5) MBTS (1.5), TMTD (0.7), ZnEtDC (0.7)	Only above 10MPa considered.	Nishimura, S. (2018) 'Database of Polymeric Materials for Hydrogen Gas		Check NBR + NBR-CB filled at low pressures to confirm trend. >12months - current timebase too short to see impacts of compression set and additions.
		NBR CB50	NBR Nipol 1042 (100), stearic acid (1), zinc oxide (5), sulfur (1.5) MBTS (1.5), TMTD (0.7), ZnEtDC (0.7), Carbon Black N330 (50)	CB filled shows trend which indicates no permeability at pressures lower than 10MPa.	Seals and Dispensing Hoses' Department of Mechanical Engineering Faculty of Engineering Kyushu University. Available at: https://www.bing.com/ck/a?7&ap=296d1ab8dce65796f614ed350843a2ee44848743d08057b6f1106e2a5331JmtdH9M8MTY1MzU3MzUzMzpzC3VpZDjHMTNTQ0ZC02C02TALTQ2YjYvTASMyOxYjMxYzIhYTY4YzEmaW5za		
		NBR CB25	NBR Nipol 1042 (100), stearic acid (1), zinc oxide (5), sulfur (1.5) MBTS (1.5), TMTD (0.7), ZnEtDC (0.7), Carbon Black N330 (25)	Filler = Large surface area suppresses volume inflation by penetrated hydrogen.	Simmons, K., Bhamidipaty, K., Menon, N., Smith, B., Naskar, A. and Veenstra, M., (2018) 'Compatibility of polymeric materials used in the hydrogen infrastructure. Pacific		
		NBR CS60	NBR Nipol 1042 (100), stearic acid (1), zinc oxide (5), sulfur (1.5) MBTS (1.5), TMTD (0.7), ZnEtDC (0.7), silica Nipol VNS (60)	High polar NBR polymer suppress hydrogen penetration and volume inflation but little difference at low pressure.	Nishimura, S. and Fujiwara, H., (2012). 'Detection of hydrogen dissolved in acrylonitrile butadiene rubber by 1H nuclear magnetic resonance'. <i>Chemical Physics Letters</i> , 522, pp.43-45.		
		NBR CS30	NBR Nipol 1042 (100), stearic acid (1), zinc oxide (5), sulfur (1.5) MBTS (1.5), TMTD (0.7), ZnEtDC (0.7), silica Nipol VNS (30)	Compression set was studied on NBR and EPDM was found to increase in the presence of high pressure hydrogen from approximately 20 to 40% in the absence of filler.	Parker (no date), Parker O-Ring chemical compatibility table for gases, fluids, solids. Available at: https://www.esprint.com/products/o-rings/o-ring-chemical-compatibility-table		
				The filler material used in these model material compounds show a decrease in volume change for NBR by 10% and 30% in EPDM from unfilled baseline compound. Volume change towards 0 at 10MPa.	Hermekens, R., van der Stok, E., de Brun, J. and Weller, J. (2016) 'Can PE and PVC gas distribution pipes withstand the impact of sustainable gases?' <i>Proceedings of the 18th Plastic Pipes Conference</i> , Berlin, Germany, 12-14 September.		
				Hydrogen molecules were bound in the matrix and also present in the free volume	Menon, N.C., Kruizinga, A.M., San Marchi, C.W., Campbell, J., Nissen, A. and Mills, B.E. (2017). 'Polymer behaviour in high pressure hydrogen helium and argon environments as applicable to the hydrogen infrastructure' (No. SAND2017-8413C). Sandia National Lab (SNL-NM), Albuquerque, NM (United States).		
				Satisfactory			
				Hydrogen has no effect on NBR			
				Limited information on impact of glass transition at low pressures			
	Ethylene Propylene Diene Monomer (EPDM)	EPDM NF	EPDM Espene 505 (100), stearic acid (1), zinc oxide (5), sulfur (1.5) MBTS (1.5), TMTD (0.5)	EPDM shown to embrittle & blister as a function of H2 content and swelling leading to volumetric change at H2x35MPaX100°Cx15hrs.	Nishimura, S. (2018) 'Database of Polymeric Materials for Hydrogen Gas		Whether catalysts containing Fe, Co, Ni, Rh, Pt or Pd were used in the initial synthesis. Analytical methods such as atomic absorption spectroscopy (AAS) or X-ray fluorescence spectroscopy (XRF) are specialised methods that have previously been used for this purpose
		EPDM CB50	EPDM Espene 505 (100), stearic acid (1), zinc oxide (5), sulfur (1.5) MBTS (1.5), TMTD (0.5), carbonblack N330 (50)	Compression set was studied on NBR and EPDM was found to increase in the presence of high pressure hydrogen from approximately 20 to 40% in the absence of filler.	Simmons, K., Bhamidipaty, K., Menon, N., Smith, B., Naskar, A. and Veenstra, M., (2018). 'Compatibility of polymeric materials used in the hydrogen infrastructure. Pacific		
		EPDM CB25	EPDM Espene 505 (100), stearic acid (1), zinc oxide (5), sulfur (1.5) MBTS (1.5), TMTD (0.5), carbonblack N330 (25)	Residual Ziegler-Natta catalysts and metallocenes were detected in field specimens. This could lead on on-going reaction. Atomic hydrogen can be produced from a gaseous supply, when additives or catalysts containing metals such as palladium are present: such reactions may result in crosslinking of unsaturated polymer chains leading to embrittlement	Bichinho, K.M., Pires, G.P., Stedile, F.C., dos Santos, J.H.Z. and Wolf, C.F., (2005). 'Determination of catalyst metal residues in polymers by X-ray fluorescence'. <i>Spectrochimica Acta Part B: Atomic Spectroscopy</i> , 60(5), pp.599-604.		
		EPDM SC60	EPDM Espene 505 (100), stearic acid (1), zinc oxide (5), sulfur (1.5) MBTS (1.5), TMTD (0.5), silica Nipol VNS (60)	The filler material used in these model material compounds show a decrease in volume change for NBR by 10% and 30% in EPDM from unfilled baseline compound. Volume change towards 0 at 10MPa.	Simmons, K., Bhamidipaty, K., Menon, N., Smith, B., Naskar, A. and Veenstra, M., (2018). 'Compatibility of polymeric materials used in the hydrogen infrastructure. Pacific		
		EPDM SC30	EPDM Espene 505 (100), stearic acid (1), zinc oxide (5), sulfur (1.5) MBTS (1.5), TMTD (0.5), silica Nipol VNS (30)	Helium ion microscopy used to reveal that phase separation of plasticizer and formation of large voids (30-40 um) are induced by hydrogen. 90MPa	Simmons, K.L., Kuang, W., Burton, S.D., Arey, B.W., Shin, Y., Menon, N.C. and Smith, D.B., (2021). 'H-Mat hydrogen permeability and degradation		
				Satisfactory	Parker (no date), Parker O-Ring chemical		
				Satisfactory	Parker (no date), Parker O-Ring chemical compatibility table for gases, fluids,		
				Satisfactory	Parker (no date), Parker O-Ring chemical compatibility table for gases, fluids,		
				Microvoid formation in the FKM O-ring upon exposure to high-pressure hydrogen was minimised over time after the ring was exposed to atmospheric pressure at room temperature, which prevented changes in its tensile properties. However, applying heat accelerated FKM O-ring oxidation	Jeon, S.K. and Bae, J.W. (2020). 'Long-Term Reliability of Fluoroelastomer (FKM) O-ring after Exposure to High Pressure Hydrogen Gas. <i>Elastomers and Composites</i> , 55(4), pp.270-276.		
				Satisfactory	Parker (no date), Parker O-Ring chemical compatibility table for gases, fluids,		
	Viton-A, Fluorocarbon rubber, O rings			Satisfactory	solids. Available at: Parker (no date), Parker O-Ring chemical compatibility table for gases, fluids,		Fundamentally ok but cant qualify
	Fluoroelastomer FKM (dipolymer)			Satisfactory	Parker (no date), Parker O-Ring chemical compatibility table for gases, fluids,		Fundamentally ok but cant qualify
	Neoprene			Satisfactory	Parker (no date), Parker O-Ring chemical compatibility table for gases, fluids,		Fundamentally ok but cant qualify
	Vulcanised rubber + Carbon Black + sulphur + zinc oxide or stearic acid			Satisfactory	Parker (no date), Parker O-Ring chemical compatibility table for gases, fluids,		Fundamentally ok but cant qualify

Table 5 (Continued) Non-metallic materials assessment

Material family	Type	Grade	Nominal composition	Performance	Reference	Rating	Comments
Pipe joining compound	Boss white, Hawk white, jet lube.....	all jointing compounds to BS EN 751-2 Class A	Linseed-oil (Linolenic Acid) + Kaolin/Ochre				Can be hydrogenated by hydrogen gas to form Stearic acid (C18H30O2 + 3H2 ---> C18H36O2). What performance shift should be expected. Impact of fillers? does stearic acid tranformation change the dispersion?
	Loctite & Similar	Dimethacrylate ester		"Shown Resistant"	Loctite (2002). Fluid compatibility chart for metal threaded fittings sealed with loctite sealants, Newline hose and fittings. Available at: https://www.new-line.com/nldocs/resources/Loctite_Fluid_Compatibility_Chart.pdf		Fundamentally ok but cant qualify
Polymers	Polyamide	PA11 and PA12, 581		Under shown conditions of ageing, the permeation coefficient is constant, equal to 2 9 108 cm ³ .cm1 .s1 .bar1 for PE sample and 8 9 109 cm ³ .cm1 .s1 .bar1 for PA11 sample at 20C under H2, within measurement uncertainty. It is unaffected by one year of ageing, whatever the experimental conditions. Analysis of the available results for tube samples suggests that the same ratio exists between the permeation coefficients of PE and PA11 tubes and that they are also essentially unaltered by ageing	Klopfner, M.H., Berne, P. and Espuche, E. (2015). 'Development of innovating materials for distributing mixtures of hydrogen and natural gas'; Study of the barrier properties and durability of polymer pipes. <i>Oil & Gas Science and Technology-Revue d'IFP Energies nouvelles</i> , 70 (2), pp.305-315.		>13months - current timebase too short to see impacts of plasticiser, residual unsaturated amides?
				After long-term aging up to 13 months in hydrogen at various pressures (5 or 2 MPa) and temperatures below and above the glass transition of PA11 and the alpha-c transition for PE (20 °C, 50 °C and 80 °C), no deleterious effect was observed on the mechanical properties of PE and PA11. Differences observed for PA11 essentially resulted from testing temperature variability close to the glass transition temperature.	Castagnet, S., Grandier, J.C., Comyn, M. and Benoit, G. (2012). 'Effect of long-term hydrogen exposure on the mechanical properties of polymers used for pipes and tested in pressurized hydrogen', <i>International journal of pressure vessels and piping</i> , 89 ,		
				Consistently with the tensile properties, no significant evolution of the crystalline microstructure after aging in hydrogen aroused from DSC experiments. Again, the clearer effect was associated with the annealing temperature in PA11.			
	PTFE	Virgin PTFE Chemically Modified PTFE Pigmented PTFE Class Filled PTFE Carbon/coke PTFE (soft amorphous carbon hard filler) Graphite Filled PTFE (pure crystalline Carbon) Carbon + Graphite + Glass Filled	Filler Content by weight % - - - 15 to 25 25 to 35 35 12 + 3 + 10	Excellent chemical resistance	Basic Properties & Grades of Filled PTFE (standard-ptfe.com)		
				Thermoplastics (PTFE shown here) showed negligible effects with helium or helium/hydrogen exposure	Simmons, K., Bhamidipaty, K., Menon, N., Smith, B., Naskar, A. and		
	PEEK			Unfilled PEEK did not show change in FTIR when exposed to hydrogen	Theiler, G. and Gradi, T. (2016). 'Environmental effects on the sliding		Fundamentally ok but cant qualify

