Application of Pulsed Eddy Current Technique in Stress and Residual Stress Measurement

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Abstract: Stress and residual stress are the main problems in the operating materials. They are the principal causes of material failure and may affect life time of component. However measurement or their predictions are typically difficult. Two common non-destructive methods, X-ray diffraction and ultrasound are not reliable methods for subsurface residual stress measurements, and destructive hole-drilling method is not absolutely precise and safe. In this study, the PEC method was applied to the qualitative and quantitative measurements of stress in aluminum alloy specimens. PEC is a high performance non-destructive testing technique but its application in stress and residual measurement is unknown. In this study a qualitative and quantitative approach for measuring residual stress by PEC technique was developed. Results indicated that pulsed eddy current responses are sensitive to stress and revealed that PEC method is capable of residual stress measurements.

Keywords: Non-Destructive Evaluation (NDE), Residual Stress Measurement, Pulsed Eddy Current (PEC), PEC Signal Processing

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1 INTRODUCTION

The stress which exists in an elastic solid body in the absence of, or in addition to, the stresses caused by an external load is residual stress. Such stresses may arise from deformation during cold working such as cold drawing or stamping, in welding from weld metal shrinkage, and changes in volume due to thermal expansion. The role of residual stress in unexpected failures and estimation of remaining life of components has attracted attention of scientists to measure the residual stress. Residual stress is one of the main reasons for unexpected failures of mechanical samples when using components and structures. Residual stresses may add to, or subtract from, stresses applied during service. Consequently, when unexpected failure occurs it is often because residual stresses have combined critically with the applied stresses, or because these stresses along with poor micro-structure and unknown defects decrease stress in a dangerous manner, that is, the stress at which failure will happen [1].

In addition, without considering presence of residual stresses one cannot anticipate components' remaining life of service in a reliable and accurate manner. Since there is uncertainty regarding absolute level and spatial distribution of residual stress, predicting residual stresses is a difficult task. This uncertainty is partly due to the fact that there is a high susceptibility to variations in the process of manufacturing stress and thus it experiences thermo-mechanical relaxation at operating temperatures. Hence, measuring residual stress directly is the only reliable way for finding actual level and its spatial profile [2], [3].

There are two ways to measure residual stress, destructive and non-destructive method. Destructive methods for measuring residual stress are based on the fact that object is deformed during cutting, since necessary components of tractions are decreased to zero at new surface because of residual stress field [1]. Hole-Drilling (ASTM E837) is a destructive method which is commonly used for measuring residual stress. Moreover, destructive methods for residual stress measurement are expensive and difficult [4], hence they may not be applied in order to predict maintenance of critical components like elements of gas-turbine engine [5].

In addition, destructive methods of residual stress measurement are not applicable on all components; therefore recently more attention has been paid to non-destructive methods. Currently X-ray diffraction is the only reliable nondestructive method for measuring residual stress, which is confined to a very thin surface layers (less than 20 μm). Data for residual stress in surface layers (depth less than 20 μm) for assessing components service life and detecting unpredictable failures are not applicable since even in relatively low temperatures there is stress relaxation on thin top layers. Therefore, this technique must be accompanied with destructive removal surface layer methods to determine residual stress in subsurface layers.

In this case, the X-ray diffraction method is no longer non-destructive [5]. As a result it is always an important challenge across NDE to achieve a cheap and portable method to measure residual stress with a sufficient depth of inspection and reasonable accuracy. Herein lots of researches have been conducted for evaluation of both applied and residual stresses. Since different materials have different character for stress measurement, scientists have used different physical phenomena and different testing techniques for stress measurement such as residual magnetic field sensing for ferrite metallic samples [6], ultrasonic wave velocity variation [7], magnetic anisotropy [8], magnetic Barkhausen noise or metal magnetic memory testing [9].

