Estimation of the defects dimension with a GMR eddy current sensor.

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Abstract

This paper presents an experimental system to detect defects in aluminum by eddy currents using a GMR sensor. In three plates of aluminum were constructed defects of 0.6, 1 and 1.4 mm of the width and depths of 0.5, 1, 1.5, 2, 4, 6 and 8 mm, the defects were scanned with the sensing axis perpendicular to the defect length in ten times. The parameters DV and DX were extracted from output voltage signal. Results of this work show that the output voltage of the GMR sensor depends of the width and the depth of the defect. DX depends only on width when the depth of defect is equal or greater than 4 mm. Fitting functions were proposed for the experimental values of DV and DX, these functions show the relationship between the physical dimensions of the defects and parameters DX and DV. Also studied the dependence of DV with the filling factor of the excitation coil.

Keywords: Eddy currents, giant magnetoresistive sensor, defect dimensions, non-destructive evaluation.

1. Introduction

Eddy current testing is a widely used method in electro-magnetic non-destructive testing for detecting cracks, corrosion, impurities and variations in heat treatment [1]. Eddy current inspection is based on Faraday’s electromagnetic induction law. A time varying magnetic flux density, \( B \), will cause a electric field:

\[
\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}
\]

(1)

When a conductor material is closed to a coil that generates a time varying magnetic field are eddy current induced in the material. The induced EC in the test material absorbs or dissipates energy from the source coil, leading to differences in the flux density. This causes variations in the electrical impedance of the sensor coil, depending on the condition of the test material. Exist two methods to measure the eddy currents response, the indirect method measured the complex impedance of the eddy current probe coil in absolute or differential mode [2, 3]. The direct method measured the magnitude change of the magnetic field directly using a magnetic field sensor. EC testing traditionally relies on indirect methods, however, the main drawback of induction coils is that their output voltage is proportional to the rate of change of the magnetic flux density rather than to its magnitude, which limits their sensitivity at low frequencies. Therefore, detection of deep flaws is difficult with induction coils. The GMR sensor responds to intensity of the magnetic field and its sensitivity is independent of the frequency from DC until units of MHz [4]. Due to this characteristic in recent years a lot of experimental systems of nondestructive testing using GMR sensors have been developed [5, 6]. Most of the works in the field of EC techniques are aimed at improving the detection capabilities of the measurement system. Today industry requirements demand the quantification of the defects dimension rather than simple detection. This is the reason whereby the principal aim of this paper is to correlate the width and depth of large defects of well defined dimensions with the output voltage of the GMR sensor. Proposed mathematical expressions show the correlation between the defect dimensions with the GMR sensor output.

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for the case of scanning the defects with the GMR sensing axis perpendicular to the defect length.

2. Operation

The EC probe is composed of a flat spiral pancake-type coil with the GMR sensor located on the coil axis as it proposed in [7]. The probe geometry is shown in Fig. 1, while dimensions of the coil used in the experimental are given in table 1. The excitation coil has two layers with ten turns each. The GMR sensor consist of four resistor in a Wheatstone bridge with two as sensing elements and the other two as dummy resistor magnetically shielded by a layer of a material with high magnetic permeability. This layer also acts as flux concentrator for the sensing elements.

![Figure 1: Schematic view of the EC probe with the GMR sensor sensing axis coplanar with the inspected surface.](image)

The GMR sensor detects the tangential component of the applied magnetic field \( H_t \) because the sensing axis of the GMR is coplanar with the inspected surface and perpendicular to the axis of the coil. For a defect-free surface the output voltage is a constant value different of zero because the flow of eddy currents induced in the material does not change. Once the GMR is close to or on top of a defect, the eddy current flow path is altered, which changes \( H_t \) due to the variation of the mutual inductance between eddy current and the excitation coil.

<table>
<thead>
<tr>
<th>Table 1: Geometric parameters of the coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside radius</td>
</tr>
<tr>
<td>Outside radius</td>
</tr>
<tr>
<td>Length of the coil</td>
</tr>
<tr>
<td>Number of turns</td>
</tr>
<tr>
<td>Diameter of the wire</td>
</tr>
</tbody>
</table>

A magnetic finite elements simulation using the freeware FEEM 4.2 was performed to obtain the tangential component of the applied field in the active region of the GMR sensor.

