RESIDUAL STRESS ASSESSMENT IN SURFACE-TREATED NICKEL-BASE SUPERALLOYS

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Abstract: Experimental results are presented to illustrate that there exists a unique window of opportunity for eddy current NDE of residual stress in surface-treated nickel-base superalloys. In light of its frequency-dependent penetration depth, the measurement of eddy current conductivity has been suggested as a possible means to allow the nondestructive evaluation of subsurface residual stresses in surface-treated components. This technique is based on the so-called electro-elastic effect, i.e., the stress-dependence of the electrical conductivity. In contrast with most other materials, surface-treated nickel-base superalloys exhibit an apparent increase in electrical conductivity at increasing inspection frequencies. This observation by itself indicates that in these materials the measured conductivity change is dominated by residual stress effects, since both surface roughness and increased dislocation density are known to decrease rather than increase the conductivity and the presence of crystallographic texture does not affect the electrical conductivity of these materials, which crystallize in cubic symmetry. Experimental results indicate that the frequency-dependent apparent eddy current conductivity of shot-peened nickel-base superalloys can be used to estimate both the absolute level of the sub-surface stress and the penetration depth of the compressive layer. The eddy current results correlate well with residual stress profiles obtained by destructive X-ray diffraction measurements both before and after partial thermal relaxation.

Introduction: Shot peening is known to improve the resistance to fatigue and foreign-object damage in metallic components due to its damage arresting qualities. This surface enhancement process, which introduces beneficial residual stresses and hardens the surface, is widely used in a number of industrial applications, including gas-turbine engines. Modern aircraft turbine engine components are designed using a damage-tolerance philosophy that allows the prediction of a given component's useful service life based on fracture mechanics and structural analysis. However, the fatigue life improvement gained via surface enhancement is not explicitly accounted for in current engine component life management processes and there would be a significant potential for increasing the predicted damage tolerance capabilities of components if beneficial residual stress considerations could be incorporated into the life prediction methodology. A major barrier to introducing subsurface residual stress information into life prediction models is the necessity to make accurate and reliable nondestructive measurements on shot-peened hardware.

Due to its frequency-dependent penetration depth, eddy current inspection is an obvious candidate for use in characterizing the residual stresses resulting from shot peening [1-9]. Unfortunately, the eddy current conductivity is affected by a great number of variables beside residual stress, such as chemical composition, microstructure, plastic deformation, hardness, surface roughness, temperature, etc. Scientific evidence indicates that, even when the eddy current measurements are conducted with sufficient precision, the obtained parameters are affected by not only the existing residual stress profile, but also by the accompanying cold work [8] and surface roughness effects [7,10,11]. The penetration depth of the cold worked region is typically one third of that of the compressive residual stress, therefore, just like the surface roughness effect, cold work effects cannot be eliminated simply by an appropriate selection of the inspection frequency. Generally, cold work exhibits itself through lattice imperfections, e.g., increased dislocation density, and localized anisotropy caused by crystallographic and morphological texture. Separation of the residual stress and cold work effects requires careful optimization of the inspection method on a case-to-case basis. For example, crystallographic anisotropy strongly affects ultrasonic surface acoustic wave (SAW) measurements in all metals except those of very low elastic anisotropy like tungsten or aluminum, but has no effect on eddy current and thermoelectric measurements in metals that crystallize in cubic symmetry, a broad category that includes essentially all engine materials with the notable exception of titanium alloys [12,13].

In most metals the stress-dependence of the electrical conductivity is rather weak and the primary residual stress effect is very difficult to separate from the secondary cold work effect and, especially in shot-peened specimens, from the apparent loss of conductivity caused by the spurious surface roughness effect. In paramagnetic materials the electrical conductivity typically increases by approximately 1% under a maximum biaxial compressive stress equal to the yield strength of the material. However, the electrical conductivity measured on shot-peened specimens typically decreases with increasing peening intensity, often as much as 1-2%, which indicates that surface roughness and cold work effects dominate the observed phenomenon. We recently found that, in sharp contrast with most other materials, shot-peened nickel-base superalloy specimens exhibit an apparent increase in electrical conductivity at increasing inspection frequencies and demonstrated that the main reason for this behavior lies in the favorable piezoresistive properties of these alloys [14].

