The Effect of Gain and Frequency on Eddy Current Testing for Copper Material Defect Inspection

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Abstract. Copper and the copper alloys are some of the most versatile materials available and used for applications in every type of industry with world consumption of exceeding 14 million tonnes per annum. In eddy current testing inspection (ECT), several forms of device calibration must be done before the assessment can be performed. The electronics equipment must be calibrated to ensure the accuracy of measurement. This paper is focused on investigate the optimum frequency and gain for copper material block. The material used to produce the sample test in this project was copper. They are many methods that involved in this project such as producing sample test and artificial defect, conductivity measure and perform calibration for copper material block. Two thickness of copper block were selected 8mm and 16 mm. Artificial defect with depth of defect 0.5 mm, 1mm and 2.0 mm are fabricate on the sample. Different frequency and gain of eddy current testing was used in order to identify the best setting for both parameters in ECT for copper material defect inspection. Experimental result showed that the thickness is directly proportional with the applied gain. From here the negative scanning will giving the good result of different slot of defect comparing the negative scanning. Besides the percentage of increment of signal amplitude being identify with increment 40% signal between 0.5mm and 1.0mm slot of defect. Lastly the depth of the slot is inversely proportional with applied gain.

1. Introduction

Various techniques are used in the assessment of defects in metal materials without damaging the metal structure and one of them is the Eddy Current Testing Technique (ECT). The use of ECT is not limited to identifying metal material damage only but it is also used to identify metal thickness, material and internal defect inspection and finally it is also used to measure electrical conductivity in heat treatment conditions for metal material [1,2]. This can be compared to other test methods where it will damage the physical and structure of the material while ECT on the other hand besides having high sensitivity for small defect measurement for rapid scan examination [3,4]. Additionally ECT can also be run without the need for contact between the surface of the metal material and the probe used and thus makes this technique suitable for monitoring disability issues[5].

A small change of the magnetic properties of the compositional material of steel or iron will to some extent will affect the eddy current testing. Therefore, low carbon steel substrates are widely used in this test by using a standard calibration and a set of standards used for the measurement of various different materials such as brackets or bolts, screws and washers [6].
Instrument calibration is an important step in eddy current inspection. The data collected from the inspection has to be calibrated for accurate defect analysis. Calibration acts as a form of compensation for variable instrument settings and probe variations[7], thus providing for a simpler comparison between measurements taken at different intervals. The process of calibration also provides for the development of simple calibration curves that map signal characteristics (such as phase angle or amplitude to flaw depth).

The physical properties of materials can be identified by using ECT in which it will identify the state of the material comprising the inner surface defects and subsurface defects, and the diversity of its thickness. Apart from that the conductivity and magnetic permeability properties can also be measured using ECT[8,9].

In this paper, test sample block of copper was produced with the depths of standard slot are 0.5mm, 1.0mm and 2.0 mm. Eddy current testing was performed within a frequency range of approximately 50Hz to 10MHz although most applications were performed well within the extremes of that range. Different gain parameters were tested in order to identify the best gain for copper ECT effect inspection.

2. Related Work

2.1. A Reference Standards
For each ECT test to be conducted, the calibration needs to be done using a reference standard (calibration block) and it was very important to obtain accurate values and readings from the instruments and probes used. It consists of a display of x and y (horizontal and vertical line) on the display screen where the clear observation that needs to be done to see changes in a signal testing. In the process of detecting defects, the standards reference consisting of materials, measurements and shapes similar to test equipment with the various types of artificial defects including drill holes, saw blades or milled walls to identify and simulate flaws[10].

To carry out the experimental process of thickness measurement, several samples as a reference standard were tested by knowing the actual thickness of the sample. The result of the signal obtained on the standard reference sample will be recorded and the recorded signal will be compared according to the thickness of the metal for the categorization process. To ensure that the inspection procedure during eddy is correct the appropriate reference standard is essential for proper calibration.

The same type of specimen material is essential during the standard calibration process. Multiple-dimensional defects including depth, width and length are used in measurement standards. It is important before the actual specimen is tested. This calibration method consists of scaling and rotating one or more to indicate the signal condition obtained. The application of the reference signal obtained on the calibration standard will be converted in the form of data and collected to compare the signal to the examination of the specimen tested [2]. Figure 1 depicts the rotation of a signal[11].

