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Subsurface Defects Evaluation using Eddy Current Testing

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Abstract

Background/Objectives: Eddy current testing is one of the most widely Non Destructive Evaluation (NDE) methods which utilized in the industry especially in oil and gas, aircraft, nuclear and coating industries. Experimental studies of eddy current testing have emerged as an important approach alongside numerical. This paper is to design, fabricate and investigate the maximum eddy current testing that can detect subsurface defect in the carbon steel S45C block. **Methods/Statistical Analysis:** The material of the artificial defect block is carbon steel (S45C) with dimension of 180mm (length) × 25mm (width) × 60mm (height). There are eight artificial defects which located 20mm parallel to the length of the block with 0.5mm diameter. The distance defect is located in between 0.5mm to 4.00mm from the surface of the artificial defect block. Weld probe with diameter size of 16mm and 9mm are used to perform the inspection. **Findings:** Experiments showed that the weld probe with diameter 16mm able to detect subsurface defect up to 4.0mm and 2.0mm for 9mm diameter weld probe. The optimum of eddy current testing frequency for carbon steel S45C is depending on the defect distance from the material surface. **Applications/Improvements:** The results prove that the maximum depth of the subsurface can be measured by using eddy current testing method, which is depending on the frequency of the exciting coil weld probe.

Keywords: Artificial Defect Block, Carbon Steel S45C, Eddy Current Testing, Gain,Nondestructive Testing, Optimum Frequency

1. Introduction

Eddy current inspection is a non-destructive technique that is widely utilized for conductive materials in the oil and gas industry. The main advantages of eddy current testing are due to its multifunction apart from defect inspection[1]. Eddy current inspection methods sensitive to minute cracks on the surface or subsurface, where intricate geometries can be inspected with minimum preparation. It is additionally subsidiary to quantify conductivity and coating thickness[2]. The instrument is portable and facile to conduct, providing immediate feedback and non-contact methods.

There are mainly two types of eddy current probes namely impedance variation probe and transmit-receive probe[3]. Impedance variation probe uses the same coil as transmitter and receiver. The secondary magnetic field which created by eddy currents oppose the primary magnetic field and changes the impedance of the coil. The impedance variation is monitored and measured by instrumentation. Transmit-receive probe use separate transmit and receive coils. Transmit coil induce eddy currents within the specimen and the receiver coil receive the induce voltage. Whereas, the variation of voltage induced in the receiver is used to characterize the defect profile in the specimen[4].

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There are many types of materials can be inspect by using eddy current testing such as 7075-T6 aluminium, AISI 4340 steel, type 304 stainless steel, 6A1-4V titanium, inconel 600, inconel 625, inconel 690 and others ferromagnetic material[5,18]. This paper describes the investigation of maximum subsurface depth that can be detected by using eddy current testing on carbon steel S45C material block. The optimum frequency of subsurface carbon steel S45C calibration block is identified. Coil excitation frequency setting for eddy current testing is in the range of 50Hz to 10MHz. The depth of eddy current magnetic field penetration decreases with incrementingofeddy current probe coil excitation frequency, magnetic permeability and electrical conductivity material.

1.1 Fundamental Theory of Eddy Current Testing

Eddy current testing methods are derived by utilizing the principle electromagnetic. Eddy current is circular electric current induced within the conductor by a changing of magnetic field in the conductor. This phenomenon explains by Faraday in its electromagnetic revelation. When a coil is applied with time varying current that brought proximate to ferromagnetic material, secondary current engendered in the ferromagnetic material[1,6]. The eddy current flows parallel to the coil winding in the specimen, but opposite in direction to that of current applied to the coil. The magnetic field in specimen associated with the eddy current which opposes the primary magnetic field. The presence of defects in the specimen block disrupts the flow of eddy current, reduce the efficacious resistance and reactance of the specimen[4]. Monitoring the voltage induced in the coil and keeping the current constant, the impedance change can be recorded to locate defects in a conducting specimen such as metallic pipes and structural frames. From the amplitude and phase variations of coil impedance, the defect can be characterized[7,8]. Note that the defect must crossover with eddy current line to be detected, and defect lying parallel to the eddy current line will not cause any transmutations in a secondary magnetic field which engender by eddy current that may not be detected[9]. The basic principle of eddy current testing method is shown in Figure 1.

