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Detection of Deep Subsurface Cracks in Thick Stainless Steel Plate

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Unlike conventional Eddy Current Test (ECT), Pulsed Eddy Current (PEC) uses a multiple-frequency current pulse through the excitation coil. In the present study, the detection of subsurface cracks using a specially designed probe that allows the detection of a deeper crack with a relatively small current density has been attempted using the PEC technique. The tested sample is a piece of 304 stainless steel (SS304) with a thickness of 30mm. Small electrical discharge machining (EDM) notches were put in the test sample at different depths from the surface to simulate the subsurface cracks in a pipe. The designed PEC probe consists of an excitation coil and a Hall sensor and can detect a subsurface crack as narrow and shallow as 0.2 mm wide and 2 mm deep. The maximum distance between the probe and the defect is 28 mm. The peak amplitude of the detected pulse is used to evaluate the cracks under the sample surface. In time domain analysis, the greater the crack depth the greater the peak amplitude of the detected pulse. The experimental results indicated that the proposed system has the potential to detect the subsurface cracks in stainless steel plates.

Keywords : Pulsed eddy current (PEC), subsurface cracks, thick stainless steel, hall sensor, peak amplitude

1. Introduction

The structural materials of nuclear power plants are composed of thick stainless steel pipes or plates. Since the interiors of these structural parts are narrow, closed Nondestructive Testing (NDT) of these components is difficult. The cracks and defects of these components are a real threat to the reliability of a structure, as they can rapidly grow and causes failures of structural integrity. The conventional ECT uses a single frequency sinusoidal excitation for the detection of defects or flaws as a function of changes in voltage, impedance, or phase. Because of limited depths of penetration and the complexity of the signal analysis, ECT was confined to limited applications [1]. Unlike a conventional ECT, PEC uses a multiple frequency sinusoidal excitation of the electric current owing to the broadband nature of a pulse. Hence it has the ability to penetrate different depths in a conductive material and provides depth information for the defects [2, 3]. PEC technology is one of the most effective methods, and is capable of performing other inspection tasks such as subsurface defect detection in complex structures [4-6]. Moreover, PEC is more economical in terms of power consumption owing to its short excitation pulse with intermittent intervals. And it doesn't need any complex electronic circuitry. Even though PEC has been considered to be a useful tool for the nondestructive evaluation of materials, Practically it is not widely accepted in the field of nondestructive testing [7, 8]. However, PEC testing has become a subject of widespread interest in NDT because of advancements in technologies such as computerized data acquisition and digital signal processing. Furthermore, PEC has the ability to measure thickness, conductivity and in particular, it provides subsurface crack measurements, crack reconstruction, and depth estimation [9, 10]. Because of the potential advantages of PEC, numerous investigations of this technique have been made, such as for the detection of wall thinning and corrosion in aircraft multilayer structures [11, 12]. PEC Technique is significantly good at detecting subsurface cracks in thick plates used in the nuclear industry. The thicknesses of tubes and nozzles that are used in nuclear power plants range up to several tenths of a millimeter, and they are made of stainless steel

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and/or Inconel alloy to protect against corrosion. The crack detecting sensitivity of PEC probes depends upon several parameters such as pulse width, coil size and coil diameter. To achieve high sensitivity, it is necessary to increase the flux through the circular coil which intern can increase the induced current density in the test specimen, The flux through the circular coil can be described by the following equation.

$$\phi = B\pi r^2$$

B is the magnitude of the magnetic flux density, which is perpendicular to the surface that is defined by the coil of radius *r*. Therefore, a large-sized coil gives good sensitivity but large size means that some resolution must be sacrificed. The reason is that there is a response to all magnetic flux lines passing through the coil winding, regardless of their spatial direction and orientation. Using a smaller coil would provide better resolution but would limit the magnitude of the eddy current that penetrates within the test object. Therefore, in order to detect the deep crack buried inside a thick sample, we have to consider many parameters such as skin depth, coil inductance, and detection sensitivity when designing a PEC probe. In the present study, a new PEC probe to detect subsurface cracks of 0.2 mm width and 2 mm depth in a 30 mm thick SS304 steel plate was developed by considering all the parameters mentioned above, and the performance of the newly designed probe was tested with a PEC system that was designed and developed for this purpose. This introduction has described the several basic elements of the system's design. The second part of this paper provides details of the system design and the experimental process; the third presents the analysis of the experimental results; and we finish with conclusions.