In the presence of elastic stress $[\tau]$ the electrical conductivity $[\sigma]$ tensor of an otherwise isotropic conductor becomes slightly anisotropic. In general, the stress-dependence of the electrical resistivity is described by the fourth-order piezoresistivity $[\pi]$ tensor [15,16]. Isotropic materials can be fully characterized by two independent parameters, namely the parallel (π_{11}) and normal (π_{12}) piezoresistivity coefficients. For easier comparison to our eddy current measurements we are going to consider the stress-induced change in the electrical conductivity rather than in the electrical resistivity. In direct analogy to the well-known acoustoelastic effect, a widely used NDE terminology for the dependence of the acoustic velocity on elastic stress, we are going to refer to the stress-dependence of the electrical conductivity as the electroelastic effect. In the three principal directions, the relative conductivity change can be expressed as follows

$$\begin{bmatrix} \Delta\sigma_1/\sigma_0 \\ \Delta\sigma_2/\sigma_0 \\ \Delta\sigma_3/\sigma_0 \end{bmatrix} = \begin{bmatrix} \kappa_{11} & \kappa_{12} & \kappa_{12} \\ \kappa_{12} & \kappa_{11} & \kappa_{12} \\ \kappa_{12} & \kappa_{12} & \kappa_{11} \end{bmatrix} \begin{bmatrix} \tau_1/E \\ \tau_2/E \\ \tau_3/E \end{bmatrix}, \tag{1}$$

where $\Delta\sigma_i = \sigma_i - \sigma_0$ ($i = 1,2,3$), $\sigma_0 = 1/\rho_0$ denotes the electrical conductivity in the absence of stress and $\kappa_{11} = -E\,\pi_{11}$ and $\kappa_{12} = -E\,\pi_{12}$ are the unitless normalized parallel and normal electroelastic coefficients, respectively, and E denotes Young's modulus. When a directional eddy current probe is used to measure the weighted average of the parallel σ_1 and normal σ_2 electrical conductivities under uniaxial stress, the effective electroelastic coefficient will be also a weighted average of the parallel κ_{11} and normal κ_{12} electroelastic coefficients. Elliptical and racetrack coils [12] usually have a modest aspect ratio of 4-5, but meandering winding magnetometers [17] offer a much sharper directionality. In the limiting case of an ideal unidirectional probe, under the influence of uniaxial stress τ_{ua}, the relative parallel and normal conductivity changes are

$$\eta_{11} = \frac{E}{\tau_{ua}}\frac{\Delta\sigma_1}{\sigma_0} = \kappa_{11} \quad \text{and} \quad \eta_{12} = \frac{E}{\tau_{ua}}\frac{\Delta\sigma_2}{\sigma_0} = \kappa_{12}\,, \tag{2}$$

respectively. In the case of shot-peened metals, essentially isotropic plane stress ($\tau_1 = \tau_2 = \tau_{ip}$ and $\tau_3 = 0$) conditions occur. Then, regardless whether non-directional circular or directional elliptical probes are used, the relative change in the measured average conductivity σ_a in the plane of stress can be written as follows

$$\eta_{ip} = \frac{E}{\tau_{ip}}\frac{\Delta\sigma_a}{\sigma_0} = \kappa_{11} + \kappa_{12}\,, \tag{3}$$

i.e., the measured conductivity change is proportional to the sum of the parallel and normal electroelastic coefficients.

Results: In order to better understand our eddy current results on shot-peened specimens, we measured the electroelastic coefficients of different metals in uniaxial compression and tension in a load frame using both non-directional circular and directional racetrack coil probes. The racetrack coils were oriented both parallel and normal to the loading direction to observe the directional dependence of stress on the apparent eddy current conductivity. We found that the electroelastic coefficients measured by the non-directional circular probe were equal to the average of those measured by the directional racetrack probe at parallel and normal orientations. For brevity, only the results of the directional measurements will be reported in here. The eddy current inspection frequency was always chosen so that the standard penetration depth ($\delta \approx 1$ mm) was much smaller than the thickness of the specimens, therefore the spurious thickness modulation caused by the Poisson effect could be neglected. All measurements were conducted over a sustained period of approximately 2 minutes so that the adverse effects of random noise and thermal drift could be sufficiently reduced via averaging. Figure 1 shows the results of electroelastic measurements in four different materials at a cyclic frequency of 0.5 Hz. It should be mentioned that special attention must be paid to the substantial difference between adiabatic and isothermal properties when dynamic calibration measurements are conducted on reference specimens using cyclic uniaxial loads above 0.02 Hz, which is fast enough to produce adiabatic conditions. In high-conductivity materials, like aluminum alloys, inherent thermoelastic temperature oscillations significantly affect the value of the measured electroelastic coefficients during dynamic loading, therefore appropriate corrections must be introduced. However, in high-temperature engine alloys of low electrical conductivity, such as nickel-base superalloys and titanium alloys, the difference between the isothermal and adiabatic parameters is fairly low, roughly one order of magnitude smaller than the measured parallel and normal electroelastic coefficients [18]. The most important conclusion one can draw from these results is that the parallel and normal electroelastic coefficients of nickel-base superalloys are both negative ($\kappa_{11} + \kappa_{12} \approx -0.9$ for Waspaloy and ≈ -1.6 for IN 718), therefore isotropic compressive plane stress conditions will significantly increase the electrical conductivity in these materials.