A promising phenomenon found by scientists is that electrical conductivity of a polycrystalline metal becomes anisotropic under influence of elastic stress. In other words, presence of elastic stress changes the electrical conductivity of the component, where this effect is called piezoresistivity. Thus, residual stresses levels can be specified by measuring electrical conductivity of the material. Since eddy current sensor is sensitive to conductivity changes, the eddy current (EC) method has the potential to provide a cheap indicator of the state of residual stress in metals and alloys [10].

In comparison with non-destructive test methods for residual stress prediction, the eddy current technique has numerous benefits such as, ability to diagnose even in the presence of the layers of paint or protection, no need for couplants, no dead zone similar to ultrasonic, ease of use as well as cost-effectiveness compared to other methods [4], [11].

Piezoresistivity effect and many other benefits of eddy current testing have made it an obvious choice to be used for characterizing the residual stresses; many scientists have worked on this method, resulting in improvement and development of the method. They have investigated effects of such factors as cold-working, inhomogeneity and hardness on accuracy of the method and have provided suitable solutions for solving limitations of this method [12-14].

Another limitation of EC testing in measuring stress is low inspection depth of this method so that it has been used in surface stress measurement [15]. In this study, this problem is investigated and appropriate solution is offered and eddy currents are used for measuring the stress in the subsurface layers.

EC testing is based on the principle of electromagnetic induction, whereby a time-alternating magnetic field of a coil induces electric (eddy) currents in an electrically conductive test piece brought into the proximity of the coil [16]. Eddy current penetration depth is frequency-dependent because of the skin effect; high frequencies tend to hold circular eddy current close to sample surface. Decreasing frequency causes eddy current flows to penetrate deeper depths, thus eddy currents have specific standard penetration depth. Standard penetration depth for EC testing is defined as follows: the depth at which the current density is exponentially reduced to 1/e of value at surface [17].

In conventional EC equipment a single sinusoidal excitation is employed. Penetration depth of eddy currents considerably limits these systems. Thus, conventional systems are suitable for examining surface and near-surface layers [17]. A solution for increasing subsurface testing depth is decreasing operational frequency so as to increase the standard skin depth for EC test. However, ratio of signal to noise is decreased in many cases. According to Faraday’s voltage law, induced voltage in coil sensors is proportionally related to change rate of magnetic field [17]. Thus, this solution isn’t applicable for subsurface residual stress measurement because conductivity changes due to stress are insignificant and high sensitivity of method is needed for measuring stress in sub-surface layers [13].

Since there may be a complex profile for residual stresses under surface of test piece, an appropriate solution is using a range of different frequencies for measuring residual stress in different depth. The aim of this study is to introduce PEC method as a novel non-destructive residual stress measurement technique for solving this problem.

In contrast to conventional eddy current (EC) methods which employ sinusoidal excitation, in the pulsed eddy current (PEC) method the probe’s driving coil is excited with broadband pulses. The changing current through the coil induces eddy currents in the test piece and the associated magnetic field in the material dissipates rapidly and exponentially as it approaches a steady state. The induced field in the test specimen can be measured by a number of different sensors as in conventional EC testing, including coils and solid state probes. In other words, the pulse excitation can be regarded as a large number of single sinusoidal tests at various frequencies in the way each of them corresponds to a different standard penetration depth. From shallow layers (high frequency signal components) and deep layers (low frequency components) simultaneously one can get information by analyzing a single pulse response [18], [19].

The PEC signal, analogous to the ultrasonic A-scan, is represented by the time domain response of the voltage induced in the sensor by the transient magnetic field at the surface of the material. This signal depends on the material characteristics and experimental parameters. Since a broad frequency spectrum is produced, unlike the conventional EC testing, the reflected signal contains depth information about the material. Physically, the pulse is broadened and delayed as it travels deeper into the highly dispersive material. Therefore, anomalies close to the surface will affect the eddy current response earlier in time than deep flaws.