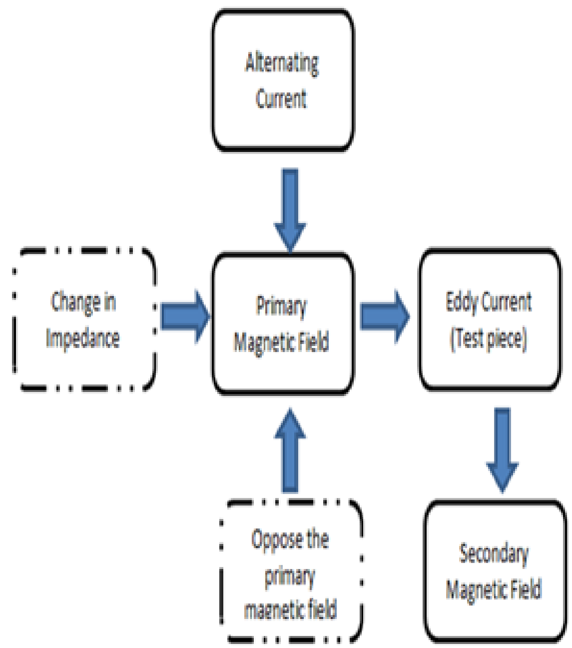

Figure 1. Diagram principle of eddy current testing method.

1.2 Penetration Depth

The density of induced eddy current decreases exponentially from the surface with depth into the specimen. The standard depth penetration for eddy current testing is the depth from the specimen surface, where the eddy current strength has dropped to 37% of its initial value at the specimen surface[10]. It depends on the testing frequency, as well as test specimen properties such as electrical conductivity and permeability[11]. The penetration depth is defined as:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{1}$$

where σ is the conductivity of a conductor under test, μ is the permeability of conductor and f is the excitation frequency. The magnitude of induced eddy currents decreases exponentially in the conductive material. Hence, the amplitude of fields in the conductor at depths along x-axis is expressed as:

$$J(x) = J_s X e^{-x/\delta} \tag{2}$$

The standard skin depth of penetration is defined as the depth where the eddy current density is about 36.8% of its surface value. Since greater penetration depth of eddy currents is needed to inspect embedded flaws, the selection of excitation frequency is critical[12]. Detecting a deeper flaw requires lower excitation frequency. Figure 2 presents how the skin depth affects the distribution of eddy current densities inside a copper plate at high and low frequencies.

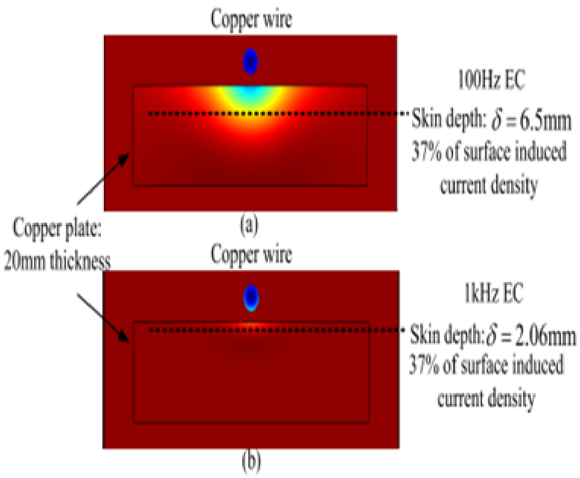

Figure 2. Skin depth effect in eddy current testing for copper. (**a**) 100Hz exciting coil frequency. (**b**) 1kHz exciting coil frequency.

1.3 Reference Standards

Test calibration or standardization is the process ofadjusting the instrument display to represent a known reference standard, so the test can be compared between the test material and the reference standard. The validity of the test depend on the validity of the reference standard[13,19]. Moreover, the test system should be checked at regular intervals against the reference standard to ensure it operates properly and set up correctly for the test that is being performed.

