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Residual Stress Profiling of Sub-surface Treated Nickel-Based Superalloy using Electromagnetic NDE Method

S. Annamalai, Z. Fan and S. Castagne

Nanyang Technological University
Rolls-Royce@NTU Corporate Lab
School of MAE
Singapore 637460
E-mail: *sannamalai@ntu.edu.sg*, *zfan@ntu.edu.sg*, *scastagne@ntu.edu.sg*

Abstract

To evaluate the whole residual stress profile of sub-surface processes, existing methods such as X-ray diffraction (XRD) or central hole drilling method (CHD) require material removal, which is inherently destructive. A non-destructive residual stress measurement method using eddy current is utilized to capture the stress depth profile. The technique is demonstrated on nickel-based superalloy Inconel 100 (IN100) treated using deep cold rolling and shot peening to show that the method developed for stress profiling can be independent of the sub-surface treatment. This paper presents the experimental results obtained with an experimental set-up based on the commercially available Nortec eddy current instrument and pencil surface probes. Test samples prepared from IN100 by deep cold rolling and shot peening for two different treatment conditions will be presented. The calculated residual stress profile using eddy current (EC) is compared with the equivalent residual stress profile using CHD for penetration depths from (100-550)µm to validate the measurement technique.

Keywords: *Eddy current; sub-surface process; deep cold rolling; shot peening; residual stress*

1. Introduction

Introducing compressive residual stress on components to improve its fatigue life can be achieved by different sub-surface treatment methods such as shot peening (SP), laser shock peening (LSP), low-plasticity burnishing (LPB) and deep cold rolling (DCR). To reliably assess the remaining life of the sub-surface treated components while in-service, the near-surface residual stress has to be characterized accurately. A nondestructive electromagnetic method using eddy current is utilized to obtain the near-surface residual stress depth profile of sub-surface treated components [1]. Nagy et al. have shown that a nondestructive method based on eddy current conductivity spectroscopy is suited to measure the residual stress of shot peened nickel-based superalloys. The objective of this paper is to study the feasibility of near-surface residual stress depth profiling of two different sub-surface treatment methods such as deep cold rolling and shot peening. The various sub-surface processes typically differ in the amount of cold work put into the material as well as the depths to which compressive residual stresses are introduced. In order to demonstrate the developed low frequency electromagnetic technique for estimating the residual stress profile can be independent of sub-surface treatment, a nickel-based superalloy Inconel 100 (IN100) is selected for this research. Eddy current has great potential because of the stress dependence on electrical conductivity. The standard depth of penetration of eddy current is inversely proportional to square root of frequency. In essence, one can change the penetration depths by changing the eddy current coil frequency. From the conductivity profile, using the known piezoresistivity of the material, the residual stress depth profile can then be calculated. Test coupons were prepared using sub-surface treatment processes such as deep cold rolling and shot peening and treatment conditions varied to induce different levels of residual stress into the material before eddy current spectroscopy was measured.

2. Equipment Details

The major components of the eddy current system are a portable Nortec 2000D+ eddy current test instrument, multiple Uniwest pencil probes (frequency range 200 KHz – 9 MHz), a multi-function DAQ to digitize analog signals, a PC based LabVIEW data acquisition software and two appropriate conductivity blocks for instrument calibration. A typical eddy current experimental setup is shown in Figure 1.

Calibration is an important step in using the test instrument interfaced to pencil probes and certified conductivity standards of known values are required for basic conductivity testing. Conductivity testing is a simple task of setting known conductivity values a priori in the instrument and testing the material once calibration is complete. The basic mode of operation of the eddy current equipment is in conductivity mode where the measured probe coil electrical impedance is transformed to another parameter known as apparent eddy current conductivity (AECC) [2]. Using any two appropriate calibration blocks of known conductivities, four reference complex impedance points are measured with and without lift-off using a non-conducting shim of known thickness (t) between the probe coil and calibration block. Then the experimental measurements of complex coil impedance on the test specimen are evaluated in terms of AECC.

Figure 1. Typical Eddy Current Experimental Set-up for Low Frequency.

