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A large blue graphic with a world map background, featuring several horizontal bars of varying lengths and colors (dark blue, light blue, white) overlaid on it.

Feasibility Study of Eddy Current Inspection of Aluminium Tanker Welds

TWI Ltd

TWI is one of the world's foremost independent research and technology organisations, with expertise in solving problems in all aspects of manufacturing, fabrication and whole-life integrity management technologies.

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The company operates a management system certificated by LRQA to BS EN ISO 9001:2008. It also has certificated management systems for health and safety (BS OHSAS 18001) and environment (BS EN ISO 14001).

(See inside back cover TWI Management System.)

TWI Report: Feasibility Study of Eddy Current Inspection of Aluminium Tanker Welds

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TWI Endorsement

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Executive Summary

Background

Following the Department for Transport (DfT) acceptance of TWI Ltd (TWI) Proposal PR23024-2 (London, 2014) as part of the DfT technical assessment of petroleum road fuel tankers, TWI was asked to supply additional Work Package extensions to supplement the original work and project management activities. In relation to specific sub-sections of the DfT research specification (DfT, 2014), this proposal is concerned with the Work Package 2 extension activities related to the feasibility of eddy current inspection of aluminium tanker welds.

Tanker welds are currently required to be non-destructively tested by radiography or by ultrasound. This presents some problems with exclusion zones¹ and access for the radiation source and receiver. As an alternative, testing using an eddy current array has been suggested, as this does not have these limitations. The eddy current testing method is a non-contact electromagnetic technique which requires minimum surface preparation (see, for example, BS EN ISO 15549:2010, General principles for single probes) and does not impose any health and safety hazards. It is usually used for detection of cracks on the surface or sub-surface of aluminium structures in the aerospace industry (RUMMEL & MATZKANIN, 1997). Another method known as Alternating Current Field Measurement (ACFM) has similar user benefits, but is primarily designed for inspection of fatigue cracks in ferritic welds. Neither method is a recognised means of detecting lack of fusion in aluminium welds, but the eddy current technique is more suitable on account of more available operating frequencies and probe designs which enables higher sensitivity for specific defect types. However, using the method to inspect aluminium tanker welds is a different application and therefore requires investigation to determine its feasibility. This summary report documents the work to do so as set out in TWI Proposal PR25526 (Rudlin, 2016).

Objective

To establish whether eddy current inspection could determine the position through-wall and size of imperfections in aluminium tanker welds.

Work Carried Out

- Obtained eddy current results on the optimised procedure from available welded repair samples;
- Assessed eddy current data and compare with radiography using Class A and Class B techniques where results are available. This task includes eddy current testing of the reference sample shown in Figure 2 at a few chosen frequencies to demonstrate the ability of the technique to detect subsurface defects;
- Selected samples with 'known' flaws from existing tanker welds assessed in earlier research (London, 2015) and investigate the effectiveness of the eddy current method in detecting the 'known' flaws;
- Inserted four reference flaws (drilled holes) into samples representative of existing aluminium tanker welds to confirm the sensitivity of the method;
- Provided a report describing the procedure and test results from each weld, including the equipment specification used.

¹ Exclusion zone: is an area to which access is restricted due to the possibility of high radiation dose rates. (Ionising radiation regulations 1999 [SI 1999 N.3232])

Conclusions

There is a good correlation between the positions of flaws detected in eddy current scans of aluminium tanker weld samples when compared with the position of flaws detected in radiography images. Indications correspond (in eddy current characteristics) to those on the reference block and give an indication of length of defects and their position below the surface.

It is possible to detect all of the defects manufactured (together with some other defects) in the circumferential weld sample[s], and the impedance plane information provides some depth information, but the height of flaws cannot currently be accurately measured at present using the eddy current technique. However, further validation of the method may make it possible to estimate the height of defects.

1 Introduction

Following the Department for Transport (DfT) acceptance of TWI Ltd (TWI) Proposal PR23024 2 (TWI, 2014) as part of the DfT technical assessment of petroleum road fuel tankers, TWI was asked to supply additional Work Package extensions to supplement the original work and project management activities. In relation to specific sub-sections of the DfT research specification (DfT, 2014), this proposal is concerned with the Work Package 2 extension activities related to the feasibility of eddy current inspection of aluminium tanker welds.

Tanker welds are currently required to be non-destructively tested by radiography or by ultrasound. This presents some problems with exclusion zones and access for the source and receiver. As an alternative, testing using an eddy current array has been suggested, as this does not have these limitations. The eddy current testing method is a non-contact electromagnetic technique which requires minimum surface preparation (see, for example, BS EN ISO 15549:2010, General principles for single probes) and does not impose any health and safety hazards. It is usually used for detection of cracks on the surface or sub-surface of aluminium structures in the aerospace industry (RUMMEL & MATZKANIN, 1997). Another method known as Alternating Current Field Measurement (ACFM) has similar user benefits, but is primarily designed for inspection of fatigue cracks in ferritic welds. Neither method is a recognised means of detecting lack of fusion in aluminium welds, but the eddy current technique is considered the more suitable account of more available operating frequencies and probe designs which provides higher sensitivity in detection of flaws in aluminium. However, using the method to inspect aluminium tanker welds is a different application and therefore requires investigation to determine its feasibility. This summary report documents the work to do so as set out in TWI Proposal PR25526 (Rudlin, 2016).

2 Objective

To establish whether eddy current inspection could determine the position through-wall and size of imperfections in aluminium tanker welds.

3 Eddy Current Principle

The eddy current technique originated from Michael Faraday's discovery of electromagnetic induction in 1831. The principle of the technique is shown schematically in Figure 1 and can be described as follows: the time varying electric current, I , within a coil generates a primary magnetic field, H , surrounding the coil (Figure 1 [a]). When this field is in the proximity of a conductive material, according to Faraday's law of induction, eddy currents are induced by the primary magnetic field in the conductive material (Figure 1[b]). According to Lenz's law, eddy currents then create a secondary magnetic field, B , which is opposite to the primary magnetic field H (Figure 1 [c]). The secondary magnetic field – the eddy current testing response – can be affected by the material's electrical conductivity, magnetic permeability, oscillation frequency of the excitation current², lift-off³ and importantly flaws including cracks and corrosion. . Inspection of complex shapes and sizes of conductive materials is possible using the technique.