Table 5 (Continued) Non-metallic materials assessment

Material family	Type	Grade	Nominal composition	Performance	Reference	Rating	Comments
Polymers	MDPE - medium density polyethylene pipe	PE80 +CBB, PE100, PE2406, PE2708	PE shall conform to BS EN 1555-1:2021	Polyethylene (PE80) pipe was exposed to 6 week of hydrogen gas exposure at 2 barg and 20°C without deterioration in mechanical properties.	Birkitt, X., Loo-Morrey, M., Sanchez, C. and O'Sullivan, L., (2021). Materials aspects associated with the		whether catalysts containing Fe, Co, Ni, Rh, Pt or Pd were used in the initial synthesis. Analytical methods such as atomic absorption spectroscopy (AAS) or X-ray fluorescence spectroscopy (XRF) are specialised methods that have previously been used for this purpose
				(Alincant et al., 2010; Briottet and Riccetti, 2016; Foulc et al., 2006) are that no incubation time is needed for hydrogen to permeate through PE, which is not the case for methane, and, at room temperature, the permeation coefficient of hydrogen through PE is four to five times higher than methane in a methane plus hydrogen gas mixture, at room temperature	Blanchard L and Briottet L (2020): "Non-combustion related impact of hydrogen admixture – material compatibility" ThyGA report Deliverable D2.4, June 2020.		
				Investigation on chemical compatibility have shown that polymer materials, and specifically PE, are not subjected to deterioration after long term exposure in dihydrogen	Blanchard L and Briottet L (2020): "Non-combustion related impact of hydrogen admixture – material compatibility" ThyGA report Deliverable D2.4, June 2020.		
				Residual Ziegler-Natta catalysts and metalloenes were detected in field specimens. This could lead on on-going reaction. Atomic hydrogen can be produced from a gaseous supply, when additives or catalysts containing metals such as palladium are present. such reactions may result in crosslinking of unsaturated polymer chains leading to embrittlement	Buchirri, K.M., Pires, G. P., Stedile, F.C., dos Santos, J.H.Z. and Wolf, C.R., 2005. Determination of catalyst metal residues in polymers by X-ray fluorescence. Spectrochimica Acta Part B: Atomic Spectroscopy, 60(5), pp.599-604.		
				Hydrogen has no effect on PE up to 20mol%	Hennrichs, K., Wittenstock, E., De Meulenaer, L., and G. Schaefer, 2013. "Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues" NREL Technical report NREL/TP-5600-51909.		
				A 20% hydrogen mixture at 58 psig (5 bar) was investigated for leakage. The leakage rates for methane and hydrogen from this blend under these conditions are 1.1 and 2.3 L/km/day, respectively. For comparison, the permeability of pure methane under similar conditions is 1.4 L/km/day	Iskov, H., Backman, M. and Nelson, H. P (2010) 'Field Test of Hydrogen in the Natural Gas Grid', 18th World Hydrogen Energy Conference 2010 - WHEC 2010, Essen, Germany, 16-21 May.		Tested for up to 4 years
				No interaction between the hydrogen and antioxidants or hydrogen and material over 4 years period. The results are valid for both the PE80 and the PE100 pipes. The structure analysis also indicates that there is no interaction between hydrogen and the Polymer. Neither in the MFR/FRR analysis nor the rheological analysis is revealing any interaction between the polymer and the transported media, hydrogen. The structure of the polymer is intact according to the analysis made after four years of exposure at 4 barg and 8 degrees celcius. This is valid for both the PE80 and the PE100 pipe materials.	Iskov, H., Backman, M. and Nelson, H. P (2010) 'Field Test of Hydrogen in the Natural Gas Grid', 18th World Hydrogen Energy Conference 2010 - WHEC 2010, Essen, Germany, 16-21 May.		
				polyethylene gas pipes PE80 and PE100 can be used for transportation of hydrogen without any adverse long-term effects on antioxidants, polymer structure or the mechanical performance of the polymer pipes.	Iskov, H., Backman, M. and Nelson, H. P (2010) 'Field Test of Hydrogen in the Natural Gas Grid', 18th World Hydrogen Energy Conference 2010 - WHEC 2010, Essen, Germany, 16-21 May.		
Historic HDPE		i.e. Dupont Aldyl "A" - MDPE	Detailed list here				Historic PE much less control and prone to embrittlement. Little data of current performance. Higher catalyst traces.
HDPE		PE100		In the case of mixture of methane and hydrogen through PE100, no particular gas-gas or gas-polymer interaction has been revealed whatever the composition as well as no pressure effect".	Klopfner, M.H., Berne, P. and Espuche, E. (2015). "Development of innovating materials for distributing mixtures of hydrogen and natural gas. Study of the barrier properties and durability of polymer pipes". Oil & Gas Science and Technology-Revue d'IFP Energies nouvelles, 70(2), pp.305-315.		whether catalysts containing Fe, Co, Ni, Rh, Pt or Pd were used in the initial synthesis. Analytical methods such as atomic absorption spectroscopy (AAS) or X-ray fluorescence spectroscopy (XRF) are specialised methods that have previously been used for this purpose
				Residual Ziegler-Natta catalysts and metalloenes were detected in field specimens. This could lead on on-going reaction. Atomic hydrogen can be produced from a gaseous supply, when additives or catalysts containing metals such as palladium are present.	Buchirri, K.M., Pires, G. P., Stedile, F.C., dos Santos, J.H.Z. and Wolf, C.R., 2005. Determination of catalyst metal residues in polymers by X-ray fluorescence. Spectrochimica Acta Part B: Atomic Spectroscopy, 60(5), pp.599-604.		
				under our conditions of ageing, the permeation coefficient is constant, equal to 2 x 10-8 cm3.cm-1.s-1.bar-1 for PE sample and 8 x 10-9 cm3.cm-1.s-1.bar-1 for PA11 sample at 20C under H2, within measurement uncertainty. It is unaffected by one year of ageing, whatever the experimental conditions. Analysis of the available results for tube samples suggests that the same ratio exists between the permeation coefficients of PE and PA11 tubes and that they are also essentially unaltered by ageing	Klopfner, M.H., Berne, P. and Espuche, E. (2015). "Development of innovating materials for distributing mixtures of hydrogen and natural gas. Study of the barrier properties and durability of polymer pipes". Oil & Gas Science and Technology-Revue d'IFP Energies nouvelles, 70(2), pp.305-315.		
				2021: In an environment with a hydrogen pressure of 3 MPa, Castagnet et al. [27] conducted a series of mechanical tests (tensile, creep, ductile fracture, etc.) on PE and PA11, which showed that the transmission of hydrogen had no obvious effect on the amorphous and crystalline phase of the material, and the influence on the mechanical experiment results of materials does not exceed 10%. In other studies under low pressure [24,28], no obvious hydrogen effect was found. Subsequently, Fujiwara et al. [32] also proved that this effect was not obvious under high pressure, which is consistent with the literature [15]. However, there are almost no experimental data that measured at both high pressure and high temperature and this needs to be further studied.	Su, Y., Lv, H., Zhou, W. and Zhang, C. (2023). "Review of the Hydrogen Permeability of the Liner Material of Type IV On-Board Hydrogen Storage Tank". World Electric Vehicle Journal, 12(3), p.130.		
				After long-term aging up to 13 months in hydrogen at various pressures (5 or 2 MPa) and temperatures below and above the glass transition of PA11 and the alpha-c transition for PE (20 °C, 50 °C and 80 °C), no deleterious effect was observed on the mechanical properties of PE and PA11. Differences observed for PA11 essentially resulted from testing temperature variability close to the glass transition temperature.	Castagnet, S., Granddier, J.C., Cornyn, M. and Benoit, G. (2012). Effect of long-term hydrogen exposure on the mechanical properties of polymers used for pipes and tested in pressurized hydrogen". International Journal of pressure vessels and piping, 89, pp.203-209.		
				No mechanism exists for hydrogen embrittlement without another catalyst for degradation	Klaine, M., 2008. "Permeability, solubility, and interaction of hydrogen		
				Four years of continuous hydrogen exposure at 4 barg and 8 degree celcius caused no influence on PE 100 HDPE natural gas pipes	Iskov, H., Backman, M. and Nelson, H. P (2010) 'Field Test of Hydrogen in the Natural Gas Grid', 18th World Hydrogen Energy Conference 2010 - WHEC 2010, Essen, Germany, 16-21 May.		
				Satisfactory	M. Loo-Morrey, ES/2018/10		

Table 5 (Continued) Non-metallic materials assessment table

Material family	Type	Grade	Nominal composition	Performance	Reference	Rating	Comments
Polymers	XLPE/PEX	Electron beam cross-linked polyethylene (PE-Xc) Chemically cross-linked polyethylene (PE-Xb)					Fundamentally ok but cant qualify
	PPS			Due to the similar chain structure to PE, degree of crystallinity, and chain orientation, it can be concluded that their permeation and solubility behavior in the presence of hydrogen will be similar. Satisfactory	https://digital.library.unt.edu/ark:/67531/metadc902701/m2/1/high_res_d/927901.pdf Birkitt, K., Loo-Morrey, M., Sanchez,		Fundamentally ok but cant qualify
	PVC	PVC-HI grade (ISO 6993-1) K-value: 65. IM>7%.		PVC pipe systems can be considered for use with hydrogen-methane based blends, and with pure hydrogen gases. Indeed, for modern materials, the industry standards such as ISO 4437, EN 1555 and ISO 6993 already anticipate this in their scope for compatible fuel gases for polymer piping systems. The phenomenon of plasticization of polymers due to sorption of certain gases is well known. Plasticization strongly impacts physical and mechanical properties; therefore, a few representative materials should be evaluated in gaseous hydrogen	https://www.teppfa.eu/wp-content/uploads/PP-EX-202109-05-Hydrogen-a-potential-future-fuel-gas.pdf Barth, R.R., Simmons, K.L. and San Marchi, C.W., 2013. <i>Polymers for hydrogen infrastructure and vehicle fuel systems</i> (No. SAND2013-8904). Sandia National Laboratories, CA. Seymour, R., van der Stok, E., de Boer, I. and Weller, I. (2016). <i>Case</i> Birkitt, K., Loo-Morrey, M., Sanchez, Hermekens, R., van der Stok, E., de Boer, I. and Weller, I. (2016). <i>Case</i> Birkitt, K., Loo-Morrey, M., Sanchez,		"A few representative materials should be evaluated in gaseous hydrogen" - PVC + PA11?
	Polyoxymethylene (POM); Polyacetyl			Hydrogen has no effect on PVC up to 20mol% Satisfactory	Birkitt, K., Loo-Morrey, M., Sanchez, Hermekens, R., van der Stok, E., de Boer, I. and Weller, I. (2016). <i>Case</i> Birkitt, K., Loo-Morrey, M., Sanchez,		
	Polyurathane			Hydrogen has no effect on POM Satisfactory	Birkitt, K., Loo-Morrey, M., Sanchez,		
	Polycarbonate			Judging from the results and the consideration, hydrogen is considered to exist as the isolated hydrogen.	Ono, H., Fujiwara, H., Onoue, K. and Nishimura, S., 2020. FT-IR study of state of molecular hydrogen in bisphenol A polycarbonate dissolved by high-pressure hydrogen gas		
Composite	Non asbestos fibre – (can include nitrile or ptf)						
	Vulcanised fibre – totally cellulose						
	Compressed asbestos fibre (CAF) gaskets				Birkitt, K., Loo-Morrey, M., Sanchez,		
	Glass or aramid-fiber reinforced thermoset (e.g., epoxy) outer only (PPS inner)			No direct conclusions but linear permeability and volume change stabilised. technical feasibility of using a commercially available spoolable glass-fiber-reinforced polymer (GFRP) pipeline for hydrogen transmission.	Smith, David & Frame, Barbara & Anovitz, Lawrence & Makselon, Christopher. (2016). Feasibility of Using Glass-Fiber-Reinforced Polymer Pipelines for Hydrogen Delivery. V06BT06A036. 10.1115/PVP2016-63683.		Hydrogen permeation into glass, impacts mech properties

Table 6 Flammability limits for methane (CH₄) and hydrogen (H₂)

Flammability	Gas	
	CH ₄	H ₂
(explosive) limit-lower (%V)	5	4
(explosive) limit-upper (%V)	15	76

Table 7 Saturation time estimates for a thickness of 0.6cm for nitrile butadiene rubber and low density polyethylene.* (Menon, 2016), ** (Fujiwara, 2021)

Diffusion coefficient (cm ² s ⁻¹)	Time-to-saturation 90% (h)	Time-to-saturation 95% (h)	Time-to-saturation 99.9% (h)
4.2E-06 (NBR, 20°C)*	8.9	10.6	20.0
1.1E-05 (LDPE, 50°C)**	3.4	4.0	7.64

Table 8 Diffusion coefficients of hydrogen in polymers

Material	Temperature Pressure (°C, bar)	Diffusion coefficient (cm ² s ⁻¹)	Reference
HDPE (PE100)	50, 900	1.4E-06	(Fujiwara H. O., 2021)
LDPE	50, 900	1.1E-05	(Fujiwara H. O., 2021)
NBR	20, 1000	4.2E-06	(Menon N. C., 2016)
FKM	20, 1000	1.9E-06	(Menon N. C., 2016)

Table 9 Examples of stabilisers, antioxidants and catalysts

Material	Stabilisers/antioxidants/catalyst
Acrylonitrile butadiene copolymer	Antioxidants (Phenolic with suitable thiogroups), Phosphites
Polybutadiene	Processing stability(combined phenol and phosphite), Phosphites/Ti-Zieger Natta catalyst
Polyamides	Cu salts/Iodide, aromatic amines and phenols
Polyethylene	Benzofuranone and Phenol phosphite /Cr or Ti catalyst
Polypropylene	Pthalates

Table 10 Appearances of metals

Metal	General appearance
Cast Iron	Dull grey, rough surface
Carbon steels	Dark grey, dull, may have some surface rust
Stainless steel	Dark grey, shinny
Copper	Reddish-brown, green "rust"
Brass and Bronze	Reddish-yellow
Aluminium	Light grey, shinny, light
Lead	Whitish grey, heavy

Table 11 Magnetic properties of metals

Metallic material	Magnetic
Carbon steel/Low alloy steel	Yes
Cast Iron	Yes
Stainless steel	Weakly (Yes for ferritic and martensitic grades)
Aluminium	No
Copper	No
Brass/Bronze	No
Lead	No

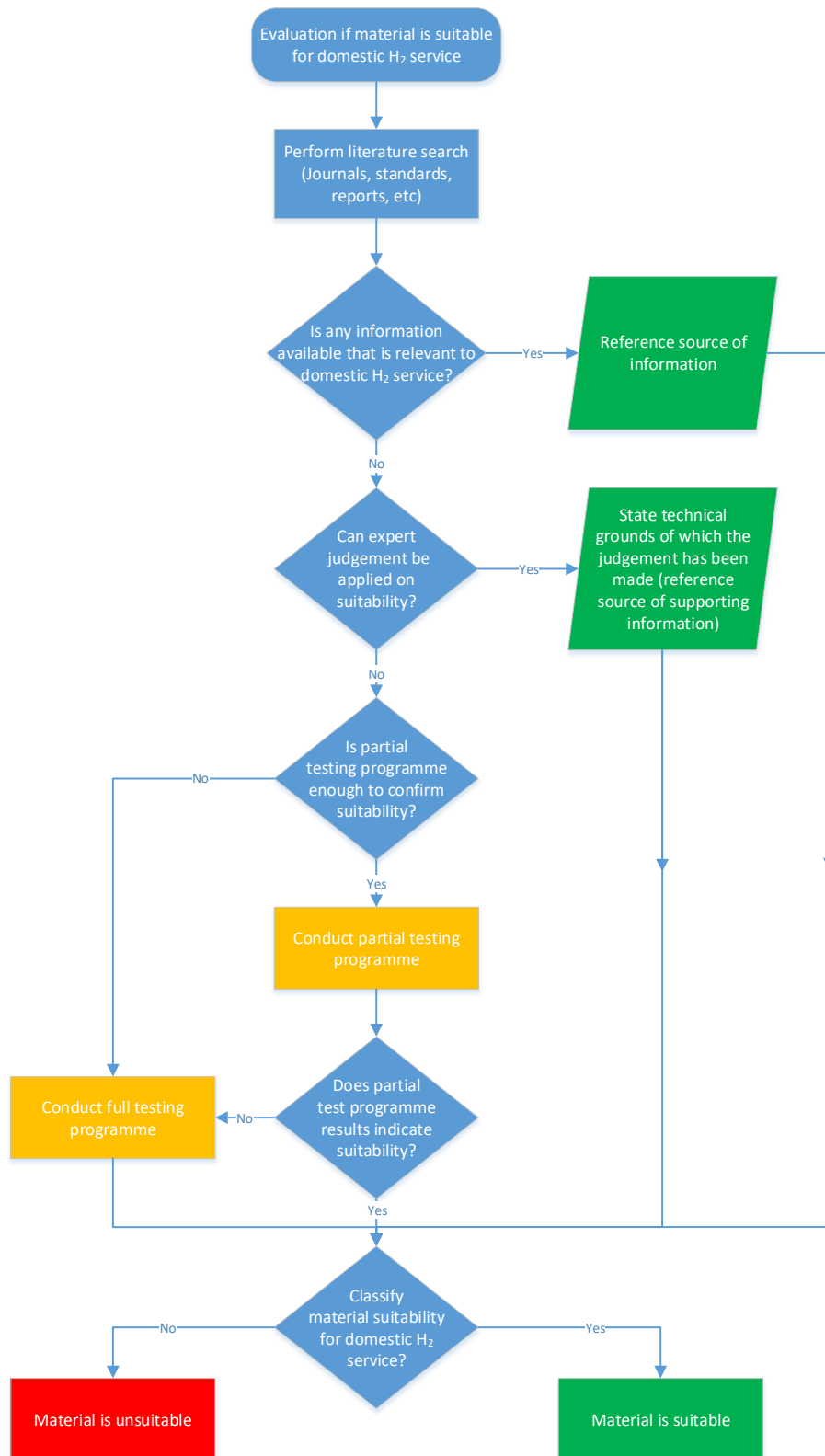


Figure 1 Material suitability to low pressure hydrogen service classification process.

