Analysis of Eddy Current Testing Detection Ability to the Varied Longitudinal Cracks on Coated Weld Metal Tee Joint of 5083 Aluminum Ship Structure

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Abstract. Due to its service, cracks sometimes occur on the coated 5083 aluminum weld metal. One method for finding crack under protective coating is by using eddy current testing (ECT). This method of nondestructive testing relies on a circular electrical path generated by the coils positioned just above the surface being examined. The purpose of this research is to analyze the sensitivity of ECT by using variety of crack dimensions on 5083 aluminum welded plate tee joint. Five test pieces, each 200 mm x 50 mm x 10 mm were used and each sample contain four cracks. Artificial cracks are fabricated using electrical discharge machining (EDM) with length and depth variations. Variations in crack length are 5.0 mm, 7.0 mm, 9.0 mm, and 15.0 mm, and variation in depth are 0.5 mm, 1.0 mm, 1.5 mm, 2.0 mm and 2.5 mm. Results obtained by the analysing height and average length of the crack signal indication are as follows: for 0.5 mm crack depth, the height of the crack signal is 5 mm; 1.0 mm depth is 11.75 mm; 1.5 mm depth is 19.75 mm; 2.0 mm depth is 26.5 mm and 2.5 mm depth is 31.25 mm. The degree of accuracy obtained for the detection of crack depth is 93.57%. For the detection of crack length, it is found that the measured average length of artificial cracks is 5 mm actual crack length has measured crack length value of 6.32 mm; 7 mm actual crack length has measured crack length value of 7.18 mm; 9 mm actual crack length has measured crack length value of 7.18 mm; 9 mm actual crack length has measured crack length value of 8.8 mm and 15 mm actual crack length has measured crack length of 14.48 mm. The degree of accuracy obtained for crack length detection is 91.31%.

1. Introduction
Material deterioration may occur when welding is not conducted properly. Continuous loading on a welded joint may also result in accelerated crack initiation along the weld metal. Crack initiation and propagation can occur most evenly on a coated weld metal that cannot be observed visually during inspection of such joints. Due to the reasons, a particular nondestructive testing (NDT) method that can penetrate through the coating layer is quite necessary.

One of the NDT method that is commonly applied to check crack propagation under the coating is eddy current testing (ECT). ECT that has high accuracy to detect open surface crack, even under a coated weld metal is generally applied on ferromagnetic and non-ferromagnetic material as long as the material under inspection is electrically conductive. Based on such problem, it is necessary to analyze the detectability of ECT against length and depth variations of cracks on welded tee joints of 5083 aluminum alloy. This research investigates the effect of length and depth of longitudinal surface cracks to the sensitivity level of detection using ECT on a welded tee joint coated with a nonconductive coating.
2. Study of Literatures

2.1. Eddy Current Testing.
Eddy current testing is a nondestructive testing method that lies on the interaction between a magnetic field and a crack on the tested material. By using eddy current testing, surface cracks on any electrically conductive materials, both ferromagnetic and non-ferromagnetic can be detected [1].

2.2. Eddy Current Principles.
Eddy current principle is based on an electromagnetic induction phenomenon. If an alternating current is flowed through the probe coil of eddy current, then a magnetic field will result. If the probe is brought to the proximity of an electrically conductive material, an eddy (circular) current is generated at the material with the largest intensity at the surface. When the probe is shifted through a crack, a change of the eddy current path causes a change in the probe impedance that is shown as a change in amplitude and phase angle on the monitor screen. The height of the amplitude and phase angle of the resultant indication indicate the depth of the crack [2]. Eddy current surface probe works well using alternating current (50 Hz to 5 MHz, 100 mA) that creates primary magnetic field. When an electrically conductive material is brought close to the coil, eddy current is induced at the material in accordance with Faraday’s law [3].

2.3. Important Factors in Eddy Current Testing.
Several important factors during eddy current testing are as follow:

2.3.1. Electrical conductivity. The ability of a material to transfer electric current is an important factor in eddy current testing. More conductive the material in conveying the electricity, the greater the eddy current created on its surface [4].

2.3.2. Magnetic Permeability. Permeability is a measurement of the ease with which a magnetic flux is established in a ferromagnetic material. Non-magnetic material such as aluminum has relative permeability of 1 [4].

2.3.3. Lift-off. When a surface coil is energized and held in air above a conductor the impedance of the coil has a certain value. As the coil is moved closer to the conductor the initial value will change when the field of the coil begins to intercept the conductor. Once the coil is on the conductor any small variation in the separation of coil and conductor will change the impedance of the coil [5].