The most common difficulties with the application of the technique are that indications from unwanted features (eg geometry, lift-off) can be greater than the flaw indications required. Various techniques are used to reduce this problem,

² Frequency is the number of occurrences of a repeating event per second.

³ Lift-off is described as the probe distance to the test material.

particularly in the probe design and the instrument set-up. However even with these changes this sometimes leads to difficulties in interpretation.

The most common application of eddy current testing uses a single coil. The use of single coil scanning was attempted in this application and gave acceptable results on the reference sample; however, inspection of the repair welds using a single coil probe was made difficult by the uneven surface. To an extent, this problem can be solved either by using a mechanical scanner to minimise the probe movements, or by using an array probe, which in effect gives an electronic scan. The second approach was adopted in this project.

In this approach – the eddy current array technique – an array of coils is used for the generation and detection of the magnetic field. Using this technique a linear array of test coils are scanned over the surface of the test sample to create 2-D images of the scanned area and any defects contained therein. Although 2-D images can present detailed flaw maps, the depth measurement has to be inferred from a detailed study of the indications and from a comparison with the indications on a reference sample with known defects. Once the relationship between actual defect depth and eddy-current signal in the image pixel corresponding to that defect has been established, this calibration then enables the depth of other defects recorded in the 2-D map to be determined.

4 Reference Sample Study

4.1 Overview

In order to generate this relationship, a reference block was made from aluminium and EDM (Electrical Discharge Machining) notches were manufactured in the block. Figure 2 shows schematics of the reference sample. The dimensions of the notches in the reference sample can be found in Table 1.

The equipment used for these tests was the Ectane (manufactured by Eddyfi) in conjunction with Magnifi software (version 3.5R6). The probe used was a Semi-Flexible large single driver probe with 33 coils of 5.5mm diameter and coverage of 128mm. This probe has a frequency range of 0.6-20KHz and works on the driver receiver topology. This probe was the only available probe owned by TWI appropriate for this application.

Figure 3 shows the probe, equipment and the reference block. Encoded scans were carried out at a frequency of 1 KHz, 2 KHz and 3 KHz and as shown in Figure 12-14 to find the optimum frequency. The probe was balanced on the non-defective part of the test sample prior to these scans.

Figure 4 shows the C-Scan of the reference sample at the chosen frequency of 2 KHz with optimised settings. It should be noted that the height of the defect shown in the C-scan in Figure 4 and Figure 12-14 is only a simple visualisation of the amplitude of the signal in 3D. Amplitude of a defect signal can be used to give an estimation of a flaw depth in comparison to calibration signals' amplitude. However amplitude of the signal cannot be taken as an absolute indicator for depth measurement since it depends not only on the depth of a defect but also on its width, morphology and scanning parameters (ie, probe pressure on the surface or small lift-off values).

Impedance plane information from each of the notches was extracted in terms of their amplitude and phase angle as in Figure 5. Phase lag is a parameter of the eddy current signal that makes it possible to obtain information about the depth of a defect within a material. Phase lag is the shift in time between the eddy current response from a disruption on the surface and a disruption at some distance below the surface. The generation of eddy currents can be thought of as a time dependent process, meaning that the eddy currents below the surface take a little longer to form than those at the surface. The eddy current equipment enables the operator to set a reference phase angle for relative measurements; the lift-off signal usually serves as the reference phase. The lift-off signal is set horizontally and from right to left, and all other angles are measured relative to this signal as shown in Figure 5. Phase angles captured from the notches on the reference sample were $b=18^\circ$, $c=83^\circ$ and $d=110^\circ$ which correspond to the surface notch 'b', subsurface notch 'c' at 2.5mm below the surface and subsurface notch 'd' at 3mm below the surface, respectively.

Defect 'e' was not detected and defect 'a' had the same phase direction as the lift-off signal. The un-detectability of defect 'e' was expected due to the small size of the defect.

According to BS 7910 Annex T (BSI, 2015), which is generally only applicable when assessing planar defects or crack-like flaws, the minimum defect sizes at the back surface that can be reliably detected using UT and RT are 3 x 15mm (height x length) and 1.2mm diameter isolated gas pores, respectively, in plates of thickness 10-25mm. These limiting dimensions are greater than the diameter of defect 'e' and the thickness of the reference sample, but are not directly relevant in that these values of reliably detectable defect sizes are for different flaw types, based on welds in ferritic steels, and are conservative estimates that can be improved with validation trials. They are however, a useful benchmark against which the current trials can be compared with other NDT methods and their detectability limits.

Once the relationship between the reference sample notches and the eddy current signals had been established, welded test samples were scanned using these settings and impedance plane information was extracted. The depth of the defects was estimated by comparing the phase angle of the defects to the reference notches. Encoded scans provide the opportunity to relate the position of the defects to the ones found in the corresponding radiographs. It should be noted that the probe used for this study is not optimised for this application and only 4-5 channels were scanned over the weld area. Results from the scans are shown in the following section.

4.2 Scan results

Figures 6-8 show the scan results from the welded test samples PC1, PF1 and PF2 (taken from work on welded repairs (London, 2016)). The scans show good correlation between the eddy current response and defects identified in the radiographic images. This correlation refers to the surface location of the flaws on the scans of the welded test samples in terms of their distance to the end of the plate when compared to the location of the flaws found on radiography images. Indications correspond (in eddy current characteristics) to those on the reference block and give an indication of length of defects and their position below the surface.

5 Circumferential Weld Scans

Four groups of 10 holes (A, B, C, D shown in Figure 9 with 8 holes representative of 10 holes) with a diameter of 0.75mm and centre spacing of 1mm were manufactured in the sample available. Table 2 shows the dimension and position of the defects and Figure 9 shows a side view of the sample and schematics of the defects.

Scans were taken from the outer surface of the sample as shown in Figure 10. It can be seen that there is a gap between the probe and the surface of the sample which affects the sensitivity.