The calibration operation requires use of a calibration standard, which is made of the same material as the test specimen[14]. Various defects with dimensions are introduced into the calibration standard, and the calibration standard is inspected prior to the test specimen. The calibration operation then generally consists of rotating and scaling of one or more reference flaws on the calibration standard[15]. The parameters which obtained by the rotation and scaling of the reference signals on the calibration standard are then applied to the data collected from inspection of the test specimen. Figure 3 depicts the rotation of a signal.

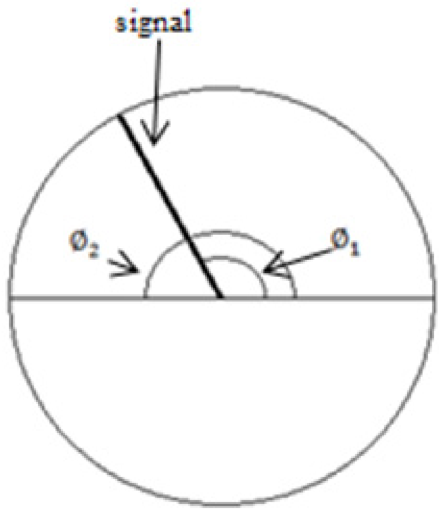

Figure 3. Signal rotation in process calibration.

The rotation and scaling parameters are computed as follows. If is the angle of the signal and it has to be rotated to an angle , then the rotation angle θ is given by[16]:

$$\theta = \varnothing_2 - \varnothing_1 \quad (3)$$

The scale factor is determined as:

$$S = \frac{r_1}{r_2} \quad (4)$$

Where S = scale factor, = desired peak to peak scaling of the signal and = original peak to peak value of the signal.

2. Method and Material

2.1 Material

A material used in fabrication of calibration block is carbon steel (S45C) which based on Japan Industrial Standards (JIS) 4051-2009. Carbon steel (S45C) is a medium strength steel. The composition of carbon steel S45C is 0.45% carbon element, 0.15% silicon element and small amount of manganese, phosphorus and sulfur[17]. This composition is illustrated in Table 1. This material is very suitable for fabrication of shaft studs, keys and normally used in oil and gas as the main material in manufacturing node shell and nozzle body. The advantages of carbon steel S45C are excelling in weldability, machineability and not effect of various heat treatments testing.

Table 1. Carbon steel (S45C) chemical composition

Element	Percentage (%)
Nickle (Ni) max	0.25
Silicon (Si)	0.17-0.37
Sulphur (S) max	0.035
Chromium (Cr) max	0.25
Phosporus (P) max	0.035
Carbon (C)	0.42-0.50
Manganese (Mn)	0.50-0.80

2.2 Design and Fabrication of Artificial Defect Block

Several steps involve in fabricating artificial defect block. The first step is designing the defect block that according to the required specification. The fabrication process for this defect block is summarized in Figure 4.

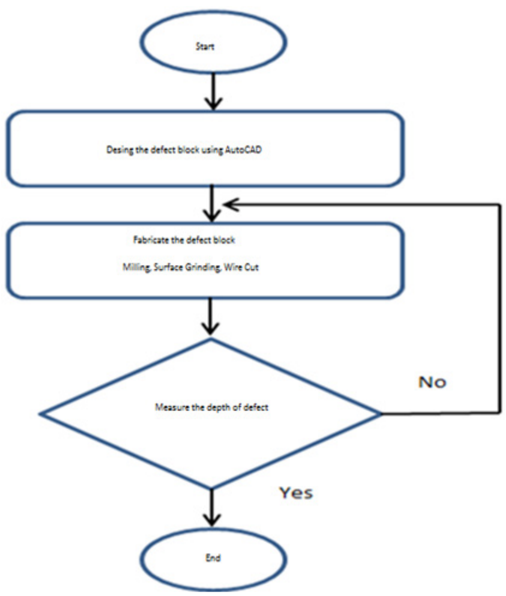

Figure 4. Fabrication steps of carbon steel artificial defect block.