![Figure 1 Rotation in Calibration](image)

The rotation and scaling parameters are computed as follows. If $\phi_1$ is the angle of the signal and it has to be rotated to an angle $\phi_2$, then the rotation angle $\theta$ is given by:
\[ \theta = \varphi_2 - \varphi_1 \] 

(1)

The scale factor is determined as:

\[ S = \frac{r_1}{r_2} \] 

(2)

Where

- \( S \) = scale factor
- \( r_1 \) = desired peak to peak scaling of the signal
- \( r_2 \) = original peak to peak value of the signal Eddy

2.2. Eddy Current Inspection Process

Eddy current inspection methods should follow these basic steps, namely:

- Selection of appropriate instruments and probes
- The selected frequency level according to the desired signal penetration depth
- Calibration standard according to the suitability of the instrument to obtain the response signal
- The surface of the probe should be placed on an empty plate surface without defects
- The movement pattern of the probe should be in the same direction over the area being inspected
- The probe orientation must be constant to avoid misinterpretation of the defect signal
- The resulting signal should be monitored to identify impedance changes resulting from defects on the plate surface.

Eddy Current Testing Applications

Eddy current capability is used for various tests because it's widely used in industry. This can be seen based on the usual inspections made using ECT, namely:

- Welding inspection - ECT is used to scan for cracks on the surface of the test material for hot and covered areas by welding.
- Conduction test - Conductivity measurement can be made using Eddy current to identify alloy and non-ferrous iron to confirm heat treatment.
- Surface inspection - External cracks for metal stocks and machine parts can be detected using ECT. It is very important for critical parts including around the fasteners in the aircraft.
- Corrosion detection - Corrosion on metal parts can be measured using ECT. In addition, sensitive signals from ECT can be used for thin metals including aircraft skins that use aluminum. By using a low frequency, it will help in detecting corrosion on the inner metal layer which is layered in two layers where it cannot be achieved by ultrasonic examination.
- Bolt hole inspection - Cracks in the bolt hole can be identified by using a bolt hole probe with an automatic rotary scanner.
- Tube inspection - This inspection consists of tube field inspection such as heat exchanger and tube alignment inspection at the manufacturing stage for cracking and sample thickness.

3. Material and Method

3.1. Material

The design of the copper sample block is similar with the existing sample block for other material. The design specification for the copper sample test block is shown in Figure 2.
Figure 2. Design for the copper sample test block

The first step in producing standard sample blocks is the grinding surface. The grinding surface will produce a smooth finish on a flat surface. It uses a rough machining process in which a rotating wheel covered in a coarse particle (grinding wheel) of a metal or non-metallic material chip wound from a work-piece produces a flat and smooth face. There are three types of surface grinders such as Horizontal-spindle, Peripheral grinding and wheel-face grinding. However, this project only used the Horizontal-spindle (peripheral) grinder of the surface type, where the edge (flat edge) of the wheel is in contact with the work-piece, producing the surface. This is the important procedure to produce a smooth surface of the copper block as to perform the eddy current testing. Figure 3 shows the copper block surface before and after the surface grinding process.

Figure 3. Copper block; a) before surface grinding b) after surface grinding

The third step produces a standard sample block of manufacturing. the manufacturing process uses a rotary cutter to remove material from the work-piece advancing (or feeding) in that direction at an angle with the axis of the tool. It covers a variety of different operations and machines, on a scale from small individual parts to large, heavy-duty manufacturing operations. It is one of the most commonly used processes in the industry and machine shops today for machining parts for a variety of precise sizes and shapes.

The cut wire is the last step to produce a sample. This machine reduced the slot depth in 0.5 mm, 1.0 mm and 2.0 mm. Wire machined electric discharge (WEDM), is also known as wire-cut EDM and cutting wire it is a thin metal strand wire, usually copper, fed through the work piece, submerged in a dielectric liquid tank, the water is usually deionized.
3.2. Methods
The steps involved in this study are summarized in Figure 4.

![Figure 4. Process of fabricate sample block](image)

The design of the sample block is performed using auto-CAD. Figure 5 shows two different block dimensions.

