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Effects of cold work on near-surface conductivity profiles in laser shock peened and shot peened nickel-base superalloy

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Abstract

This paper reports on a study of the effects of cold work induced by surface enhancement treatment on conductivity profiles in nickel-base superalloys, as part of the on-going efforts aimed at evaluating the feasibility of characterizing near-surface residual stress profiles in peened engine components using a swept frequency eddy current (SFEC) technique. The approach is based on the empirical piezoresistivity effect that correlates conductivity changes with residual stress, but recent studies have shown that conductivity changes induced by peening processes are also influenced by metallurgical factors such as cold work. In this study, conductivity deviation profiles were obtained by model-based inversion of SFEC signals from a set of aged Inconel 718 samples, which were either shot peened or laser shock peened to produce different residual stress and cold work profiles. The laser shock peened samples exhibit a larger increase in surface conductivity and deeper conductivity profiles, which are attributed to a smaller amount of surface cold work and deeper residual stress profiles created by laser shock peening than by shot peening.

Keywords

cold working, eddy currents, internal stresses, laser materials processing, shot peening, superalloys, surface conductivity, Astronomy and Physics, QNDE

Disciplines

Materials Science and Engineering | Physics

Comments

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EFFECTS OF COLD WORK ON NEAR-SURFACE CONDUCTIVITY PROFILES IN LASER SHOCK PEENED AND SHOT PEENED NICKEL-BASE SUPERALLOY

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ABSTRACT. This paper reports on a study of the effects of cold work induced by surface enhancement treatment on conductivity profiles in nickel-base superalloys, as part of the on-going efforts aimed at evaluating the feasibility of characterizing near-surface residual stress profiles in peened engine components using a swept frequency eddy current (SFEC) technique. The approach is based on the empirical piezoresistivity effect that correlates conductivity changes with residual stress, but recent studies have shown that conductivity changes induced by peening processes are also influenced by metallurgical factors such as cold work. In this study, conductivity deviation profiles were obtained by model-based inversion of SFEC signals from a set of aged Inconel 718 samples, which were either shot peened or laser shock peened to produce different residual stress and cold work profiles. The laser shock peened samples exhibit a larger increase in surface conductivity and deeper conductivity profiles, which are attributed to a smaller amount of surface cold work and deeper residual stress profiles created by laser shock peening than by shot peening.

Keywords: Surface Conductivity and Carrier Phenomena, Surface Treatments, Swept Frequency Eddy Current, Residual Stress

PACS: 73.25.+i, 81.65.-b, 07.05.Hd, 07.05.Tp, 07.07.Df, 07.50.-e

INTRODUCTION

Jet engine components, for example rotors, are often surface-treated to improve fracture toughness by methods such as shot peening, which introduces compressive residual stresses that impede potential crack growth. Significant benefits, such as component service life extension and high levels of system reliability, can be gained by maintaining the compressive residual stress state [1]. Eddy current has been identified as a leading candidate for nondestructive characterization of residual stresses in engine components, particularly in nickel-base superalloys [2]. Correlations between EC signals and residual stresses in shot-peened alloys have been reported, and were attributed to the piezoresistivity effect, which refers to stress-induced changes in electrical conductivity [3,4]. Despite the significant potential of EC, several challenges have been identified

against development of the measurement technique for residual stress characterization. In particular, it has been found in recent studies that the EC responses of Inconel 718 to shot peening depend on the underlying microstructures [5-8]. These findings indicate the confounding effects of metallurgical factors on EC residual stress measurements, and raised doubts about the applicability of the empirical piezoresistivity relationship to shot-peened surfaces without modification or compensation for the competing effects of peening-induced changes in the material conditions.

To this end, a comprehensive study of the microstructure effects was carried out based on the hypothesis that near-surface conductivity deviations induced by shot peening could be contributed by several competing factors, including (i) residual stress via piezoresistivity; (ii) microstructure such as peening-induced surface damages or variations in secondary phase content, and (iii) cold work (e.g. lattice defects, dislocations). The study reported in this paper was specifically aimed at examining the effects of cold work on conductivity profiles and EC signals. The approach is to compare changes in swept frequency EC (SFEC) signals induced by shot peening (SP) and laser shock peening (LSP). These two processes were used to produce different residual stress and cold work profiles, so that their correlations with conductivity profiles can be examined. Specifically, LSP is known to produce significantly smaller amount of cold work than SP. The residual stress profiles induced by LSP can extend to more than 1mm below the peened surfaces [9], significantly deeper than those created by SP which typically extend to about 200 μm in depth. In this work, a set of aged Inconel 718 samples was either SP at different Almen intensities, or LSP using different laser power densities. The conductivity profiles of the SP and LSP samples were obtained by means of model-based inversion of SFEC signals measured from the samples at frequencies between 100 kHz to 60 MHz. Surface residual stress and cold work were measured by a conventional x-ray diffraction method in order to aid interpretation of the observed difference in surface conductivity between the SP and LSP samples.