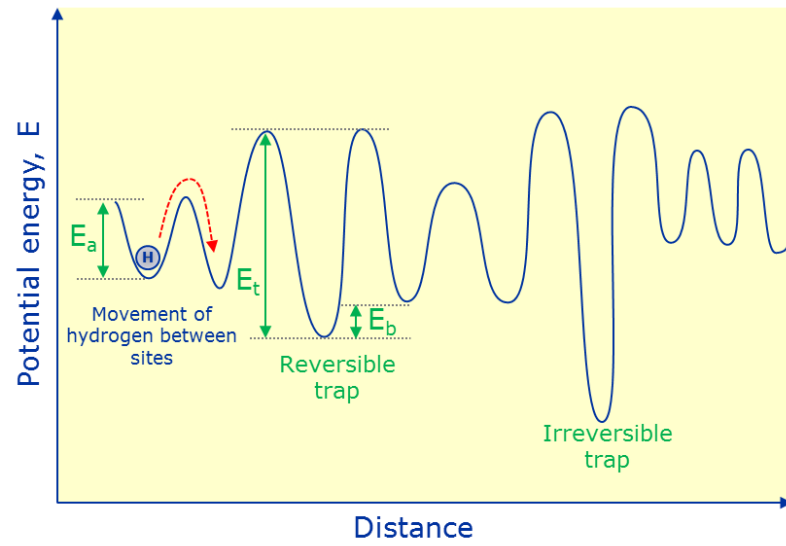
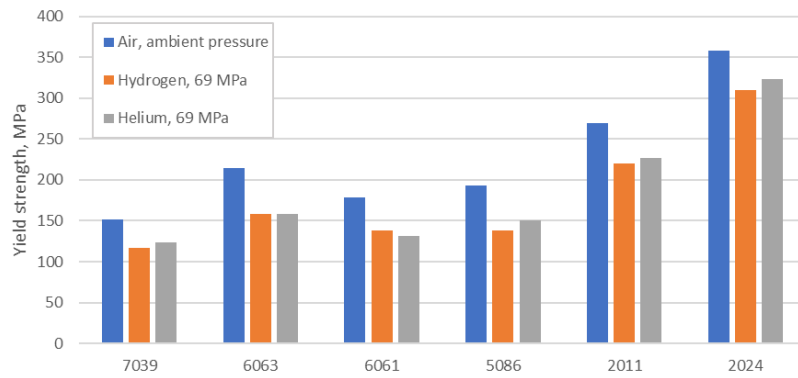
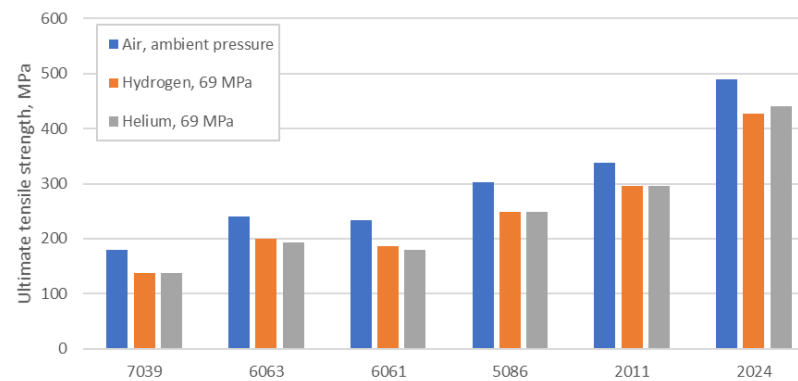


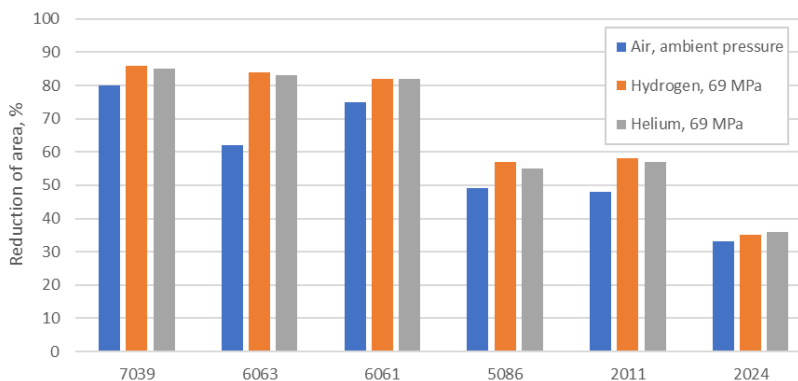
Figure 2 illustration of hydrogen traps represented as energy wells with differing binding energies.



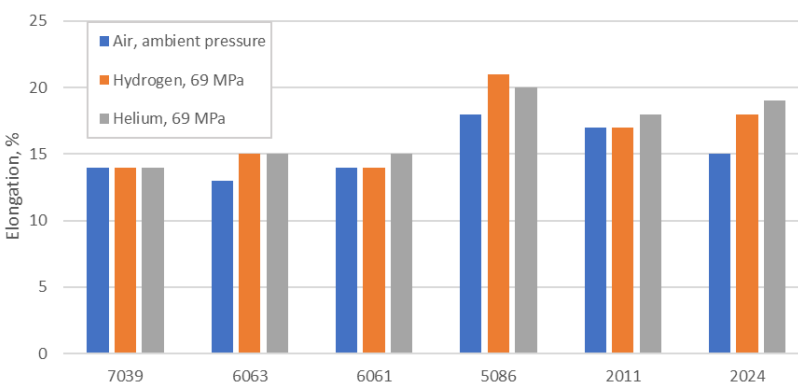
a)



b)



c)



d)

Figure 3 Effect of hydrogen on tensile properties of various aluminium alloys. Plots produced based on the data from Louthan and Caskey (1976).

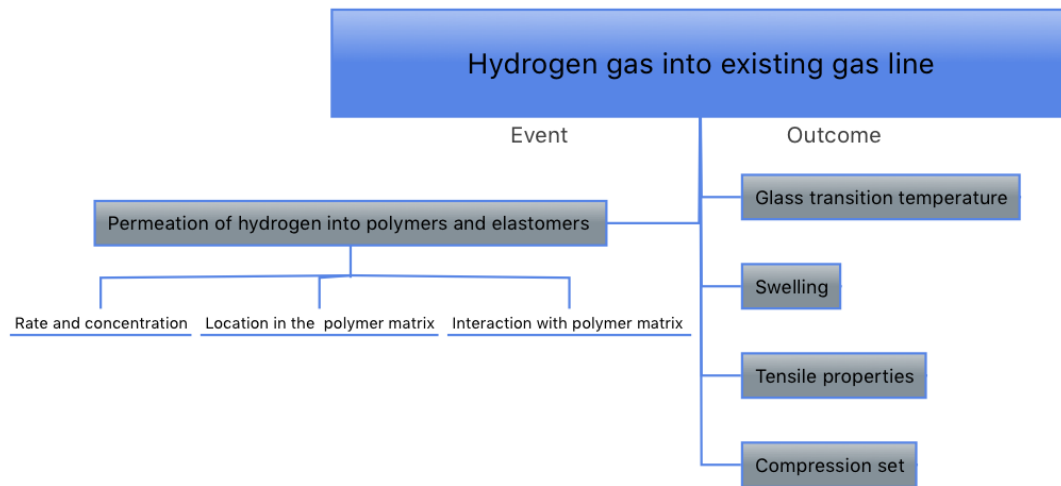


Figure 4 Ingress into the matrix on exposure to hydrogen gas and the thermoplastic and elastomer properties that represent a change.

TWI Ltd Management System

TWI operates a certificated Management System designed to ensure that Customer requirements are met and that all work carried out is conducted in a planned and controlled manner. Customer satisfaction is a key measure of the success of TWI, which remains committed to delivering world-class solutions. To this end:

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- Close and frequent contact with the Customer by the Project Leader throughout the project. In particular, any changes in key personnel involved in the project or equipment availability will be discussed together with any potential project delays or contractual changes.
- Regular management reviews are held throughout the life of a project and upon its completion. These cover project finances, technical progress and adherence to schedule.
- Project Customers are formally contacted on project completion to determine their satisfaction with the work carried out. Moreover, TWI senior management welcomes Customer feedback on project progress at all times during the course of the work. Significant lapses in service will be subject to a structured management review so that inadequate procedures can be identified and improved.



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Fax: +44 (0)1223 892588
Web: www.twi-global.com

VAT Number GB 700 1708 89

Registered Number 03859442 England

Appendix B

Malleable iron composition and data



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Cambridge CB21 6AL, United Kingdom
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E-mail: chemanal@twi.co.uk

CHEMICAL ANALYSIS REPORT

ANALYSIS METHOD		ICP & Combustion		CLIENT					TWI REPORT NO	
MATS DEPT QA REF NO									S/22/24	
MATERIAL SPECIFICATION									ANALYSIS DATE	
				REF/ORDER NO					34739/3	
				DATE RECEIVED					27/09/22	
									INVOICE NO	

SAMPLE NUMBER	ELEMENT, % (m/m)								
	C	Cr	Cu	Mn	Mo	Ni	P	S	Si
M01-CHEM	3.44	0.06	0.06	0.42	<0.01	0.02	0.036	0.14	1.23
	ELEMENT, % (m/m)								

COMMENTS: The samples were analysed by a UKAS accredited laboratory.

PAGE	1	OF	1	SENIOR ANALYST	SIGNATURE	DATE ISSUED
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Note: the chemical analysis results detailed above apply only to the sample(s) of material submitted to the laboratory.



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CHEMANAL

ANALYSIS METHOD		Inert Gas Fusion/Thermal Conductivity Detection & Hot Extraction		CLIENT		TWI REPORT NO H22/11	
MATS DEPT QA REF NO		MCS-ANA-WI-040+046				ANALYSIS DATE 07&08/12/22	
MATERIAL SPECIFICATION						INVOICE NO	
				REF/ORDER NO	34739/3	DATE RECEIVED	10/11/22
SAMPLE NUMBER	ELEMENT (ppm)						
	Res H*		DH**				
	M01 CAST IRON AS RECEIVED		3 <0.5				
	M01-10 CAST IRON POST TEST		3 <0.5				
		ELEMENT, (ppm)					
COMMENTS: *Residual hydrogen analysed by melt extraction. ** Diffusible hydrogen was analysed by hot extraction at 400°C.							
PAGE 1 OF 1		SIGNATURE			DATE ISSUED		



FLAT TENSILE 34739 M01-01

Test date	27/10/2022
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

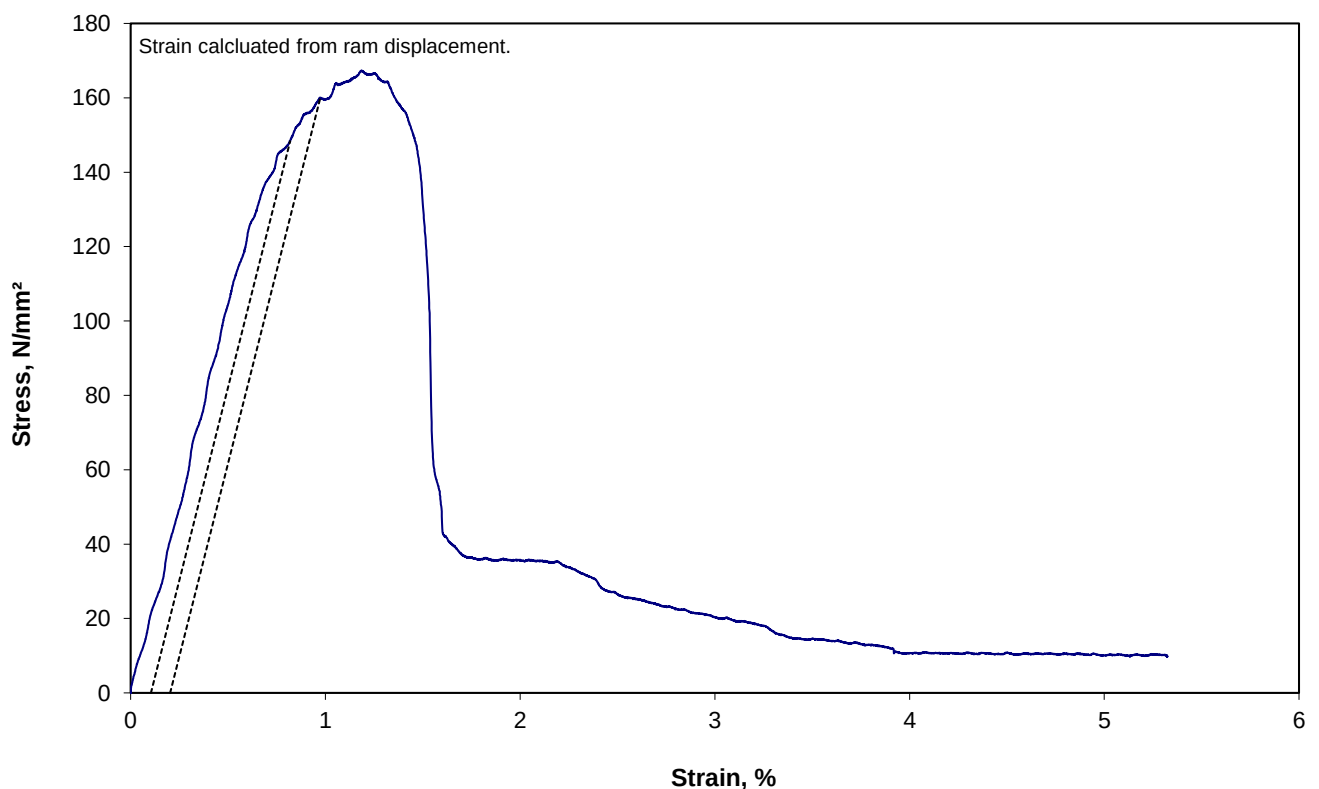
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	6.07 mm
Initial Thickness	2.22 mm
no extensometer in use	
Initial XSA	13.491 mm ²
Final XSA	13.074 mm ²
Estimated Youngs modulus	20747 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	26.55 mm
Initial Gauge length	48.51 mm
Final gauge length	49.37 mm
Initial Stressing rate	0.216 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000266 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.217	2.00	148.3
0.2	0.259	2.16	160.0
UTS		2.26	167.4
Reduction in area		3.09 %	
Elongation		1.78 %	





FLAT TENSILE 34739 M01-02

Test date	27/10/2022
Technician	
Test machine	INSTRON 8801 B752
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

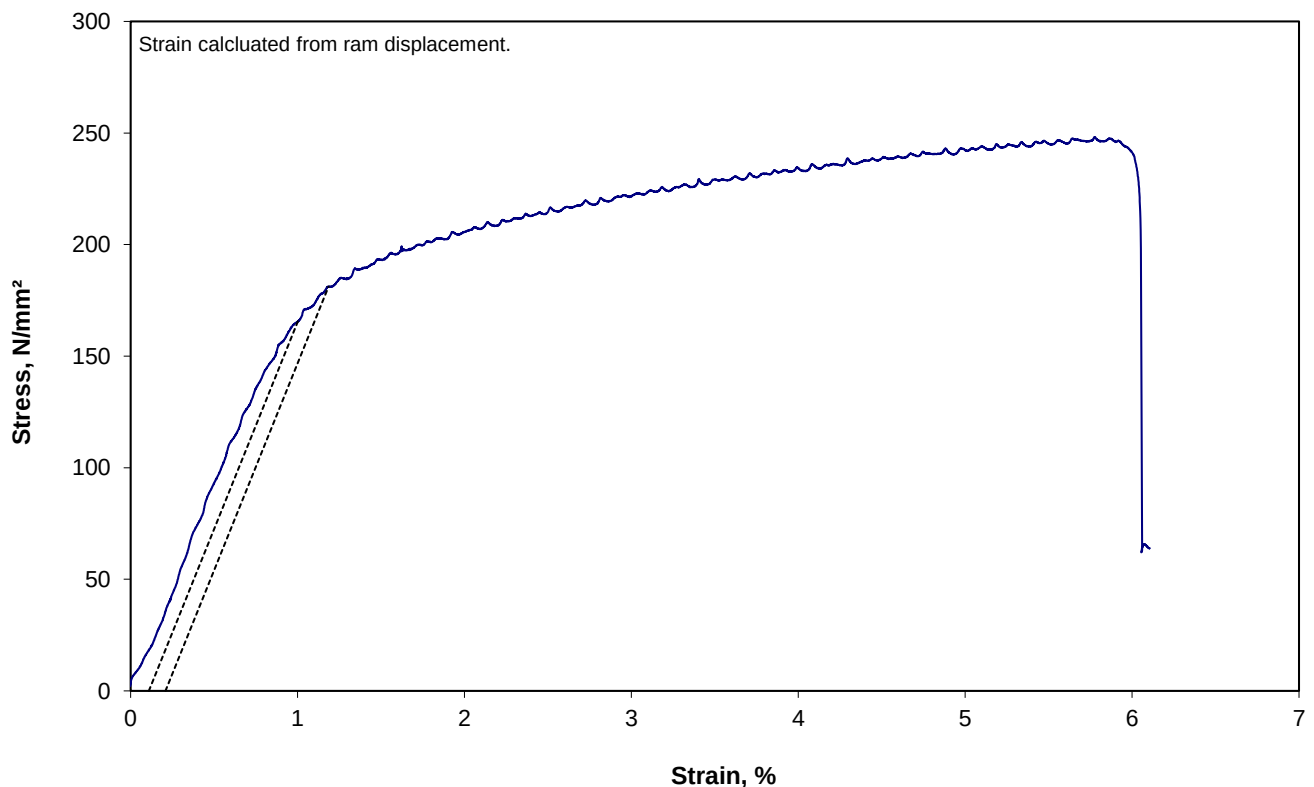
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	6.07 mm
Initial Thickness	2.16 mm
no extensometer in use	
Initial XSA	13.130 mm ²
Final XSA	12.719 mm ²
Estimated Youngs modulus	18545 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	25.86 mm
Initial Gauge length	48.51 mm
Final gauge length	50.48 mm
Initial Stressing rate	0.183 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000259 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.259	2.17	165.5
0.2	0.307	2.38	181.2
UTS		3.26	248.2
Reduction in area		3.13 %	
Elongation		4.06 %	