2. Development of PEC System

2.1. System design

First, the PEC system consists of a pulse generator, a pulse amplifier, the probe having a driving coil with a magnetic field detecting sensor (Hall sensor), a sensitive differential amplifier with variable gain to amplify the output voltage from the Hall sensor, an A/D converter, and a computer with signal processing software. A rectangular signal with specified pulse width from the waveform generator is fed to a pulse amplifier which drives the excitation coil in the probe. The exciting signal frequency and duty cycle can be adjusted by the specially designed pulse generator to improve the penetration depth. Fig. 1(b) shows the PEC probe schematic. The Probe is composed of a cylindrical ferrite core and bobbin

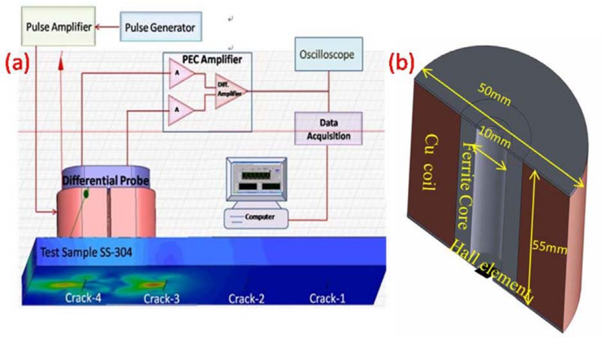

Fig. 1. (Color online) Schematic diagram: (a) PEC experimental setup; (b) Cross sectional view of the probe.

wound with a copper coil of 132 turns. The inner and outer diameters of the probe are respectively 10 mm and 50 mm and the height of the probe was chosen to be 55 mm to obtain good spatial resolution. A Hall sensor is positioned in the center of a ferrite core and serves as a pickup sensor to detect the induced signal from the test specimen, the resultant induced field from the sample surface. The configuration of the system and the probe setup are shown in Fig. 1.

2.2 PEC Signal Measurements

The tested sample is SS304 steel of 30 mm thick, 250 mm in width and 300 mm in length. To simulate the cracks in a steel pipe, small EDM notches 0.2 and 0.4 mm wide were made on one side of the sample at different depths of 2, 4 and 6mm from the sample surface (opposite the probe position). During the PEC measurements the probe was placed on the opposite side of the crack surface to detect subsurface defects in the test sample. The PEC probe was fixed to an X-Y scanner to perform the scanning process on the defect-free side of the test sample. A Lab VIEW-based data acquisition program was developed to continuously monitor the variations in the crack of the sample, and to display the data on a computer screen. The time domain feature which is the peak value of the detected pulse is used to detect the subsurface cracks in the stainless steel test sample while scanning. In brief, a high-current pulse is used to drive the excitation coil in the probe. The pickup Hall sensor measures the resultant vertical magnetic field which is the vector sum of the field generated by the excitation coil and the opposing field generated from the induced eddy currents in the test sample.

3. Experimental Results and Analysis

A strong pulse having a pulse width of 10 ms and 26 A current excites the PEC probe. This square-shaped excitation current provides a wide spectrum of frequencies which causes the propagation of a rapidly attenuating traveling wave governed by the diffusion equation [13]. The crack is positioned about 30 mm from the probe surface. The pulse width and driving current were selected via Maxwell simulation considering the skin depth relation.