2.4. Standard Depth of Penetration.
The standard depth of penetration is defined as the depth at which the eddy current density is about 37% of the density at the surface. A depth of penetration formula using resistivity, frequency, and permeability can be expressed as shown below.

\[ \delta = K \frac{\rho}{f\mu_{rel}} \]  

(2.1)

Where:
- \(\delta\) = Standard depth of penetration
- \(K\) = 50 (for millimeter) or 1.98 (for inch)
- \(\rho\) = Resistivity (in micro-ohm-centimeter)
- \(f\) = Frequence (in hertz)
- \(\mu_{rel}\) = 1 (for non-ferromagnetic materials)
\[ 1 \times SDP = \frac{I}{e} = 37\% \quad (2.2) \]

\[ 3 \times SDP = \frac{I}{e^3} = 5\% = EDP \quad (2.3) \]

Knowledge of “standard” and “effective” depths of penetration (SDP and EDP) shows how eddy currents are distributed in the material and how strong they are in the area of interest.

2.5. Aluminum.
Aluminum is the most available non-ferrous metal in earth. Aluminum is available in nature as stable oxide, that cannot be reduced as for other metals reduction process. Electrolysis is the only process to reduce aluminum oxides. This research uses aluminum 5083, an alloy with 4.5% Mg which is strong, easily welded, and has excellent performance in corrosive environment [6].

2.6. Gas Metal Arc Welding (GMAW).
GMAW (Gas Metal Arc Welding) uses the heat of an electric arc between a continuous bare wire filler metal electrode and the work. Shielding is obtained entirely from externally supplied inert gas such as argon or helium, an active gas such as CO\(_2\), or some combination thereof [7].

3. Research Methodology

3.1. Test Coupons Preparation.
Five tee joint plates of 200 mm x 50 mm x 10 mm each are prepared and welded using GMAW process.

3.2. Artificial Crack.
Artificial cracks are manufactured using electric discharge machine with variation in depth and length. Figures below show the size of the artificial cracks.

Figure 3.1. Crack positions on test piece no. 1.

Figure 3.2. Crack positions on test piece no. 2.
3.3. Application of Nonconductive Coating.
Nonconductive coating of 200 microns thick is applied on each welded joint surface. The thickness of the coating can be measured using dry film thickness (DFT) gauge.

3.4. Eddy Current Testing Apparatus.
Testing apparatus shall be prepared prior to testing:

3.4.1. Calibration Block. A calibration block, made of the same material as the material being tested shall be prepared. This block contains some artificial cracks with known depth in order to calibrate the testing machine prior to be used.
3.4.2. *Eddy Current Surface Probe*. An Ether NDE surface probe, right angle type, single and absolute coil configuration with 30 kHz frequency is used for the testing.

3.4.3. *Eddy Current Testing Machine*. A Nortec 600D eddy current machine is used for the testing.

3.5. *Testing Steps*.

Testing of the welded joints is conducted using following steps:

3.5.1. *Preparation of Test Sample and Calibration Block*. Calibration of the machine and testing of the test sample shall be conducted on a nonconductive pad in order to eliminate the effect of any conductive material to the eddy current testing on the test samples.

3.5.2. *Calibration of the Machine*. Prior to testing, the eddy current machine shall be calibrated using the aluminum calibration block. Calibration verification shall be conducted prior to and after testing of each test sample to ensure that the setting of the machine is still stable.

3.5.3. *Testing of the Sample*. Scanning of the test sample is carried out on the area of weld metal that contain artificial cracks. Before scanning, the machine shall be nulled, that is the process of equalize the impedance between the probe and the machine. During nulling, the probe shall be positioned on the weld metal, away from the crack locations.

3.5.4. *Scanning*. During scanning of the probe, the resultant crack indications that appears on the machine’s screen shall be monitored and recorded. Scanning shall be carried out on all of the artificial cracks on all test samples. All the indications shall be recorded and analysed.

4. *Analysis*

4.1. *Calibration of Eddy Current Machine*.

Calibration results of the machine against the aluminum test block is shown on Figure 4.1 and Table 4.1.

![Figure 4.1. Signals obtained from artificial cracks on calibration block.](image-url)
Table 4.1. Height of Calibration Signals.

| Crack Depth (mm) | Signal Height (mm) |
|------------------|--------------------|
| 0.5              | 4.0                |
| 1.0              | 12.0               |
| 1.5              | 19.0               |
| 2.0              | 25.0               |
| 2.5              | 29.0               |

4.2. Scanning of Crack Depth.
Scanning is carried out on all of the artificial defects located on all of the weld metal surface of the test samples. Based on the depth of the crack, height of signal indications is obtained as follow:

4.2.1. Scanning of Crack Depth on Test Piece No. 1.

Figure 4.2. Crack depth signals height on test piece no. 1.