This frequency dependent measured AECC is inverted for the depth-dependent profile of electrical conductivity [3-9]. Since the conductivity change produced by subsurface treated nickel alloy IN100 is rather weak and it does not vary sharply with depth, the proposed inversion technique is a localized point-by-point absolute AECC measurement over the frequency range. This procedure neglects the exponential decay of the eddy current and integrating effect of this distribution below the surface. Instead it assumes that the measured AECC corresponds directly to the actual electrical conductivity at half the standard depth of penetration. The main advantage of this two-step approach is that the measured AECC is independent of equipment or type of probe coil used for measurement.

Following the inversion procedure, the actual conductivity profile $\sigma(z)$ can be predicted from the measured frequency dependent AECC $\sigma_a(f)$ and is given by

$$\sigma(z) \approx \sigma_a\left(\frac{1}{4\pi z^2 \mu_1 \sigma_1}\right) \qquad (1)$$

where

μ_i − Magnetic permeability of the material
σ_i − Electrical conductivity of the material
z − Penetration depth of eddy current

The estimated residual stress profile of the sub-surface treated sample is obtained solely using the piezoresistivity relationship of conductivity to stress [1].

$$\frac{\Delta\sigma_1}{\sigma_0} = \kappa_{\mathrm{ip}}\frac{\tau_{1\mathrm{p}}}{E} \qquad (2)$$

Here, $\Delta\sigma_{\mathrm{i}} = \sigma_{\mathrm{i}} - \sigma_0$ (i = 1, 2, 3) denoted the conductivity change due to the presence of stress, σ_0 is the bulk electrical conductivity, κ_{ip} is the electroelastic coefficient and τ_{ip} is the elastic stress in the material. The bulk electrical conductivity of the test coupon was measured at the lowest frequency (f = 200 KHz), where the standard depth of penetration is approximately 1.35mm, i.e., sufficiently deep to avoid the effects of sub-surface processes. A dimensionless isotropic electroelastic coefficient (κ_{ip} = 1.58) for IN100 [8] is utilized.

A simple schematic representation of the method to obtain eddy current stress depth profile is shown in Figure 2.

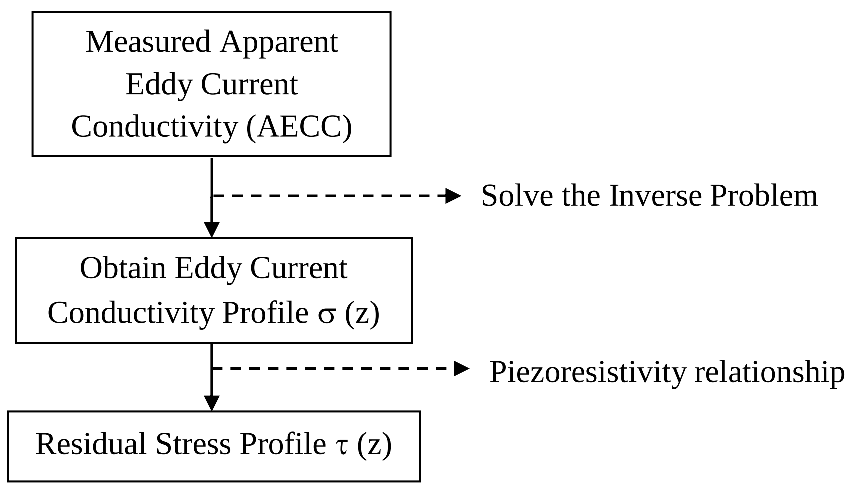

Figure 2. A schematic to obtain Stress Depth Profile using Eddy Current method.

3. Experimental Results

Results of the experimental investigations for residual stress depth profiling of Nickel alloy IN100 in sub-surface processes deep cold rolling (DCR) and shot peening (SP) are discussed. Sub-surface processes such as DCR and SP can induce compressive residual stresses that are not the same in the lengthwise and crosswise directions after sub-surface treatment. In situations that involve directional stresses acting at a point, it is convenient to define an effective stress that represents a combination of stresses, such as Von Mises equivalent stress. The residual stress profile obtained using the nondestructive eddy current technique is then compared with the Von Mises equivalent residual stress obtained from destructive central hole drilling method (CHD) to validate the accuracy of the nondestructive measurement technique. Each of the residual stress spectra are then normalized to the maximum equivalent residual stress measured by CHD method, for penetration depths of (100-550)µm. The percentage AECC change recorded is with respect to a baseline AECC measured at a frequency equal to 200 KHz. The measured AECC change typically increases as much as 1-2% with increasing induced stress in DCR process as shown in Figure 3. Conditions I and II refers to two different stress depth profiles induced separately into two IN100 test coupons.

