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MAGNETIC FIELD FREQUENCY OPTIMISATION FOR MFL IMAGING USING QWHE SENSORS

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ABSTRACT

Magnetic particle and other Magnetic Flux Leakage (MFL)-based methods typically use high-strength (> 0.7 T) low-frequency (≤ 50 Hz) magnetic fields [1] for practicality purposes. The rationale behind this is in the availability of high strength permanent magnets and the ability to easily create stronger electromagnets at low frequency (using 50 Hz mains). As such, most MFL-based methods typically use frequencies which are practical to achieve the high field strengths required for near sample saturation or due to magnetic field sensor and detection media insensitivity to weaker field strengths.

Over the past five years, The University of Manchester has developed pioneering magnetic field imaging scanners and techniques using Quantum Well Hall Effect (QWHE) sensors [2], exploiting their unique combination of sensitivity and linearity over the large dynamic range (20 nT to 2 T ≈ 160 dB) with a compact size (200 µm). Previous research has shown that this sensitivity enables the detection of surface-breaking cracks and other flaws down to 1 mm in length in mild steel welds [3] using comparatively low strength applied magnetic fields (5 to 100 mT) by mapping the MFL response across samples under test.

Because of these relatively low-strength applied magnetic fields required, QWHE sensors have the potential to be used as key components in low-power (i.e. portable) magnetic field scanners, using magnetic field frequencies which are better suited to the frequency response of the material of the sample under test.

As such, this research focuses on the optimization of applied magnetic field frequencies within the range of DC to 1 kHz for MFL detection of surface-breaking flaws in mild steel welds via magnetic field mapping using QWHE sensors.

Keywords: NDT, NDE, magnetic particle, magnetic flux leakage, eddy current testing, alternating current field measurement, Quantum Well Hall Effect sensor, Hall Effect, 2-dimensional electron gas.

NOMENCLATURE

V_H	Hall voltage produced by Hall sensor (mV)
K_H	Hall sensor sensitivity (mV mA^{-1} mT^{-1})
I_B	Hall sensor biasing current
B_z	Tangential magnetic field component measured by Hall sensor.
t	Thickness of biasing channel in Hall sensor (nm)
n	Electron concentration within Hall sensor biasing channel (nm^{-2})
e	Electron charge
L	Length of biasing channel in Hall sensor (µm)
W	Width of biasing channel in Hall sensor (µm)

1. INTRODUCTION

Mild steel welds are typically inspected using magnetic particle (MPI) testing, sometimes using another complimentary method for further evaluation of indications (e.g. conventional eddy current testing (ECT) for more accurate sizing and depth estimation). The success of MPI is due to its quick inspection time and versatility across different sample geometries, along with its ease to perform. However, the most important aspect of MPI is that the indications from it are images of the flaws found, resulting in easy flaw characterization. For ECT, the higher frequencies used and measurement of secondary effects (i.e. complex impedance changes in a detector coil) result in a much more sensitive technique due to much thinner penetration depths of the magnetic field, often with a much smaller footprint. As a consequence of this sensitivity, ECT is more prone false indications, and can be affected by surface condition and sample

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geometry changes, with inspections taking considerably longer than MPI.

The large disparities in performance between MPI and ECT arise due to the different physical phenomena they use to detect the presence of flaws. MPI uses MFL to detect flaws based on their material (typically air) having a different magnetic permeability to that of the material of the sample under test. In contrast, conventional ECT detects the difference in electrical conductivity between the flaw material and sample under test. As such, these distinct methods use very different magnetic fields parameters, as shown below in Figure 1:

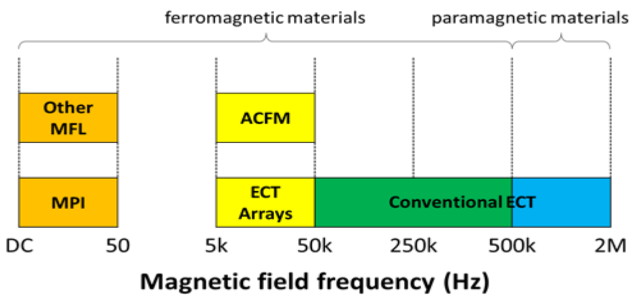

FIGURE 1: *A PLOT SHOWING THE TYPICAL MAGNETIC FIELD FREQUENCIES USED BY THE MOST COMMON NDT&E METHODS FOR FLAW DETECTION INCLUDING MAGNETIC PARTICLE INSPECTION (MPI) AND ALTERNATING CURRENT FIELD MEASUREMENT (ACFM).*