![Figure 5. Different of thickness; a)125mm x 25mm x 8mm b)125mm x 25mm x 16 mm](image)

The first selected dimension for the sample block was used on the calculated frequency is higher than the eddy current set. The process of surface grinding is necessary to produce the smooth sample block. The copper was grinded about 200 mm, thus it did not affect the copper. After the grinding process, the copper block was cut into two pieces. The copper block is cut to two different thicknesses; the first dimension is 125mm x 25mm x 8mm and the second is 125mm x 25mm x 16mm. The dimensions are selected for the best frequency when using weld probe. The copper block was cut using a band sewing machine. Figure 6 shows the process of copper cutting.
3.3. Conductivity Measurement For Copper Block

In order to perform the conductivity testing, the conductivity probe was connected to eddy current flaw detector. The mode was automatically changed to conductivity. Figure 7 shows the configuration of eddy current flaw detector for conductivity testing and Table 1 show the configuration setting for the copper sample block.

Table 1. Configuration setting ECT instrument for Copper measurement

| CAL 1       | CAL 2       |
|-------------|-------------|
| 60.6 % IACS | 8.45% IACS  |

The average calculation of the electrical conductivity for copper block was measured using (3).

\[
\text{Electrical conductivity} = \frac{\sum A + B + C + D}{4}
\]  

(3)
The standard depth of penetration has been defined as the depth at which the Eddy current density is about 37% of the surface density. In order to find the frequency of the copper block ($\delta$), the standard depth of penetration must be 37% of the copper block thickness. The step of the finding the copper block frequency is summarized in Figure 8.

The thickness of the copper block are 8mm and 16 mm ($\pi$) is 3.14, (f) is test frequency (Hz) for two different thickness 16mm and 8mm,$(\mu)$ is magnetic permeability (1.25664 x 10$^{-9}$H/mm), the electrical conductivity based on International Annealed Copper Standard (% IACS) $(\sigma)$ is calculated from the average in Table 2.

### Table 2. Conductivity of Copper block

| Thickness Side | Conductivity IACS% 8 mm | Conductivity IACS% 16 mm | Conductivity Ms/m 8 mm | Conductivity Ms/m 16 mm |
|----------------|-------------------------|--------------------------|------------------------|-------------------------|
| A              | 102.67                  | 101.64                   | 58.83                  | 58.92                   |
| B              | 102.58                  | 101.69                   | 59.10                  | 59.01                   |
| C              | 102.52                  | 101.54                   | 58.98                  | 59.08                   |
| D              | 102.44                  | 101.60                   | 59.99                  | 58.95                   |
| Average        | 102.55                  | 101.61                   | 59.22                  | 58.99                   |

Formula to calculate of copper block frequency is given in (4).

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$ (4)
4. Result and Discussion
The measurements for the sample block were performed on the 8mm and 16mm thickness sample block. The positive scanning and negative scanning were inspected for all slots at different gain to find the most suitable gain for each slot. The sample block has three slots with depth of 0.5mm, 1.0mm and 2.0mm. Each slot will be measured three times to find the best accuracy.

Frequency of 280 kHz was used for 8mm sample block according to the Table 3. Three different slots were measured with each slot measured three times to get the best accuracy. Three experiments supposed to produce the same reading. However, due to human error the readings were fluctuating each time the experiment was performed as in Table 3.

| Slots | Experiment | Phase | Signal Amplitude |
|-------|------------|-------|------------------|
| 0.5 mm | 1          | 110.2° | >93.7%           |
|       | 2          | 110.9° | >92%             |
|       | 3          | 111.0° | >97.5%           |
|       | 1          | 112.2° | >100%            |
| 1.0 mm | 2          | 110.9° | >100%            |
|       | 3          | 109.8° | >100%            |
|       | 1          | 110.2° | >100%            |
| 2.0 mm | 2          | 109.8° | >100%            |
|       | 3          | 109.8° | >100%            |

Figure 9 shows the signal amplitude of 8mm sample block based on gain 63.3 dB tests for three different slots. Based on Table 4 and Figure 9 the different of signal amplitude can be seen. The most suitable slots to be used with 63.3 dB is 0.5mm. It is because the signal amplitude of slot 0.5mm is 97.5%. Meanwhile, the FSH reading compared to slots 1.0mm and 2.0mm exceed 100% FSH.

![Figure 9. Signal amplitude of positive scanning for 63.3 dB; a) 0.5mm b) 1.0mm c) 2.0mm](image_url)
Table 4 shows reading for the negative scanning with the same gain used in positive scanning.

