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A Comparative Study of Electromagnetic NDE Methods and Quantum Well Hall Effect Sensor Imaging for Surface-Flaw Detection in Mild Steel Welds

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Abstract

Following on from the success and industrial interest in Non-Destructive Evaluation (NDE) applications of Quantum Well Hall Effect (QWHE) sensors, a study was conducted to establish the detection capabilities and general performance of low frequency QWHE imaging for surface-breaking flaw detection and comparing them to Magnetic Particle Inspection (MPI), Eddy Current Testing (ECT) and Alternating Current Field Measurement (ACFM).

In this study, a probe consisting of a QWHE sensor, illuminating electromagnet and sensor circuitry was controlled using an automated XY scanner with a measurement step size of 250 µm to simulate an integrated array of QWHE sensors of 250 µm pitch. This probe was used to apply a 3 mT 100 Hz frequency magnetic field to map the surface magnetic field and Magnetic Flux Leakage (MFL) response of five bespoke dressed mild steel weld samples made by Sonaspection.

These samples contained 15 surface-breaking flaws of varying length from 3 to 11 mm; mainly longitudinal toe and centre-line cracks, representative of certain typical industrial requirements of one of our industrial partners.

The same samples were also subjected to MPI, ECT and ACFM provided by leading industrial companies using their own qualified personnel, equipment and procedures. The outcomes and performance of each NDE technique including QWHE imaging were then compared and evaluated.
1. Introduction

An initial study was performed to quantitatively assess the general performance and detection capabilities of Quantum Well Hall Effect (QWHE) sensor-based magnetic imaging and compare them to those of existing electromagnetic NDE techniques.

Samples of mild steel with dressed welds and artificial flaws (synthesised by Sonaspection Ltd) were subjected to MPI, ECT, ACFM and QWHE imaging on a double-blind trial basis but each technique was not particularly optimised to achieve the “best” results in this study. MPI was conducted at BAE Systems using a standard 50 Hz ~1.2 T yoke, contrast paint and kerosene particle spray according to their normal procedures. ECT was performed by Rolls-Royce Nuclear where the probes used were not necessarily optimised for steel weld inspection – probes and frequencies used were not “best case”. However, they were mounted on an XY measurement system to obtain limited imaging capabilities. ACFM was performed manually using a standard AMIGO probe, more suited to larger gross-sized flaws. Their twin-field probes optimised for weld inspections were not available at the time of this study.

QWHE imaging was achieved using a probe consisting of a single QWHE sensor, sensor circuitry and electromagnet to provide an applied 3 mT 100 Hz magnetic field. This probe was controlled using an XY scanner with measurement step size of 250 µm to simulate that of an integrated array of QWHE sensors, separated by a pitch of 250 µm. It must be noted that a step size of < 100 µm could have been used but was deemed unfair and unrepresentative to the overall aims of QWHE imaging. In addition, a frequency of 100 Hz for the applied magnetic field was used throughout the QWHE imaging trial. To this date, there has been no research into an optimal inspection frequency or measurement step for QWHE imaging.

The outcomes of each NDE inspection technique were compared, evaluating:
- the amount of flaws detected (not probability of detection)
- any additional indications
- approximate indication signal amplitude to background floor level
- sizing accuracy
- inspection time

General performances, including the main advantages and limitations are also evaluated.
2. Comparative Study

This section includes information on the samples used in this study, as well as an overview of each NDE technique used in the comparative study and a summary of their individual performances.

2.1 Samples

Five weld samples were manufactured by Sonaspection, with a total of 15 flaws representative of those encountered by BAE Systems predominantly centre-line and toe cracks of various lengths ranging from 3 mm to 11 mm, longitudinal to the direction of the welds (Figure 1(a) to 1(e)).

Each sample measured 150 mm x 150 mm with a thickness of 20 mm, each containing a full penetration weld whose caps and roots were ground flush. The parent metal was generic mild steel with electrical and magnetic properties comparable to AISI 1010. Sketches of these samples are given below (plan view):

Figure 1(a). Sample 6441-01 sketch. 11 mm toe crack, 10 mm toe crack, 13 mm linear porosity.

Figure 1(b). Sample 6441-02 sketch. 8 mm toe crack, 8 mm toe crack, 8 mm centre-line crack.
Figure 1(c). Sample 6441-03 sketch. 5 mm toe crack, 5 mm toe crack, 5 mm linear porosity cluster.

Figure 1(d). Sample 6441-04 sketch. 5 mm toe crack, 5 mm toe crack, 4 mm centre-line crack.

Figure 1(e). Sample 6441-05 sketch. 3 mm toe crack, 3 mm toe crack, 3 mm centre-line crack.