Figure 2 a) shows the simulation of magnetic flux density produced by the excitation coil along the surface of the GMR sensitive area, where the excitation coil has the dimensions shown in the table 1. Fig. 2 b) shows the maximum value of the tangential component of the applied magnetic field in the active region of the GMR sensor. The maximum value of \( H_t \) is about 75 A/m (0.94 Oe), which is a value detected by the GMR sensor in a defect-free surface or even when it is not close to the conductive material.
3. GMR sensor characteristics

A GMR sensor of the type AA002-02 manufactured by NVE was used. The sensor response was measured in the laboratory. The dc sensitivity of the GMR sensor is 86 mV/mT for a dc voltage of 5.15 V supplied to the bridge. The bridge is connected to a set of four nickel-metal hydride batteries with a nominal voltage of 1.2 V each. The sensitivity can be expressed as 16.7 mV/V mT because the sensor output is linear with the bridge voltage. Figure 3 shows the sensor response as measured in the laboratory.

4. Experimental setup

Figure 4 shows the block diagram of the experimental setup for EC measurement. A sinusoidal voltage signal is selected with amplitude of the 860 mVpp and frequency of 20 kHz in the Agilent 33220A function generator. This signal is fed into a dual amplifier LM2879T, which supplies a current $I_{\text{rms}} = 780$ mA to the excitation coil. The maximum applied magnetic field is about 48 mT at the center of the excitation coil. The penetration depth in the aluminium used in the experiments, for the applied frequency, is approximately 0.6 mm. The EC probe is scanned over the surface in the aluminium plates in the X direction.
using a PIC16LF876A to control the position of the EC probe. The GMR sensing axis is along the X direction and perpendicular to defect length. The output voltage of the sensor was amplified (G = 10) using an instrumentation amplifier INA118P and low-pass filtered, which helps extracting the dc component of the signal proportional to the defect. All defects were scanned ten times and the average value of the extracted parameters were obtained in order to correlate the GMR output voltage with the width and depth of the defects used in this work.

Figure 5 shows the dimensions of the three plates used in this work with their respective machined defects. Each plate has a set of seven defects with nominal depths (d) of 0.5, 1, 1.5, 2, 4, 6, and 8 mm, and a defect nominal width (w) of 0.6 mm, 1 mm and 1.4 mm, respectively. The defects were mechanically constructed using Cardinal cutting disk of the type 2.5 x 1/64 x 1 inches (100 teeth), 6 x 1/32 x 1 inches (150 teeth) and 2 x 3/64 x 5/8 inches (62 teeth), respectively.

Table 2 shows the actual values of defects with nominal widths $w_1 = 0.6$ mm, $w_2 = 1.0$ mm, and $w_3 = 1.4$ mm, and nominal depths $D_1 = 0.5$ mm, $D_2 = 1.0$ mm, $D_3 = 1.5$ mm, $D_4 = 2$ mm, $D_5 = 4$ mm, $D_6 = 6$ mm, and $D_7 = 8$ mm. The width and depth of each defect were measured.
using a Mitutoyo Digital Slide Caliper Model CD-8 CXW and a Starret Electronic Indicator No-3600 Series, respectively. Both devices have a resolution of 0.01 mm.

Table 2: Actual defects dimensions related to the nominal width (w₁, w₂, w₃) and depths. (D₁, D₂, D₃, D₄, D₅, D₆, D₇). All values are given in mm.

<table>
<thead>
<tr>
<th>Nominal depth (mm)</th>
<th>Nominal width w₁ = 0.6 mm</th>
<th>Nominal width w₂ = 1 mm</th>
<th>Nominal width w₃ = 1.4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual depth</td>
<td>Actual width</td>
<td>Actual depth</td>
</tr>
<tr>
<td>D₁ = 0.5</td>
<td>0.56 ± 0.02</td>
<td>0.5 ± 0.02</td>
<td>0.53 ± 0.02</td>
</tr>
<tr>
<td>D₂ = 1</td>
<td>1.02 ± 0.02</td>
<td>0.53 ± 0.02</td>
<td>1.06 ± 0.02</td>
</tr>
<tr>
<td>D₃ = 1.5</td>
<td>1.51 ± 0.02</td>
<td>0.53 ± 0.03</td>
<td>1.55 ± 0.02</td>
</tr>
<tr>
<td>D₄ = 2</td>
<td>2.18 ± 0.02</td>
<td>0.53 ± 0.02</td>
<td>1.96 ± 0.02</td>
</tr>
<tr>
<td>D₅ = 4</td>
<td>3.56 ± 0.02</td>
<td>0.53 ± 0.03</td>
<td>4.01 ± 0.02</td>
</tr>
<tr>
<td>D₆ = 6</td>
<td>6.08 ± 0.02</td>
<td>0.55 ± 0.02</td>
<td>5.56 ± 0.02</td>
</tr>
<tr>
<td>D₇ = 8</td>
<td>7.4 ± 0.02</td>
<td>0.56 ± 0.03</td>
<td>7.64 ± 0.02</td>
</tr>
</tbody>
</table>