FLAT TENSILE 34739 M01-03

Test date	28/10/2022
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

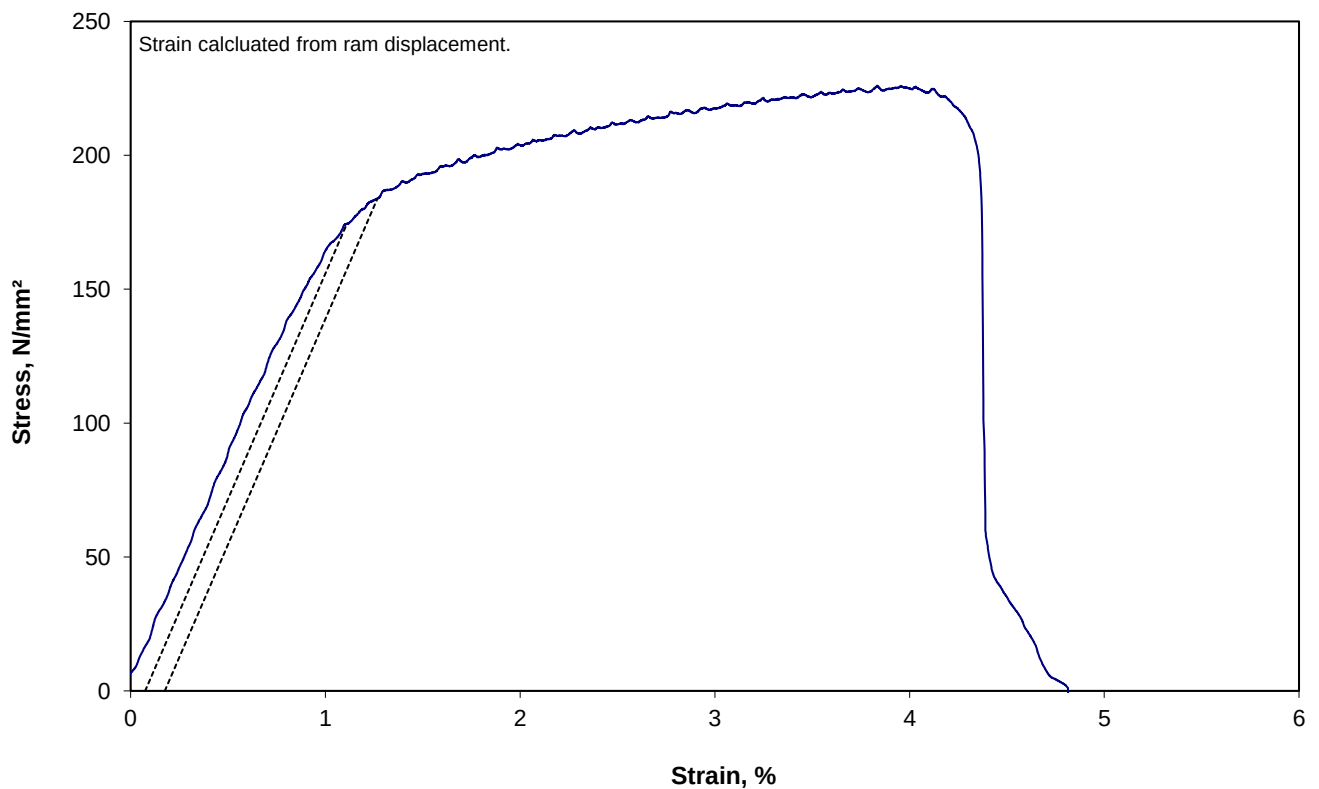
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	6.15 mm
Initial Thickness	2.15 mm
no extensometer in use	
Initial XSA	13.218 mm ²
Final XSA	12.566 mm ²
Estimated Youngs modulus	16837 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	25.88 mm
Initial Gauge length	48.48 mm
Final gauge length	49.56 mm
Initial Stressing rate	0.172 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000259 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.287	2.31	174.4
0.2	0.328	2.43	183.8
UTS		2.99	226.0
Reduction in area		4.93 %	
Elongation		2.23 %	





FLAT TENSILE 34739 M01-04

Test date	28/10/2022
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

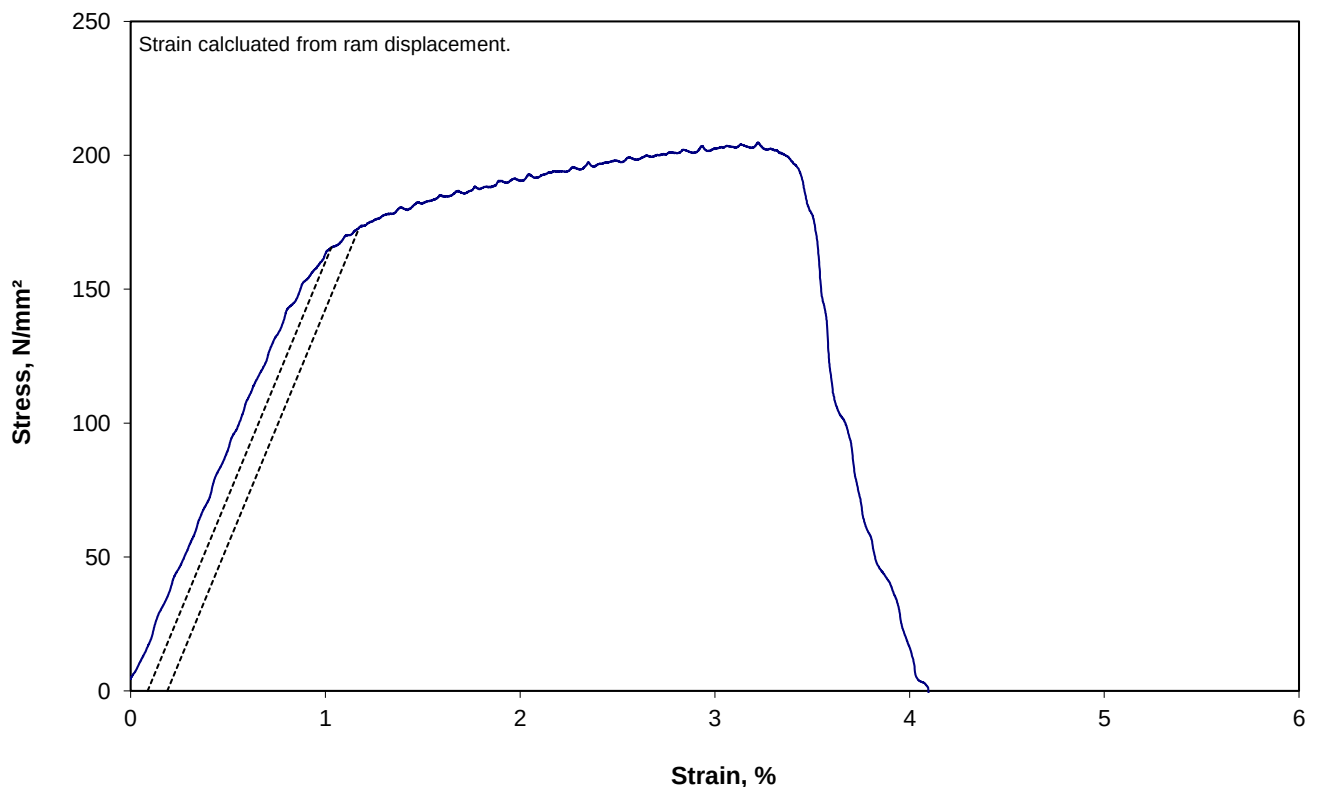
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	6.10 mm
Initial Thickness	2.19 mm
no extensometer in use	
Initial XSA	13.336 mm ²
Final XSA	12.857 mm ²
Estimated Youngs modulus	17551 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	26.08 mm
Initial Gauge length	48.43 mm
Final gauge length	49.43 mm
Initial Stressing rate	0.178 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000261 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.269	2.21	165.6
0.2	0.306	2.30	172.6
UTS		2.73	204.9
Reduction in area		3.59 %	
Elongation		2.08 %	





FLAT TENSILE 34739 M01-05

Test date	31/10/2022
Technician	
Test machine	INSTRON 8801 B752
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

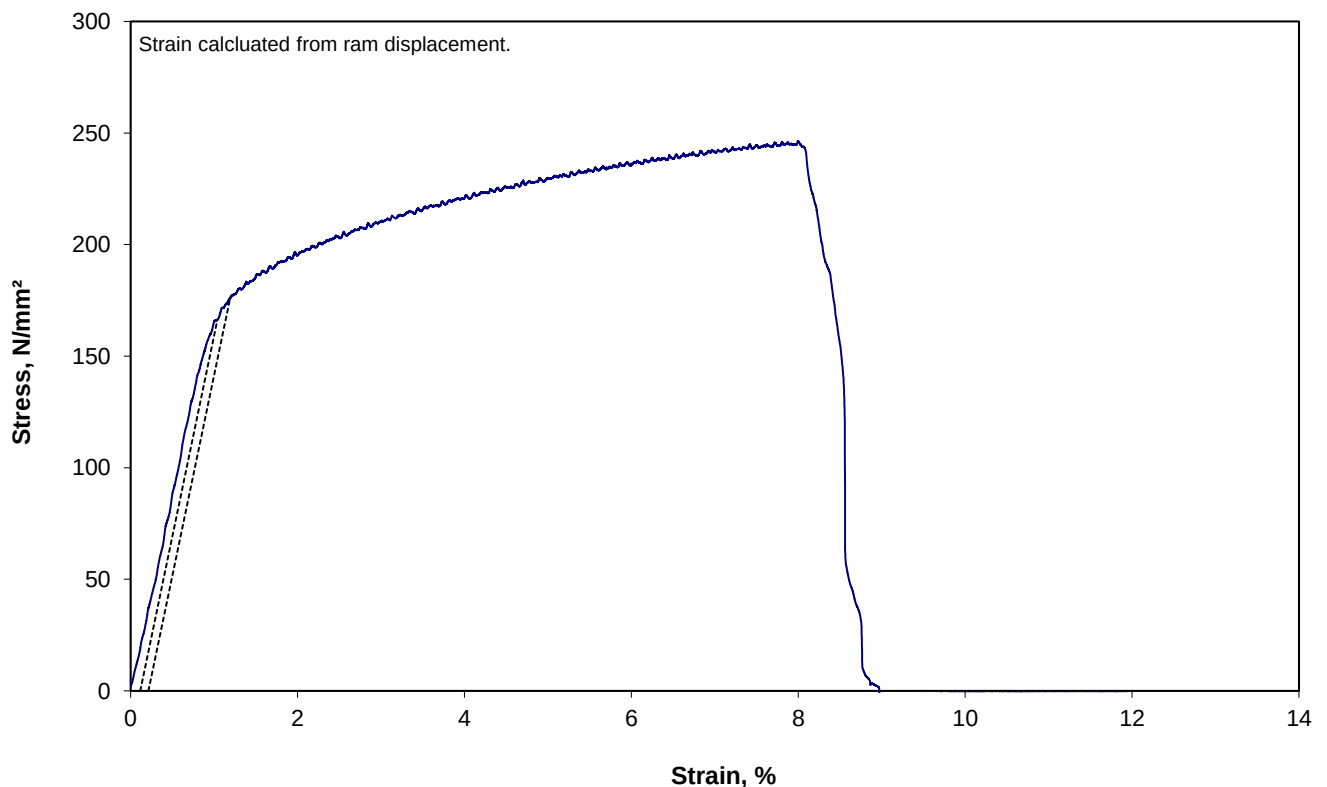
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	6.04 mm
Initial Thickness	2.19 mm
no extensometer in use	
Initial XSA	13.242 mm ²
Final XSA	12.350 mm ²
Estimated Youngs modulus	17972 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	26.00 mm
Initial Gauge length	48.47 mm
Final gauge length	50.83 mm
Initial Stressing rate	0.186 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.00026 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.270	2.20	166.3
0.2	0.310	2.33	175.6
UTS		3.26	246.3
Reduction in area		6.73 %	
Elongation		4.87 %	





FLAT TENSILE 34739 M01-06

Test date	31/10/2022
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

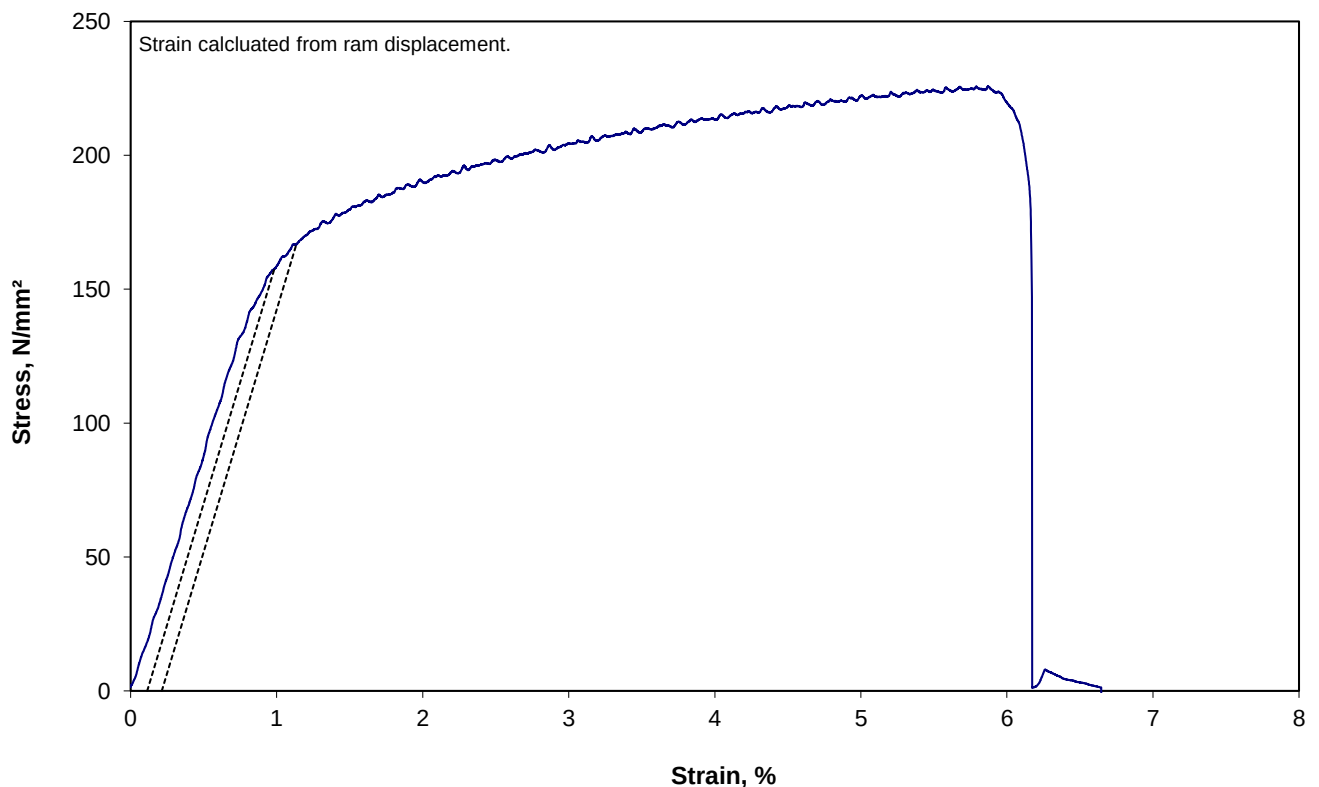
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	6.03 mm
Initial Thickness	2.19 mm
no extensometer in use	
Initial XSA	13.211 mm ²
Final XSA	12.663 mm ²
Estimated Youngs modulus	18095 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	26.05 mm
Initial Gauge length	48.42 mm
Final gauge length	50.19 mm
Initial Stressing rate	0.183 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.00026 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.256	2.08	157.4
0.2	0.295	2.20	166.7
UTS		2.98	225.8
Reduction in area		4.15 %	
Elongation		3.67 %	