The results are shown in Figure 11. The scan was performed at 800Hz to increase the depth of penetration of the eddy currents. All of the manufactured defects (together with some other defects) were detected in these scans and impedance plane information was collected for the manufactured defects to give an indication of the position of the manufactured defects.

6 Conclusions

There is a good correlation between the surface locations of flaws detected in eddy current scans of aluminium tanker weld samples when compared with the location of flaws detected in radiography images. Indications correspond (in eddy current characteristics) to those on the reference block and give an indication of length of defects and their position below the surface.

It is possible to detect all of the defects manufactured (together with some other defects) in the circumferential weld sample[s], and the impedance plane information provides some depth information, but the height of flaws cannot currently be accurately measured at present using the eddy current technique.

7 Suggestions for Further Work

A review of the feasibility of eddy current inspection of aluminium tanker welds to be carried out to identify possible improvements in the estimation of the height of the defects in aluminium welds.

Develop eddy current models to investigate the optimal probe parameters in order to find the best probe size and configuration. This modelling investigation work can help increase the sensitivity of test.

Increase the information obtained from the impedance plane by using a wider range of known reference notches. Alternatively, eddy current models can be used to obtain such information, but partial validation of the models on smaller number of notches would be necessary.

Sectioning of the scanned areas of weld samples to validate the eddy current information to better determine the capabilities of the technique.

8 References

BSI, 2015. *Guide to methods for assessing the acceptability of flaws in metallic structures BS 7910 : 2013+A1 : 2015*. s.l.:BSI Standard Publication.

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Rudlin, J., 2016. *Feasibility study of eddy current inspection of aluminium tanker welds'. TWI Proposal PR25526 (extension of DfT Welding Technical Support Contract)*. s.l.:TWI Ltd.

RUMMEL, W. D. & MATZKANIN, G. A., 1997. *Non-destructive evaluation*. Austin,TX: Non-destructive Testing Information Analysis Centre (NTIAC).

Table 1 Dimensions of the reference block notches, all dimensions in mm (See Figure 2)

Defect ID	h	w	l	L
a	1.0	0.3	100	0
b	0.5	0.2	25	0
c	2.5	0.2	25	2.5
d	2.0	0.2	25	3
e	2.5	0.5 (Diameter)	0.5 (Diameter)	2.5

- 1 h: Height of the notch;
- 2 w: Width of the notch;
- 3 l: Length of the notch;
- 4 L: (Ligament) Distance below the scanning surface to the top of the notch.

Table 2 Position and dimension of the defects in Figure 9 all measurements in mm)

	A	B	C	D
D1	8	8	12	12
D2	7	9	8	10
D3 (10-D2)	3	1	2	0

*D3: Position of the holes below the scanning surface.

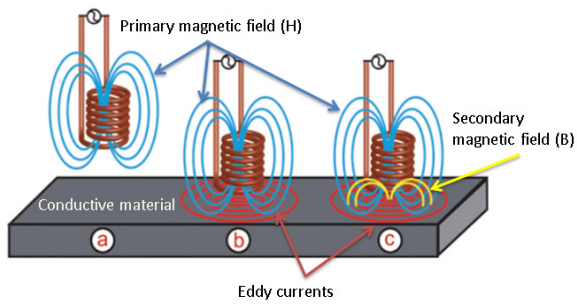


Figure 1 Eddy current principle.

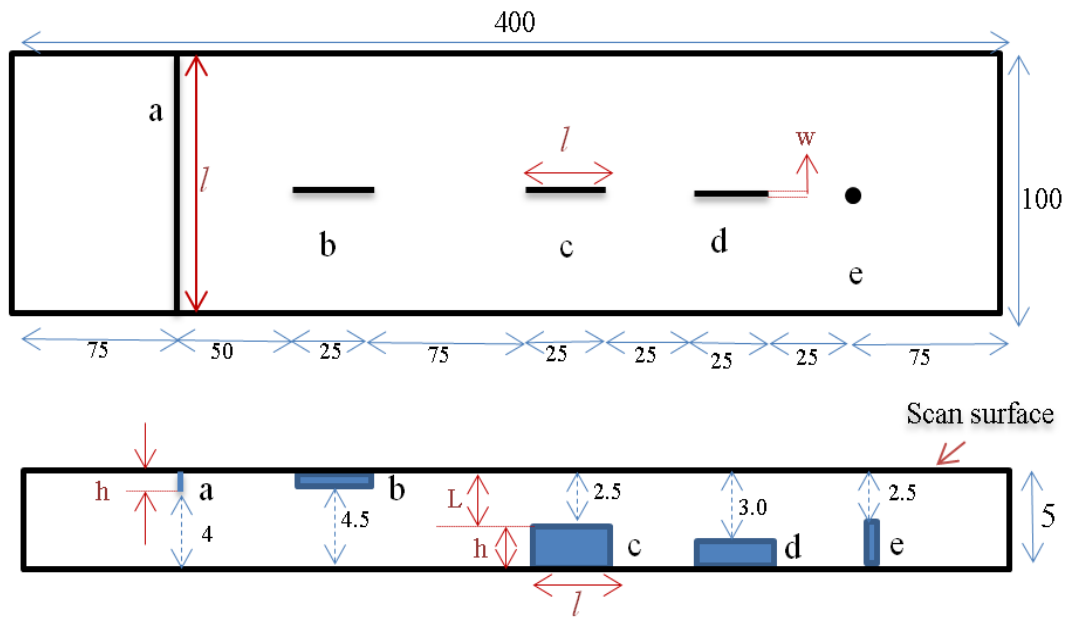


Figure 2. Schematics of the reference sample (all dimensions are in mm, not to scale):
a) Top view;
b) Side view.