In this study, the PEC method was applied to the qualitative and quantitative measurements of residual stress in aluminum alloy specimens. First, a brief explanation to eddy currents in terms of the basic principles of the methods for residual stress measurement is provided. Then, test method and the way of receiving signal and data collection procedure is studied. Finally, the analysis and discussion of data gathered from PEC tests will be presented.

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2 THEORIES

The ultrasonic waves propagate in two main kinds in materials (Fig. 1):

The piezoresistive effect describes electrical resistance change in a material because of elastic stress. The electrical conductivity tensor [σ] of an otherwise isotropic conductor becomes slightly anisotropic in the presence of elastic stress [τ]. In principal coordinates:

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\end{bmatrix}=\begin{bmatrix}\sigma_0 & 0 & 0\\ 0 & \sigma_0 & 0\\ 0 & 0 & \sigma_0\end{bmatrix}+\begin{bmatrix}K_{\parallel} & K_{\perp} & K_{\perp}\\ K_{\perp} & K_{\parallel} & K_{\perp}\\ K_{\perp} & K_{\perp} & K_{\parallel}\end{bmatrix}\begin{bmatrix}\tau_1\\ \tau_2\\ \tau_3\end{bmatrix} \qquad (1)$$

Under uniaxial stress (τ1 = τ and τ2 = τ3 = 0), and the so-called gauge factor 'γ' is defined as follows:

$$\gamma=\frac{1}{\varepsilon}\frac{\delta R}{R_0}\approx\left(1+2\upsilon\right)-\frac{1}{\varepsilon}\frac{\delta\sigma}{\sigma_0}=\left(1+2\nu\right)-K_{\parallel}\frac{E}{\sigma_0} \qquad (2)$$

where, δσ is the change in electrical conductivity and 'ν' and 'E' show Poisson’s ratio and Young’s modulus, respectively. δ R/R0 is the ratio of the relative resistance change and ε = τ/E is the axial strain. It was verified that the gauge factor is usually considerably higher than the first term $1+2\upsilon\approx1.6$ of purely geometrical origin [5], where '$K_{\parallel}$' is negative. In case the average electrical conductivity 'σ_0' is measured by a unidirectional circular eddy current probe under uniaxial stress, the effective electro-elastic coefficient

'K_0' will equal to the algebraic average of the parallel and normal electro-elastic coefficients, i.e.,

$$\frac{\delta\sigma_0}{\tau_1} = K_0 = \frac{1}{2}\left(K_{\parallel} + K \perp\right) \tag{3}$$

Considering relationship in Eq. (3), component stress can be assessed by measuring conductivity changes created due to stress using circular eddy current probe. In other words, since PEC responses are according to conductivity changes due to stress; hence stress in component may be found by analysing responses of eddy current pulse.

3 EXPERIMENTS

- **Samples**

Using wire-cut operation, aluminum alloy (Al-2024) sheets were cut to the dimensions of 20x250x4 mm. Due to previous manufacturing processes (rolling and wire-cut), there were residual stresses and plastic strain in the specimens. Therefore, the samples initially were annealed at 330^{o}C temperature for 1 hour. Then, they were slowly cooled down to room temperature.

- **Residual stress simulation in specimens**

Stresses are the result of external loads and residual stresses in the components [20]. As mentioned above, residual stresses are the elastic stresses which are retained within a body since no external loads are acting. Residual stresses occur due to misfit among different regions of the material, component or assembly. In other words, residual stresses have the same role in a structure's strength as common mechanical stresses; some researchers define internal stress due to external loads in exactly the same way as residual stress. When no external loads act, the applied stress is zero everywhere; thus using this definition, internal stress is identical to residual stress.

If a residually-stressed, elastically homogeneous body is loaded elastically, then internal and residual stress are again identical. However, there are cases in which the definitions differ, such as elastic mismatch stresses in composite materials. Consequently, in majority of cases residual stresses and applied elastic stresses have the same characteristics. Thus, the method capable of measuring elastic stress will often be able to measure residual stresses. That's why scientists use tension machine for creating calibration curve for residual stresses measurement [4], [10], [21], [22].