The design was performed by using Auto CAD design software. The drawing of the defect block is illustrated in Figure 5. The artificial defect slot A has a 0.5mm depth from the surface of the block. The defect B has 1.0mm subsurface depth and 1.5mm subsurface defect for slot C. The depth defect slot D,E,F,G and H have increased gradually to 0.5mm. The last depth defect is 4.0mm for slot H.

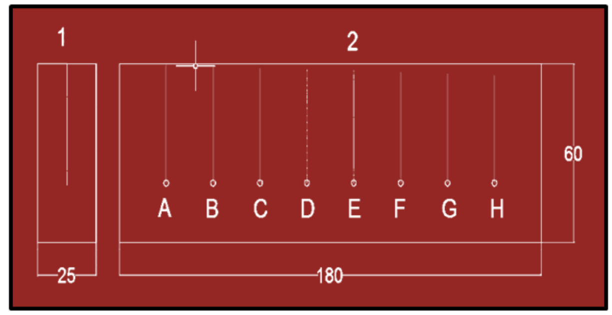

Figure 5. Side view of the calibration block.

The first step in producing the artificial defect block is surface grinding. Surface grinding will produce a smooth finish on flat surfaces. It uses an abrasive machining process in which a spinning wheel covered in rough particles (grinding wheel) cuts chips of metallic or non-metallic substance from a work-piece producing a flat and smooth face. There are three types of surface grinders such as the horizontal-spindle, peripheral grinding and wheel-face grinding. However, this calibration block fabrication will only use the horizontal-spindle (peripheral) type surface grinders. The periphery (flat edge) of the wheel is in contact with the work-piece which producing the flat surface.

The second step of producing the artificial defect block is milling. Milling process uses the rotary cutters to remove material from a work-piece advancing (or feeding) in a direction at an angle with the axis of the tool. It covers a wide variety of different operations and machines, on scales from small individual parts to large and heavy duty milling operations. It is one of the most commonly used processes in industry and machine shops today for machining parts to precise sizes and shapes.

The wire cut is the last step. The machine will cut the subsurface depth of the slot in 0.5mm, 1.0mm, 2.0mm, 2.5mm, 3.0mm, 3.5mm and 4.0mm. Wire Electrical Discharge Machining (WEDM) which also known as wire-cut EDM and wire cutting is a thin single-strand metal wire that usually brass, which is fed through the work piece, submerged in a tank of dielectric fluid and typically deionized water.

2.3 Electrical Conductivity Measurement

Conductivity test was conducted at the TATIUC Eddy Current Lab. The measurement is taken 6 times in 8 different points on the defect block and average value of the measurement point,whichis taken as the reading of conductivity material. Figure 6 shows the point of the conductivity testing that be performed.

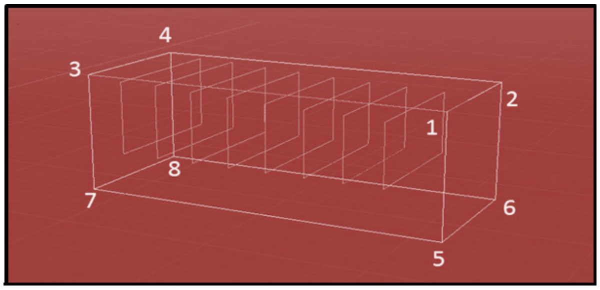

Figure 6. Point of conductivity measurement on carbon steel S45C defect block.

3. Results and Discussion

The measurements for the artificial defect block were performed by using 16mm and 9mm diameter probe. The maximum depth that can be detected by both probes was performed by using the defect block. The defect block has eight slots with a depth of 0.5mm, 1.0mm, 2.0mm, 2.5mm, 3.0mm, 3.5mm and 4.0mm. Each slot will be measured three times to find the best accuracy. The material conductivity of carbon steel is 3.18% of the International Annealed Copper Standard. Table 2 shows the conductivity test result of the carbon steel block.