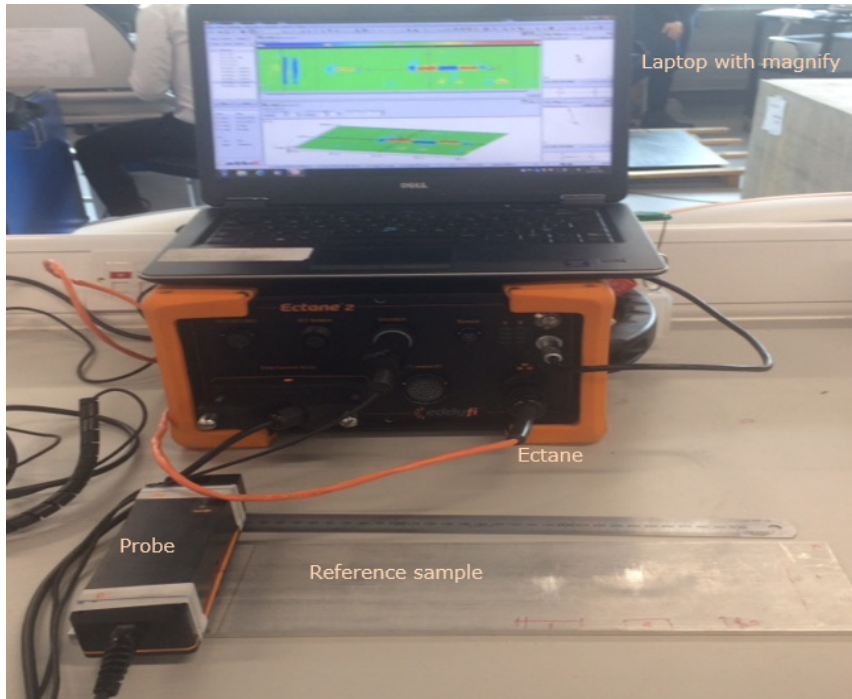


Figure 3 Equipment used in the experiments.

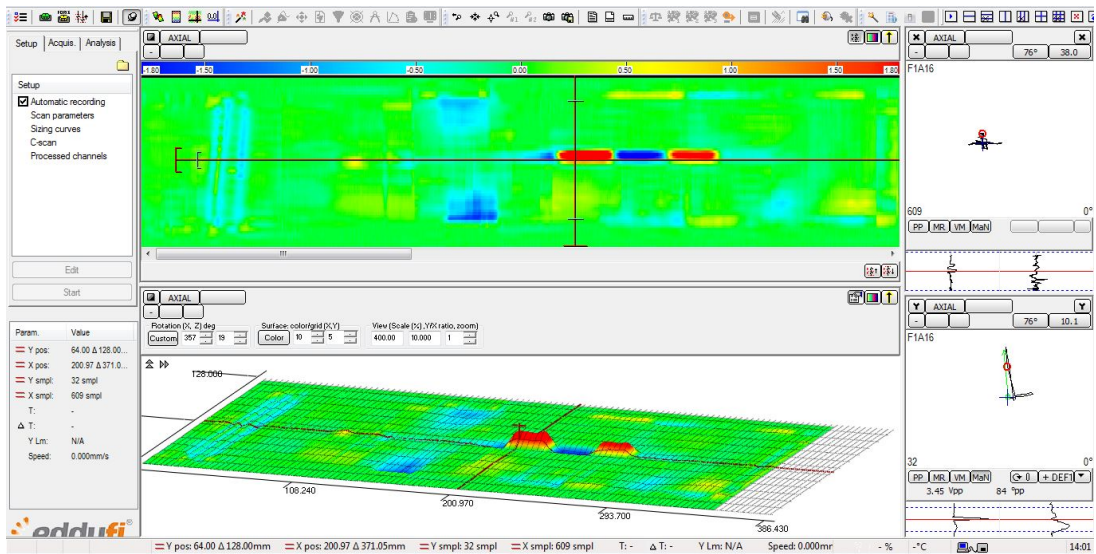


Figure 4 C-Scan and impedance plane obtained from the reference sample.

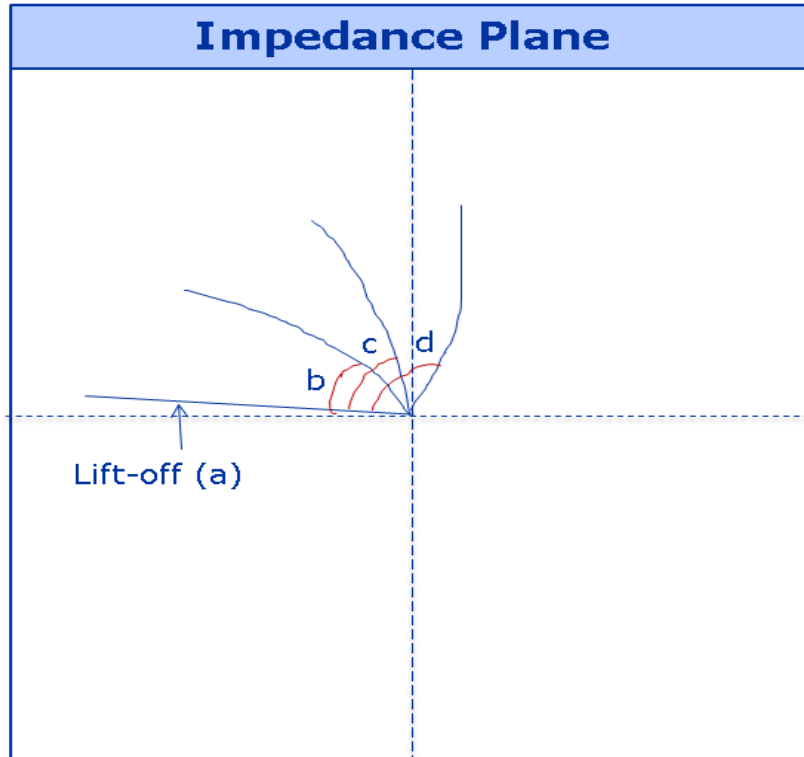


Figure 5 Impedance plane with reference phase angles.