The first question is whether the apparent eddy current conductivity (AECC) difference between peened and unpeened surfaces diminishes with thermal relaxation or not. To answer this question, we inspected four shot-peened Waspaloy specimens of different peening intensity both before and after full thermal relaxation. Figure 2a shows the residual stress profiles as measured by X-ray diffraction (XRD). An important byproduct of the XRD stress measurement is the cold work distribution over depth in terms of plastic strain as shown in Fig. 2b, which is based on the width of the particular diffraction peak of interest (311). We can conclude that the peening intensity has a relatively strong effect on the degree and depth of the resulting cold work in shot-peened samples, with the highest degree of plastic strain occurring just below the surface at each peening intensity. In addition to the XRD data obtained from intact specimens (solid symbols), Figs. 2a and 2b also show the corresponding data obtained after full relaxation for 24 hours at 900 ºC (empty symbols). It is evident that essentially complete stress relaxation occurred in the specimens. In comparison, roughly one-fifth of the original cold work effect, which can be fully eliminated only by actual recrystallization, survived below the surface. Figure 3 shows the AECC differences recorded on these intact and fully relaxed Waspaloy specimens. Within the uncertainty of the eddy current measurement, the AECC difference completely vanished, which indicates that it is not only very sensitive to thermal relaxation, but also that it is mostly sensitive to the residual stress contribution since the cold work effect did not entirely disappear.

The next question is whether the AECC difference decays gradually with thermal relaxation or not, which is extremely important from the point of view of detecting partial relaxation. To answer this question, a Waspaloy specimen of Almen 8A peening intensity was gradually relaxed by repeated heat treatments of 24 hours each at increasing temperatures in 50-ºC steps from 300 ºC to 900 ºC in protective nitrogen environment. Figure 4 shows the decaying AECC difference between the peened and unpeened parts after each heat treatment. These results clearly indicate that the measured AECC difference gradually decreases during thermal relaxation and almost completely disappears after the 13th 24-hour heat treatment at 900 ºC, which is very promising for the possibility of sub-surface residual stress assessment in shot-peened Waspaloy.

The most crucial question is whether the AECC difference is proportional to the remaining residual stress throughout thermal relaxation or not. To answer this question, we subjected a couple of Waspaloy specimens of Almen 16A peening intensity to different thermal conditions, followed by eddy current conductivity and X-ray diffraction stress and cold work measurements. These samples were treated with three different thermal profiles at (i) 600 °C for 24 hours, (ii) 600 °C for 24 hours followed by 650 °C for 24 hours, and (iii) 900 °C for 24 hours and then compared to the original, as-received, shot peen condition. The XRD residual stress and cold work profiles for each case are shown in Fig. 5. There is a rather strong relaxation after the first heat treatment of 24 hours at 600 °C, which is somewhat surprising as one would think that the shot peening induced residual stress would be more persistent in Waspaloy. However, we already found in the previous series of measurements on a Waspaloy specimen of Almen 8A peening intensity, which is supposed to be thermally more stable because of the lower level of cold work present in the specimen, that significant relaxation occurs at temperatures as low as 500 °C (see Fig. 4), therefore these XRD results are not entirely unexpected. One possible explanation for this early relaxation is that these Waspaloy specimens were stress annealed prior to shot peening, which typically puts the material in its softest state. Another unexpected result is shown in the XRD cold work profiles where the degree of cold work is slightly higher in case (ii) than in case (i). This discrepancy is unusual, but the precise pedigree of the Waspaloy we used is unknown and samples may have come from plate stock with different rolling conditions.

