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DIRECTIONAL AND NONDIRECTIONAL GALVANOMAGNETIC GAUGE FACTOR MEASUREMENTS FOR RESIDUAL STRESS ASSESSMENT IN IN718

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ABSTRACT

Galvanomagnetic stress assessment exploits the sensitivity of the Hall coefficient in conducting materials on elastic deformation that is measured by the galvanomagnetic gauge factor. Earlier investigations based on the so-called transverse galvanomagnetic potential difference method considered only the galvanomagnetic gauge factor for current flow parallel to the applied uniaxial stress. However, typical surface treatments, such as shot peening, produce essentially isotropic plane state of residual stress, which means that the effects of parallel and normal stress components are inherently summed for any direction of current flow. The outcome could be either enhancement of the sensitivity or almost complete cancellation. Both parallel and normal galvanomagnetic gauge factors were measured with directional contact sensing at 16 Hz as well as the average galvanomagnetic gauge factor with nondirectional inductive sensing at 260 kHz. These tests showed that the galvanomagnetic gauge factors of fully hardened IN718 exhibit favorable behavior for residual stress profiling in surface-treated components because their values are the same $\kappa = +2.7$ within the estimated measurement uncertainty of ±0.1 for both parallel and normal stress orientations.

Keywords: stress measurement, Hall effect, gauge factor

NOMENCLATURE

B_z	bias magnetic field
E	Young's modulus
f	inspection frequency
I	injected current
R_H	Hall coefficient
t	specimen thickness
V_H	Hall voltage
Z_H	Hall impedance
δ	standard penetration depth
κ	galvanomagnetic gauge factor
ν	Poisson's ratio
τ	uniaxial stress

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1. INTRODUCTION

Recently, a series of experimental studies investigated the feasibility of galvanomagnetic stress measurement based on the dependence of the Hall coefficient in conducting materials on elastic deformation [1-4]. The galvanomagnetic gauge factor is defined as follows

$$\kappa = \left(\frac{\Delta R_\mathrm{H}}{R_\mathrm{H0}}\right) \Big/ \left(\frac{\tau}{E}\right), \tag{1}$$

where R_H0 is the Hall coefficient of the unstressed material, ΔR_H is the change of the Hall coefficient with respect to R_H0 under uniaxial stress τ, and E is Young's modulus [3]. This study was aimed at addressing one of the remaining open questions concerning the feasibility of the new galvanomagnetic nondestructive evaluation technique developed for residual stress profiling in surface-treated aircraft engine alloys. In past research, only the directional transverse galvanomagnetic potential difference technique was used to measure the galvanomagnetic gauge factor with the current flow being parallel to the applied uniaxial stress. However, typical surface treatments, such as shot-peening, produce an essentially isotropic plane state of residual stress, which means that the effects of parallel and normal stress components are inherently summed for any direction of current flow. It was found earlier in the case of the stress dependence of the electric conductivity [5] that the outcome of such summation could be either an enhancement of the sensitivity to residual stress by as much as a factor of two when the two sensitivities are of equal sign and approximately equal in magnitude, e.g., in nickel-base superalloys, or an almost complete cancellation when the two sensitivities are of opposite sign and approximately equal in magnitude, e.g., in titanium and aluminum alloys. Therefore, galvanomagnetic gauge factor measurements were conducted in fully hardened IN718 alloy to verify that the parallel and normal directional gauge factors measured using the classical transverse potential drop method are close to each other and their average is equal to the nondirectional gauge factor measured by a novel technique based on inductive sensing.

2. DIRECTIONAL GAUGE FACTOR MEASUREMENT

The low-frequency Hall coefficient measurement system previously described in [3] was used for directional gauge factor measurements at 16 Hz. Directional galvanomagnetic gauge factors characterize the stress dependence of the Hall coefficient with the current flow being either parallel or normal to the uniaxial applied stress. In order to verify that the parallel and normal galvanomagnetic gauge factors are both positive and of similar magnitude in fully hardened IN718, first the two gauge factors were measured separately using directional Hall coefficient measurements as shown in Figure 1. According to the Reverse-Field Reciprocity principle [6], the (a) parallel and (b) normal Hall coefficients must be the same if the polarity of the magnetic field is also flipped when the current injection and voltage sensing loops are switched.

