Surface Crack Detection in Dressed Steel Welds Using Advanced Quantum Well Hall Effect Sensors

Document Version
Final published version

Link to publication record in Manchester Research Explorer

Citation for published version (APA):
Watson, J. M., Liang, C.-W., Ahmad, E., Sexton, J., & Missous, M. (2017). *Surface Crack Detection in Dressed Steel Welds Using Advanced Quantum Well Hall Effect Sensors*. Paper presented at The 56th Annual British Conference of Non-Destructive Testing, Telford, United Kingdom.

Surface Crack Detection in Dressed Steel Welds Using Advanced Quantum Well Hall Effect Sensors

J. M. Watson, C.W. Liang, E. Ahmad, J. Sexton and M. Missous
School of Electrical and Electronic Engineering, University of Manchester
Sackville Street Building, Manchester, M13 9PL
james.watson-6@postgrad.manchester.ac.uk

Abstract

A review of the different applications and developments of using Quantum Well Hall Effect (QWHE) sensors for NDE applications is provided. In addition, a method for using a QWHE sensor-based device to sensitively map the magnetic field across an NDE weld sample was performed.

A QWHE sensor-based AC–DC magnetometer developed at the University of Manchester, with a bandwidth of 1.5 kHz and a minimum detection limit of 500 nT, was used to obtain direct magnetic field measurements of a dressed steel weld sample. The linear surface-breaking defect present in the sample had dimensions of 14 mm length, 1.75 mm depth and a 40 μm gape.

The sample was illuminated using an AC magnet capable of operating between 0 – 2 kHz. The RMS magnetic field strengths used in this investigation varied between 3 to 33 mT. Results from this study confirm that the Magnetic Flux Leakage (MFL) caused by the surface-breaking defect can be detected across the entire 50 Hz – 1.2 kHz range using the highly sensitive QWHE sensor-based magnetometer.

Introduction

Over recent years, the development of semiconductor devices at University of Manchester has produced highly sensitive Quantum Well Hall Effect (QWHE) sensors using AlGaAs-InGaAs heterostructures. Similar to generic silicon-based Hall sensors, these gallium arsenide-based sensors are able to reliably measure the magnetic field strength (flux density) as well as the direction; but with magnitudes as low as 100 nT (0.5% Earth's magnetic field) to ~ 10 T [1].

Although the application of standard Hall sensors in NDE is not new, their higher sensitivity, high linearity, standard compact size (3 mm x 3 mm x 1 mm), large dynamic range, as well as their ability to withstand high temperature and high energy radiation make QWHE sensors more versatile and suitable for a variety of NDE applications. It must be noted that the dimensions provided above are limited by the semiconductor packaging, which could be significantly reduced if needed, with the active element (sensor itself) measuring 210 µm x 210 µm or less.

The ultimate aim of this research is to develop devices and techniques suitable for industry to replace, or add value to existing techniques that inspect for surface-breaking, or very near surface (< 1mm) defects including Magnetic Particle Inspection (MPI), Eddy Current Testing (ECT) and Alternating Current Field Measurement (ACFM).

To date, this has been achieved at the University of Manchester by developing a magnetometer using a single QWHE sensor, to take point-readings of a magnetic field. Further development will include increasing the capabilities of the magnetometer to take readings at higher magnetic field frequencies (from 400 kHz upwards to 1 MHz) for use in ACFM-style measurements.

In addition, 256 QWHE sensors have been successfully incorporated into a 16 x 16 array to map the magnetic fields across an 8 cm x 8cm inspection area, producing a real-time magnetovision (magnetic camera) system [2-3]. Currently, this magnetic camera is able to operate between DC – 300 Hz, limited by its sample/frame rate, due to the large amounts of data collected. However, this proof of concept design has successfully demonstrated how arrays of QWHE sensors can be used to easily map low frequency magnetic fields.