In this study, a tension test machine with maximum load capacity of 50 KN was used to apply tensile stress to the specimens as shown in Fig. 3. Since piezoresistive coefficient in tensile and compressive stress is the same only tensile measurement was used [23]. The elastic deformation was isothermal because the static loading was applied in a low rate; therefore, there is no need for thermal correction on conductivity changes as recommended by Prof. Nagy [19]. Loading was applied stepwise starting at 0 N, with increments of 500 N. The applied load was kept unchanged at each step for 20 seconds before PEC signals data acquisition.

- **PEC test setup and feature extraction**

PEC test setup consists of a pulse generator which excites the probe's driving coil. The second stage consists of a powerful low-noise amplifier, model SR-560, used to amplify and de-noise the measured signals from probe's pickup coil. The reflection circular probe used in this study was made by Eng NDT Corporation. The probe consists of a 14 mm outer diameter driving coil and a concentric 6.35 mm outer diameter pickup coil. This probe has an operating frequency range of 100 Hz - 5 kHz.

The probe was clamped to specimen by a plastic jaw. Next, the amplified signal was provided to a digitizer connected to the computer for signal data acquisition at sampling rate of 1GS/s. The PEC experimental setup in this study is shown in Fig. 1. Lift-off effect was neglected due to no gap and movement between probe and sample.

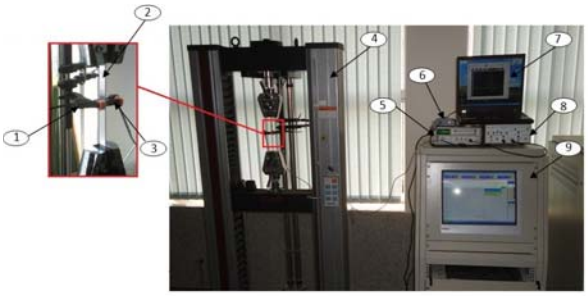

Fig. 1 The PEC setup in this study. 1: plastic jaw, 2: sample, 3: PEC probe, 4: test machine, 5: pulse generator, 6: digital scope, 7: computer, 8: low-noise amplifier, 9: test machine controller

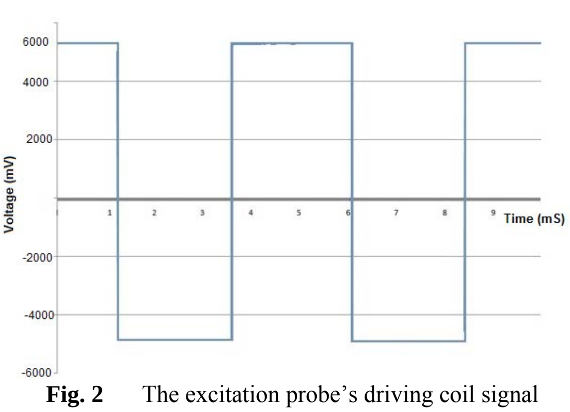

Fig. 2 The excitation probe's driving coil signal

The probe's excitation frequency was set at 200 Hz. The excitation probe's driving coil signal and PEC response are shown in Figs. 2 and 3 respectively.

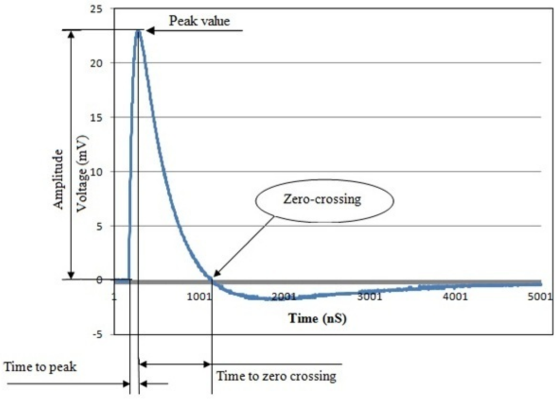

Fig. 3 PEC response signal

4 RISULTS AND DISCUSSION

The experimental data was acquired by a circular coil probe. As explained above, the PEC response of the circular coil probe is corresponding to the average electrical conductivity (average of the longitudinal and transverse components of electrical conductivity). The PEC responses of pickup coil corresponding to specific stresses were analyzed.