It should be noted that the eddy current induction is discontinuous because the magnetic field that is created by the coil remains constant between the square pulse edges in the time domain. The generation of the eddy currents in a sample is due to the variation of the magnetic field resulting from the coil when an alternating current passes through it. Therefore the magnitudes of the eddy currents always depend on the rate of change of the excitation field. In contrast with the conventional eddy current methods, in this experiment the field source is driven by a square wave current, as is shown in Fig. 2. The typical induced signal due to the square-shaped excitation current is shown in Fig. 2. The metal attenuates and delays the pulsed field as it passes through it. Also, cracks and other electrical discontinuities cause the electromagnetic pulse to be scattered back to the surface. These characteristics can be used to indicate the conditions inside the metal. The output signal from the Hall sensor can yield information about the presence and depth of any defects. Three classes of cracks have been formed in the sample, one class has 20 mm length and 0.2 mm width and depths of 2, 4, and 6 mm. Another class has same length, but the width is 0.4 mm, and the depths are of 3, 5 and 7 mm. The last class consists of three entirely different length-width-depth combinations: $9 \times 0.2 \times 3$, $22 \times 0.3 \times 7$, and $25 \times 0.3 \times 15$ mm. The PEC probe was placed exactly on the crack from the opposite the side into which the cracks were machined and measurements were taken. The dimension of the cracks and the corresponding measured values of the PEC responses while scanning the probe over each respective crack is given in Table 1.

Fig. 3 shows the PEC response that was measured by the Hall sensor corresponding to the crack depths of class 1. The class 1 cracks have lengths of 20 mm and widths of 0.2 mm, and different depths of 2, 4, and 6 mm. The deeper crack of 6 mm depth, for which the distance between the probe and the top of the crack is 24 mm, shows the maximum pulse amplitude, and the detected pulse amplitude decreases with decreasing crack depth. The received signal shape is of interest for the purpose of interpretation, a slow rise to a peak followed by a rapid decay. The induced signal of class 2 cracks also shows the same trends, with increasing crack depth yielding increasing peak amplitude. The peak amplitude of the induced signal from defects mainly depends upon the crack depth, but not much upon the crack width. The trends of peak amplitude with depth of class 2 cracks is similar to those of class 1 even though the width of the class-2 cracks is twice that of class 1. The magnitude of the peak amplitude depends on the position and size of the defect and is proportional to the amount of metal loss. The peak amplitude of the induced signal increases with increasing crack depth. In the analysis of the PEC signal, different parts of the sensor signal gives information about different depths– the shape of the scattered field pulse contains information about the interior of the specimen. The defect depth can be discerned from the pulse broadening of the detected signal at the probe surface. The deeper the defects, the longer will be the delay in the detected PEC pulse, causing pulse broadening. This delay in the detected signal is due

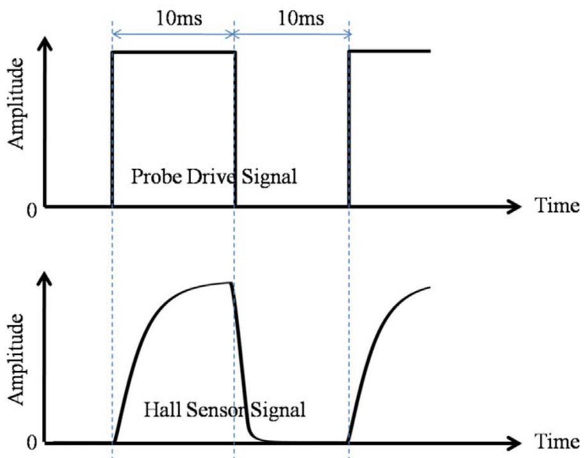

Fig. 2. (Color online) Typical probe excitation signal and Hall signal detected at the Hall sensor.

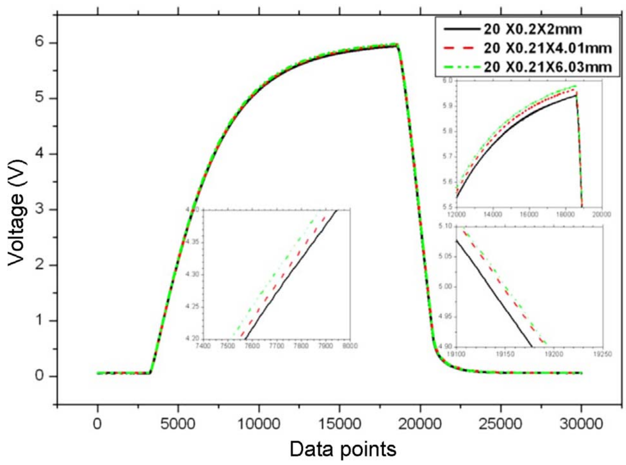

Fig. 3. (Color online) Variation of the PEC response for the class 1 cracks.