The obvious future application of this device is to be used as an MPI and ECT alternative (or add value to), replacing the use of magnetic particles or eddy current probes with an array of QWHE sensors, where an NDT operator can scan a sample quickly and efficiently, without the use of potentially hazardous chemicals, sprays or high-strength magnetic fields. The advantages being a larger inspection area, conceptually simpler than ECT and measuring the actual magnetic flux density of leakage, i.e. $\mathbf{B}_{\mathrm{MFL}}$ (in contrast to only detecting the presence of magnetic flux $\mathbf{\Phi}_{\mathrm{MFL}}$ or the impedance change in a detector coil). In particular, the application of this magnetic camera research has generated interest and funding from BAE Systems (Submarines), where the oil suspension in MPI sprays negatively impacts on their manufacturing process. As such, over the next few years, a magnetic camera will be developed which is tailored to the needs and requirements of BAE Systems.

Lastly, a 2-D scanner was also developed, using an alternate linear array of differently orientated QWHE sensors. This unique arrangement enables the device to detect different components ($\mathbf{B}_x$ and $\mathbf{B}_z$) of the magnetic field at the same point in space. This allows users in real-time to map the magnetic field in 2-D, allowing for more advanced defect profiling [4].

The research of using QWHE sensors for NDE applications is still in its early stages in terms of technology readiness. However, the proof of concept devices that have already been made, as well as their active continual development, shows real promise to provide alternative electromagnetic NDE methods, with instantaneous and quantitative output, increased sensitivity and defect detectability.

In conjunction with these device developments, the research into analysis of magnetic field (namely eddy current measurement and B-H curve measurement) for material characterisation [5] during inspections will also be explored. It is also intended to critically test QWHE sensor-based methods and compare them with similar electromagnetic methods including MPI, ECT and ACFM. Factors to test include detectability (probability of missing a defect), smallest detectable defect, local resolution, information gained from inspection, time to take inspection, ease to perform inspection and numerous others. This testing will commence in October 2017 and will be facilitated and overseen by BAE Systems to maintain integrity, quality standards and ensure non-bias.

The next sections provide a method of using a QWHE-sensor based magnetometer to take field measurements in a low frequency ACFM-style inspection, carried out using a real industrial sample of a surface crack in a dressed steel weld.

Sample

The sample used in this investigation was provided by BAE Systems (Submarines) NDT department. It is a mild steel plate, of dimensions 16 cm length, 14 cm width with a thickness of 2.5 cm. It has a dressed weld running through the length of the sample, with a linear surface breaking crack of dimensions 14 mm length, 1.75 mm depth and 40 µm gape. It must be noted that this defect is not visible to the naked eye.

The length of the defect was determined by BAE Systems using MPI with a tolerance of 2 mm. Its depth was also determined by BAE Systems by performing an Ultrasonic Phased Array TFM image which is shown below in Fig. 1:

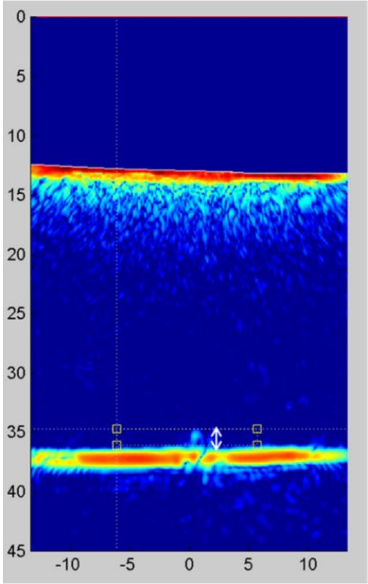


Fig. 1 – An Ultrasonic Phased Array TFM image of the sample used in this investigation, showing a crack depth of between 1.25 and 1.75 mm.

The actual width of the defect was measured in our group using a high magnification digital microscope.

Method

The QWHE sensor-based magnetometer was used to manually take point measurements of the magnetic field across the surface of the sample. In particular, the magnetic field component perpendicular to the sample, $\mathbf{B}_z$, was measured. These measurements were combined to create a map of the magnetic field across the sample surface, for each inspection at each frequency.