5. Result and Discussion

Fig. 6 shows the GMR output voltage of three defects that have the same nominal depth D₅ = 4 mm and nominal widths of w₁ = 0.6 mm, w₂ = 1 mm, and w₃ = 1.4 mm. When the EC probe is in a defect-free surface, the output voltage is about 0.25 V, the signal background level in fig. 6, corresponding to a detected magnetic field of about 0.3 mT as obtained from the sensor characteristic of fig. 3, considering that the output voltage of the GMR sensor is amplified ten times. In fig. 2 a) the maximum value of $H_t$ was about 0.094 mT and the effect of the flux concentrators in the sensitive elements is defined by [8]:

$$\text{Field at sensor elements} \cong (\text{Applied Field}) \times (60\%) \times (\text{FC length} / \text{gap between FCs})$$  \hspace{1cm} (2)

Hence the actual field at the sensitive elements of the sensor will be about 0.23 mT, which supports the experimental results shown in fig. 6.

![Figure 6: GMR output signal for defects with d = 4 mm and widths of 0.6 mm, 1 mm and 1.4 mm. The GMR sensing axis is perpendicular to defect length.](image)

Fig. 6 shows that the output voltage of the GMR sensor depends on the width, a defect of the same depth and different widths, the maximum amplitude of the output voltage corresponds to the defect with higher width. Fig. 7 shows how the parameters DV and DX were defined in order to obtain a relation between the GMR output voltage and the defect dimensions. DV is
defined as the voltage difference between the maximum and minimum values of the output signal, and DX is defined as the difference in position, expressed in mm between them.

Fig. 8 shows the DX average values of the studied defects. Each plate has seven defects with one nominal width and seven different nominal depths. Fig. 8 shows that DX depends on the width and the depth of defect. The maximum value of DX is when the depth of the defect is 0.5 mm. The value of DX decreases when the depth of the defects increases. When the depth of defect is equal or greater than 4 mm DX has similar values and we can see that there is no overlapping between any points with their standard deviation. Then it can define that DX depends only on the width when the depth of the defect is equal or greater than 4 mm. The letter A in fig. 8 shows the DX value of the defect with \( w = 1 \) mm and \( d = 2 \) mm. The DX value related to the defect is bigger than the respective values for the defects with nominal depths of 4, 6, and 8 mm. From table 2, the actual width of this defect is 1.02 mm and for the other three defects are 0.91, 0.91, and 0.93 mm, respectively. The width difference of 0.1 mm between the first defect and the mean value of the other three defects influences the DX difference for the same nominal width.

Fig 9 shows the experimental values of DX and the corresponding fit function. The average value was obtained from all measurement taken from defects with the same nominal width of each aluminium plate. The fit function is:
\[ DX = y_0 + A_1 e^{-d/t_1} \] (3)

Table 3 shows the fitting parameters using equation 3 for each nominal width. \( y_0 \) depends on the width of the defect and the experimental values of DX are similar to the values of \( y_0 \) for each width for a defect depth equal or greater than 4 mm. According to the results in fig. 9 and in table 3 it is possible to say that the fit function of the experimental values of DX does not give a direct estimation of the defect width due to overlap between two points when the defect depth is smaller than 2 mm. Additionally, the fitting parameters \( A_1 \) and \( t_1 \) are not related to the dimensions of the defects or with a physical parameter of the excitation coil. But, the proposed fit function shows a relationship between the parameter DX and the physical dimensions of the defects.