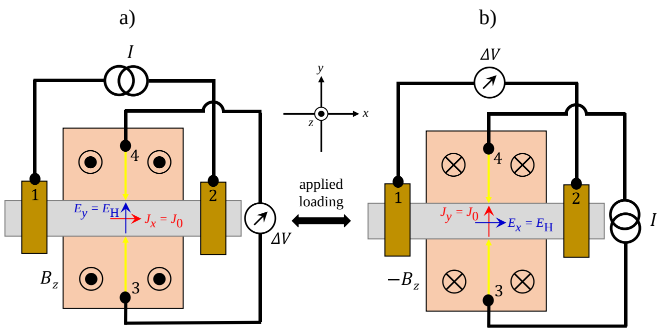

FIGURE 1: MEASUREMENTS OF THE PARALLEL AND NORMAL GALVANOMAGNETIC GAUGE FACTORS USING THE REVERSE MAGNETIC RECIPROCITY PRINCIPLE.

Figure 2 shows the directionally measured Hall coefficient and galvanomagnetic gauge factor at different levels of plastic strain in fully hardened IN718. The parallel and normal Hall coefficients of fully hardened undeformed IN718 were found to be $R_{Hp} = 9.5\times10^{-11}$ m^3/C and $R_{Hn} = 9.3\times10^{-11}$ m^3/C while the corresponding galvanomagnetic gauge factors were $\kappa_p = 2.6$ and $\kappa_n = 2.7$, respectively. It should be mentioned that the measured raw values were corrected for the changing thickness of the 1-mm-thick specimens due to the Poisson effect. These results indicate that there cannot be significant directional difference between the parallel and normal galvanomagnetic gauge factors relative to the loading direction, therefore, assuming linear superposition, the sum of the parallel and normal gauge factors can be used for inversion purposes under isotropic plane-stress conditions. However, these results are direct consequences of the Reverse-Field Reciprocity principle, therefore additional efforts were made to measure the nondirectional Hall coefficient and galvanomagnetic gauge factor of fully hardened IN718 with inductive sensing.

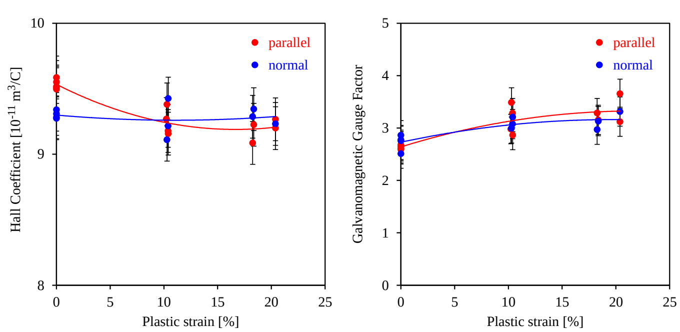

FIGURE 2: DIRECTIONALLY MEASURED HALL COEFFICIENT AND GALVANOMAGNETIC GAUGE FACTOR AT DIFFERENT LEVELS OF PLASTIC STRAIN IN FULLY HARDENED IN718.

3 NONDIRECTIONAL GAUGE FACTOR

The nondirectional galvanomagnetic gauge factor can be directly measured using the recently developed technique based on inductive sensing of the so-called Hall-Corbino current [7]. In the presence of a uniform static magnetic flux density B_z normal to the surface, the magnetic Lorentz force produces an azimuthal Corbino current which in turn generates a normal dynamic magnetic field that can be exploited for inductive measurement of the Hall coefficient using a sensing coil positioned concentrically around the injection point as it is shown in Figure 3. The Hall impedance is defined as the induced Hall voltage divided by the injection current, i.e., $Z_H = V_H/I$. Such nondirectional stress-dependent Hall impedance measurements were conducted on fully hardened IN718 specimens in its intact state (no plastic deformation) using inductive sensing. It was determined that the optimal experimental arrangement consisted of a magnetic bias of $B_z = 0.22$ T. The induced Hall voltage was detected with a dual double-sided coil of 80 turns and 3.3 mm average coil radius.

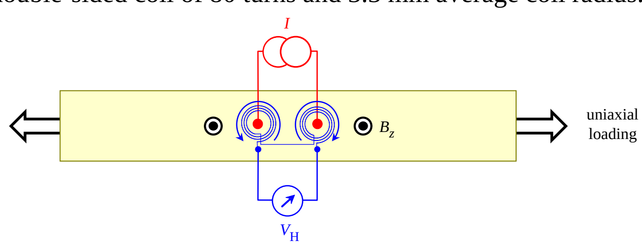

FIGURE 3: SENSING AND CURRENT INJECTION LOOPS CONFIGURED FOR STRESS-DEPENDENT HALL COEFFICIENT MEASUREMENT WITH INDUCTIVE SENSING.