Fig. 4 illustrates the PEC signal for load and no load cases. After preprocessing the PEC response signals, useful signal features exhibiting suitable variation to stress should be selected. The PEC signal is often presented in time domain. There are several time-domain features, namely time to peak, peak value, rising point and zero crossing which are used to evaluate material properties and identify defects (see Fig. 3) [24], [25]. Since peak value showed higher sensitivity to stress changes compared to other features of received signals (see Fig. 4), hence this feature was used as the stress measurement criteria in this study.

Therefore, first of all, the peak value of the signal was measured prior to loading. Then, the peak value was measured at each loading step. Finally the difference between the peak values of signal with load and without load was calculated (DVP), as shown in Fig. 4.

This analytical technique also eliminates the influence of sidelong factors such as temperature and humidity on the test results. MATLAB software was used for extracting accurate peak value from signals by doing mathematical operations.

In order to investigate relationship between changes of PEC response and applied stress qualitatively, DVP diagram in terms of stress is given in Fig. 5.

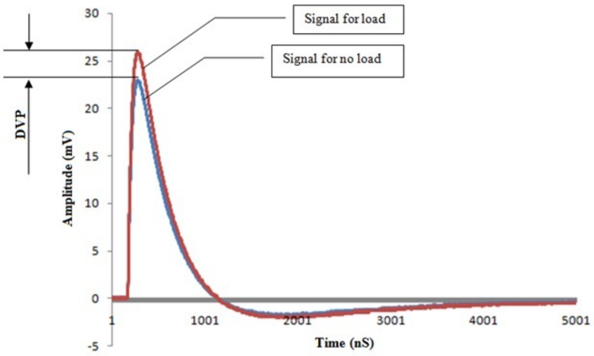

Fig. 4 PEC signal for load and no load cases

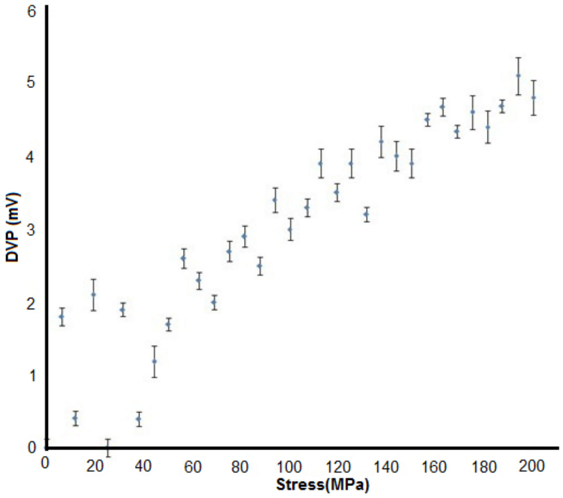

Fig. 5 The PEC response to applied stress

Qualitative investigation of diagram in Fig. 5 indicates that variation in applied stress on work piece results in PEC response variation. In other words, increase in applied stress leads to increase in DVP. This result is in consistency with results obtained by other researchers such as Nagy who proved that eddy current responses are directly proportional to the stress, where he used them to measure residual stresses in super alloy components [19]. However, in this study the PEC method was used to inspect the whole thickness with very low attenuation instead of EC method.

Since these changes have a specific trend (DVP increases with increase in applied stress), PEC response may be used as a criterion for measuring stress quantitatively like EC technique. In order to estimate residual stresses by PEC method quantitatively, the system should be calibrated. The calibration curve can be made by finding a curve best fitted to experimental data.