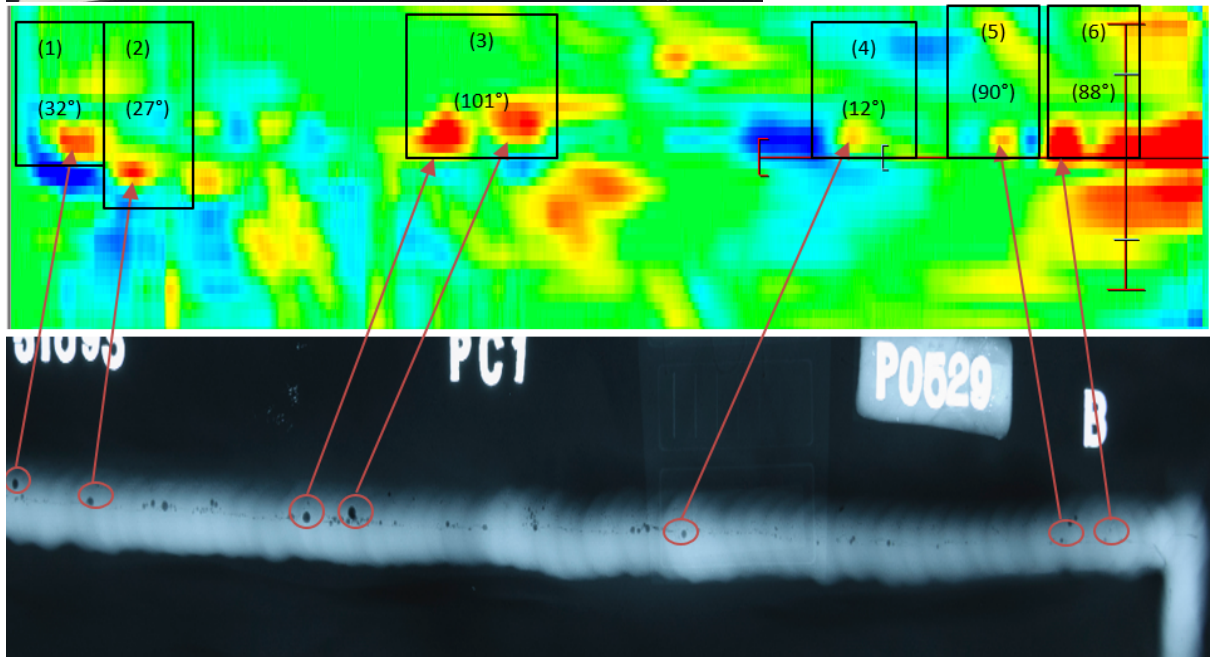
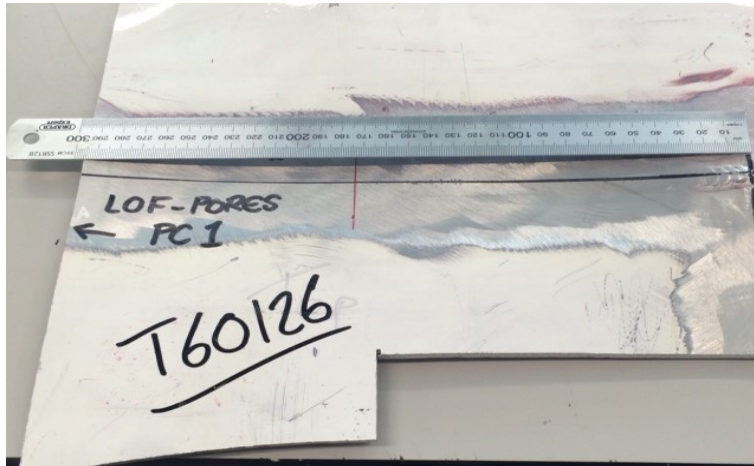


Figure 6 PC1

Estimation of the defect positions are:

- 1 and 2) 0.5mm below surface with phase angle of 32° and 27° respectively;
- 3) 3 mm below surface with the phase angle of 101° ;
- 4) Surface 0.5 mm deep with the phase angle of 12° ;
- 5) And 6) 3 mm below surface with phase angle of 90° and 88° respectively.

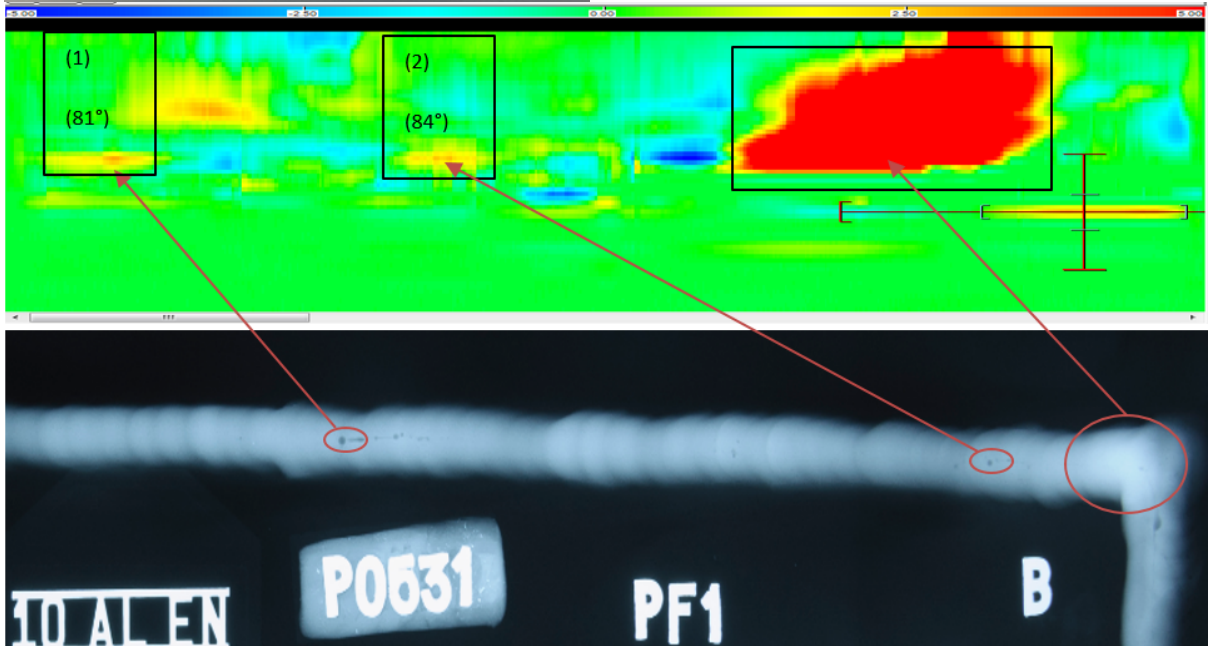


Figure 7 PF1

Estimation of the defect positions are:

- 1) 2.5 mm below surface with phase angle of 81° ;
- 2) 2.5 mm below surface with phase angle of 84° .

