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DUAL-MODE GALVANOMAGNETIC CHARACTERIZATION OF SHOT-PEENED IN18 COUPONS

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ABSTRACT

Recently developed high-frequency Hall coefficient and eddy current conductivity measurement techniques were used to characterize fully hardened shot-peened IN718 coupons of Almen 4A, 8A and 12A intensity in both as-peened and thermally relaxed state. The experimentally obtained Hall impedance and conductivity spectra were inverted using a dual-mode inversion technique into residual stress and cold work depth-profiles. It was found that the Hall impedance decreases in shot-peened IN718 with the magnitude of the change increasing with peening intensity and decreasing with thermal relaxation. In contrast, typical conductivity changes are an order of magnitude lower, but measurements on Almen 12A deviated from this trend due to lift-off issues caused by the curvature of the coupon. The inverted residual stress profiles before and after thermal relaxation clearly indicated a significant decrease in the compressive residual stress levels due to thermal relaxation. The inverted residual stress and cold work profiles were compared with XRD results. Although, the quantitative agreement leaves much to be desired at this point, the qualitative agreement is promising for future studies.

Keywords: Residual stress, Hall effect, inversion

NOMENCLATURE

F_{11}	galvanoelastic gauge factor
F_{12}	galvanoplastic gauge factor
F_{21}	electroelastic gauge factor
F_{22}	electroplastic gauge factor
R_H	Hall coefficient
Z_H	Hall impedance
Γ	apparent eddy current conductivity
ν_p	Poisson ratio during plastic flow
σ	electrical conductivity

1. INTRODUCTION

Nondestructive evaluation (NDE) of the near-surface residual stress profiles is considered essential for reliable and accurate prediction of the remaining service life of shot-peened engine components. Currently, the only established method to assess near-surface residual stress is based on X-ray diffraction (XRD) measurements, which is destructive in nature. This study involved collecting experimental Hall impedance spectra over the frequency range 100 kHz – 30 MHz using a novel inductive sensing technique [1] and apparent eddy current conductivity (AECC) spectra from 300 kHz to 100 MHz [2] on shot-peened IN718. Since the residual stress to cold work ratio is changing during thermomechanical relaxation, measurements were conducted on both as-peened and thermally relaxed IN718. This experimental data was inverted into residual stress and cold work depth-profiles using a dual-mode inversion technique [3] and then compared to XRD data.

2. MATERIALS AND METHODS

Twelve 1/8”-thick 3”-by-3” IN718 coupons were heat treated using a process that involved solution annealing at 982°C for 30 minutes, aging at 704°C for 8 hours, and post aging at 649°C for 8 hours. This process strengthens the material due to precipitate hardening, increasing the hardness to 42-44 HRC. Nine of these coupons were shot peened by Metal Improvement Co. at three different peening intensities (Almen 4A, 8A, and 12A) with 100% nominal coverage, while the remaining three coupons were left unpeened and were used as reference coupons. The thickness of the coupons had to be restricted to 3 mm due to the current size limitation of the Hall impedance measurement system [1]. The relatively small thickness causes the coupons to curve a little as the result of shot-peening and this curvature limits the accuracy of high-frequency eddy current measurements. Finally, one coupon from each peening intensity group was thermally relaxed by heat treatment at 600°C for 100 hours that significantly decreases the cold work and the peak residual stress levels near the surface of shot-peened IN718. XRD measurements were conducted on both as-peened and thermally relaxed coupons.

The dual-mode inversion process makes use of (i) the measured relative Hall impedance change and AECC change spectra, (ii) a simplistic approximation, and (iii) the four

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experimentally determined gauge factors, $F_{11} = 5.9$, $F_{12} = -0.52$, $F_{21} = -1.46$, $F_{22} = -0.146$ [3]. The galvanoelastic F_{11} and electroelastic F_{21} gauge factors measured under uniaxial stress were multiplied by two to account for the isotropic biaxial stress prevailing at the surface when applied to shot-peened components. Next, a correction factor to account for the difference between the ways plastic deformation occurs during calibration of destructive XRD measurements conducted under uniaxial compressive stress and shot peening that produces incompressible flow in the surface layer had to be established. In both cases, the material acts like an incompressible fluid with a Poisson ratio of $\nu_p = 0.5$. In addition, the depth of a single indentation during the shot-peening process is much smaller than the thickness of the specimen, therefore on a local basis the specimen can be assumed to be semi-infinite. Therefore, the plastically deformed surface layer cannot extend laterally like the reference specimen can during XRD calibration tests under uniaxial compression. Instead, the direct plastic deformation that is normal to the surface is accompanied by in-plane plastic deformation produced by the reaction forces that cancel the in-plane expansion of the surface layer produced by the direct action of peening. As a result, the effects of plastic deformation on the Hall coefficient and the electric conductivity are also effectively doubled, i.e., F_{12} and F_{22} measured under uniaxial stress should be doubled to account for the conditions existing during shot peening.