Investigation of diagram in Fig. 5 indicates that the responses of pulsed eddy current related to stresses under 50 MPa are more scattered than PEC responses related to stresses above 50MPa. It may be attributed to low measurement threshold of used machines or insignificant conductivity changes in low stresses. Anyway, if data related to stresses under 50MPa are used for calibration curve development, it directly influences on calibration curve accuracy and measurement accuracy is reduced. Thus, data related to stresses under 50MPa was not used to generate calibration curve in this study.

Hence, in order to determine stresses by this method, it is suitable to classify the data into two categories, 1) low stress, 2) high stress. The threshold between low stress and high stress is 50MPa for this specific aluminum. In this study, at first, it is specified if residual stress is above or below 50MPa qualitatively in order to select category. Then, quantitative value of high stresses will be found by using calibration curve.

This classification may be useful in most cases, as in the present case. Residual stresses may be added to/or subtracted from the applied stresses. Therefore, when unexpected failure occurs, it is often due to the fact that the residual stresses have the same direction along external loading and combine critically with the applied stresses.

Consequently, if residual stresses are low, therefore they are not critical for unexpected failure. But on the other hand, if the residual stresses are high, this method must be calibrated and can estimate the residual stresses. So the residual stress evaluation system which was developed in this study, includes three modules namely, feature extraction, classification, and estimation, as shown in Fig. 6.

Before calculating calibration curve, four data were randomly put aside for testing the accuracy of PEC method when used as tool for measuring residual stress. These four data are called test data points. The four testing points in this study were the PEC responses for the following stresses: 50 MPa, 100 MPa, 150MPa, and 200 MPa.

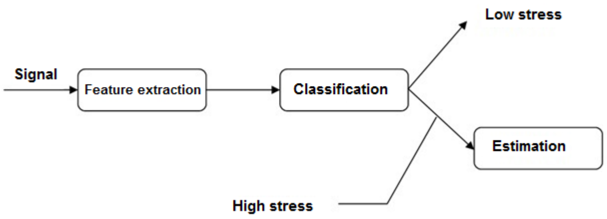

Fig. 6 Residual stress evaluation system

The calibration curve in the case of higher stresses can be made by finding a curve best fitted to experimental data. At first, the data was smoothed by moving average method which replaces each data point with the average of the neighboring data points. This process is equivalent to low pass filtering and eliminates the actual data noise. Then, least squares method was used for fitting data by a linear curve. In Fig. 7, the actual data, excluded data, smoothed data, testing point and calibration curve are shown.

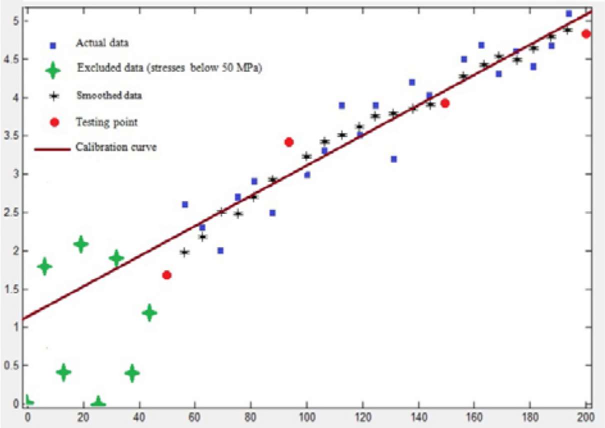

Fig. 7 Actual data, excluded data, smoothed data, testing point and calibration curve

After extrapolating the calibration curve, it should be evaluated to see whether the calibration curve fits the data poorly or strongly, and to see if it is able to show data trend. In this study residual value which has been recommended for calibration curve evaluation was used as curve evaluation criterion. The residuals from a fitted model are defined as the differences between the response data and the fit to the response data at each predictor value.