Table 2. Average of conductivity for carbon steel block

Point	Value
1	3.7% IACS
2	3.6% IACS
3	3.59% IACS
4	3.62% IACS
5	3.59% IACS
6	3.42% IACS
7	3.5% IACS
8	3.53% IACS
Average	3.57% IACS

3.1 Inspection Results for Weld Probe 16mm Diameter

In order to investigate the maximum depth of defects that can be detected by weld probe 16mm, the inspection was carried out by using a different frequency range from 50kHz to 100kHz. A gain parameter which controls the size of the signal was set for maximum signal amplitude, and the signal position is 45° to the right bottom corner. Figure 7 shows the signal of eddy current testing measurement by using different frequency for different depth subsurface.

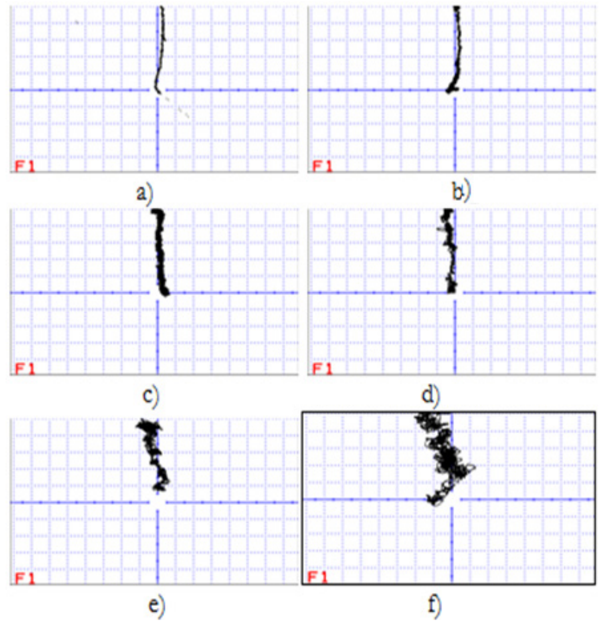

Figure 7. Eddy current testing signal. (**a**) 100kHz and 50.2dB for 0.5mm subsurface. (**b**) 90kHz and 60.2dB for 1.0mm subsurface. (**c**) 80kHz and 65dB 1.5mm subsurface.(d)74kHz and 69dB for 2.0mm subsurface. (**e**) 72kHz and 69dB for 2.5mm subsurface. (**f**) 69kHz and 72dB for 3.0mm subsurface.

Table 3. Subsurface defect depth detection of weld probe 16mm diameter

Subsurface Depth (mm)	Frequency (kHz)					Average Frequency (kHz)
	1	2	3	4	5	
0.5	100	100	100	100	100	100
1.0	91	90	89	90	90	90
1.5	80	79	78	81	81	80
2.0	77	72	73	74	74	74
2.5	72.5	72.5	71	72	72	72
3.0	68	70.5	70	69	69	69
3.5	-	-	-	-	-	-
4.0	-	-	-	-	-	-

Eddy current inspection by using 16mm weld probe, and 69kHz frequency was able to detect defects up to

3.0mm under the surface carbon steel S45C. After the defect deeper than 3.0mm, the inspection cannot detect defect although the frequency is set to low. The optimum frequency for different subsurface depth is summarized in Table 3.

Based on Table 3, lower probe frequency increase the depth defect detection of eddy current testing. The maximum defect depth of weld probe eddy current testing able to detect is 3.0mm with frequency setting is 69kHz.

3.2 Inspection Results for Weld Probe 9mm Diameter

Weld probe with a smaller diameter will produce lower eddy current around the probe, thus reduce the depth subsurface defect inspection ability. The signal of eddy current testing measurement for weld probe 9mm diameter by using different frequency is shown in Figure 8.