EXPERIMENTAL DETAILS

A set of double-aged Inconel 718 samples was used in this study. The samples were first solutionized at 954°C for one hour and then air-cooled. They were then aged at 732°C for eight hours, furnace cooled to 635°C and aged at 635°C for another eight hours, before they were air-cooled to room temperature. The heat-treated samples were cut into square blocks that measure 3" \times 3" \times 5/8" (76 mm \times 76 mm \times 16 mm). The bulk conductivity of the samples was measured to be 1.454% IACS using a conductivity gage operated at 60 kHz. The sample hardness was measured to be 46 HRC in the Rockwell C-scale.

Laser peening of the samples was performed by a commercial service vendor at three laser power levels, namely 6 GW/cm², 8 GW/cm², and 10 GW/cm², without the use of an ablative layer. The laser spot size was 3.85 mm by 3.85 mm for the 6 GW/cm² specimens and 3.0 mm by 3.0 mm for the other two laser power levels. The laser pulse width was 18 ns for all specimens.

Swept frequency EC measurements were carried out over two different, but overlapping, frequency bands using (i) a differential pair of 12 mm, 14-turn spiral coils fabricated on a printed circuit board (PCB) and a network analyzer (Agilent E5061A) for measurements from 1 MHz to 60 MHz, and (ii) an air-core 244-turn pancake coil together with an impedance analyzer (Agilent 4292A) for frequencies between 100 kHz and 5 MHz [8]. For each experimental setup, three sets of SFEC measurements were carried out to obtain the vertical component signals $V_{EX} \equiv \text{Im}\left\{\frac{(S_T - S_R)_{EXPT}}{(S_L - S_R)_{EXPT}}\right\}$, where S_R ,

S_L , and S_T , denote the reference signal measured from a pristine sample, the lift off signal and the test signal measured from a SP or LP sample, respectively.

SWEPT FREQUENCY EC SIGNALS

Figure 1 shows the vertical component signals obtained before and after LSP at different power levels. The peening-induced signal changes, which were obtained by subtracting the baseline data from the signals measured after LSP, are shown in Fig. 1(d). In general, the signals at frequencies up to 20 MHz were found to become more positive after laser peening. This implies that the sub-surface conductivity increases after LSP, consistent with the compressive residual stresses induced by the peening process. Such conductivity changes appear to extend deep into the materials, considering the fact that the skin depth at 1 MHz, where a significant increase in EC signal is observed, is estimated to be about 550 μm . In contrast, the signals at higher frequencies (greater than ~ 20 MHz) tend to become smaller after LSP. The signal change becomes increasing more negative as the laser power increases, suggesting the presence of a surface layer with a reduced conductivity due to peening-induced surface damages which have been observed in our previous studies [8].