This magnetometer device has a detection limit of 500 nT and is able to detect magnetic field frequencies from DC to 1.5 kHz. Based on these parameters, a range of magnetic field frequencies were used (50, 100, 200, 500 and 1000 Hz), creating a map of the magnetic field at each frequency. The magnetic field applied to the sample was performed by a C-shaped electromagnet, with measurements taken between the legs of the magnet, in a similar fashion to MPI. This electromagnet had dimensions 9.5 cm width, 3 cm depth and 8 cm height; with a 3.8 cm separation between the legs and N number of turns. The current driving this electromagnet was controlled using an Agilent 33500B Waveform Generator with a custom-built amplifier to provide upwards of 0.2 A RMS at 1000 Hz. This driving current was checked for AC integrity using a Rhode & Schwarz HMO1022 Digital Oscilloscope.

This set up is shown below in Fig. 2:

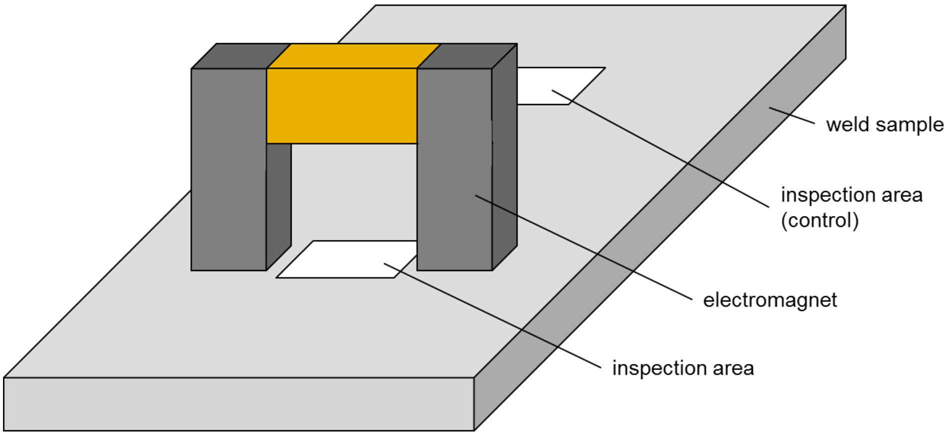


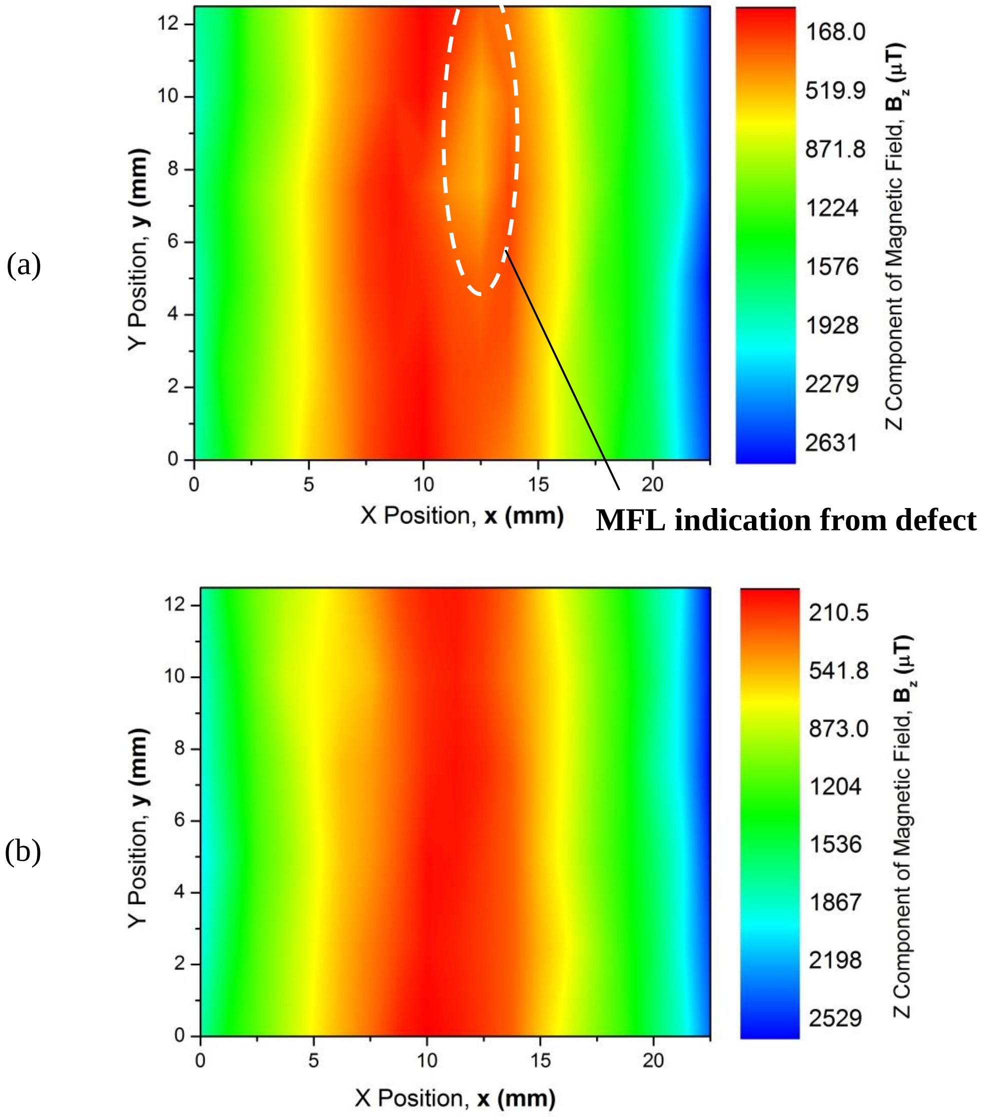
Fig. 2 – A diagram illustrating the experimental set up.