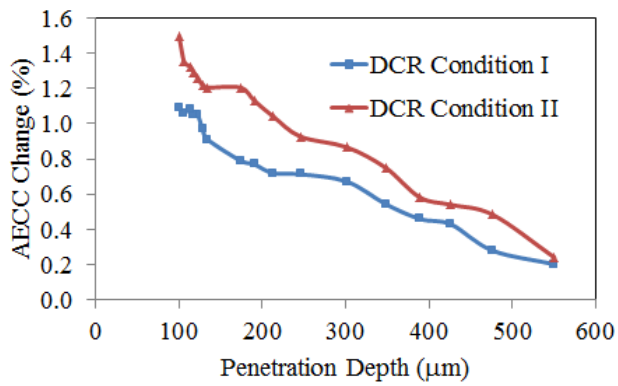

Figure 3. Measured AECC change as a function of depth in IN100 for DCR sub-surface process.

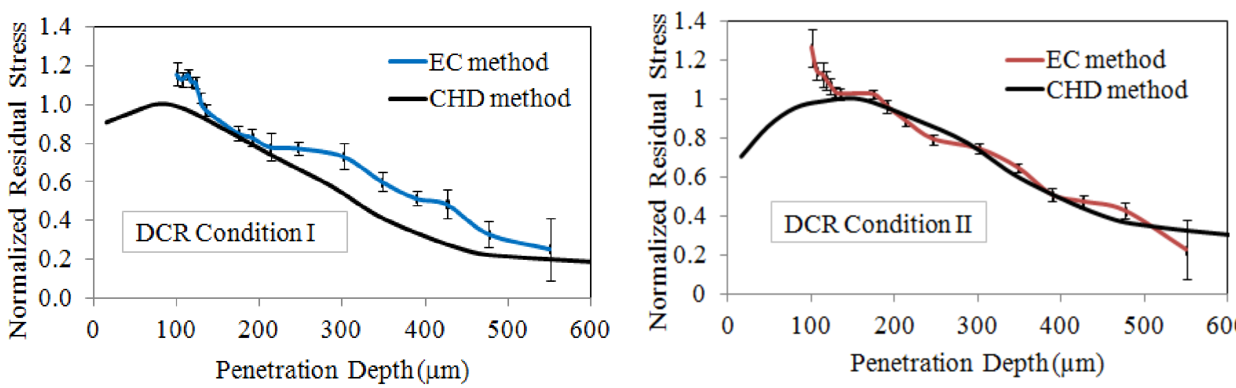

Figure 4. The estimated residual stress profile by nondestructive eddy current (EC) method (plotted with 1-standard deviation) versus the equivalent residual stress profile measured destructively by central hole drilling (CHD) method for condition I(left) and condition II(right) in deep cold rolling (DCR) sub-surface process.

In order to increase the confidence level of these measurements, a number of repeat conductivity measurements were performed. The sample size at each chosen frequency was atleast 80 measurements. From the analysis of Figures 3 and 4, one can observe that the AECC change shows very similar dependence on the same depth to that of the residual stress measured by eddy current method. For IN100 residual stress has the same influence on the eddy current conductivity: when residual stress increases, the conductivity also increases. As seen in Figure 4, comparison of estimated residual stress profiles between the nondestructive eddy current method and destructive central hole drilling method reveals there is fairly good agreement between the two methods for penetration depths of (100–550)µm. Results obtained from DCR treated coupons (conditions I and II) indicated that, within the uncertainty of the measurement, the maximum deviation between the two residual stress profiles is within 25%. Eddy current conductivity is a mixed signal that contains information about prevailing residual stress along with a few other influences. The most probable reason for the deviation of curve closer to the surface could be due to plastic strains produced by prior cold work [10-13]. Studying the influence of the cold work as well as sought near-surface residual stress profile (<100µm), requires use of specially designed eddy current probes and measurement systems to extend the inspection frequency range far beyond the 9 MHz. Thus probe design and development is of high interest to obtain good performance for eddy current conductivity spectroscopy of surface treated components.