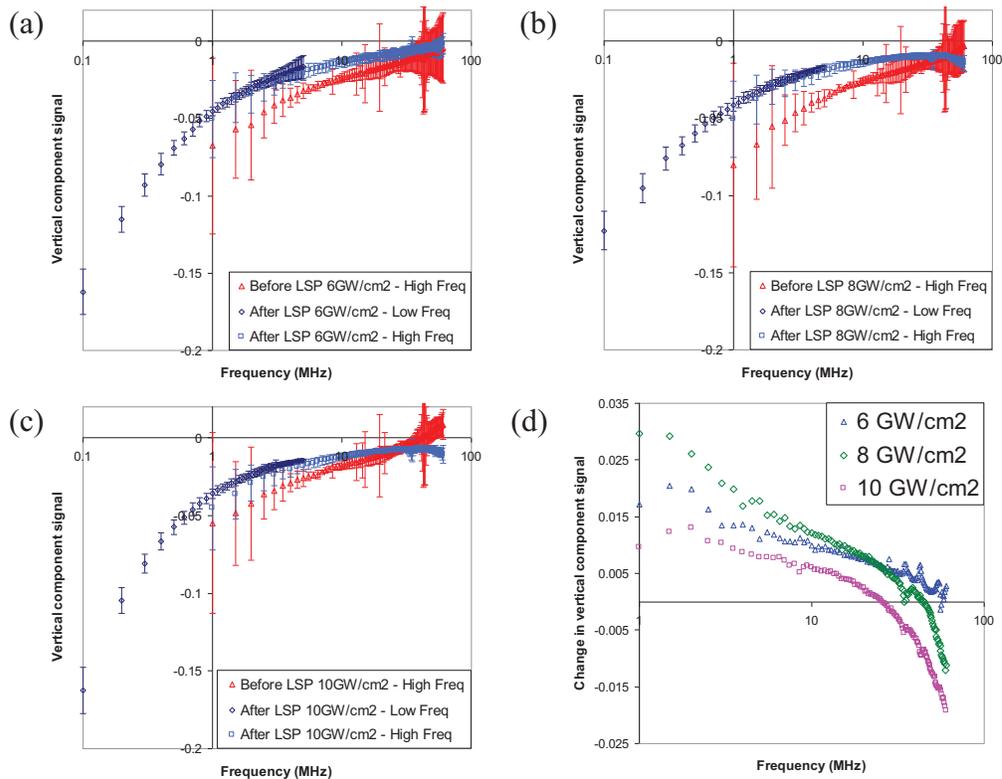


FIGURE 1. Swept frequency vertical component EC signals V_{EX} measured from the Inconel 718 samples before and after they were laser shock peened at (a) 6 GW/cm², (b) 8 GW/cm² and (c) 10 GW/cm². The results obtained after LSP consist of two sets of data measured at low frequencies (100 kHz to 5 MHz) and high frequencies (1 MHz to 60 MHz) using an air-core 244-turn pancake coil and a differential pair of PCB spiral coils, respectively. (d) Changes in vertical component signals versus frequency due to laser shock peening.

The vertical component EC signals measured from the samples before and after SP are shown in Fig. 2. It is evident that the shot peened samples exhibit a different trend in the peening-induced signal changes (Fig. 2(d)) from the LSP samples. Specifically, the signals at high frequencies ($> \sim 20$ MHz) become more positive after SP, indicating an increase in the near-surface conductivity. In contrast, the low frequency signals become lower as the Almen intensity increases, suggesting that the peening-induced conductivity changes are primarily present in the near-surface layer and gradually diminish with depth, unlike those observed in the LSP samples that extend to greater depths.

CONDUCTIVITY PROFILES BY MODEL-BASED INVERSION

The SFEC signals were converted into conductivity profiles using the matched filter approach based on a perturbation theory [8]. Specifically, the theoretical V-component V_{TH} is expressed in terms of a small relative conductivity deviation profile $\Delta\sigma(z)/\sigma_0$ as

$$V_{TH} = -\frac{1}{l} \text{Im} \int_0^{\infty} \exp((-2-2j)z/\delta) \frac{\Delta\sigma(z)}{\sigma_0} dz, \quad (1)$$

where l is the additional coil liftoff ($\cong 25 \mu\text{m}$ in our measurements), and $\delta = \sqrt{l/\pi\mu_r\mu_0\sigma_0 f}$ is the skin depth which depends on the frequency f , conductivity σ_0 , relative permeability μ_r , and the permeability of free space μ_0 . In this work, the conductivity profiles $\Delta\sigma(z)/\sigma_0$ of both SP and LP samples are described by a linear combination of three simple functions as