FLAT TENSILE 34739 M01-07

Test date	02/11/2022
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

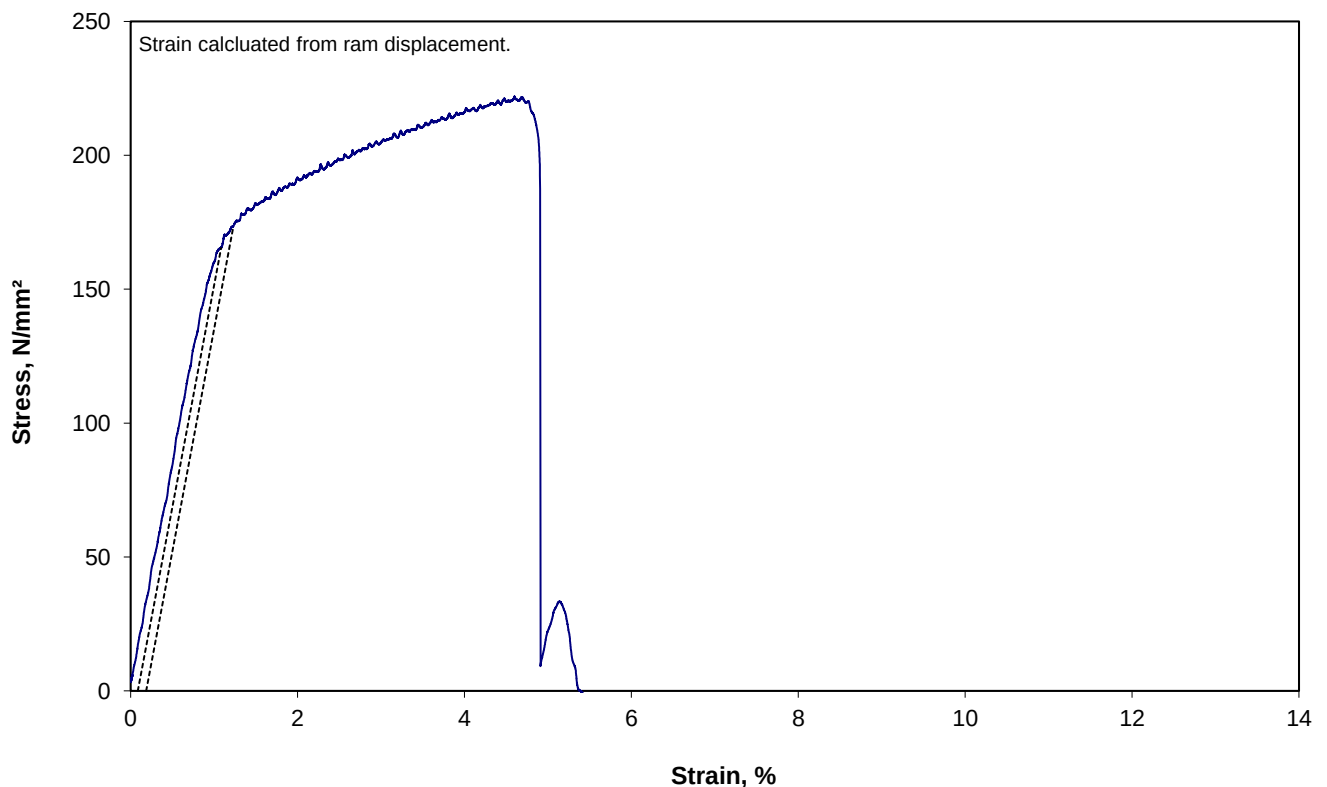
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	6.11 mm
Initial Thickness	2.18 mm
no extensometer in use	
Initial XSA	13.348 mm ²
Final XSA	12.697 mm ²
Estimated Youngs modulus	16586 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	26.28 mm
Initial Gauge length	48.55 mm
Final gauge length	49.98 mm
Initial Stressing rate	0.167 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000263 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.285	2.21	165.4
0.2	0.324	2.32	173.6
UTS		2.96	222.0
Reduction in area		4.87 %	
Elongation		2.95 %	





FLAT TENSILE 34739 M01-08

Test date	04/11/2022
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

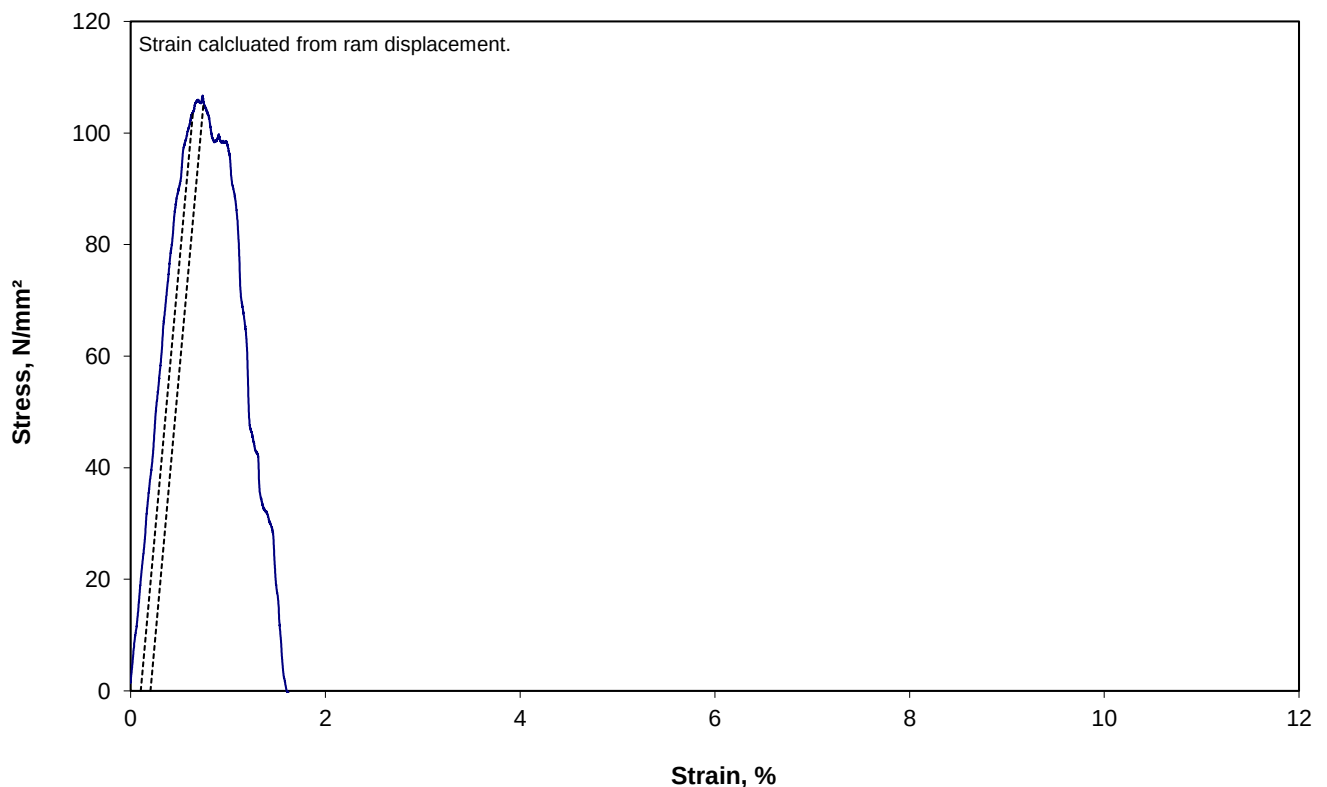
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	6.11 mm
Initial Thickness	2.18 mm
no extensometer in use	
Initial XSA	13.340 mm ²
Final XSA	13.046 mm ²
Estimated Youngs modulus	19339 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	26.47 mm
Initial Gauge length	48.48 mm
Final gauge length	49.01 mm
Initial Stressing rate	0.192 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000265 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.169	1.38	103.8
0.2	0.198	1.41	105.4
UTS		1.42	106.7
Reduction in area		2.20 %	
Elongation		1.08 %	





FLAT TENSILE 34739 M01-09

Test date	08/11/2022
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

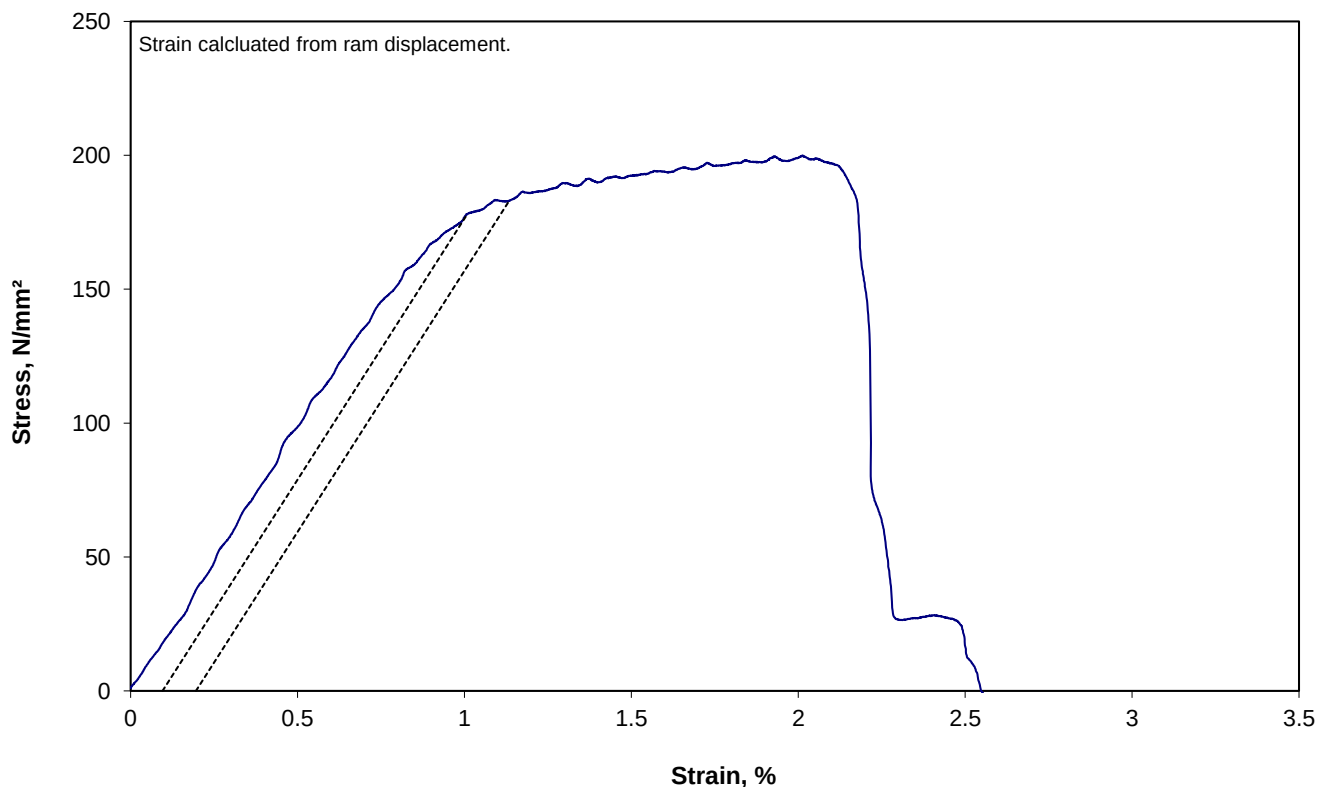
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	6.12 mm
Initial Thickness	2.17 mm
no extensometer in use	
Initial XSA	13.311 mm ²
Final XSA	12.766 mm ²
Estimated Youngs modulus	19502 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	27.47 mm
Initial Gauge length	48.44 mm
Final gauge length	49.14 mm
Initial Stressing rate	0.196 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000265 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.277	2.37	177.9
0.2	0.311	2.44	183.0
UTS		2.66	200.0
Reduction in area		4.10 %	
Elongation		1.45 %	