Measurements were taken across a 25 mm length x 15 mm width area, where the defect was purposefully located half in-half out of this zone. Measurements were taken at 1.25 mm intervals across the 25 mm length, in 6 rows spaced 2.5 mm apart.

A control was also taken at each frequency by moving the electromagnet and sensing area 35 mm up the length of the weld to a defect-free zone.

Experiment Results

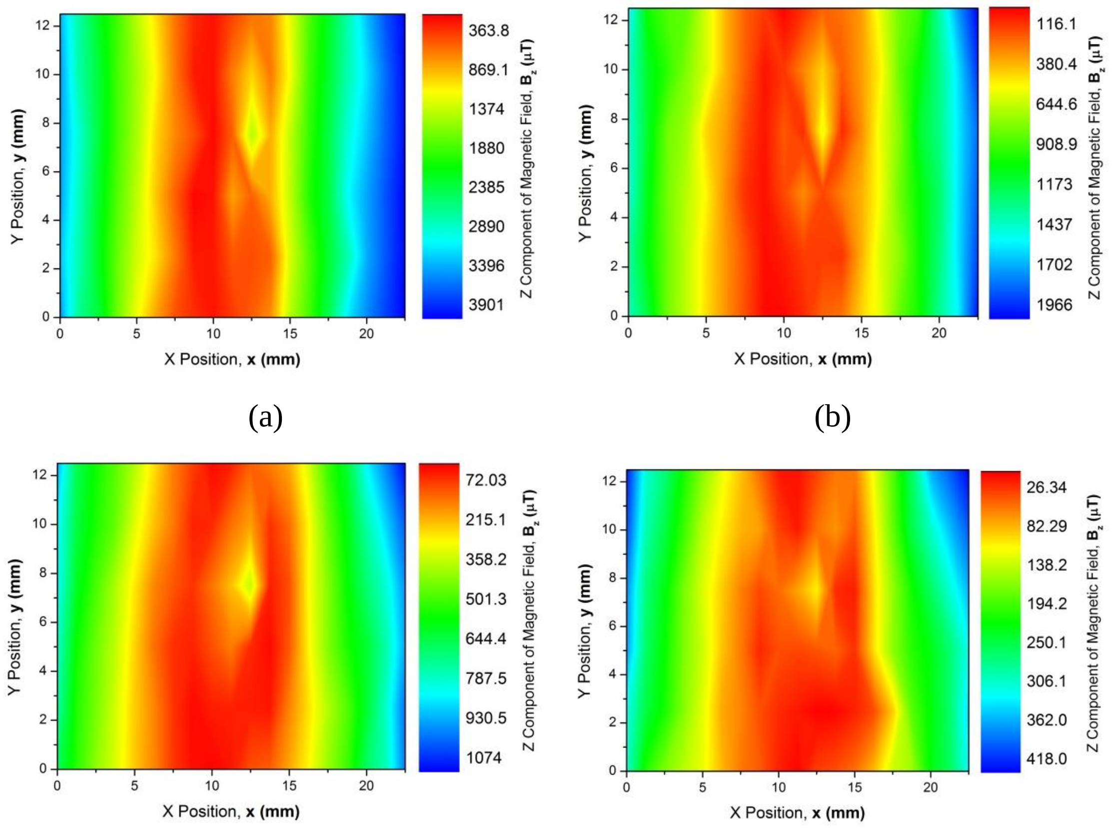
The results of these inspections are shown below in Fig. 3.