4.2.2. Scanning of Crack Depth on Test Piece No. 2.

Figure 4.3. Crack depth signals height on test piece no. 2.
4.2.3. Scanning of Crack Depth on Test Piece No. 3.

Figure 4.4. Crack depth signals height on test piece no. 3.

4.2.4. Scanning of Crack Depth on Test Piece No. 4.

Figure 4.5. Crack depth signals height on test piece no. 4.

4.2.5. Scanning of Crack Depth on Test Piece No. 5.

Figure 4.6. Crack depth signals height on test piece no. 5.
Based on the figures above, the height of each signal can be determined and tabulated in Table 4.2 as follow.

| Test Piece # | Crack Code | Signal Height (mm) |
|--------------|------------|--------------------|
| Test Piece 1 | A1         | 4.0                |
|              | A2         | 5.0                |
|              | A3         | 5.0                |
|              | A4         | 4.0                |
| Test Piece 2 | B1         | 10.0               |
|              | B2         | 10.0               |
|              | B3         | 13.0               |
|              | B4         | 14.0               |
| Test Piece 3 | C1         | 19.0               |
|              | C2         | 20.0               |
|              | C3         | 20.0               |
|              | C4         | 20.0               |
| Test Piece 4 | D1         | 27.0               |
|              | D2         | 25.0               |
|              | D3         | 28.0               |
|              | D4         | 26.0               |
| Test Piece 5 | E1         | 32.0               |
|              | E2         | 32.0               |
|              | E3         | 31.0               |
|              | E4         | 30.0               |

4.3. Scanning of Crack Length.
Crack length is determined by moving the probe along the longitudinal direction of a crack and by noting change of the crack signal indication’s height on the machine’s screen. Crack ends can be determined when the highest indication of the crack drops 6 dB, or a half.

4.3.1. Scanning of Crack Length on Test Piece No. 1.

Table 4.3. Measured crack length on test piece no. 1.

| Crack Code | Actual Length (mm) | Measured Length (mm) |
|------------|--------------------|----------------------|
| A1         | 5.0                | 6.04                 |
| A2         | 7.0                | 6.90                 |
| A3         | 9.0                | 9.60                 |
| A4         | 15.0               | 15.12                |

4.3.2. Scanning of Crack Length on Test Piece No. 2.

Table 4.4. Measured crack length on test piece no. 2.

| Crack Code | Actual Length (mm) | Measured Length (mm) |
|------------|--------------------|----------------------|
| B1         | 5.0                | 6.47                 |
| B2         | 7.0                | 7.32                 |
| B3         | 9.0                | 8.85                 |
| B4         | 15.0               | 14.50                |
4.3.3. Scanning of Crack Length on Test Piece No. 3.

Table 4.5. Measured crack length on test piece no. 3.

| Crack Code | Actual Length (mm) | Measured Length (mm) |
|------------|--------------------|----------------------|
| C1         | 5.0                | 6.16                 |
| C2         | 7.0                | 7.41                 |
| C3         | 9.0                | 8.40                 |
| C4         | 15.0               | 16.03                |

4.3.4. Scanning of Crack Length on Test Piece No. 4.

Table 4.6. Measured crack length on test piece no. 4.

| Crack Code | Actual Length (mm) | Measured Length (mm) |
|------------|--------------------|----------------------|
| D1         | 5.0                | 7.18                 |
| D2         | 7.0                | 6.63                 |
| D3         | 9.0                | 9.49                 |
| D4         | 15.0               | 13.64                |

4.3.5. Scanning of Crack Length on Test Piece No. 5.

Table 4.7. Measured crack length on test piece no. 5.

| Crack Code | Actual Length (mm) | Measured Length (mm) |
|------------|--------------------|----------------------|
| E1         | 5.0                | 5.77                 |
| E2         | 7.0                | 7.66                 |
| E3         | 9.0                | 7.87                 |
| E4         | 15.0               | 13.13                |

4.4. Sensitivity Values of the Eddy Current Testing

Sensitivity values is determined by calculating the ratio of the number of cracks located on each test piece against the number of cracks that can be detected by the testing system.

Table 4.8. Sensitivity values of the eddy current system.

| Test Piece #   | No. of Actual Crack | No. of Crack Detected |
|---------------|---------------------|-----------------------|
| Test Piece 1  | 4                   | 4                     |
| Test Piece 2  | 4                   | 4                     |
| Test Piece 3  | 4                   | 4                     |
| Test Piece 4  | 4                   | 4                     |
| Test Piece 5  | 4                   | 4                     |
| Total         | 20                  | 20                    |

Based on the above table, the eddy current testing system can detect all the artificial crack located on all the test piece. Then it can be said that the sensitivity of the testing system is 100%.