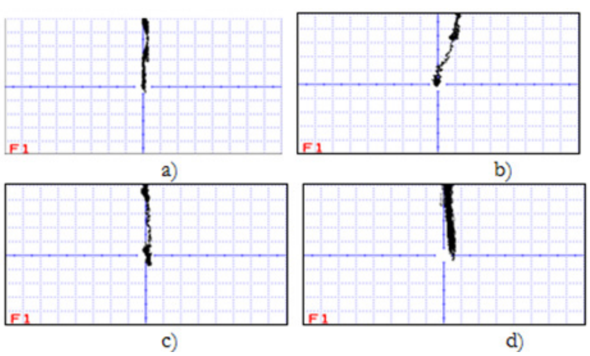

Figure 8. Eddy current testing signal. (**a**) 100 kHz and 60dB for 0.5 mm subsurface. (**b**) 90kHz and 70dB for 1.0mm subsurface. (**c**) 80kHz and 75dB for 1.5mm subsurface. (**d**) 70kHz and 78dB for 2.0mm subsurface.

Maximum depth of subsurface defects that can be detected by a 9mm diameter of weld probe which only 2mm. This happens where the small diameter probe reduces the eddy current which generated by the exciting coil inside the probe and cause depth penetration by skin effect reduced. The optimum frequency of 9mm diameter weld probe for different subsurface depth is summarized in Table 4.

Table 4. Subsurface defect depth detection of weld probe 9mm diameter

Subsurface Depth (mm)	Frequency (kHz)					Average Frequency (kHz)
	1	2	3	4	5	
0.5	100	100	100	100	100	100
1.0	90	90	89	88	91	90
1.5	73	75	70	70	75	73
2.0	68	66.5	70	64	64	67
2.5	-	-	-	-	-	-
3.0	-	-	-	-	-	-
3.5	-	-	-	-	-	-
4.0	-	-	-	-	-	-

Weld probe 9mm diameter and 16mm have an optimum frequency of 100kHz and 90kHz for 0.5mm and 1.0mm subsurface depth. However, for subsurface depth more than 2.0mm, the frequency for weld probe 9mm diameter need to setting lower than weld probe 16mm to produce clear eddy current testing defect signal. Comparison depth defect detects by both weld probes with different frequency eddy current testing is shown in Figure 9.

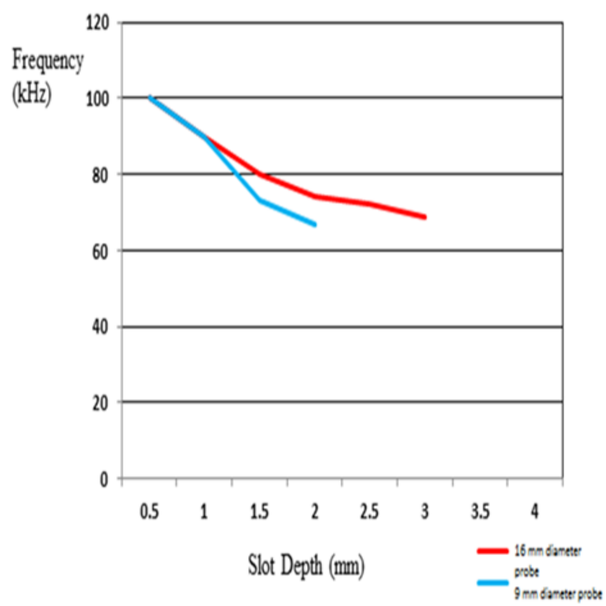

Figure 9. Comparison of depth defect detects by 9mm diameter weld probe and 16 mm diameter weld probe by using different frequency eddy current testing.

4. Conclusion

In this paper, the maximum depth of defects that can be detected by two different diameters of weld probe has been investigated. Artificial defect for carbon steel S45C was fabricated. The artificial defect also can be used as a calibration block for carbon steel S45C. Weld probe with diameter 16mm can detect a maximum depth of 4.0mm by using 69kHz eddy current testing, and probe with diameter 9.0mm able to detect subsurface defect only up to maximum 2.0mm. The results prove that the maximum depth of the subsurface can be measured by using eddy current testing method, which is depending on the frequency of the exciting coil weld probe.

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