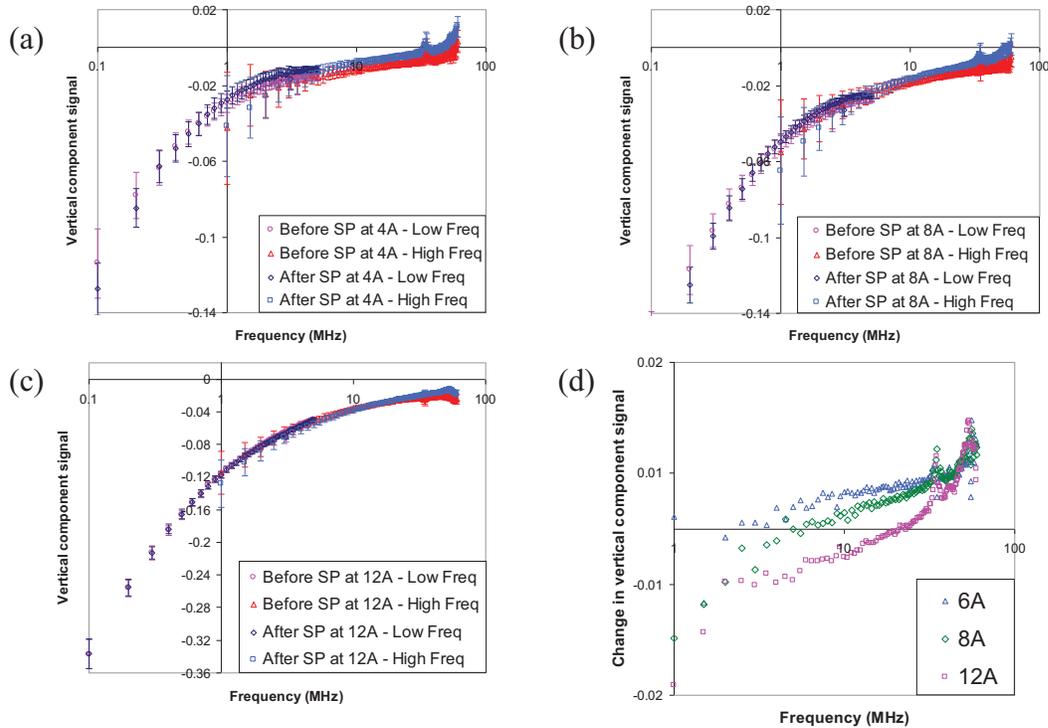


FIGURE 2. Swept frequency vertical component EC signals V_{EX} measured from the Inconel 718 samples before and after they were shot peened at (a) 4A, (b) 8A and (c) 12A. (d) Changes in vertical component signals versus frequency due to shot peening.

$$\frac{\Delta\sigma(z)}{\sigma_0} = g(\zeta, \varepsilon, a_1, a_2, a_3) = a_1 + a_2\theta(\zeta) + a_3 \frac{\varepsilon\zeta}{\varepsilon^2 + \zeta^2} e^{-\zeta} \quad (2)$$

where $\theta(\zeta) = \begin{cases} 1 & (\zeta \leq 1) \\ 0 & (\zeta > 1) \end{cases}$, $\zeta = z/d$ and ε, d, a_1, a_2 , and a_3 are fitting profile parameters. The

first term on the right hand side of Eq. (2) represents a constant conductivity shift arising from any bulk conductivity difference between the peened samples and the reference sample used in the SFEC measurements. The second term is a step function that accounts for the surface damages caused by the peening processes, which have been observed in our previous studies of shot peened Inconel 718 [8]. The third term is a peak function with an exponential decay that describes the typical residual stress profiles created by the peening processes. Substituting Eq. (2) into (1) leads to

$$(4l/\delta)V_{TH} = a_1 + a_2 [1 - e^{-\xi} (\cos \xi + \sin \xi)] - a_3 \varepsilon \xi \operatorname{Im}[e^{j\phi} E_1(j\phi) + e^{-j\phi} E_1(-j\phi)], \quad (3)$$

where $\phi \equiv \varepsilon [1 + (1+j)\xi]$, $\xi \equiv \frac{2}{\delta_0} d \sqrt{\frac{f}{f_0}}$, and $E_1(z) = \int_z^\infty t^{-1} \exp(-t) dt$. The left hand side of Eq. (3) is proportional to the product of \sqrt{f} and V_{TH} , while the right hand side is simply a function of \sqrt{f} . By fitting Eq. (3) to the data in the form of $\sqrt{f}V_{EXP}$ vs. \sqrt{f} , the profile parameter ε, d, a_1, a_2 , and a_3 and hence the conductivity profile $\Delta\sigma(z)/\sigma_0 = g(\zeta, \varepsilon, a_1, a_2, a_3)$ were determined.

Figure 3(a) shows the best fits of Eq. (3) to the vertical component signals measured from the LSP samples. The corresponding conductivity deviation profiles $\Delta\sigma(z)/\sigma_0$ are shown Fig. 4(a) where the step function (i.e. the second term of Eq. (2)), which describes the surface damages, has been removed so that the remaining profiles represent the conductivity changes due to the combined effects of residual stress and other competing factors, such as cold work. All the LSP samples show positive $\Delta\sigma(z)/\sigma_0$ over the entire depth range, presumably due to the piezoresistivity effect of the compressive residual stresses induced by LSP. Both the height and depth position of the profile peak increase monotonically as the laser power increases.