Residual = data – fit

Residual values for each data are shown graphically in Fig. 8.

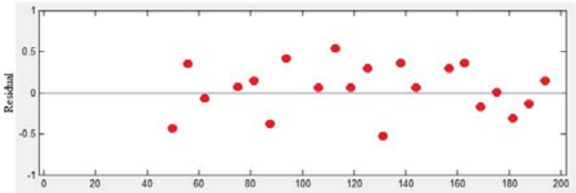

Fig. 8 Residual values for calibration curve evaluation

Since the residuals appear to behave randomly, it suggests that the model fits the experimental data well. However, if the residuals display a systematic pattern, it is a clear sign that the model fits the data poorly. To acquire the accuracy and ability of PEC method to determine residual stresses, the calibration curve was examined with the four experimental testing points and the error was calculated. Stress in test points was obtained from calibration curve and compared to the actual stress value for error calculation. Error is the difference between actual stress and stress obtained from calibration curve. It is typical to express error in percent, so the error in testing point was calculated using Eq. (4).

$$Error = \frac{\text{actual stress} - \text{stress obtained from calibration curve}}{\text{actual stress}} \times 100 \quad (4)$$

Table 1 shows error in test points.

Table 1 Error evaluation

Applied stress (MPa)	Stress measured by calibration curve (MPa)	Error (%)
50	44.9	10.2%
100	114.67	14.67%
150	140.07	6.6%
200	185.779	7.1%

As demonstrated in table 1, the average error of this method is 9.64% which is acceptable compared to other methods such as hole drilling, ultrasonic and eddy current. As an example, Beaney reported an error of 16% for stress calculation by hole-drilling [26]. This error led to perfect yield strength.

The error may be due to environmental errors such as humidity and temperature variation during the experiment or due to equipment errors such as probe sensitivity, accuracy of tensile machine or scope resolution. These errors may be diminished by performing the experiment in isolated room and using more accurate experimental apparatus. In order to verify the test repeatability, tensile experiments were carried out several times on the specimen. Based on the data analysis, the same trend of data was obtained and no significant changes were observed, while the average repeatability error was below 4% for experimental data.

4 CONCLUSION

This study introduced the PEC as a new tool for residual stresses measurements. Results indicated that pulsed eddy current responses are sensitive to stress, and can be used for residual stress measurements. PEC technique has some advantages in comparison with other common non-destructive methods such as X-ray diffraction, ultrasound, hole drilling and conventional eddy current method for residual stresses measurement. These advantages include ability to diagnose the stress even with layers of paint, no need for couplants, no dead zone similar to ultrasonic, simple use as well as cost effectiveness compared to hole drilling method and finally, adequate penetration depth in opposition to the conventional eddy current method. In this study, a quantitative approach was developed by application of signal processing methods to PEC signals to measure the residual stresses of an aluminum specimen, then a calibration curve was generated based on experimental data. After signal analysis, the main results of PEC method in application to stress measurement may be summarized as follows:

1-The peak value of PEC signal increases with increase in tensile stress.

2-The estimated stress can first be classified in two groups: low stresses and high stresses, which are useful in unexpected failure estimation.

3-A linear curve fits the pulse eddy current data strongly and it is able to show data trend very well so it may be used as calibration curve for stress measurement.

Finally, calculation of error in this method indicated that PEC method may be used for evaluating applied stresses and residual stresses, which are in consistency with previous works.

Future work will concentrate on separating the residual stress and plastic deformation effect on PEC signals by applying suitable calibration strategies and using appropriate frequencies. Furthermore, investigating metal type and effect of metallurgical factors such as age hardening or grain size texture on stress measurement by PEC are in our scope as future works. Since this study was part of a research project on new aluminum forming process, the proposed method was only applied to aluminum alloy. For future works, the method will be expanded to different materials to determine the limits.

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