**Figure 9:** Nominal values of DX and Fit function for each nominal width as a function of the defect depth.

Table 3: Fitting parameters of the experimental values of DX

<table>
<thead>
<tr>
<th>Fitting parameters</th>
<th>Width (w) (mm)</th>
<th>Width (w) (mm)</th>
<th>Width (w) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w = 0.6</td>
<td>w = 1</td>
<td>w = 1.4</td>
</tr>
<tr>
<td>( y_0 )</td>
<td>2.5</td>
<td>2.9</td>
<td>3.3</td>
</tr>
<tr>
<td>( A_1 )</td>
<td>1.3</td>
<td>0.85</td>
<td>2.13</td>
</tr>
<tr>
<td>( t_1 )</td>
<td>0.67</td>
<td>1.4</td>
<td>0.81</td>
</tr>
<tr>
<td>( \chi^2 )</td>
<td>0.0007</td>
<td>0.005</td>
<td>0.002</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.991</td>
<td>0.94</td>
<td>0.993</td>
</tr>
</tbody>
</table>
Fig. 10 shows the average value of DV for each nominal width. DV depends on the width and depth when the depth of the defect is greater than 2 mm, and magnitude of volt increases as a function of the defect depth for each nominal width. The inset of fig. 10 shows that there is an overlap of the values of DV between the defects with nominal width of 1 mm and 1.4 mm. Table 2 shows that the actual depths of the defects with nominal width w = 1 mm is greater than the depth of the defects with nominal width of w = 1.4 mm and 0.6 mm. The difference in depth is of 4 to 8 %. Additionally if comparing the actual widths of the defects, the average difference between the defects with w = 0.6 and the defects with w = 1 mm is about 0.503 mm while the average difference between the defects with w = 1 mm and the defects with w = 1.4 mm is about 0.336 mm. When the width of the defects increase in 0.336 mm with respect to the defects with w = 1 mm the amplitude of DV rises. When decreasing the depth of the defects in 8 percent with respect to defects with w = 1 mm the amplitude of DV decreases why DV depends on the depth. The variation in the depth of the defects explains why there is an overlapping of the values of DV for the defects with width of 1 mm, and 1.4 mm. Values of DV of the defects with w = 0.6 mm and w = 1 mm have not overlap because the depth of defects with w = 0.6 mm is less than the depth of defects with w = 1 mm. Additionally the width of defects is increases in 0.533 mm. It is that DV depends on width and the depth of defect.

Fig. 11 shows the DV average value and their respective fit function of the defects with nominal widths w1 = 0.6 mm, w2 = 1 mm, and w3 = 1.4 mm, respectively. The fit function is:

\[
DV = a(1 - f^d)
\]  

(4)

where \(a\) is a fitting parameter, \(f\) is the fill factor of the excitation coil, and \(d\) is the defect nominal depth. The coil filling factor is defined as [9]:

\[
f = \frac{d_{\text{out}} - d_{\text{in}}}{d_{\text{in}} + d_{\text{out}}}
\]  

(5)

\(d_{\text{out}}\) and \(d_{\text{in}}\) are the coil outer and inner diameters, respectively. For the excitation coil used here \(f = 0.533\). The coil filling factor \(f\) was kept constant.

Figure 10: DV average values for each nominal width as a function of the defect depth. The inset shows the overlap of the values of DV when the depth of the defects is \(d = 0.5\) mm, \(d = 1\) mm, and \(d = 1.5\) mm.
Table 4 shows the fitting parameters using equation 4 each nominal width, where $a$ depends on width of the defect.

According to the results in fig. 11 and in table 4 the fit function of the experimental values of DV depends on width and depth of the defect. Additionally, the fitting parameters $b$ is related with physical dimensions the excitation coil. Equation 4 is not enough for estimate the depth of defect why DV depends on two variables. But, the proposed fit function shows a relationship between the parameter DV and the physical dimensions of the defect.

### 6. Conclusions

An experimental system using eddy current techniques with a GMR sensor was developed. In three plates a set of mechanical defects were built with seven nominal depths (0.5, 1, 1.5, 2, 4, 6, and 8 mm) and three nominal widths (0.6, 1, and 1.4 mm), respectively. Experimental data shows that the output voltage depends on the width and depth of the defects. Parameters DV and DX were defined from the GMR output voltage. Fitting functions were proposed for the experimental values of DV and DX. These functions give a relationship between the GMR
output signal with the defect dimensions, which could help to estimate the defect dimensions. DV and DX depend on both defect dimensions: the width and the depth. DX depends on two variables that are not related to the defect dimensions or the physical characteristics of the excitation coil while DV depends on the fill factor of the excitation coil. This work does not establish a procedure to estimate the defect dimensions but shows that DX and DV help to correlate the GMR sensor signal with the actual dimensions of the defects and can be used to estimate the defect dimensions.

Acknowledgments

This work was partially supported by the projects IPN-SIP-20110953. E. R-P thanks CONACyT and PIFI-IPN for the scholarships.

References