For each case, eddy current conductivity measurements were performed between 100 kHz and 10 MHz. As before, differential measurements were made between peened and unpeened surfaces using automatic scanning. As shown in Figure 6, the eddy current measurements are consistent with the XRD data in that case (i), i.e., the 600-° C, 24-hour thermal treatment, caused a dramatic change in shot peen condition, as compared to the original. A comparison of the eddy current data for case (i) and case (ii) suggests only a modest change in condition between the two, and case (iii) indicates virtually complete elimination of shot peen effects in the measured AECC. Overall, the decay of the AECC difference between the peened and unpeened specimens is roughly proportional to the decay of the sub-surface residual stress, although a more quantitative comparison has not been attempted yet. It should be mentioned that there are numerous analytical and numerical methods that could be exploited to invert the frequency-dependent AECC [19-22]. The conductivity profiles obtained from such inversion then could be used directly to assess the existing residual stress profile based on the empirically determined electroelastic coefficients of the material. These efforts will be part of our follow-up study.

Conclusions: Our preliminary experiments indicate that there exists a unique "window of opportunity" for eddy current NDE in nickel-base superalloys. We identified five effects that contribute to this fortunate constellation of material properties. First, the parallel stress coefficient of the electrical conductivity has a large negative value while the normal coefficient is smaller but also negative. As a result, the average stress coefficient is also large and negative, therefore the essentially isotropic compressive plane state of stress produced by most surface treatments causes a significant increase in the electrical conductivity parallel to the surface. Second, the electrical conductivity in nickel-base superalloys is rather low (~1.5 %IACS) therefore the penetration depth is relatively high at a given frequency (~250 µm at 5 MHz). Therefore, at typical inspection frequencies we can detect the increasing conductivity due to the highly persistent residual stresses at larger depths that cannot be measured in a nondestructive way by X-ray diffraction, which is sensitive to the very unstable near-surface residual stresses only. Third, the hardness is relatively high therefore the spurious surface roughness is relatively small for typical Almen intensities (3A-8A) used on engine components, therefore the apparent conductivity drop due to this artifact is also relatively small. Fourth, for the same reason, eddy current measurements are relatively insensitive to the conductivity reduction caused by increased dislocation density due to cold work, which causes the thermal instability of the near-surface residual stress in the first place. Fifth, these materials crystallize in cubic symmetry, therefore the electrical conductivity does not exhibit crystallographic anisotropy. As a result, the spurious crystallographic texture below the surface does not affect the measurement at all. Based on these findings, we plan to conduct a comprehensive study to further investigate this unique opportunity for electromagnetic NDE of nickel-base superalloys.