FLAT TENSILE 34739 M01-10

Test date	10/11/2022
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

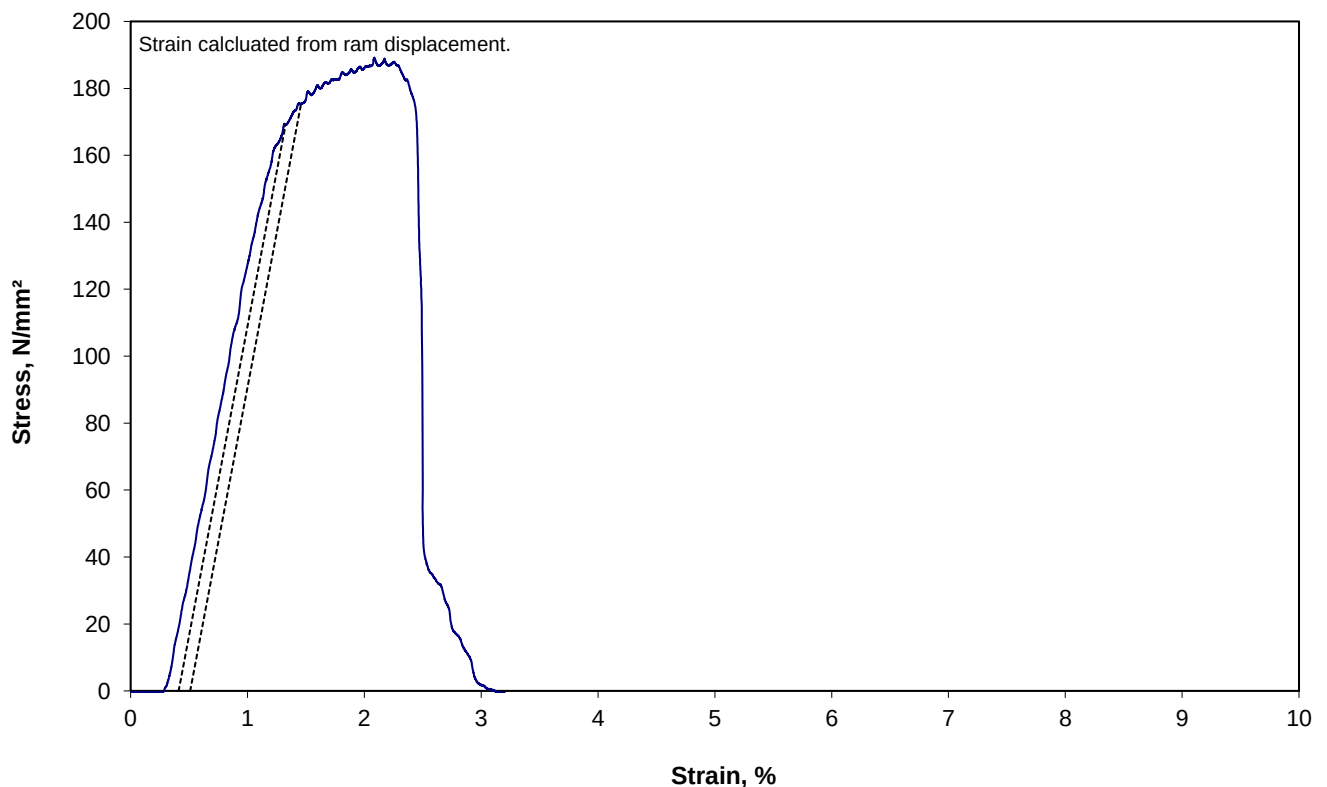
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	6.07 mm
Initial Thickness	2.18 mm
no extensometer in use	
Initial XSA	13.209 mm ²
Final XSA	12.480 mm ²
Estimated Youngs modulus	18480 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	26.61 mm
Initial Gauge length	48.52 mm
Final gauge length	49.51 mm
Initial Stressing rate	0.188 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000266 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.353	2.23	169.0
0.2	0.388	2.32	175.4
UTS		2.50	189.2
Reduction in area		5.52 %	
Elongation		2.04 %	





FLAT TENSILE 34739 M01-11

Test date	25/11/2022
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

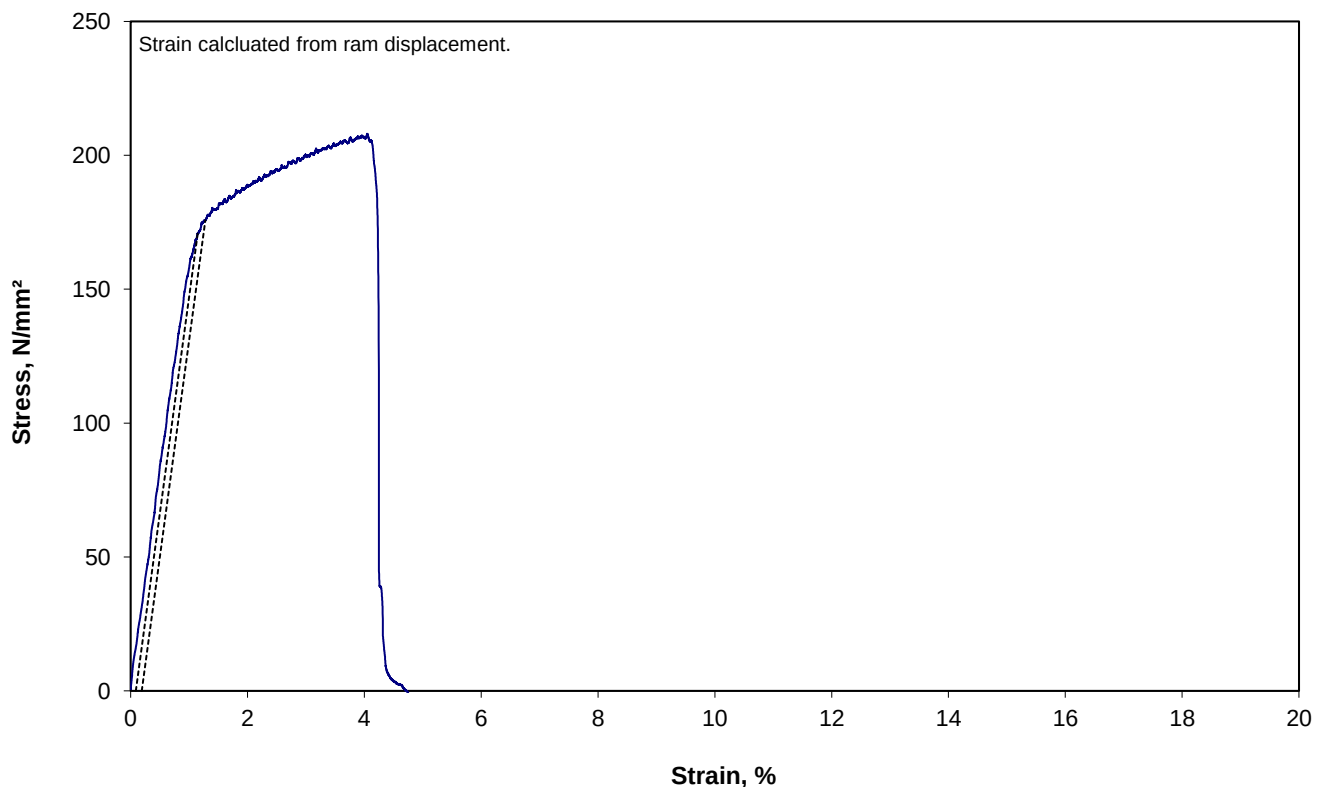
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	6.08 mm
Initial Thickness	2.18 mm
no extensometer in use	
Initial XSA	13.245 mm ²
Final XSA	12.773 mm ²
Estimated Youngs modulus	16128 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	25.82 mm
Initial Gauge length	48.52 mm
Final gauge length	49.68 mm
Initial Stressing rate	0.165 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000258 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.297	2.26	170.8
0.2	0.330	2.33	175.7
UTS		2.76	208.0
Reduction in area		3.57 %	
Elongation		2.40 %	





FLAT TENSILE 34739 M01-12

Test date	30/11/2022
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

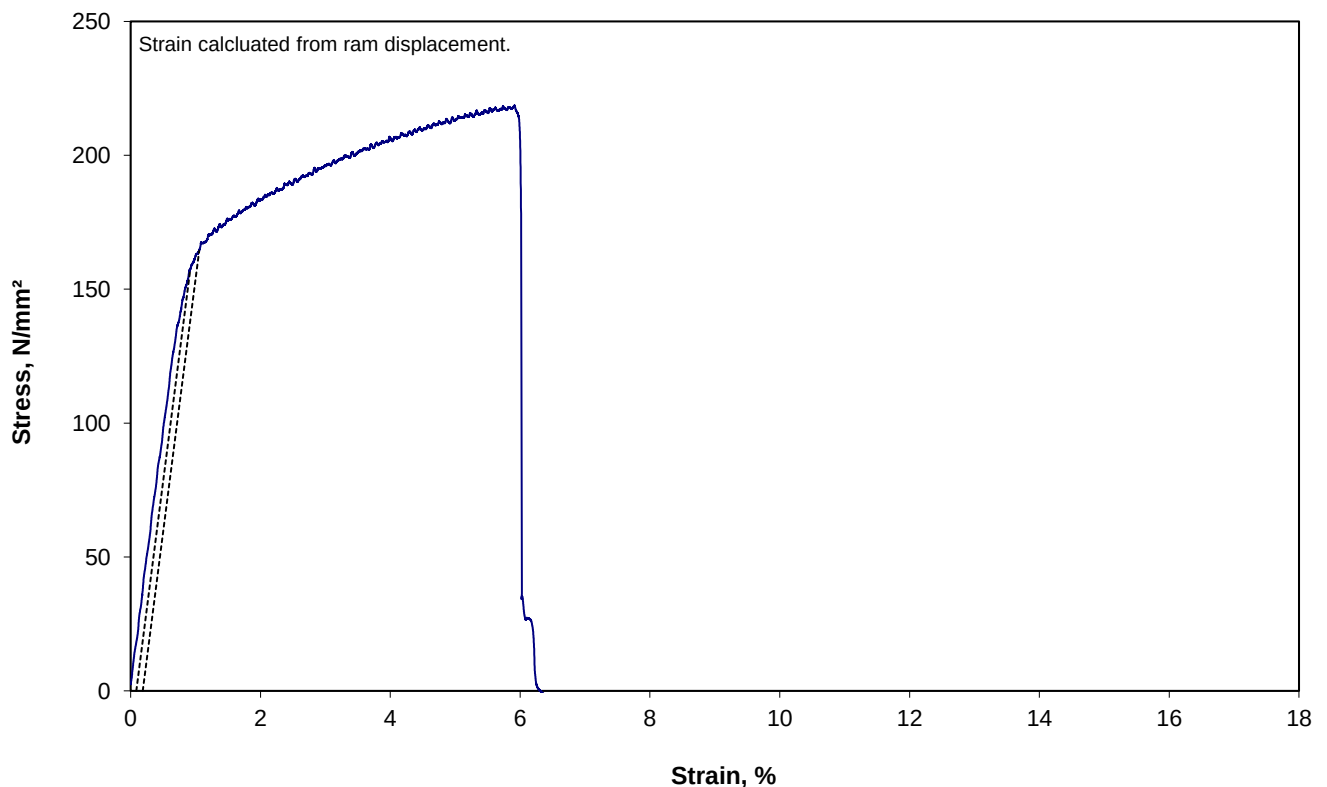
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	6.09 mm
Initial Thickness	2.17 mm
no extensometer in use	
Initial XSA	13.218 mm ²
Final XSA	12.553 mm ²
Estimated Youngs modulus	18945 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	26.19 mm
Initial Gauge length	48.48 mm
Final gauge length	50.06 mm
Initial Stressing rate	0.186 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000262 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.241	2.08	157.5
0.2	0.276	2.17	164.3
UTS		2.89	218.6
Reduction in area		5.04 %	
Elongation		3.26 %	



Certificate of Analysis

Air Products N.V.
Leonardo Da Vinci laan 19C - Bus 4
B-1831 DIEGEM
Date Printed: 15 JUL 2022

Container Type: X47S - 47L Steel Cylinder
Outlet Valve Connection: BS4
Net Weight: 0.700 kg
Grade Code: BIP PLUS
Fill Pressure @ 15 °C: 200.0 bar-g
Fill Pressure @ 15 °C: 203.943 kg/cm²
Contents @ 0 °C, 1013 mbar: 8.006 Nm³

Material 138744 Hydrogen	Mfg. Date 06 JUL 2022	Analysis Date 15 JUL 2022	Best if Used By 06 JUL 2027
Inspection Lot 040008792450		Source Location 0234	

LOWER LIMIT	UPPER LIMIT	NOMINAL VALUE	ACTUAL VALUE	UNIT	EXPANDED UNCERT.	NO REPS STD DEV	PHASE	ANALYTICAL	
								FREQ	METHOD
Oxygen			< 0.10	ppm(V)				I	
Nitrogen			< 0.20	ppm(V)				I	
Moisture			< 0.02	ppm(V)				I	
THC			< 0.01	ppm(V)				I	
CO+CO2			< 0.05	ppm(V)				I	
Hydrogen			99.99996	%(V)				I	

REMARKS:

This certificate is issued electronically and is valid without a signature

Analytic Freq : I = Individual analysis, B = Batch analysis, C = Calculated value, S = Source.
The suffix (m) in the Unit of Measure refers to mass.

The expanded uncertainty has been calculated with a coverage factor k=2.

This certificate is produced in accordance with ISO 6141.

The results shown above are traceable to national or international standards through a rigorous preparation system in which International Reference Materials, ISO 6142 and ISO 6143 are used.

To obtain details about the applicable traceability, please contact us.

Do not use below a pressure of 3 bar (excluding product supplied at less than 10 bar).
Maintain storage and use temperature between -10 and 50 °C.

Appendix C

Lead composition and data

CHEMICAL ANALYSIS REPORT

ANALYSIS METHOD		AA-ICPGEN		CLIENT						TWI REPORT NO S/23/4-1		
MATS DEPT QA REF NO		REF/ORDER NO 34739/3 DATE RECEIVED 22/02/23						ANALYSIS DATE 13/03/23				
MATERIAL SPECIFICATION								INVOICE NO				
SAMPLE NUMBER	ELEMENT, ppm											
	Na*	Mg*	Al*	Si*	K*	Ca*	Cr*	Mn*	Fe*	Co*	Ni*	Cu*
M02-Chem	<10	<10	539	142	<10	<10	<10	<10	<10	<10	<10	481
M02-Chem	ELEMENT, ppm											
	Zn*	Ga*	As*	Se*	Sr*	Ag*	Cd*	In*	Sn*	Sb*	Tl*	Ba*
	<10	<20	<10	<10	<10	29	<10	<20	<10	<10	<50	<10
COMMENTS: Analysed by a UKAS accredited laboratory. Analysed on "As Received" basis. * Not within the scope of the UKAS accreditation. .												
PAGE 1 OF 2						SIGNATURE			DATE ISSUED 23/03/23			

Note: the chemical analysis results detailed above apply only to the sample(s) of material submitted to the laboratory.



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E-mail: chemanal@twi.co.uk

CHEMICAL ANALYSIS REPORT

ANALYSIS METHOD		AA-ICPGEN/Leco		CLIENT				TWI REPORT NO		
MATS DEPT QA REF NO								S/23/4-2		
MATERIAL SPECIFICATION								ANALYSIS DATE		
				REF/ORDER NO				34739/3	DATE RECEIVED	22/02/23
										INVOICE NO
SAMPLE NUMBER		ELEMENT, ppm								
		Pt*	Au*	Hg*	Tl*	C	S	O		
M02-Chem		<10	<10	<10	<50	32	<10	145		
M02-Chem		ELEMENT, % by difference								
		Pb*								
		99.86								
COMMENTS: Analysed by a UKAS accredited laboratory. Analysed on "As Received" basis. * Not within the scope of the UKAS accreditation.										
.										
PAGE		2	OF	2	SIGNATURE			DATE ISSUED		23/03/23

Note: the chemical analysis results detailed above apply only to the sample(s) of material submitted to the laboratory.