MFL indication from defect

Fig. 3 – Graphs showing the measured magnetic field distribution across the sample with an inspection frequency of 50 Hz, where (a) defect is present, (b) control.

Fig. 3 (b) shows the typical response from a defect-free, control area, i.e. a smooth continuous change in the magnetic field. In contrast, the MFL signal from a defect is shown as an abnormality as in Fig. 3 (a). Similarly, the outcomes of the inspections for the other frequencies are shown below. Since each control resembled Fig. 3 (b), the controls have not been provided to save space.



(a) (b)

(c) (d)

Fig. 4 – Graphs showing the magnetic field distribution across the sample with a defect present, with an inspection frequency of: (a) 100 Hz, (b) 200 Hz, (c) 500 Hz and (d) 1000 Hz.

Fig. 3 and Fig. 4 were compiled in OriginPro 8.5.1 using the in-built contour fill plot function. The linear palette levels were automatically set to each inspection's highest and lowest data values, with 8 major levels and 32 minor levels.

Experiment Analysis

By comparing the inspection image to the control, it is clear that this method was successfully able to detect the defect at all frequencies used. The abnormalities shown in each inspection with a defect present are the MFL produced from the defect.

Due to ∓0.5 mm misalignment between the measurements with and without defects, the control could not sufficiently normalise the data by simple subtraction. In addition, high-pass filtering and normalisation using interpolated results could not successfully be used as there were not enough data points. This highlights one of the limitations of manual scanning and the importance in developing a technique where the spatial resolution (amount of measurements per unit area) is significantly increased. This could be achieved through autonomous position tracking and data acquisition, and/or finely pitched sensor arrays.

The highest MFL measurements, also known as peak MFL, $\mathbf{B}_{\mathrm{MFL}}$, from each frequency are given below:

Frequency of Applied Magnetic Field (Hz)	Strength of applied magnetic field, $\mathbf{B}_0$ (mT)	Peak MFL measurement, $\mathbf{B}_{\mathrm{MFL}}$ (mT)	Ratio $\frac{\mathbf{B}_{\mathrm{MFL}}}{\mathbf{B}_0}$
50	32.7	0.529	0.016
100	76.8	0.146	0.019
200	20.6	0.582	0.028
500	9.8	0.368	0.038
1000	3.0	0.111	0.037

Table.1 – Table outlining the peak MFL measurement at each frequency inspected.

As Table 1 shows, proportionally the strongest MFL measurement from the inspection was found using a 500 Hz applied magnetic field. This is in agreement with the findings of E. Ahmad that each material has its own characteristic frequency response to magnetic field (a combination of material response, eddy current contribution, etc.) [5];

this suggests that each conductive material has its own distinct optimal inspection frequency, at which the MFL caused by the defect and eddy current interactions will be maximum. This investigation suggests that for this sample composed of mild steel, the optimum inspection frequency is around 500 Hz. For a more accurate value, more inspections with smaller steps in frequency would be needed.