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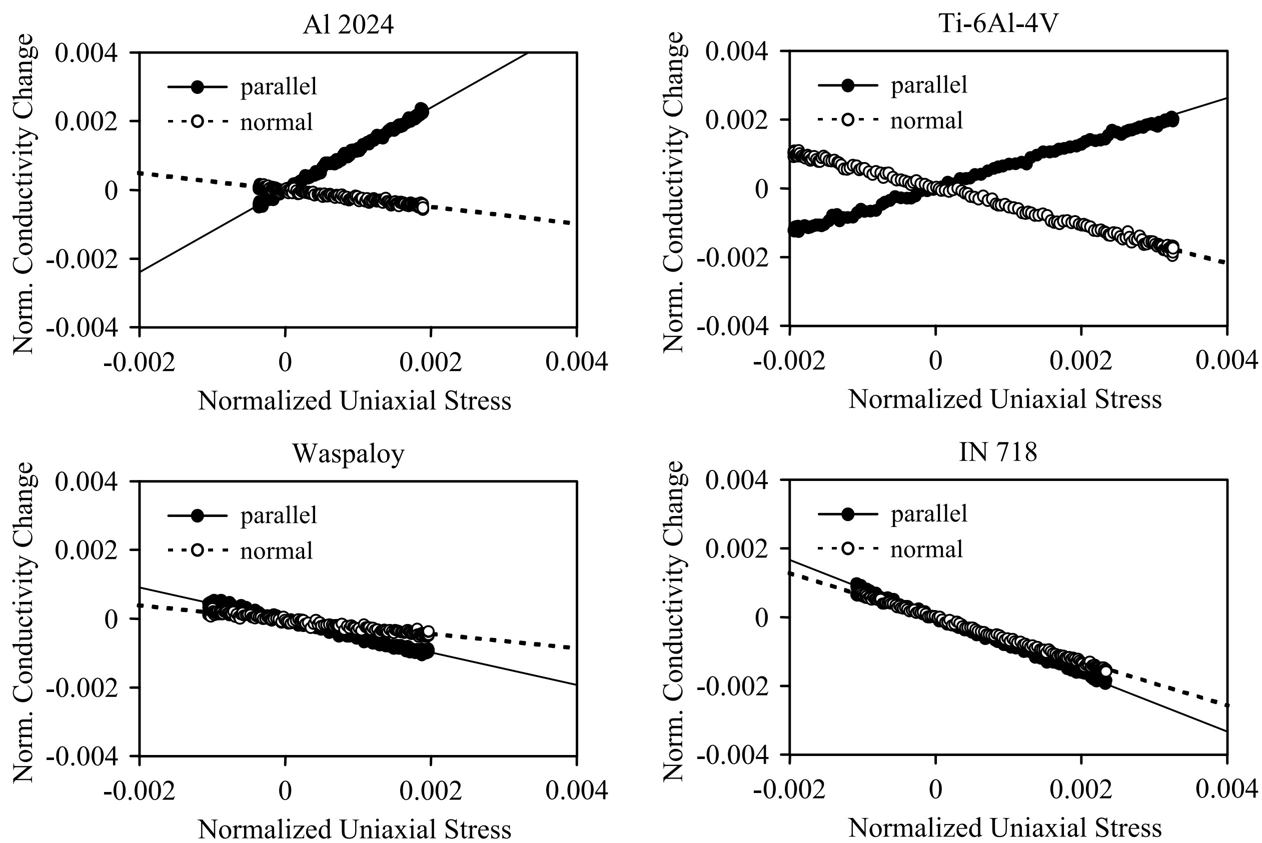

Figure 1 Electroelastic measurements in four different materials using a directional eddy current probe parallel and normal to the applied uniaxial load.