Sonaspection used MPI and manual ultrasonic testing to validate these sketches. Also, the manufactured flaws were designed to provide MPI indications, meaning that for other methods their indications are not necessarily as clear.
2.2 Magnetic Particle Inspection

Considered the easiest and most common NDE technique for magnetic materials, MPI is a fast and efficient method for inspecting large surface areas whilst providing instantaneous results as an image (1). It has low start-up and running costs as well as being comparatively easy to use and qualify procedures in industry. However, in practice it suffers from a low detection limit of ~3 mm and poor probability of detection, depending on the specific industrial application (2). It does not provide any depth measurements nor accurate length measurements in practice, along with false indications being common, particularly when the sample geometry acts as an MFL site (e.g. fillet welds). It requires surface preparation, including pre-cleaning and is invasive as coatings must be removed (3). It is also a messy technique which not only requires post-inspection cleaning but can contaminate some production line stages.

MPI was performed by BAE Systems using an industry standard 50 Hz ~1.2 T yoke, white contrast paint spray and kerosene-based black magnetic ink media. A 3-lines “Burmah-Castrol strip” magnetic flux indicator was used to validate the strength and performance of the equipment, as standard to their procedures (Figure 2(a) and 2(b)).

![Figure 2(a). MPI indication of centre-line crack on sample 6441-04.](image1)

![Figure 2(b). MPI indication of linear porosity cluster on sample 6441-03.](image2)

This method was able to detect all the flaws, with no false indications. In addition, all of them were sized and positioned correctly within a 1 mm error. It must be noted that “error” is based on any difference to the validating MPI performed by Sonaspection, giving preferential bias to MPI over the other NDE techniques.

2.3 Eddy Current Testing

Known as a much more sensitive electromagnetic technique, modern equipment allows ECT inspections to be set-up and performed easily. It also provides instantaneous results usually through the real-time plotting of a complex impedance plane (4). Compared to other techniques, it boasts a good detection limit and probability of detection in practice (2), its sensitivity providing accurate flaw sizing as well as depth estimates using calibrations (5). In most applications, ECT is non-invasive meaning that non-conducting coatings do not have to be removed. However, flaw characterisation is difficult with ECT, particularly when using complex impedance plane analysis. As with
other sensor-based electromagnetic methods, it is sensitive to lift-off and sample geometry, the main drawback being having a comparatively slow inspection time based on the small footprint of ECT probes \(^6\). This makes it ineffective at inspecting large surface areas, with false indications common in practice due to its sensitivity.

Rolls-Royce conducted the ECT using equipment which was not necessarily optimised for mild steel welds; these were Zetec absolute probes of frequency 2.5 MHz and 6 MHz along with a standard XY measurement stage to provide limited imaging capabilities (Figure 3(a) and 3(b)). A standard ECT calibration block was used to provide flaw depth estimates.

Due to time constraints, only 4 of the samples were tested. However, all the flaws from the samples tested were found, including the smallest 3 mm cracks. This method did produce 4 additional indications relating to microstructures, 2 of comparable magnitude to flaw signals, the other 2 with lower magnitudes. The noise from one such microstructure (suspected lack of fusion) is shown in Figure 3(a) above. 63% of flaws were sized within 1 mm error, the remaining within 2 mm error. Similarly, 82% were positioned within 1 mm error, the remainder within 2 mm error.

### 2.4 Alternating Current Field Measurement

Still considered as an emerging NDE technique, ACFM is mainly used for detection and accurate sizing of gross flaws of in service structures in inaccessible places, such as offshore rigging \(^7\). Compared with other techniques, the equipment is designed entirely with the end user in mind, meaning that ACFM inspections are very easy to set-up and perform, with instantaneous results in real time through the ASSIST program. In practice, it is very accurate at sizing flaw length and depths using the ASSIST algorithms and indication database. There is a large coverage from a single probe with minimal surface preparation needed. This technique is non-invasive meaning non-conducting coatings do not have to be removed \(^8\). However, as with other sensor-based electromagnetic methods, ACFM is sensitive to lift-off and sample geometry; and can be difficult to characterise flaws. The AMIGO equipment has a poor detection limit as its main application is gross flaw detection. As such, it must be noted that optimised ACFM equipment could have a much better detection limit.

ACFM was performed by TSC Inspection Systems, the leading manufacturer of ACFM equipment, using their equipment which was not optimised for mild steel welds. Manual measurements were taken using a standard 50 kHz AMIGO probe (Figure 4(a) and 4(b)).
Three of the smallest flaws (one 4 mm and two 3 mm cracks) were undetected as expected, since the equipment applications are of completely different scales. However, 90% of the flaws that were detected were sized correctly or within 1 mm error, the remainder within 2 mm error. The manual scanning meant that none of the flaws were positioned correctly, although they were all within 2 mm error.

2.5 Quantum Well Hall Effect Sensor Imaging

The University of Manchester developed an XY scanner and QWHE sensor probe (Figure 5(a)) to apply a ~3 mT 100 Hz magnetic field and map the MFL caused by each flaw (Figure 5(b)) \(^{(9)}\). The active QWHE sensing area was 160x160 µm\(^2\).