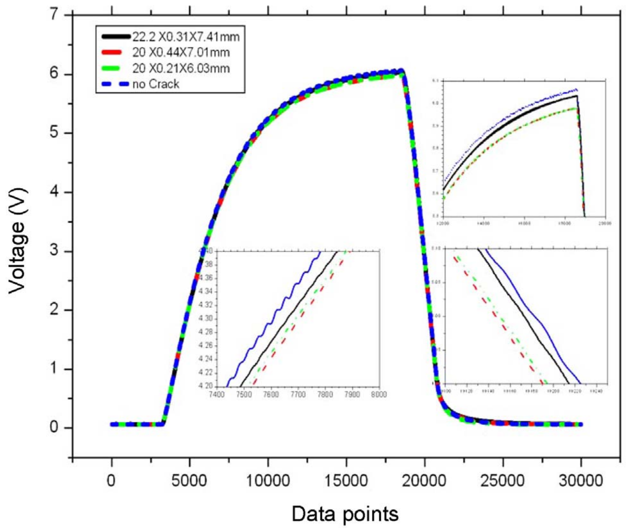

Fig. 4. (Color online) The PEC signal response to cracks of similar crack depth and different crack width.

its longer path through highly dispersive conducting media. That is, the signal due to the defects nearer to the probe surface returns faster while the corresponding signal from a defect farther from the probe takes more time to reflect back to the probe surface. This could also be thought of in terms of phase velocity. The fact is that the lower-frequency components propagate at slower rates through the material; higher-frequency components take less time [14]. Consequently, by considering the time domain features such as rise time and decay time, along with the peak amplitude interpretation, a clear indication is given of the depth of the crack– nearer defects appear at an earlier time on the detected waveform, and deeper flaws affect the waveform later in time, as shown in Fig. 3.

In order to know the effects of crack width on the PEC signal, the experimental results for the same crack length and depth, but different crack widths have been compared. The peak amplitude decrease with increasing crack width is shown in Fig. 4, and this trend is also confirmed in the Table 1. This is because the total volumes of defects below the coil increase with increasing crack width, which results in a lower inductance, causing a decrease of peak amplitude.

Table 1. Dimensions of three different classes of cracks and the corresponding measured values of PECresponses.

Crack class	Crack dimensions	Peakpoint (time)	Peak amplitude (V)
1	20 × 0.2 × 2 mm	18578	5.94302
	20 × 0.21v4.01 mm	18583	5.96945
	20 × 0.21 × 6.03 mm	18587	5.98328
2	20 × 0.41 × 2.99 mm	18586	5.93043
	20 × 0.44 × 4.99 mm	18572	5.95229
	20 × 0.44 × 7.01 mm	18579	5.98239
3	9 × 0.18 × 3.01 mm	18577	5.98577
	22.2 × 0.31 × 7.41 mm	18590	6.0364
	25.3 × 0.33 × 14.79 mm	18576	6.06815

4. Conclusions

A nondestructive evaluation (NDE) method to detect the subsurface cracks using PEC has been devised and demonstrated for cracks in a 30 mm thick stainless steel plate. Three classes of cracks have been machined on the sample. One class consists of cracks with 20 mm length and 0.2 mm width, and depths of 2, 4 and 6 mm. Time domain features of the detected pulse were used to detect the cracks, such as the pulse amplitude. The peak amplitude of the induced signal increases with increasing crack depth. The other parts of the induced signal showed the same trend, and the measured parameters indicate the characteristics of subsurface cracks well. The results show that the proposed PEC technique has the potential to detect thick subsurface cracks.

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