Note scan is close to edge.

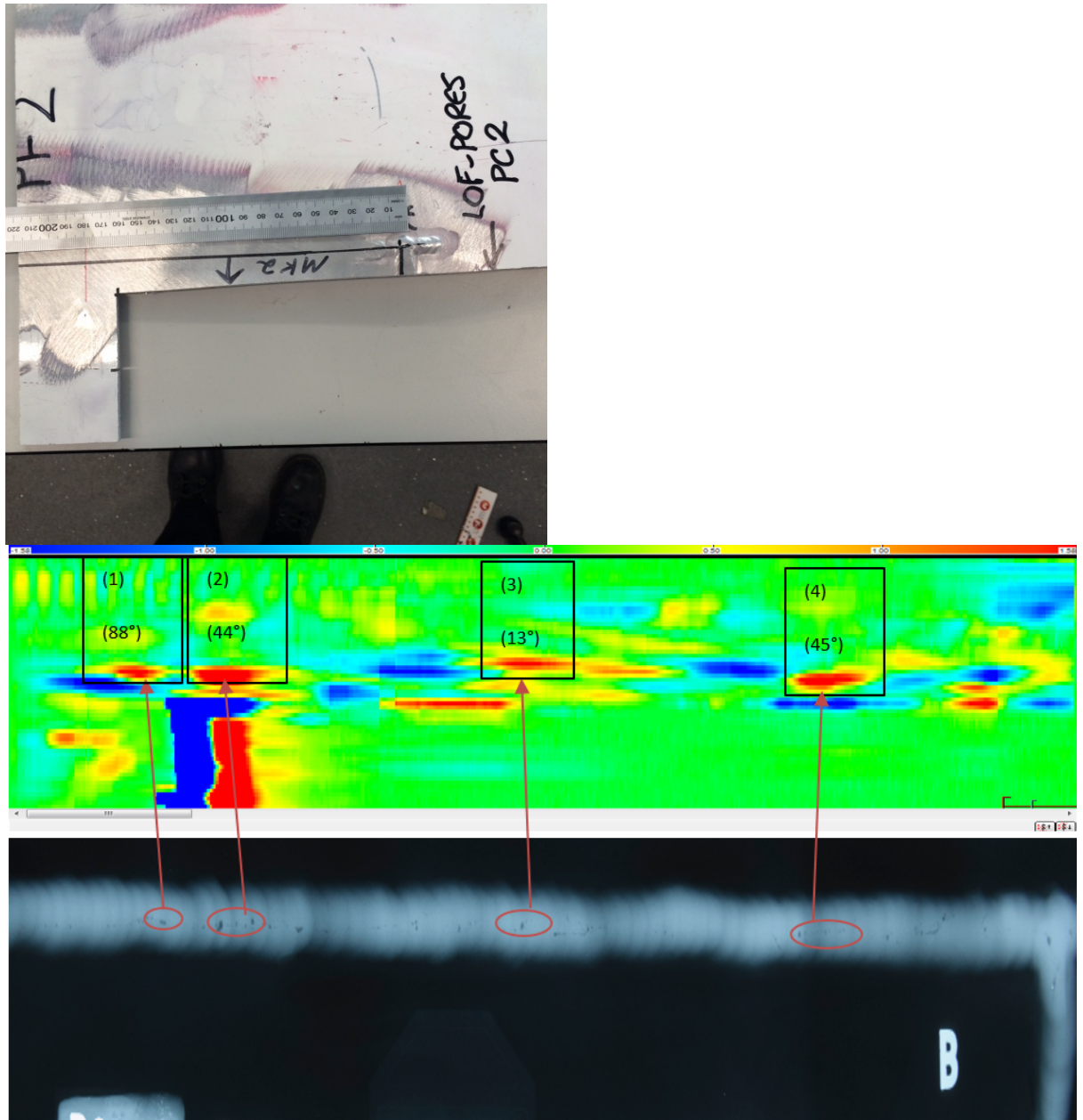


Figure 8 PF2

Estimation of the defect positions are:

- 1) 2.5 mm below surface with phase angle of 88° ;
- 2) 1.0 mm below surface with phase angle of 44° ;
- 3) Surface with phase angle of 13° ;
- 4) Surface.

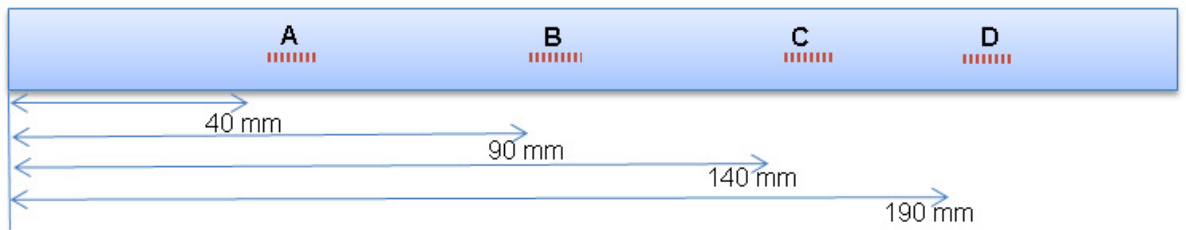
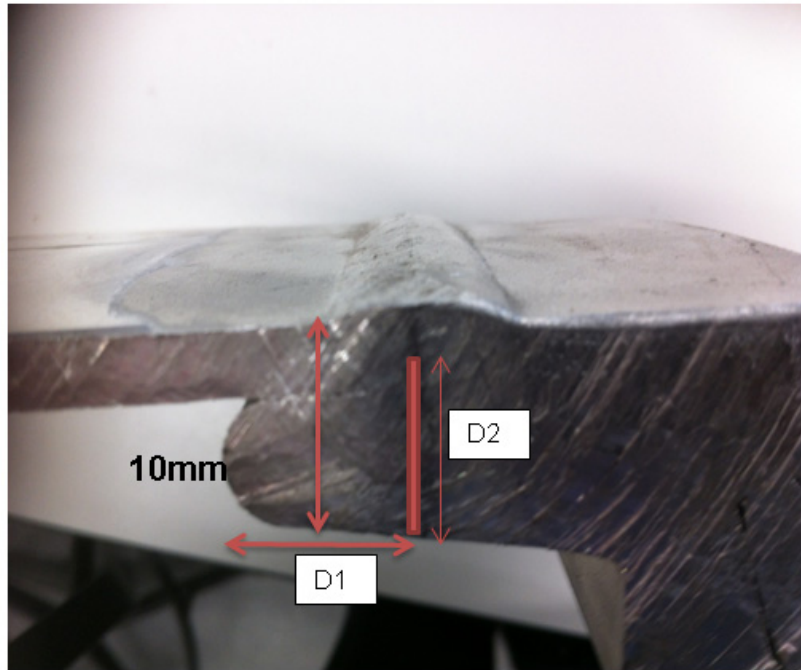