MAT C17-02/02

CHEMICAL ANALYSIS REPORT

ANALYSIS METHOD		Inert Gas Fusion/Thermal Conductivity		CLIENT		TWI REPORT NO	
MATS DEPT QA REF NO		MCS-ANA-WI-046				H23/04	
MATERIAL SPECIFICATION						ANALYSIS DATE	
				REF/ORDER NO		34739/3	
				DATE RECEIVED		27/02/23	
						INVOICE NO	
SAMPLE NUMBER		ELEMENT (ppm)					
		H					
		M02 AS RECEIVED 123					
		M02 TESTED 342					
		ELEMENT, (ppm)					
The samples were degreased in acetone.							
PAGE		1		OF		2	
				SIGNATURE		DATE ISSUED	
						01/03/23	



FLAT TENSILE 34739 M02-01 LEAD

Test date	09/12/2022
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

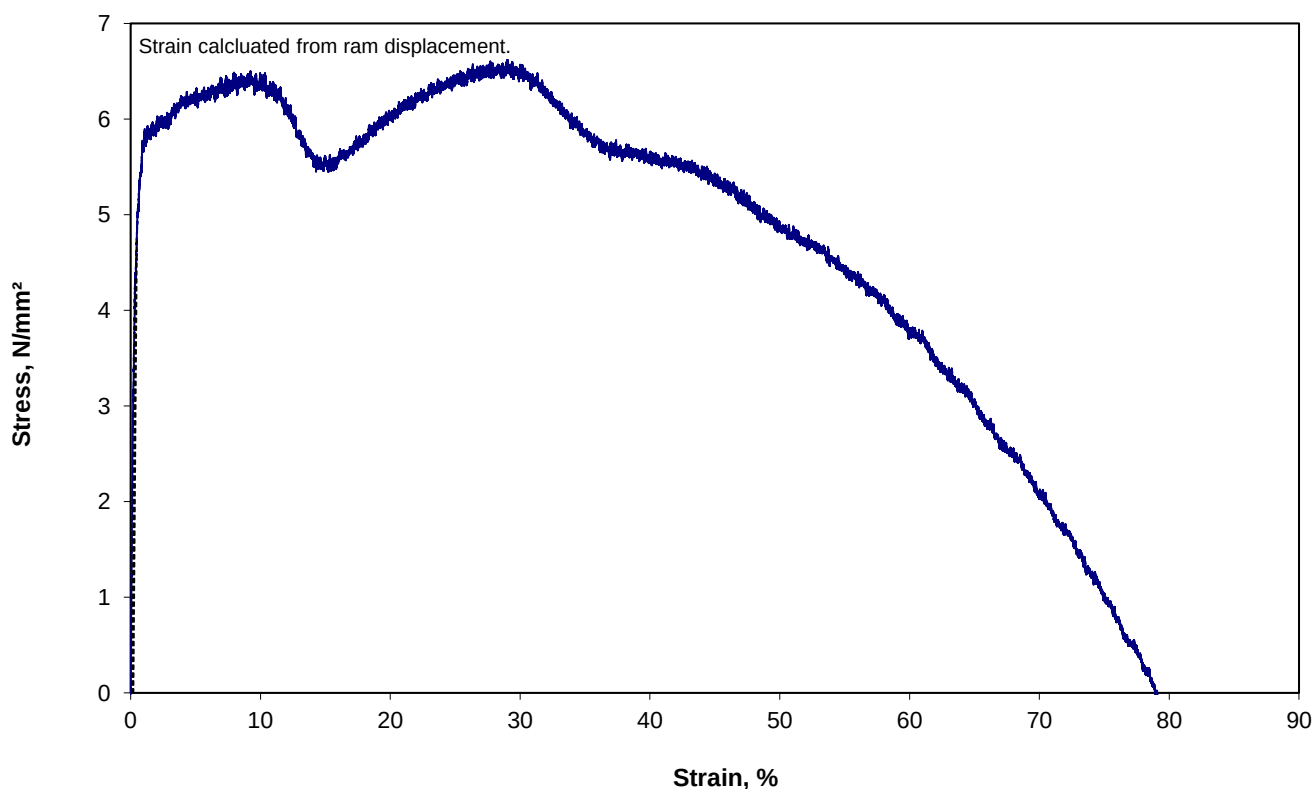
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	5.96 mm
Initial Thickness	3.61 mm
no extensometer in use, this is a lead specimen	
Initial XSA	21.528 mm ²
Final XSA	3.162 mm ²
Estimated Youngs modulus	1749 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	10.09 mm
Initial Gauge length	34.43 mm
Final gauge length	42.39 mm
Initial Stressing rate	0.013 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000101 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.036	0.09	4.3
0.2	0.048	0.10	4.7
UTS		0.14	6.6
Reduction in area		85.31 %	
Elongation		23.12 %	





FLAT TENSILE 34739 M02-02 LEAD

Test date	26/01/2023
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

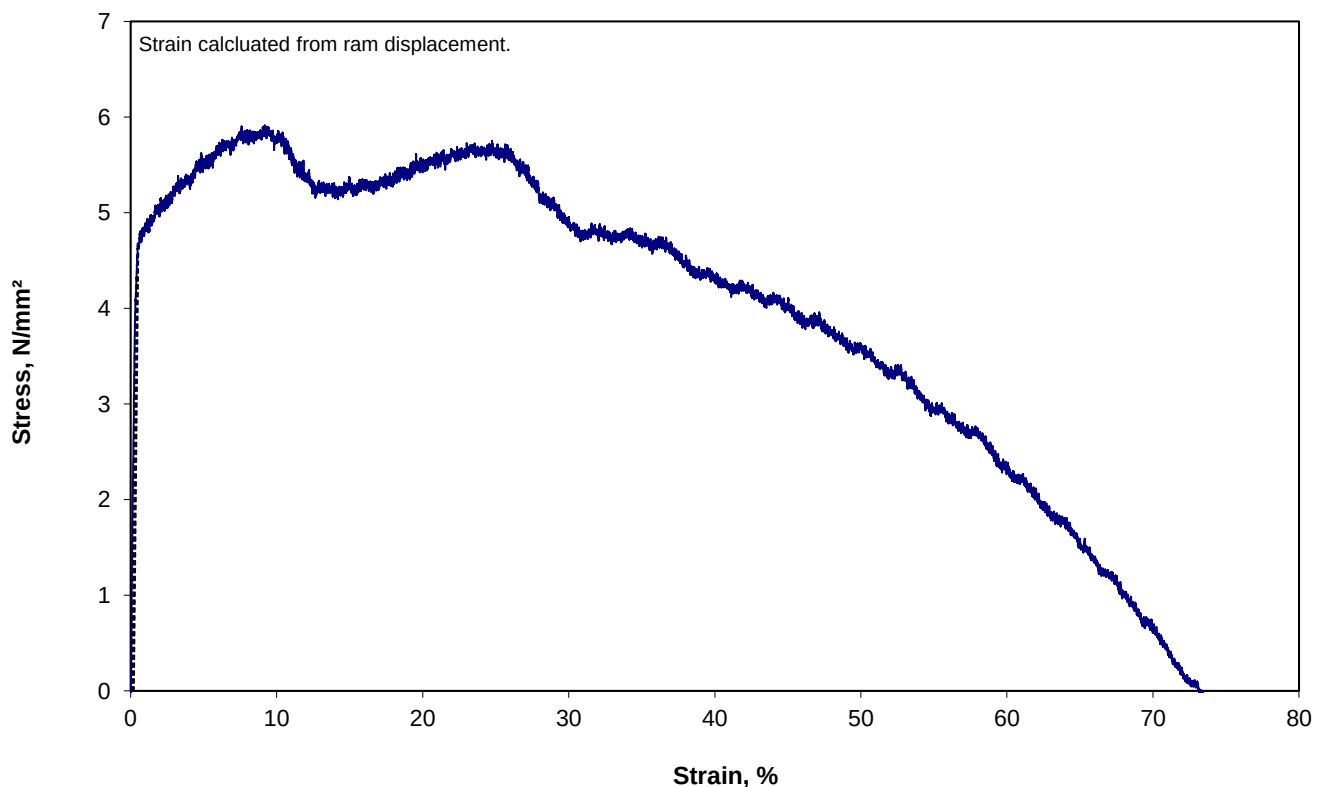
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	5.99 mm
Initial Thickness	4.08 mm
no extensometer in use, this is a lead specimen	
Initial XSA	24.420 mm ²
Final XSA	3.004 mm ²
Estimated Youngs modulus	1500 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	10.97 mm
Initial Gauge length	33.85 mm
Final gauge length	42.65 mm
Initial Stressing rate	0.013 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.00011 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.045	0.11	4.4
0.2	0.058	0.11	4.6
UTS		0.14	5.9
Reduction in area		87.70 %	
Elongation		26.01 %	





FLAT TENSILE 34739 M02-03 LEAD

Test date	27/01/2023
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

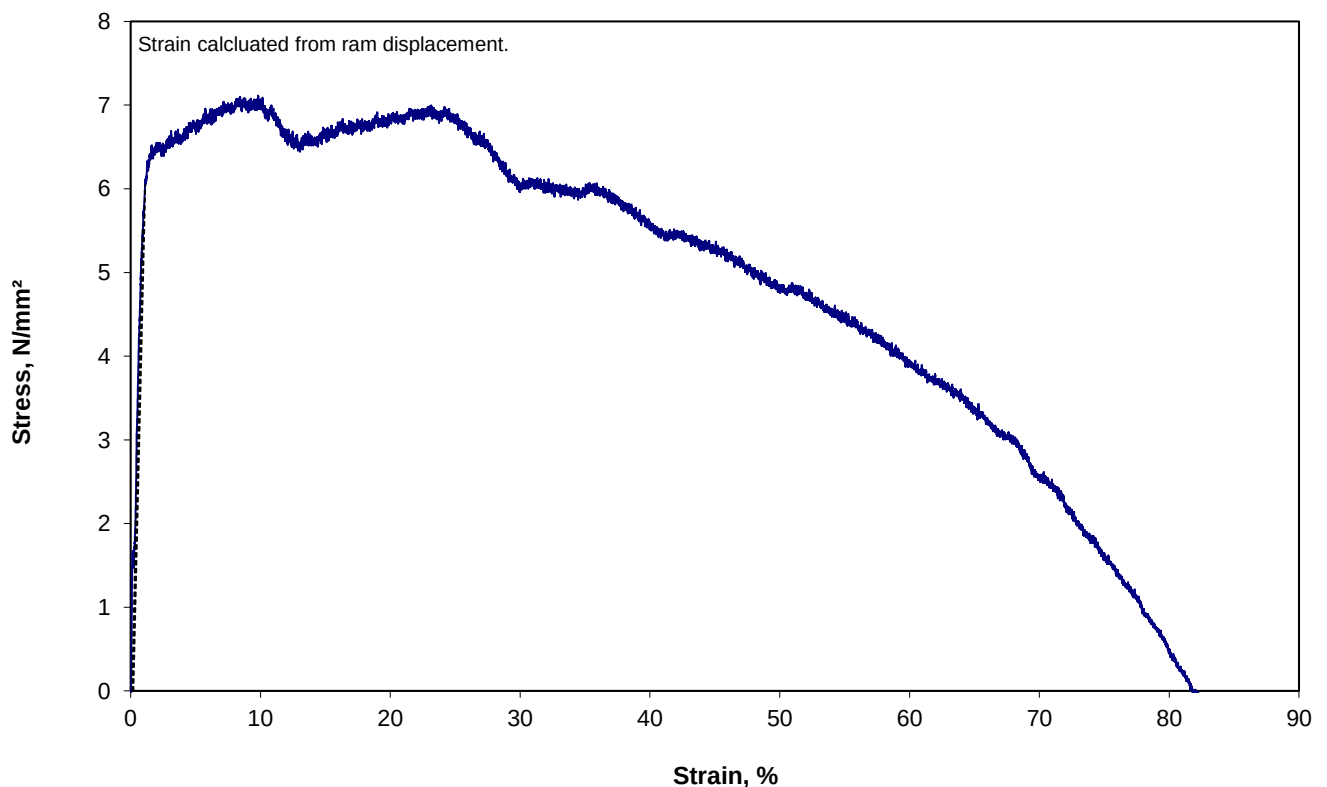
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	5.94 mm
Initial Thickness	4.07 mm
no extensometer in use, this is a lead specimen	
Initial XSA	24.158 mm ²
Final XSA	2.640 mm ²
Estimated Youngs modulus	672 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	11.47 mm
Initial Gauge length	34.46 mm
Final gauge length	43.90 mm
Initial Stressing rate	0.005 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000115 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.108	0.13	5.5
0.2	0.128	0.15	6.0
UTS		0.17	7.1
Reduction in area		89.07 %	
Elongation		27.41 %	





FLAT TENSILE 34739 M02-04 LEAD

Test date	28/01/2023
Technician	
Test machine	INSTRON 8801 B752
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

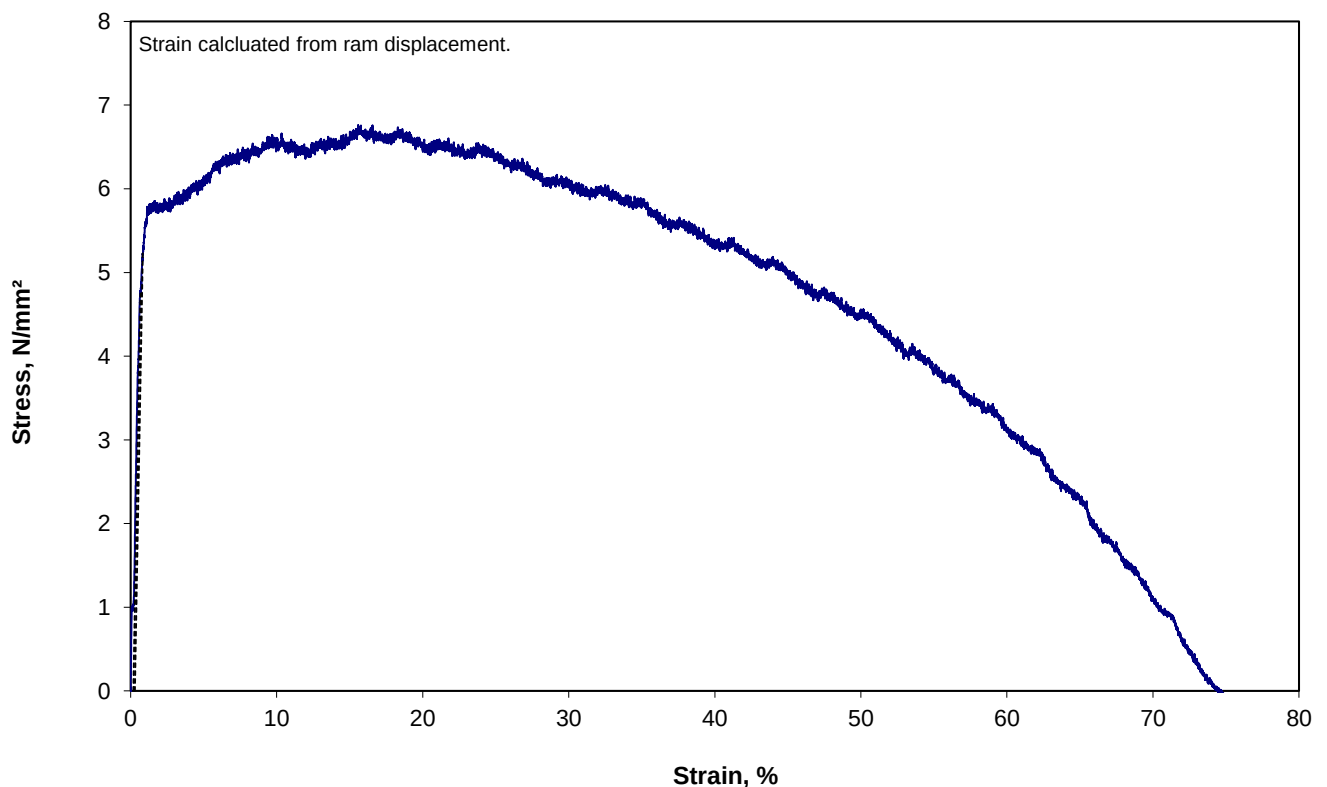
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	5.98 mm
Initial Thickness	4.13 mm
no extensometer in use, this is a lead specimer	
Initial XSA	24.741 mm ²
Final XSA	2.938 mm ²
Estimated Youngs modulus	979 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	11.42 mm
Initial Gauge length	34.40 mm
Final gauge length	43.19 mm
Initial Stressing rate	0.011 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000114 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.077	0.12	4.7
0.2	0.094	0.13	5.2
UTS		0.17	6.8
Reduction in area		88.13 %	
Elongation		25.57 %	