Based on the material properties and inspection frequency of 100 Hz, a standard depth of penetration of ~0.6 mm is approximated. A measurement step of 250 µm was used, simulating a representative QWHE sensor array of 250 µm pitch. The differential of the magnetic field was then calculated and mapped in real time whilst the scan was
ongoing. This is mathematically described in Equation (1), where $B_{xy}$ represents the output value for that measurement step (nT), $x$ and $y$ denoting position (µm) and $d$ representing the measurement step size (µm) – controlled at 250 µm throughout this study.

$$B_{xy} = B_{xy} - B_{(x-\Delta)(y-\Delta)}$$

(1)

QWHE images for each sample were compiled using the array of $B_{xy}$ data, normalised using greyscale (Figure 6(a)).

Figure 6(a). Unprocessed QWHE image of sample 6441-01 normalised using greyscale – the two toe cracks appear as bright white indications within the weld boundary line.

Figure 6(b). Annotated QWHE image of sample 6441-01 highlighting the indications of the toe cracks, as well as weld boundaries, heat affected zones and other microstructures. Blue rectangle used in Figure 8.
Basic post-processing hill shading imaging techniques were used to identify further areas of research (i.e. microstructure) as shown in Figure 7. This created shadow-like artefacts from the contours produced by all MFL responses.

![Figure 7. Processed QWHE image of sample 6441-01 with 45° hill shading to highlight microstructural information contained within QWHE images.](image)

The above images show that low frequency QWHE imaging not only can identify the existence of flaws but is also sensitive to microstructural changes. As such, an intensity plot is given below in Figure 8, showing the relative intensity differences between the MFL from cracks and the MFL response from microstructures. This plot was created by compiling the data within the blue rectangle slice on Figure 6(b) onto a single intensity vs. position graph.

![Figure 8. An intensity plot showing the relative magnitudes of MFL response from flaws and microstructures.](image)

Figure 8 shows that the intensity of MFL responses from cracks are far larger than those of microstructures, emphasising that QWHE sensors are not “over-sensitive” for crack detection applications. This initial work suggests that gross microstructural changes (such as lack of weld fusion) give MFL responses that are still \( \frac{4}{3} \) the magnitude of cracks, giving this technique an approximate SNR of 3 (~4.8 dB) at this stage.
As with the other NDE methods in this study, QWHE imaging was not optimised as the effects of numerous inspection parameters have yet to be explored and hence optimised: namely the frequency of the applied magnetic field and the illumination set up (electromagnets and/or coils). The measurement step of 250 µm pitch represented a QWHE sensor array of pitch 250 µm, where it must be noted that measurement steps of < 100 µm could have been used but were deemed unrepresentative of end goal realistic QWHE imaging sensor array pitches (10)(11)(12).

QWHE images for each sample cap and root side were obtained. Using these, all the flaws were detected using the unprocessed images. Several additional indications were found, believed to be from microstructural variations within the samples as previously discussed. All of these had magnitudes well below the MFL response of the flaws as illustrated by Figure 8. In this trial, it was found that using basic post-processing 45° hill shading imaging techniques, flaw sizing was within 2 mm of error which is a promising start to future research in flaw profiling. Due to the low technology readiness level of the XY scanner, no reliable positioning could be achieved at this stage.

2.6 Overview

It was expected that MPI would appear to have performed more favourably with the nature of the samples and how the sample sketches were validated. Also, it must be noted that ACFM was performed manually and the AMIGO equipment is not optimised for any flaws of this small scale.

However, it can be seen from the table below that QWHE imaging performed comparably to ECT in this controlled setting, with the additional information of microstructure of which it will be possible to ignore in future using post-processing techniques (based on the magnitude of MFL response from microstructure being far lower than that of flaws).

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<td><strong>flaws found</strong></td>
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<td>official drawings based on manufacturers own MPI inspections</td>
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<tr>
<td>defective microstructure: 2 of similar intensity to flaw signal, 2 with intensities lower than flaw signals</td>
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<tr>
<td>confusion with porosity</td>
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<tr>
<td>indication signal amplitude to background ratio</td>
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<tr>
<td>Sizing accuracy</td>
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<td>Inspection time</td>
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It is also believed that there are several near-surface flaws which have been detected using QWHE imaging which were undetected by ECT and ACFM due to their very small depths of penetration. MPI’s limited sensitivity will not have detected these either. Future investigation using other NDE techniques including Ultrasonic Phased Array / Total Focussing Method, radiography and destructive techniques will be used to evaluate the cause of these additional indications.

3. Conclusions

In this initial study, the detection capabilities and general performance of MPI, ECT and ACFM were compared to low frequency QWHE imaging, for the specific application of surface-breaking flaws in dressed mild steel welds.

This study showed that QWHE imaging can be used to detect surface-breaking flaws, with the possibility to also evaluate microstructure (intensity of microstructure MFL responses far lower than those of flaws). It was found that in this controlled setting, QWHE imaging performed comparably to ECT in terms of detection capability and SNR, with QWHE sensors providing full imaging capabilities.

As such, future work will be undertaken to develop the maturity of the QWHE imaging technique:

- frequency optimisation for crack detection
- measurement step (sensor array pitch) optimisation for crack detection with largest inspection area possible
- develop imaging enhancement techniques and automated crack detection algorithms
- develop database of MFL responses from cracks of known dimensions for flaw reconstruction
- develop multi-frequency / pulsed applied magnetic field technologies for QWHE imaging

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