Similar to the LSP samples, the SP samples also exhibit positive $\Delta\sigma(z)/\sigma_0$, and the conductivity increase in the sub-surface region is larger for a high Almen intensity (Fig. 4(b)). Nevertheless, the conductivity profiles of the LSP and SP samples show two distinctive differences. The LSP samples in general exhibit a larger conductivity increase at the peened surfaces than the SP samples, and sustain a finite conductivity increase up to 0.5 mm. In contrast, the conductivity increase observed in the SP samples decays more rapidly and becomes negligible at 0.5 mm. The deeper conductivity profiles found in the LSP samples are attributed to the fact that residual stresses created by LSP may extend to more than 1 mm in depth, whereas those induced by SP are typically limited to about 200 μm below the peened surfaces.

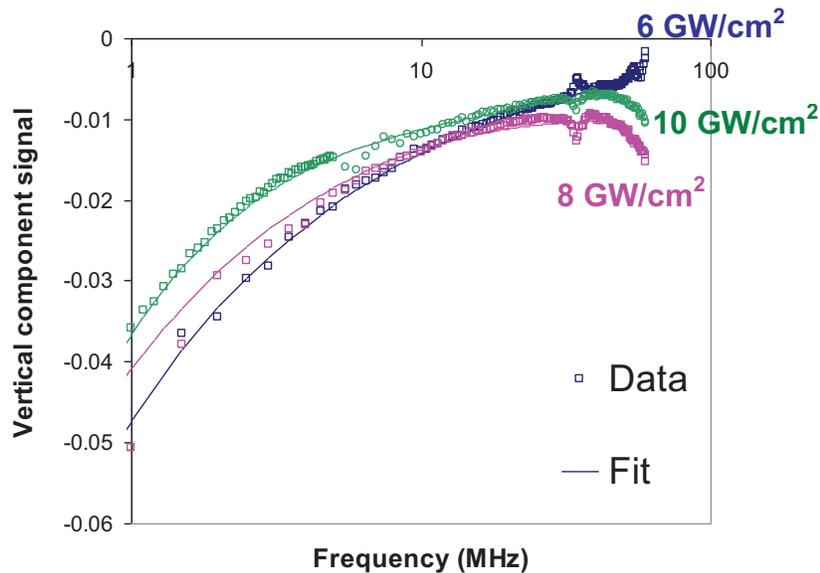


FIGURE 3. Measured (symbols) and modeled (solid lines) vertical component EC signals versus frequency (in the \log_{10} scale) for the Inconel 718 samples laser shock peened at 6 GW/cm², 8 GW/cm² and 10 GW/cm².

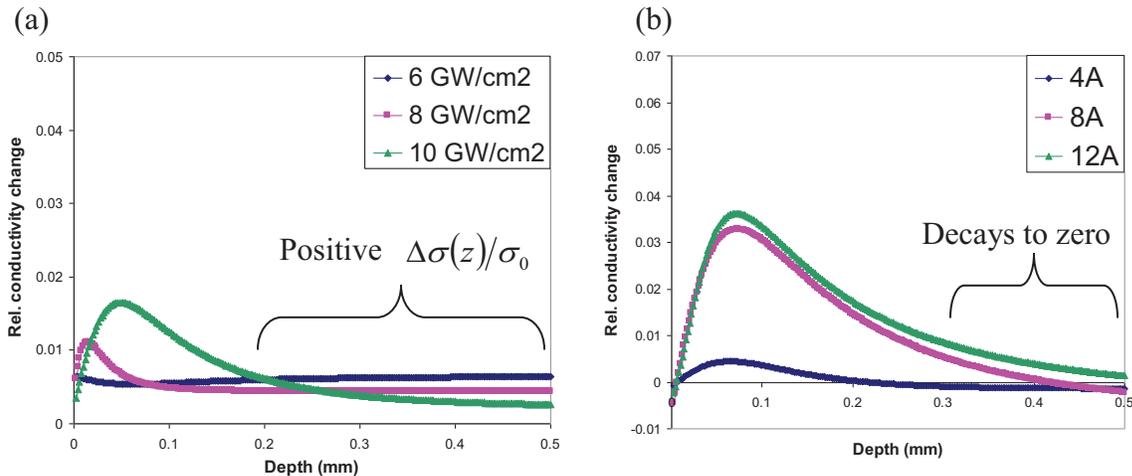


FIGURE 4. Inverted conductivity deviation profiles of the (a) LSP samples, and (b) SP samples, after removing the effects of surface damages that are represented by the step function in Eq. (3). Note that the LSP samples maintain positive conductivity change up to 0.5 mm, whereas for the SP samples the conductivity increase observed in the near-surface region in decays to approximately zero at 0.5 mm.