FLAT TENSILE 34739 M02-07 LEAD

Test date	07/02/2023
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

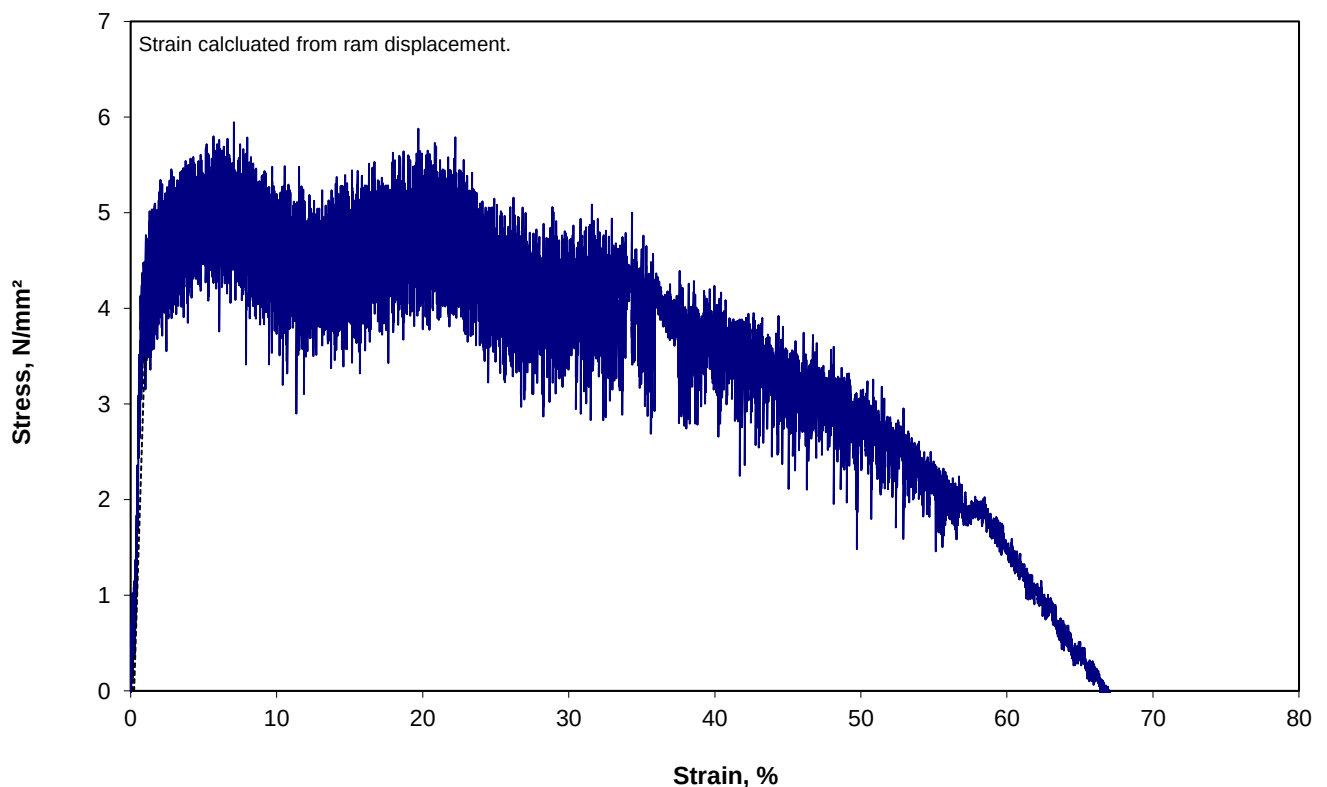
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	5.99 mm
Initial Thickness	4.08 mm
no extensometer in use, this is a lead specimer	
Initial XSA	24.409 mm ²
Final XSA	2.183 mm ²
Estimated Youngs modulus	483 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	11.69 mm
Initial Gauge length	34.01 mm
Final gauge length	43.92 mm
Initial Stressing rate	0.007 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000117 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.026	0.01	0.4
0.2	0.113	0.09	3.5
UTS		0.15	5.9
Reduction in area		91.06 %	
Elongation		29.13 %	





FLAT TENSILE 34739 M02-08 LEAD

Test date	10/02/2023
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

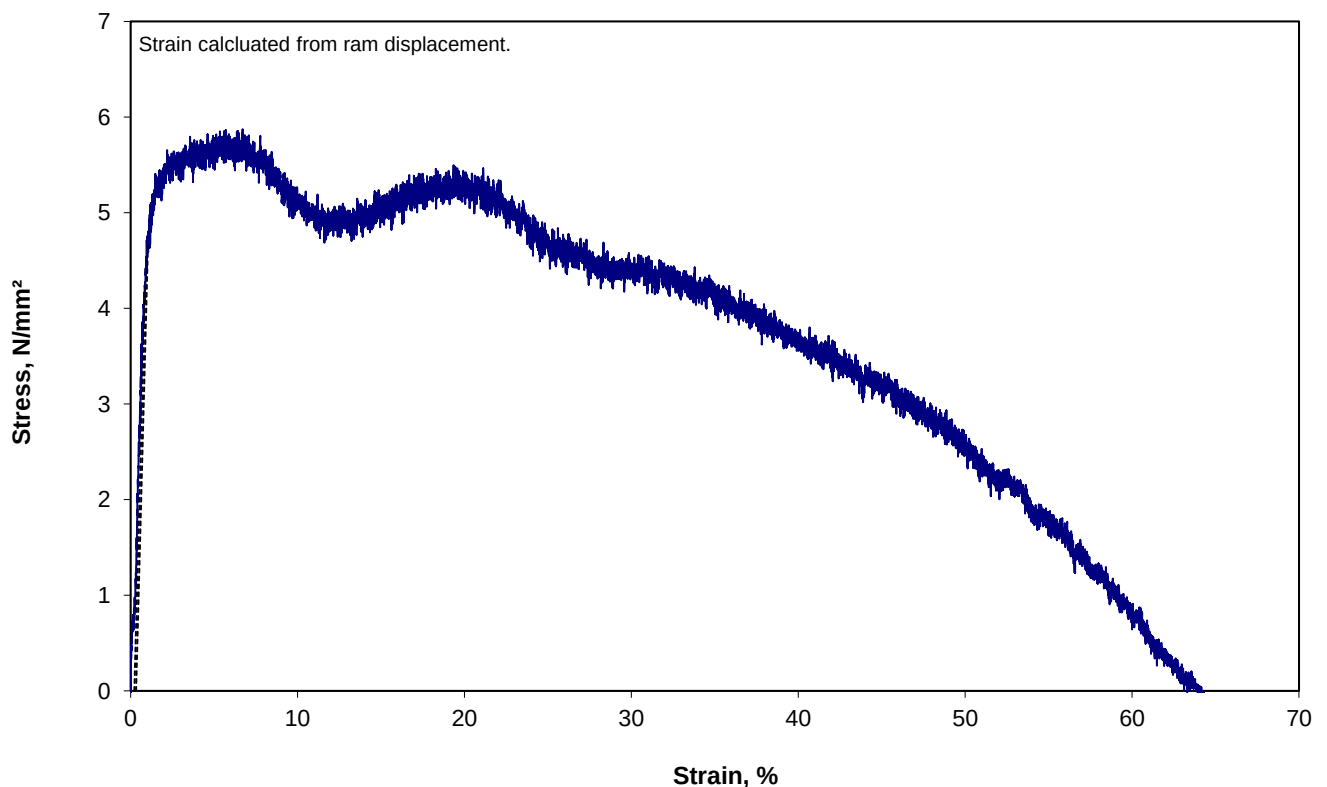
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	5.97 mm
Initial Thickness	4.07 mm
no extensometer in use, this is a lead specimen	
Initial XSA	24.272 mm ²
Final XSA	2.979 mm ²
Estimated Youngs modulus	647 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	11.19 mm
Initial Gauge length	33.82 mm
Final gauge length	41.99 mm
Initial Stressing rate	0.007 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.000112 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.097	0.10	4.2
0.2	0.116	0.11	4.7
UTS		0.14	5.9
Reduction in area		87.73 %	
Elongation		24.14 %	





FLAT TENSILE 34739 M02-09 LEAD

Test date	14/02/2023
Technician	
Test machine	INSTRON 8801 B753
Control mode	DISPLACEMENT BS
Test standard	EN 10002-1:2001

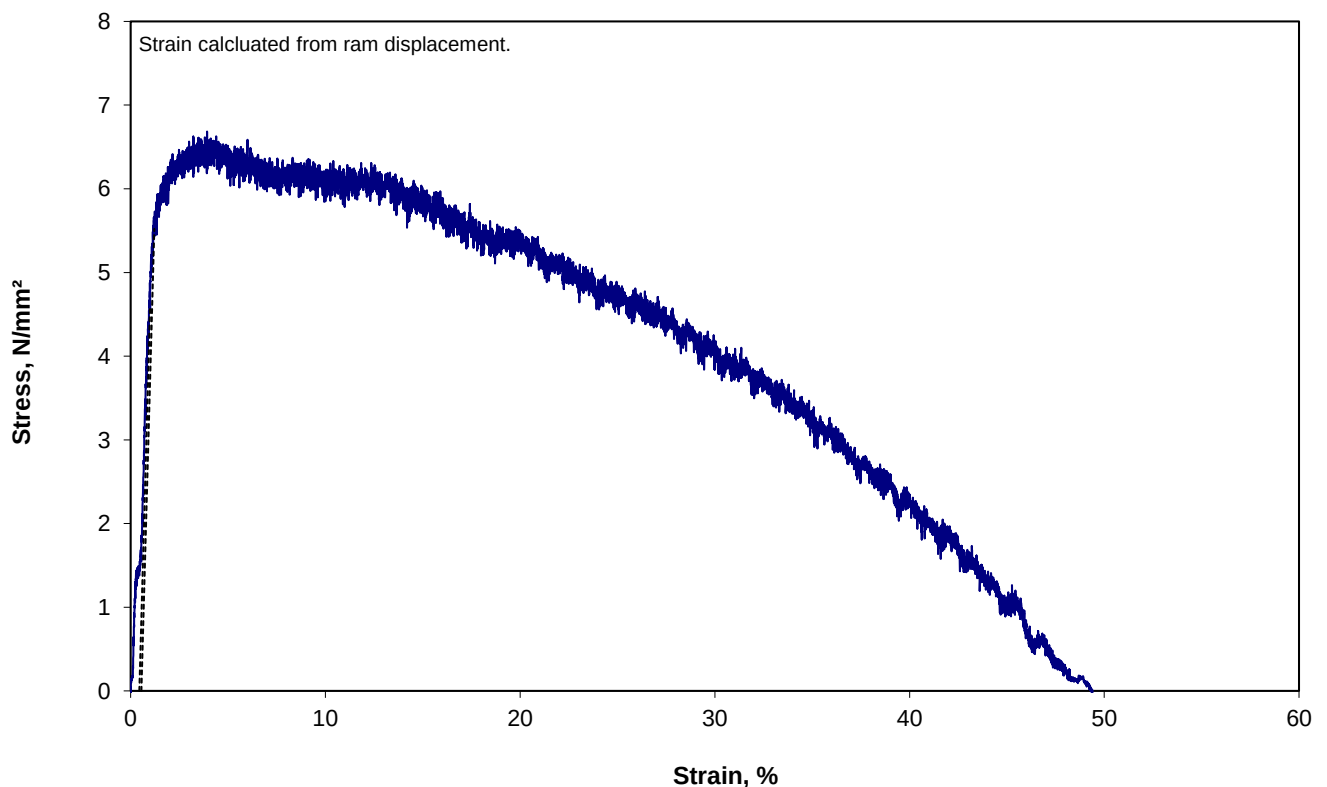
Client	BEIS
Project leader	
Investigator's signature	
Compiled by	
Signed	

SPECIMEN DETAILS

Initial Width	6.05 mm
Initial Thickness	3.93 mm
No extensometer in use	
Initial XSA	23.797 mm ²
Final XSA	2.576 mm ²
Estimated Youngs modulus	831 N/mm ²
Test temperature	23.0 °C
Extensometer gauge length	11.01 mm
Initial Gauge length	34.02 mm
Final gauge length	40.93 mm
Initial Stressing rate	0.004 N/mm ² /s
Initial Straining rate	0.000010 Strain/s
Initial Displacement rate	0.00011 mm/s

RESULTS

Strain %	Extension mm	Load kN	Stress, Rp N/mm ²
0.1	0.110	0.11	4.6
0.2	0.134	0.13	5.5
UTS		0.16	6.7
Reduction in area		89.18 %	
Elongation		20.31 %	



Certificate of Analysis

Air Products N.V.
Leonardo Da Vinci laan 19C - Bus 4
B-1831 DIEGEM
Date Printed: 15 JUL 2022

Container Type: X47S - 47L Steel Cylinder
Outlet Valve Connection: BS4
Net Weight: 0.700 kg
Grade Code: BIP PLUS
Fill Pressure @ 15 °C: 200.0 bar-g
Fill Pressure @ 15 °C: 203.943 kg/cm²
Contents @ 0 °C, 1013 mbar: 8.006 Nm³

Material 138744 Hydrogen	Mfg. Date 06 JUL 2022	Analysis Date 15 JUL 2022	Best if Used By 06 JUL 2027
Inspection Lot 040008792450		Source Location 0234	

LOWER LIMIT	UPPER LIMIT	NOMINAL VALUE	ACTUAL VALUE	UNIT	EXPANDED UNCERT.	NO REPS STD DEV	PHASE	ANALYTICAL	
								FREQ	METHOD
Oxygen			< 0.10	ppm(V)				I	
Nitrogen			< 0.20	ppm(V)				I	
Moisture			< 0.02	ppm(V)				I	
THC			< 0.01	ppm(V)				I	
CO+CO2			< 0.05	ppm(V)				I	
Hydrogen			99.99996	%(V)				I	

REMARKS:

This certificate is issued electronically and is valid without a signature

Analytic Freq : I = Individual analysis, B = Batch analysis, C = Calculated value, S = Source.
The suffix (m) in the Unit of Measure refers to mass.

The expanded uncertainty has been calculated with a coverage factor k=2.

This certificate is produced in accordance with ISO 6141.

The results shown above are traceable to national or international standards through a rigorous preparation system in which International Reference Materials, ISO 6142 and ISO 6143 are used.

To obtain details about the applicable traceability, please contact us.

Do not use below a pressure of 3 bar (excluding product supplied at less than 10 bar).
Maintain storage and use temperature between -10 and 50 °C.

TWI Ltd Management System

TWI operates a certificated Management System designed to ensure that Customer requirements are met and that all work carried out is conducted in a planned and controlled manner. Customer satisfaction is a key measure of the success of TWI, which remains committed to delivering world-class solutions. To this end:

All technical activities, project management, examination and training services are controlled by a management system that is certificated by LRQA and conforms with the requirements of ISO 9001, ISO 14001 and BS ISO 45001.

TWI is also certificated to TickITplus Foundation Level for 'Systems and Software Development and Support.'

TWI is a UKAS accredited testing laboratory (No. 0088). Specific details are given on the UKAS Schedule of Accreditation, available at www.ukas.org. Reports may contain information not included in the TWI schedule of accredited tests. Enquiries concerning accreditation of tests should be directed to the Quality and Safety Group.

The Management System operated by TWI includes the following features that are particularly relevant to ensuring successful projects:

- Close and frequent contact with the Customer by the Project Leader throughout the project. In particular, any changes in key personnel involved in the project or equipment availability will be discussed together with any potential project delays or contractual changes.
- Regular management reviews are held throughout the life of a project and upon its completion. These cover project finances, technical progress and adherence to schedule.
- Project Customers are formally contacted on project completion to determine their satisfaction with the work carried out. Moreover, TWI senior management welcomes Customer feedback on project progress at all times during the course of the work. Significant lapses in service will be subject to a structured management review so that inadequate procedures can be identified and improved.



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