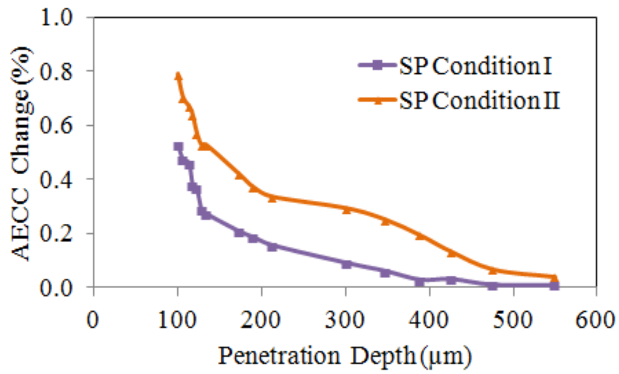

Figure 5. Measured AECC change as a function of depth in IN100 for SP sub-surface process.

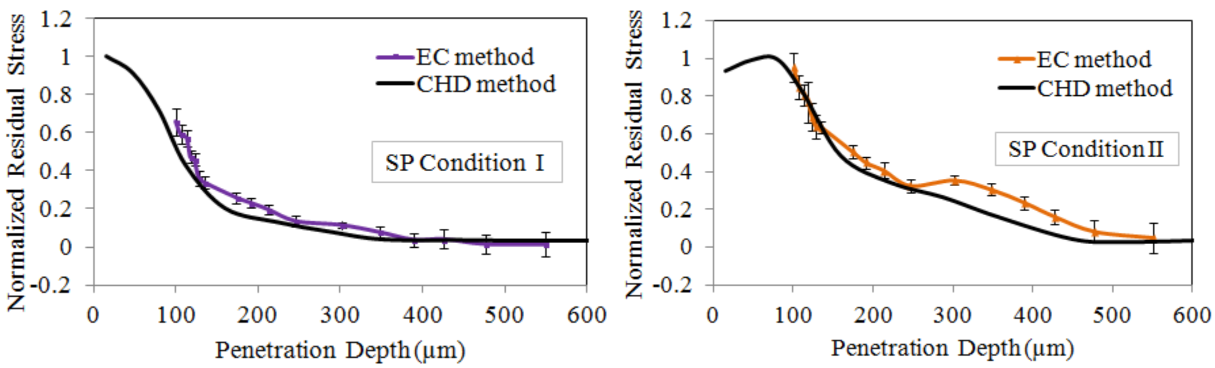

Figure 6. The estimated residual stress profile by nondestructive eddy current (EC) method (plotted with 1-standard deviation) versus the equivalent residual stress profile measured destructively by central hole drilling (CHD) method for condition I(left) and condition II(right) in shot peening (SP) sub-surface process.

Experimental observations indicate that there is a conductivity change due to shot peening process (< 1% AECC change) as shown in Figure 5. This once more confirms that stress influences conductivity and in this case has lead to an increase in electrical conductivity. The residual stress profiles reconstructed from the measured AECC spectra for conditions I and II in shot peening sub-surface process is shown in Figure 6. The general agreement between the nondestructive eddy current residual stress profile and equivalent residual stress profile measured by destructive central hole drilling method is very good for penetration depths of (100-550)µm. These results have indicated that within the uncertainty of measurement, the maximum deviation between the two profiles was less than 20% for both shot peened conditions I and II. It is worth noting that the sensitivity of eddy current conductivity spectroscopy is fairly low as seen in Figure 5, but still sufficient for residual stress profiling in certain surface-treated nickel-based superalloy such as IN100. Similar to DCR process, the plot of estimated residual stress profile of shot peened test coupon is obtained solely using the piezoresistivity relationship of conductivity to stress. The effect of cold work or other factors that may influence the conductivity of the material is not factored into the equation at these depths.

4. Conclusions

Existing methods for characterization of near-surface residual stress of sub-surface processes are inherently destructive. Currently, feasibility for nondestructive residual stress profiling by eddy current conductivity spectroscopy of nickel-based superalloy IN100 is demonstrated for penetration depths of (100-550)µm. Experimental observations reported in this paper indicate that the technique adopted for stress profiling of nickel-alloy IN100 treated using deep cold rolling (DCR) or shot peening (SP) is independent of sub-surface treatment. In order to reconstruct the critical near-surface part of the residual stress profile in sub-surface processes requires inspection frequencies to be far beyond the 9 MHz. The influence of cold work on the eddy current conductivity is also one of the contributing factors for overestimation of stress near to the surface (100 µm). Therefore a deeper understanding of its influence and its correlation to stress will be the task for future work.

5. Acknowledgements

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