SURFACE RESIDUAL STRESS AND COLD WORK

The surface residual stresses and plastic strain (cold work) of the LSP and SP samples were characterized by the conventional $\sin^2\psi$ x-ray diffraction method, in order to aid in interpretation of the observed differences in surface conductivity changes induced by the two peening processes. As shown in Fig. 5, both the LSP and SP samples have compressive residual stresses at the peened surfaces, with the former showing lower residual stress levels than the latter. The SP samples nevertheless exhibit broader peaks than the LSP samples (Table I), indicating a larger amount of surface cold work produced by SP than by LSP.

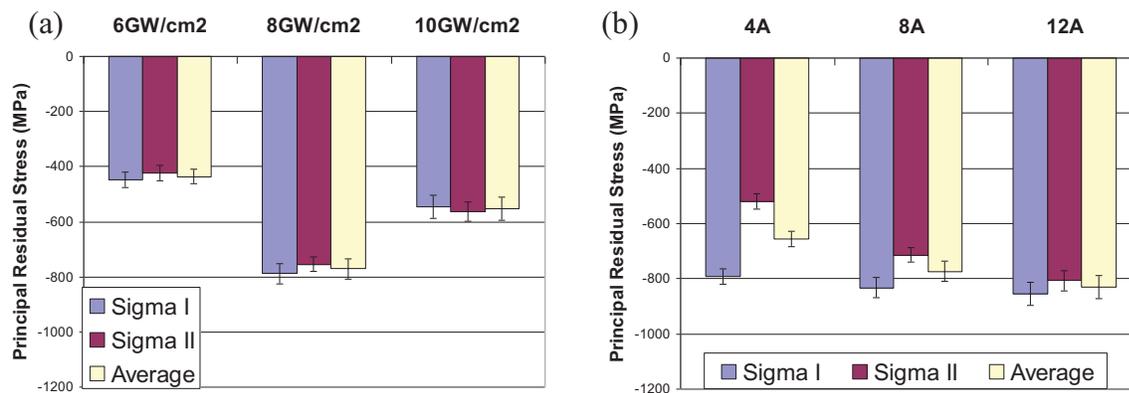


FIGURE 5. Principal in-plane residual stresses (Sigma I and II) measured from the (a) LSP samples, and (b) SP samples by the standard $\sin^2\psi$ XRD method. Also shown are the average values of the principal residual stresses.

TABLE I. Full width half maximum of the (220) diffraction peak measured at the surfaces of the LSP and SP Inconel 718 samples.

Peening condition	Laser shock peened			Shot peened		
	6 GW/cm ²	8 GW/cm ²	10 GW/cm ²	4A	8A	12A
Peak width	1.548°	1.752°	1.371°	2.228°	2.297°	2.710°

The observed surface conductivity is affected by the competing effects of compressive residual stress and cold work induced by the peening processes. The latter tends to reduce the conductivity due to increased electron scattering by lattice defects such as dislocations and substructures. Although the SP samples show higher levels of surface compressive residual stress, they also suffered a larger amount of cold work, which could negate the effects of compressive residual stress on conductivity and result in a lower surface conductivity than that of the LSP samples.

CONCLUSIONS

The competing effects of peening-induced residual stress and cold work on near-surface conductivity have been studied by performing swept frequency EC measurements on Inconel 718 samples subjected to shot peening and laser shock peening. The results of model-based inversion of conductivity deviation profiles of the peened samples show the presence of a thin surface damaged layer typically less than 20 μm thick. Both the shot peened and laser shock peened samples exhibit an increase in conductivity throughout the depth range of 0.5 mm due to the piezoresistivity effect of the compressive residual stresses induced by the peening processes. The conductivity increase observed in the laser shock peened samples extends to larger depths than that in the shot peened samples, attributed to the fact that laser peening can produce deeper residual stress profiles than shot peening. The shot peened samples in general show lower levels of surface conductivity than the laser peened samples. This can be interpreted in terms of the larger amount of surface cold work observed in the shot peened samples, which reduces conductivity and hence negates the piezoresistivity effect of the compressive residual stresses.

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