In the low- and high-frequency regions the Hall impedance is proportional to the inspection frequency and its square root, respectively, while in the transition region the frequency dependence is more irregular [7]. The relative sensitivity of the Hall impedance to applied elastic stress is measured as a unitless gauge factor κ_Z that, following the definition of the galvanomagnetic gauge factor given earlier in Eq. (1) is defined as the ratio of the relative change of the Hall impedance $\Delta Z_H/Z_{H0}$ divided by the axial elastic strain τ/E. Here and elsewhere, tabulated nominal values of Young's modulus ($E = 200$ GPa) and Poisson's ratio ($\nu = 0.3$) were used in the calculations. Unfortunately, it was not possible to increase the inspection frequency beyond $f = 300$ kHz with our inherently low-frequency measurement system built around a hydraulic load frame [3]. The best results were obtained at $f = 260$ kHz, which happens to be in the transition region where the plate thickness t is comparable to the standard electromagnetic penetration depth δ. Figure 4 shows the results of an experiment where 1,282 raw data points were collected at five different stress levels, and averaged over ≈60-minute intervals. The axial load was changed periodically between intervals through five different stress ranges between 70 MPa and 560 MPa. The best fitting linear regression line of the measured data yields a raw gauge factor of $\kappa_Z = 2.73$. However, additional thickness and conductivity corrections will have to be applied to account for additional changes in the Hall impedance due to stress besides that of the Hall coefficient.

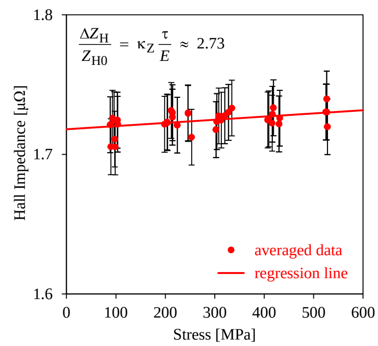

FIGURE 4: HALL IMPEDANCE MAGNITUDE VERSUS STRESS MEASURED WITH NONDIRECTIONAL INDUCTIVE SENSING AT 260 KHZ.

For the purposes of conductivity and thickness corrections, it is beneficial to rewrite Eq. (1) for the nondirectional galvanomagnetic gauge factor $\kappa_\circ$ in terms of dimensionless gauge factors of the Hall impedance κ_Z, electric conductivity κ_σ and plate thickness κ_t as follows

$$\kappa_\circ = \kappa_Z - F\kappa_\sigma - \nu\kappa_t , \quad (2)$$

where $F = -0.73$ is the known electroelastic coefficient of IN718 [5]. COMSOL Multiphysics FE simulations were used to correct the measured Hall impedance for the reduction in specimen thickness and change of conductivity due to elastic strain. Figure 5 shows the thickness and conductivity gauge factors as functions of frequency for a $t = 1$ mm thick IN718 plate. From Figure 5, $\kappa_t = -0.83$ and $\kappa_\sigma = 0.38$ at $f = 260$ kHz. Substituting these values into Eq. (2) yields a corrected nondirectional galvanomagnetic gauge factor of $\kappa_\circ \approx 2.76$ which agrees closely with the above reported directional values.

4. CONCLUSION

The previously developed transverse galvanomagnetic Hall coefficient technique was modified to facilitate non-contact inductive sensing that exploits the Hall-Corbino effect. The nondirectional galvanomagnetic gauge factor of fully hardened IN718 was found to be $\kappa_\circ \approx 2.76$. This value agrees well with the average of the independently measured parallel and normal directional galvanomagnetic gauge factors, i.e., $\kappa_\circ = \frac{1}{2}(\kappa_p + \kappa_n)$. This result illustrates that the inductive Hall-Corbino effect is sensitive to biaxial residual stress in fully hardened IN718 and

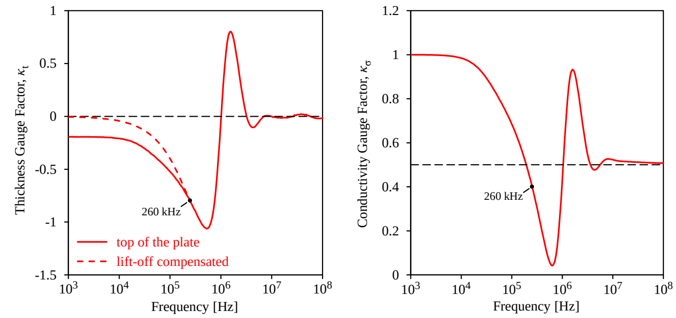

FIGURE 5: THICKNESS AND CONDUCTIVITY GAUGE FACTORS VERSUS FREQUENCY OBTAINED BY FE SIMULATIONS FOR A 1-MM-THICK IN718 PLATE.

can be exploited for residual stress assessment in surface-treated IN718 components that exhibit isotropic plane state of stress below the surface.

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