Conclusion

Although the defect on the inspected steel sample was invisible to the naked eye and having a gape of only 40 µm, the MFL signals were easily detectable using the QWHE sensor-based magnetometer. The MFL signals could easily be measured using QWHE sensors since they are a factor of over 200 times their detection limit. This is further demonstrated by the fact that the applied magnetic fields were approximately 5% of the typical strength used in MPI inspections.

As such, this investigation highlights the sensitivity of the QWHE sensors and demonstrates how this, combined with their high linearity, compact standard size, large dynamic range, as well as their ability to withstand high temperature and radiation make QWHE sensors versatile and suitable for a variety of NDE applications.

However, this particular technique suffered from numerous limitations that prevent it from being effectively used in industry. These include:

- Low spatial resolution and misalignment prevented successful normalisation of data / subtraction of background magnetic field.
- Repetitive, tedious inspections where MFL signal could be missed easily.
- Results are very sensitive to changes in stand-off distance.

The purpose of this investigation was to demonstrate how QWHE sensors can be developed for NDE applications. Although this method was able to clearly detect the MFL signal from a surface-breaking linear crack, there are several important factors to be addressed in future QWHE-sensor application to the NDE field. It is these factors that have begun to be addressed in the work of the magnetic camera, the handheld scanner, as well as side-line projects such as the scheduled development of a robotic X-

Y measurement stage. These include the development of an integrated electromagnet to provide the applied magnetic field for various QWHE sensor-based NDE devices, such as the handheld scanner [4] and magnetic camera.

Currently, this style of low frequency ACFM-style measurements is used to successfully validate simulations, using them to study the behaviour of the magnetic field around defects in more detail. The consistent and systematic use of this approach will lead to a better understanding of the behaviour of magnetic fields, particularly in AC, around defects as used in our research regarding 3-D defect profiling. In addition, these style simulations are being used to study the effects of stand-off, investigating the critical distances between sensor and sample needed to still collect meaningful data. Finally, we use validated simulations to investigate the critical pitch of sensor arrays, to help maximise the sensing area without losing critical information about the magnetic field distribution or requiring an unachievable bitrate or processing power (amounts of sensors).

Acknowledgements

This research is being funded by RCNDE as part of an iCase PhD studentship with BAE Systems (Submarines) providing industrial sponsorship. There is also funding given in terms of a scholarship by Worshipful Company of Scientific Instrument Makers (WCSIM). University of Manchester supervisor: Prof. Mohamed Missous. BAE Systems (Submarines) supervisor: Mr. Thomas Barber.

References

[1] Haned, N. and Missous, M. (2003). Nano-tesla magnetic field magnetometry using an InGaAs–AlGaAs–GaAs 2DEG Hall sensor. Sensors and Actuators A: Physical, 102(3), pp.216-222.

[2] Liang, C.W. (2017). A High Spatial Resolution Magnetovision Camera Using High-Sensitivity Quantum Well Hall Effect Sensors. PhD. The University of Manchester.

[3] Liang, C.W., Ahmad, E., Balaban, E., Sexton, J. and Missous, M. (2016). A Quantum Well Hall Effect Magnetovision System for Non-Destructive Testing. 19th World Conference on Non-Destructive Testing.

[4] Biruu, F.A., Balaban, E., Ahmad, E. and Missous, M. Quantum well Hall-effect sensor based Handheld Magnetic Scanner with Programmable Electromagnetic Coil for Non-destructive Testing of Ferromagnetic and Non-ferromagnetic Materials. 55th Annual Conference of BINDT, 12th-14th September 2016, Nottingham, UK, Proceedings ISBN 978-0-903-132-62-1.

[5] Ahmad, E., Liang, C.W., Watson, J.M. and Missous, M. Non-Destructive Detection of Metallic Objects under AC magnetic Field Illumination. 56th Annual Conference of BINDT, 5th-7th September 2017, Telford, UK.