Figure 9 Circumferential Weld with 4 group of 10 holes (8 holes are shown in the figure as representative of 10 holes)
 a) Side View;
 b) Top view.



Figure 10 Top view and side view of the circumferential weld (showing the lift-off).

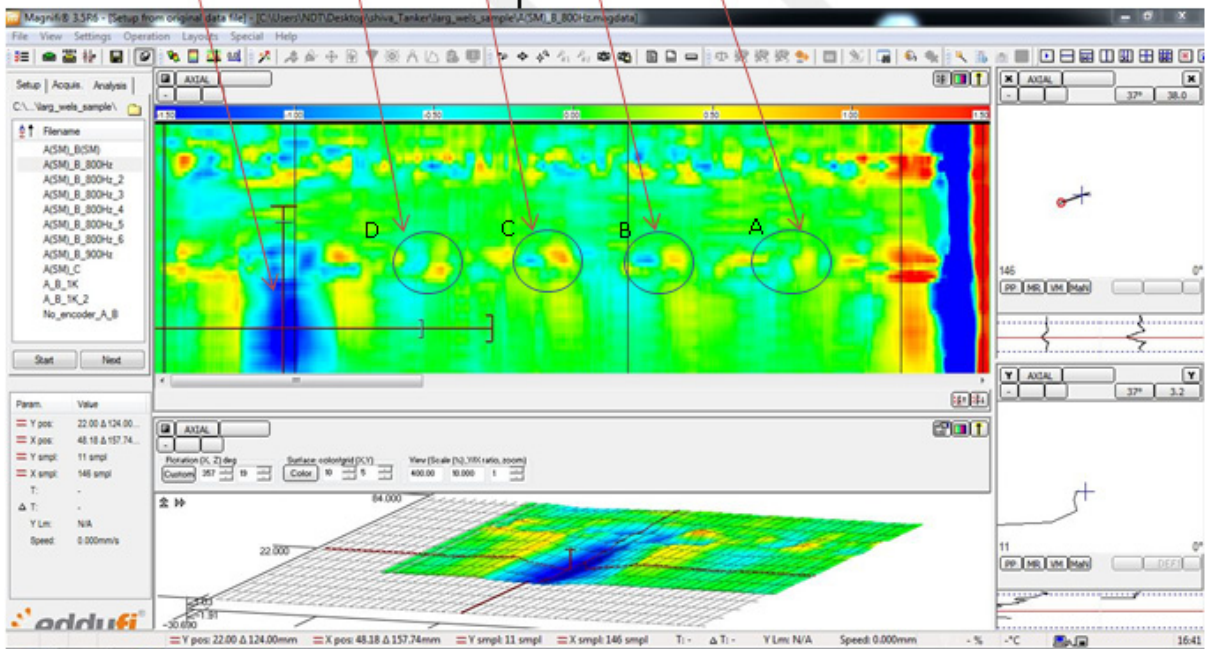
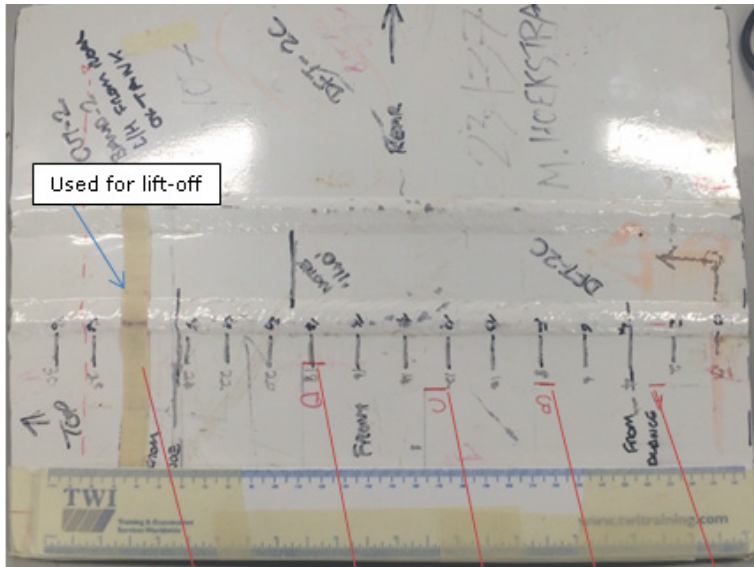


Figure 11. Top view of the sample, C-Scan and impedance plane.
 The scan was encoded and information extracted from the impedance plane include:
 A: 28° and 0.55 Vpp (Voltage peak to peak, measured from the null point point);
 B: 16° and 2.34 Vpp;
 C: 29° and 1.68 Vpp;
 D: 17° and 1.27 Vpp.