3. RESULTS AND DISCUSSION

A dual-mode galvanomagnetic NDE technique consisting of high-frequency inductive Hall impedance and eddy current conductivity measurements was developed to characterize as-peened and thermally relaxed IN718 at three different peening intensities [3]. Three as-peened IN718 coupons per each of the three peening intensity groups and a similar unpeened Almen 0 group were used to obtain the relative Hall impedance change $\Delta Z_H/Z_{H0}$ and AECC change $\Delta\Gamma/\Gamma_0$ spectra for shot-peened IN718, as shown in Figure 1 where the dashed lines represent predictions based on COMSOL simulations. The obtained experimental results indicate that, while the Hall impedance spectrum in shot-peened IN718 starts to significantly decrease around 1-2 MHz, the AECC spectrum undergoes only slight change all the way up to 100 MHz. The maximum relative AECC change of about 1% was measured in the case of Almen 8A peening intensity at 100 MHz. The magnitude of change associated with Hall impedance was 3.6% for Almen 4A, 8.5% for Almen 8A and 9.8 % for Almen 12A at 10 MHz, which is about one order of magnitude higher compared to that of AECC change in shot-peened fully hardened IN718. This is because the effect of cold work and residual stress add up in the case of Hall impedance measurements but more or less cancel each other in the case of AECC measurements.

These results were compared to predictions based on numerical simulations which use Hall coefficient $\Delta R_H(z)/R_{H0}$ and electric conductivity $\Delta\sigma(z)/\sigma_0$ depth profiles as input parameters. These profiles were calculated using the established residual stress and cold work profiles obtained from destructive

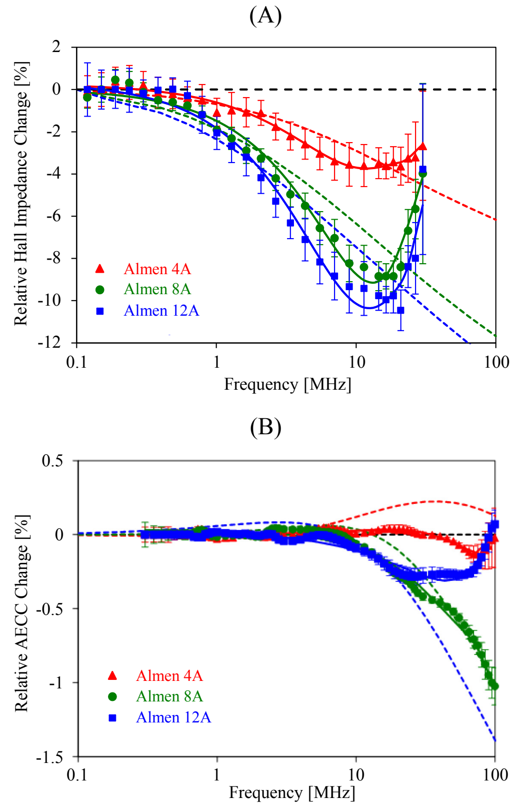

FIGURE 1: RELATIVE (A) HALL IMPEDANCE AND (B) AECC CHANGE SPECTRA FOR AS-PEENED IN718 COUPONS AT THREE DIFFERENT PEENING INTENSITIES.

XRD results and the four corrected gauge factors of the material. The trend in the measured relative Hall impedance change for shot-peened IN718 was reasonably well predicted by numerical simulations both in terms of the direction and magnitude of change. However, the trend in the measured relative AECC change for shot-peened IN718 is less well predicted. This is acceptable at this stage given the rather small AECC changes predicted and the curvature of the coupons which creates lift-off issues at high frequencies.