4.5. Ratio of Signal Height against the Depth of the Artificial Cracks

In accordance with the testing that is already conducted to all of the test piece, analysis is then conducted to obtain the effect of the artificial crack depth variation to the height of signal indications. Table 4.9 indicates the average height of signal indications against crack depth.
Table 4.9. Average height of signal indication against crack depth.

| Crack Depth (mm) | Average Height of Crack Indications (mm) |
|------------------|-----------------------------------------|
| 0.5              | 5.00                                    |
| 1.0              | 11.75                                   |
| 1.5              | 19.75                                   |
| 2.0              | 26.50                                   |
| 2.5              | 31.25                                   |

Figure 4.7. Average height of crack indications.

Figure 4.7 can be used to predict any crack depth when the height of any signal indication in screen monitor is known. Prediction of crack depth can be done using polynomial interpolation as follow:

\[ y = (9.846 \times 10^{-7})x^4 + 0.000010959 x^3 - 0.00211293 x^2 + 0.104345x + 0.029111 \]  \hspace{1cm} (4.1)

where:
- \( y \) = Crack depth to be calculated (mm)
- \( x \) = Height of signal indication (mm)

4.6. Ratio of Actual Crack against Artificial Crack Length.

Based on the scanning results to the crack length located on all test pieces, analysis is then conducted to obtain the effect of the artificial crack length against the average measured crack length.

Table 4.10. Average measured crack length against actual crack length.

| Actual Crack Length (mm) | Average Measured Crack Length (mm) |
|--------------------------|-----------------------------------|
| 5.0                      | 6.32                              |
| 7.0                      | 7.18                              |
| 9.0                      | 8.80                              |
| 15.0                     | 14.48                             |
4.7. Discussion.
For the purpose to obtain standard and effective depth of penetrations a calculation is carried out using formula of SDP and EDP as follow.

\[
\delta = K \frac{\rho}{f \mu_{ret}} = 50 \sqrt{\frac{5.95}{30000 \times 1}} = 0.704 \text{ mm}
\]

\[
EDP = 3 \times SDP = 3 \times 0.704 = 2.112 \text{ mm}
\]

The standard depth of penetration is 0.704 mm and the effective depth of penetration is 2.112 mm in Aluminum alloy 5083 using 30 kHz eddy current surface probe. Eddy current testing, based on the testing results, has good accuracy and detectability on each artificial crack manufactured on each test piece. The following calculations is carried out to determine the percentage of accuracy of the crack depth and length.

4.7.1. Crack Depth. The following table shows the accuracy of detection against crack depth carried out by the eddy current system.

| Test Piece # | Crack Depth (mm) | Percentage of Accuracy (%) | Average Accuracy (%) |
|--------------|------------------|-----------------------------|----------------------|
| Test Piece 1 | 0.5              | 87.5%                       | 93.57%               |
| Test Piece 2 | 1.0              | 98.0%                       |                      |
| Test Piece 3 | 1.5              | 96.1%                       |                      |
| Test Piece 4 | 2                | 94.0%                       |                      |
| Test Piece 5 | 2.5              | 92.3%                       |                      |

4.7.2. Crack Length. Table 4.12 shows the accuracy of detection against crack length.

| Actual Crack Length (mm) | Measured Crack Length (mm) | Percentage of Accuracy (%) | Average Accuracy (%) |
|--------------------------|-----------------------------|-----------------------------|----------------------|
| 5.0                      | 6.324                       | 73.52%                      | 91.31%               |
| 7.0                      | 7.184                       | 97.37%                      |                      |
| 9.0                      | 8.802                       | 97.80%                      |                      |
| 15.0                     | 14.484                      | 96.56%                      |                      |

5. Conclusions

5.1. The eddy current testing system has 100% sensitivity for the artificial crack detection on Aluminum 5083 weld joint since the method can detect all the cracks on all the test pieces.

5.2. Standard Depth of Penetration (SDP) and Effective Depth of Penetration (EDP) of Aluminum 5083 are 0.704 mm and 2.112 mm respectively when tested using a 30 kHz eddy current surface probe.

5.3. The deeper the crack, the higher the signal indications.

5.4. Percentage of accuracy in detecting crack depth on tee joint of Aluminum 5083 welded plate coated with 200 microns is 93.57% while the percentage of accuracy for crack length detection is 91.31%.

5.5. Crack ends is determined by noting change when the highest crack signal indications drop to 50%.
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