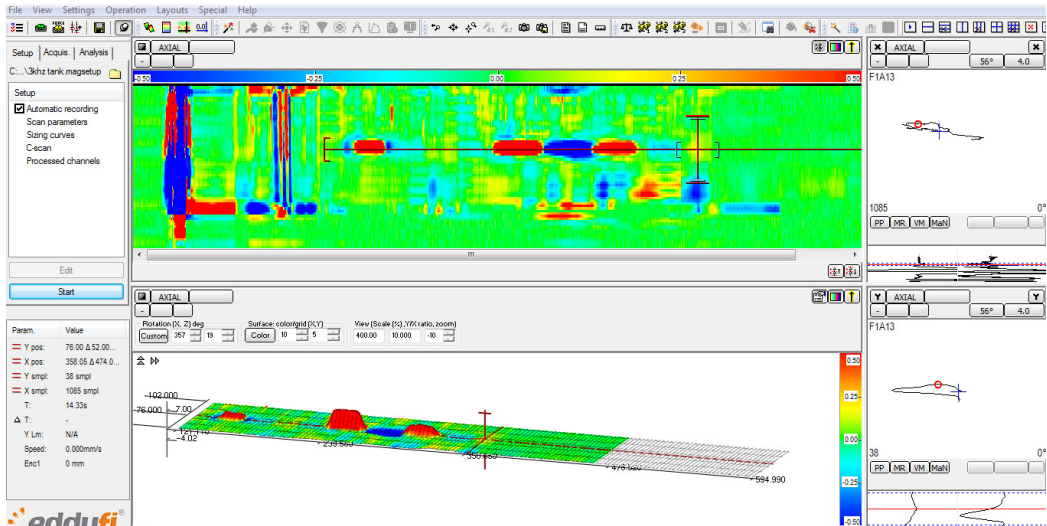


Figure 12 Eddy current array scan at 3kHz.

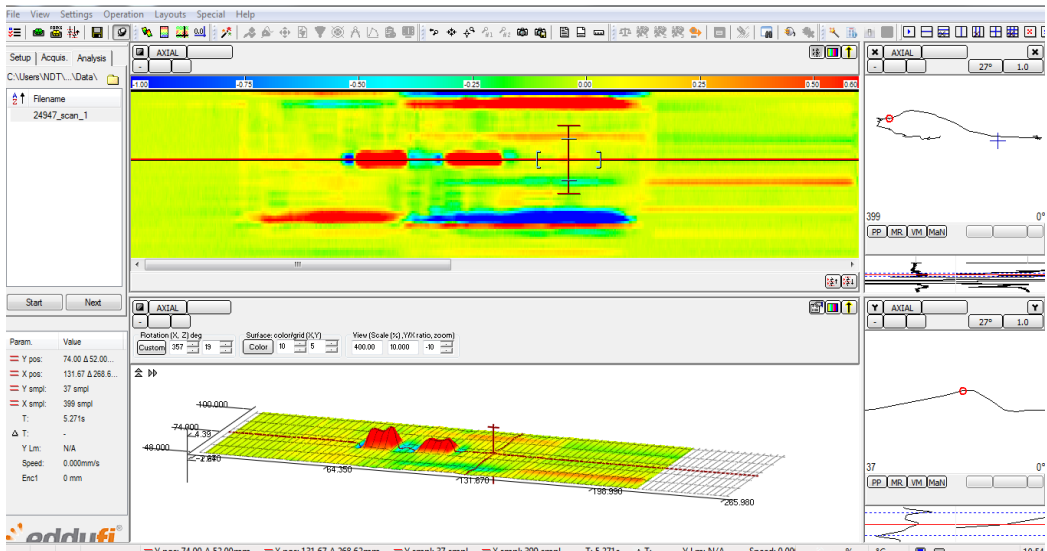


Figure 13 Eddy current array scan at 2Khz.

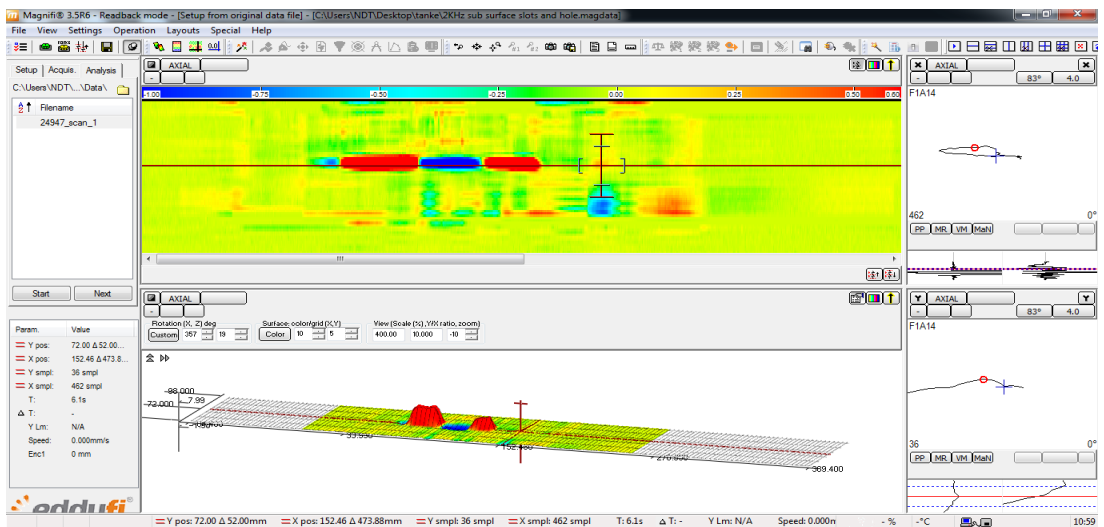


Figure 14 Eddy current array scan at 1Kkz.

TWI Management System

TWI operates a Management System designed to ensure that customer requirements are met and that any 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 are controlled by a management system that complies with the general requirements of the BS EN ISO 9000:2008 series of standards.
- Project management, examination and training services are audited by LRQA as complying with BS EN ISO 9001:2008 and software development in accordance with TickITplus, Certification Number 0925004.
- 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.
- Examination activities are assessed by PCN to BINDT requirements and by TWI Certification Ltd to CSWIP requirements.
- TWI is certificated by LRQA to BS EN ISO 14001:2004, certificate number LRQA 4000756.
- TWI's Occupational Health and Safety Management System is certificated to BS OHSAS 18001:2007 by LRQA, certificate number 4004571.

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

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



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