Similar Hall impedance and eddy current measurements were conducted on one thermally relaxed coupon from each peening intensity group that was exposed to 600°C for 100 hours. The results are plotted in the Figure 2, where the dashed lines represent COMSOL simulation predictions. This was done to establish that the dual-mode inspection technique, which measures the changes in two separate material properties, along with the favorable gauge factors in the case of fully hardened IN718, offers a possible way to separate the effects of residual stress and cold work in shot-peened IN718 despite the varying cold work to residual stress ratio in thermally relaxed IN718. The measured relative Hall impedance change significantly decreases for thermally relaxed IN718 compared to as-peened IN718. This indicates that the observed change in the magnitude of Hall impedance is sensitive to decreasing residual stress and cold work levels. This conclusion was also verified

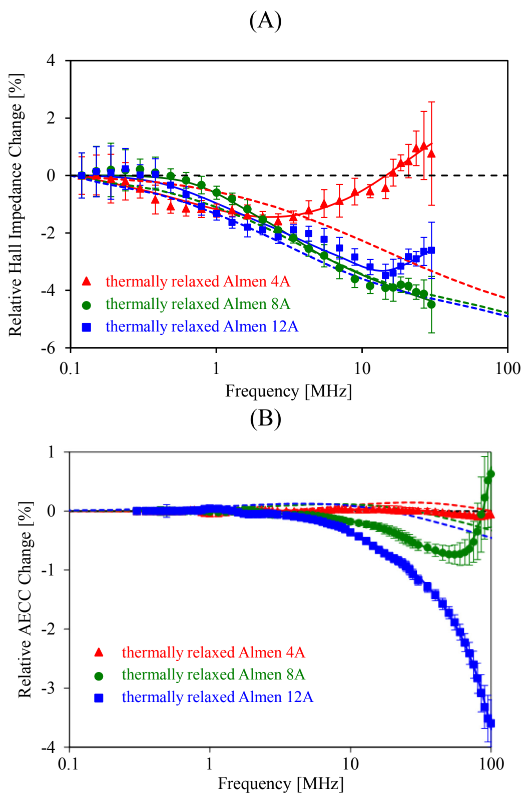

FIGURE 2: RELATIVE (A) HALL IMPEDANCE AND (B) AECC CHANGE SPECTRA FOR THERMALLY RELAXED IN718 COUPONS AT THREE DIFFERENT PEENING INTENSITIES.

by numerical simulations, where the predictions were in reasonable agreement with the measured data. However, in the case of AECC measurements on thermally relaxed IN718, the changes measured were excessive when compared to predictions based on numerical simulations for Almen 8A and 12A. This discrepancy is most likely due to the lift-off issues associated with the uncorrected curvature of highly peened IN718 coupons. Finally, the Hall impedance change and AECC change spectra measured on as-peened and thermally relaxed IN718 were inverted using simplistic approximations [3]. The inverted residual stress depth-profiles are plotted in Figure 3, where the solid lines represent XRD results.

4. CONCLUSION

The proposed dual-mode inspection technique, along with the favorable gauge factors in the case of fully hardened IN718, offers a possible way to separate the effects of residual stress and cold work in shot-peened IN718 despite the varying cold work to residual stress ratio in thermally relaxed IN718. The inverted residual stress profiles before and after thermal relaxation clearly indicated a significant decrease in the compressive residual stress levels due to thermal relaxation. Although, the quantitative agreement between the destructive XRD and the inverted dual-mode NDE residual stress and cold work depth profiles leaves much to be desired, it should be remembered that this was the very first absolute comparison without any adjustable parameters, i.e., without any empirical calibration. Under these circumstances, the obtained results are fairly promising.

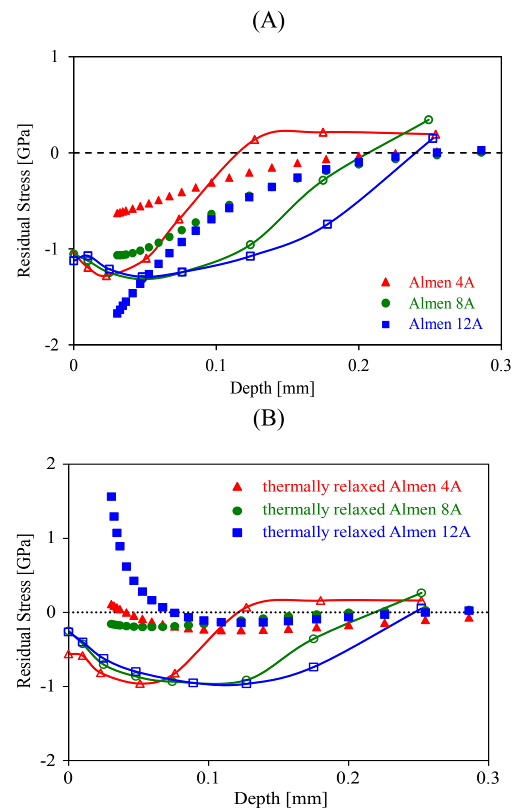

FIGURE 3: RESIDUAL STRESS DEPTH-PROFILES IN (A) AS-PEENED AND (B) THERMALLY RELAXED IN718 COUPONS AT THREE DIFFERENT PEENING INTENSITIES.

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