Advancements in mechanical and electrical engineering as well as digital signal processing have allowed some NDE equipment companies to develop lower frequency ECT arrays which are less dependent on surface condition and sample geometry. However, Figure 1 shows that there is a distinct gap between 50 Hz and 5 kHz of magnetic field frequencies used for flaw detection in ferromagnetic materials. The reason behind this is that:

- MFL-based methods currently rely on applying high-strength (> 0.7 T) low-frequency (≤ 50 Hz) magnetic fields in order to detect flaws using relatively insensitive magnetic particles and silicon-based Hall sensors.
- ECT-based methods currently rely on applying low strength (< 1 mT) high frequency (≥ 5 kHz but typically ≥ 50 kHz) to generate enough eddy currents within a frequency range more sensitive for small pickup coils.

Consequently, it can be deduced that the frequency gap is due to the insensitivities of the detection media and sensors combined with the impracticalities of applying fields of enough strength within this region. Therefore, it can be further deduced that MFL is not performed at frequencies which are optimized to the frequency response of the materials being tested, giving QWHE sensors a pioneering position in NDE to be practically able to perform surface-breaking flaw detection in mild steel via MFL imaging using low-strength (≤ 100 mT) and therefore low-power consumption (i.e. portable) applied fields.

QWHE sensors have this unique combination of sensitivity and linearity over their large dynamic range (20 nT to 2 T ≈ 160 dB) due to their development over the past 20 years at The University of Manchester. During this time, their design, structure and growth processes have evolved and continue to be developed and refined for different industrial applications (e.g. microstructure analysis). Despite the different sizes available (application dependent), they all follow the behavior and characteristics of having high sensitivity and linearity over a large dynamic range, by utilizing the Hall Effect as shown in Equation 1 below:

$$V_H = K_H \cdot I_B \cdot B_z \tag{1}$$

where

$$K_H = \frac{1}{t \cdot n \cdot e} \tag{2}$$

Equation 2 shows that the sensitivity of Hall sensors is dependent on t and n, the thickness of the biasing channel and the electron concentration within the biasing channel respectively. QWHE sensors achieve their sensitivity using an AlGaAs-InGaAs heterostructure which allows this biasing channel to only be 12 nm thick, using a quantum well to confine electrons within a 2-Dimensional Electron Gas (2DEG) with increased electron concentration using donor supply layers. This structure is shown below in Figure 3:

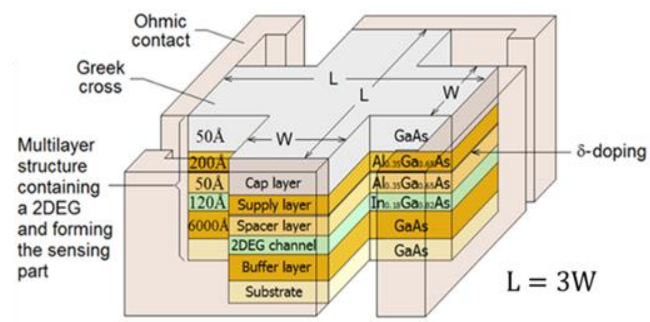

FIGURE 2: *A DIAGRAM TO SHOW THE TYPICAL HETEROSTRUCURE AND GREEK CROSS SHAPE OF QWHE SENSORS FROM UNIVERSITY OF MANCHESTER.*

The University of Manchester has developed a magnetic field scanner capable of finely controlling the XYZ movement of a probe consisting of a low noise QWHE sensor circuit and illuminating electromagnet capable of applying DC to 1 kHz magnetic field. This probe is shown in Figure 3 below:

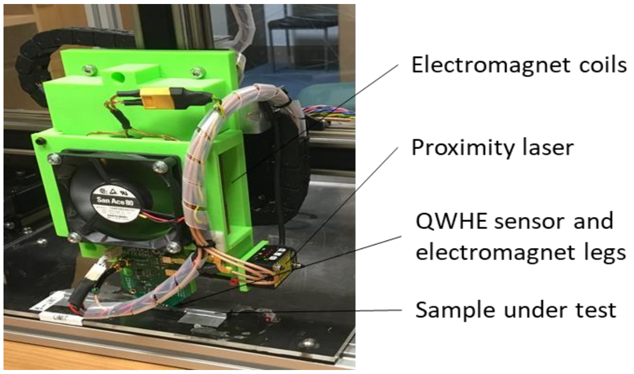

FIGURE 3: *LABELLED PHOTOGRAPH OF MAGNETIC FIELD SCANNER PROBE WITH QWHE SENSOR CIRCUIT AND ILLUMINATING ELECTROAMGNET.*

This probe was specifically designed to apply DC to 1 kHz magnetic field, of mT strength, to the sample under test using the QWHE sensor circuit to map the MFL response. This relationship between electromagnet and sensor is shown below in Figure 4:

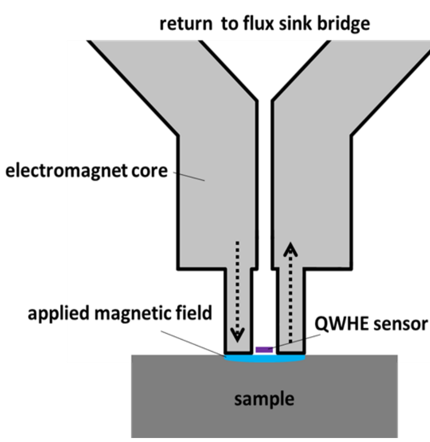

FIGURE 4: *DIAGRAM SHOWING ELECTROMAGNET AND QWHE SENSOR POSITIONING IN THE PROBE.*

Lift-off distance between the probe and sample was controlled using a proximity laser to initially map the sample, with a Z direction motor module to autonomously compensate for any changes, keeping the probe at a controlled lift-off of desired distance when performing the magnetic field mapping. Measurement step size (i.e. X and Y pixel size) was able to be controlled by the user, with a lower limit of ≥ 10 µm (for microstructural analysis), with typical values being 100 µm for high resolution and 250 µm for quick scans for flaw detection.

2. MATERIALS AND METHODS

In this work, three mild steel NDE weld validation samples were used, with surface-breaking flaws ranging from 1 mm to 10 mm in length. These allowed for a spread in measurements to observe any differences in MFL frequency response which could be related to crack length. Figure 5 below illustrates the main features of the samples used:

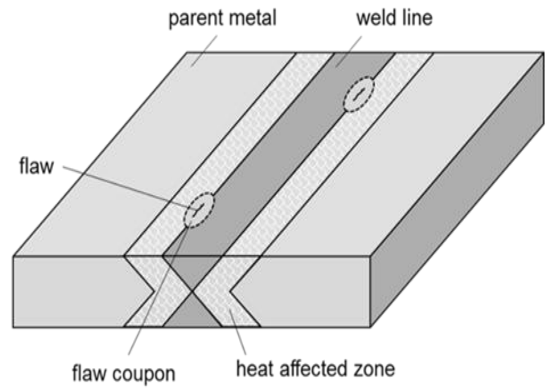

FIGURE 5: *DIAGRAM SHOWING THE GENERAL LAYOUT AND FEATURES OF THE SAMPLES USED.*

MFL imaging was performed on these samples with field frequencies varying from DC to 1 kHz, with applied strengths of < 15 mT. 100 µm measurement steps were used with a controlled lift-off of 1 mm.

The noise floor of each image, for each frequency, was then determined and compared to the signal MFL response from the flaws. The signal to noise ratio for each image, and therefore for each applied frequency, was determined.

3. RESULTS AND DISCUSSION

Testing is still ongoing (as of 29th March 2019) however preliminary trials suggest an optimum frequency of between 500 and 600 Hz for the grade of mild steel of these samples, as at this frequency the noise believed to originate from microstructure is significantly reduced, resulting in a much lower noise floor.

4. CONCLUSION

Testing is still ongoing (as of 29th March 2019).

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