**Table 4. Negative test scanning using 63.3dB gain**

| Slots | Experiment | Phase | Signal Amplitude |
|-------|------------|-------|-----------------|
| 0.5 mm| 1          | 110.2° | 55%             |
|       | 2          | 110.9° | 52.50%          |
|       | 3          | 111.0° | 55%             |
|       | 1          | 112.2° | 97.50%          |
| 1.0 mm| 2          | 110.9° | 90%             |
|       | 3          | 109.8° | 97.50%          |
|       | 1          | 110.2° | >100%           |
| 2.0 mm| 2          | 109.8° | >100%           |
|       | 3          | 109.8° | >100%           |

Figure 10 shows the signal amplitude of 8mm sample block in negative scanning based on gain 63.3 dB tests for three different slots. Based on Table 5 and Figure 10 the different of signal amplitude can be clearly seen. The negative scanning thus, the same slot (0.5mm) was confirmed as the best slot to be used with chosen gain.

Table 5 summarizes the eddy current testing reading measured for three slots in sample block with 58.6 dB gain. The same frequency was maintained as the same thickness of sample block measured.

**Figure10. Signal amplitude of negative scanning for 63.3 dB; a) 0.5mm b) 1 0mm c) 2.0mm**

Table 5. Positive test scanning using 58.6 dB gain

| Slots | Experiment | Phase | Signal Amplitude |
|-------|------------|-------|-----------------|
| 0.5 mm| 1          | 110.2° | >92.5%          |
|       | 2          | 110.9° | >91.4%          |
|       | 3          | 111.0° | >95%            |
|       | 1          | 112.2° | >100%           |
| 1.0 mm| 2          | 110.9° | >100%           |
|       | 3          | 109.8° | >100%           |
|       | 1          | 110.2° | >100%           |
| 2.0 mm| 2          | 109.8° | >100%           |
|       | 3          | 109.8° | >100%           |
Figure 11 shows the signal amplitude of 8mm sample block based on gain 58.6 dB test for three different slots. Based on TABLE.V and Fig.11 the different of signal amplitude can be seen. The most suitable slots to be used with 58.6 dB is 1.0mm. It is because the signal amplitude of slot 1.0mm is 97.5%. Meanwhile, the FSH reading compared to slots 0.5mm was not achieved the highest FSH and the signal amplitude for 2.0mm exceeded 100% FSH.

**Figure 11.** Signal amplitude of positive scanning for 58.6 dB a) 0.5mm b) 1.0mm c) 2.0mm

The same procedures were applied to measure the 16mm thickness copper sample block. Table 6 shows summary of the Eddy current testing reading taken for three slots in the sample block. The frequency applied was different as the thickness of the block is different. From the calculation in (4), Frequency of 71 kHz was used for 16mm thickness sample block.

Table 6 shows the summary of the suitable frequency and gain to be used with copper sample block for two different thicknesses.

| Thickness Slots(mm) | 8 mm (Gain) | 2.0 (Gain) | 16 mm (Frequency) | 2.0 (Gain) |
|----------------------|-------------|------------|-------------------|------------|
| Frequency (kHz)      | 280         | 71         | Gain (dB)         | 64.3       |
| 0.5                  | 63.3        | 58.6       | 53.7              | 59.7       |
| 1.0                  |             |            | 69.5              |            |
| 2.0                  |             |            |                   |            |

5. Conclusion
In this paper the copper calibration block has been designed and fabricated. These calibration blocks were meant to be used when testing defect on copper material. Two different thicknesses were produces which are 8mm and 16mm thickness. The appropriate frequency and gains best used with the block were identified and recorded. The results proved that the depth of slots is inversely proportional with the gain used. The dB gain gave the high impact on the signal amplitude. From here 63.3dB gain shows the good result especially on the defect slot 0.5mm and 1.0mm in the negative test scanning. When the width slots are increased then the signal amplitude achieve to 100%. An average of 0.5mm slot shows the 53.75% signal amplitude and 1.0mm slot is 93.75%. It shows the increasing of signal amplitude until 40%. The positive test scanning gave 100% signal amplitude start on 1.0mm slot and above. By comparing on positive and negative scanning the negative scanning shows the good result on amplitude signal because of diversity of signal amplitude based on different slot of defect.

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