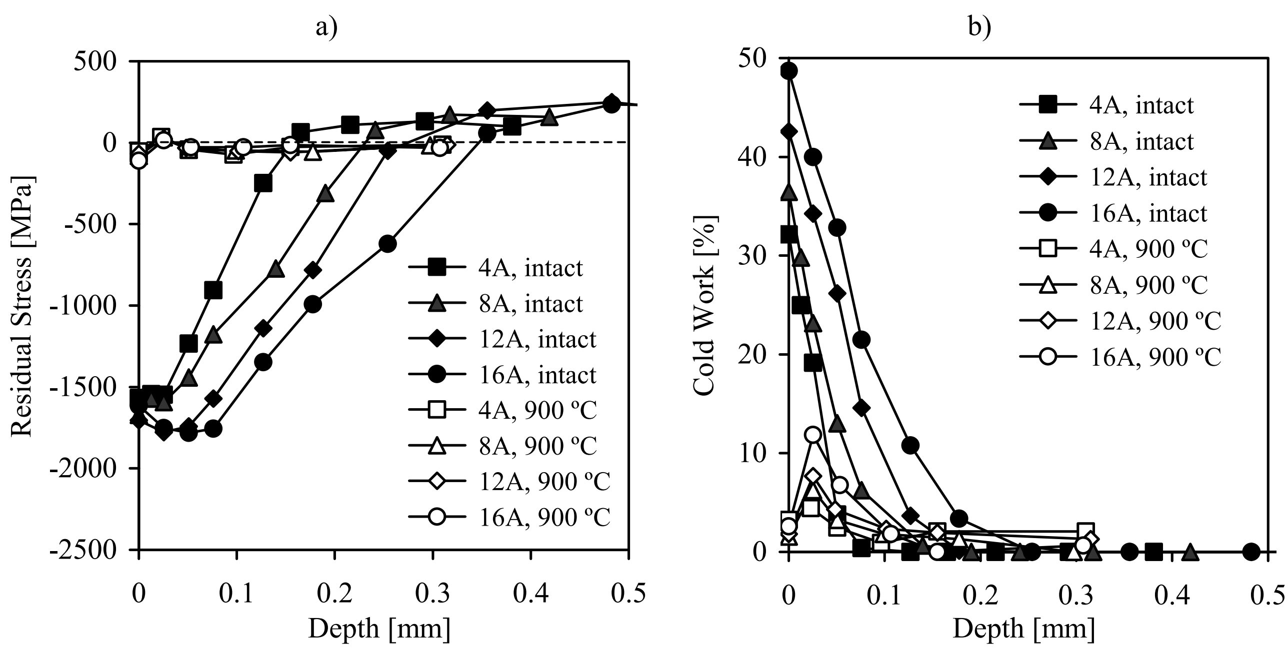

Figure 2 X-ray diffraction (a) residual stress and (b) cold work profiles in a series of shot-peened Waspaloy samples before and after full relaxation (24 hours at 900 ºC).

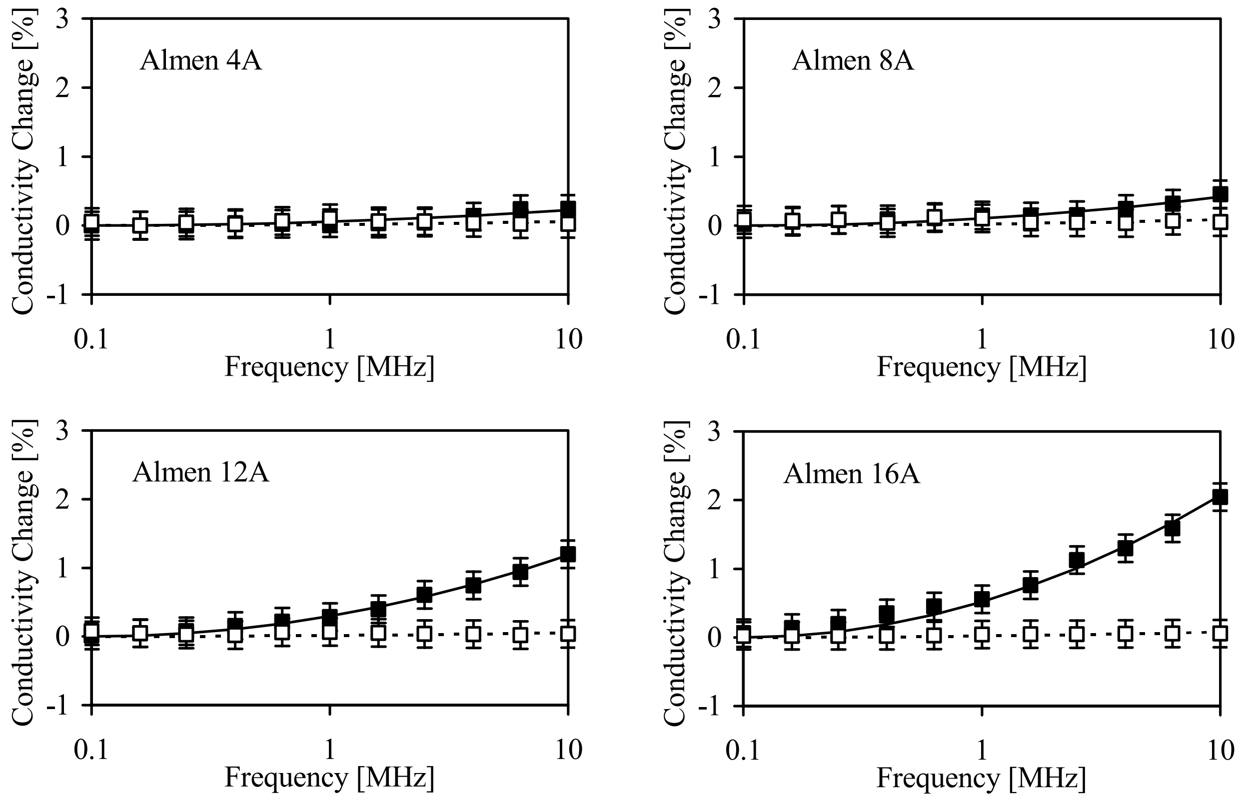

Figure 3 AECC differences recorded on intact (solid symbols) and fully relaxed (empty symbols) Waspaloy specimens (the solid and dashed lines represent corresponding trend lines).

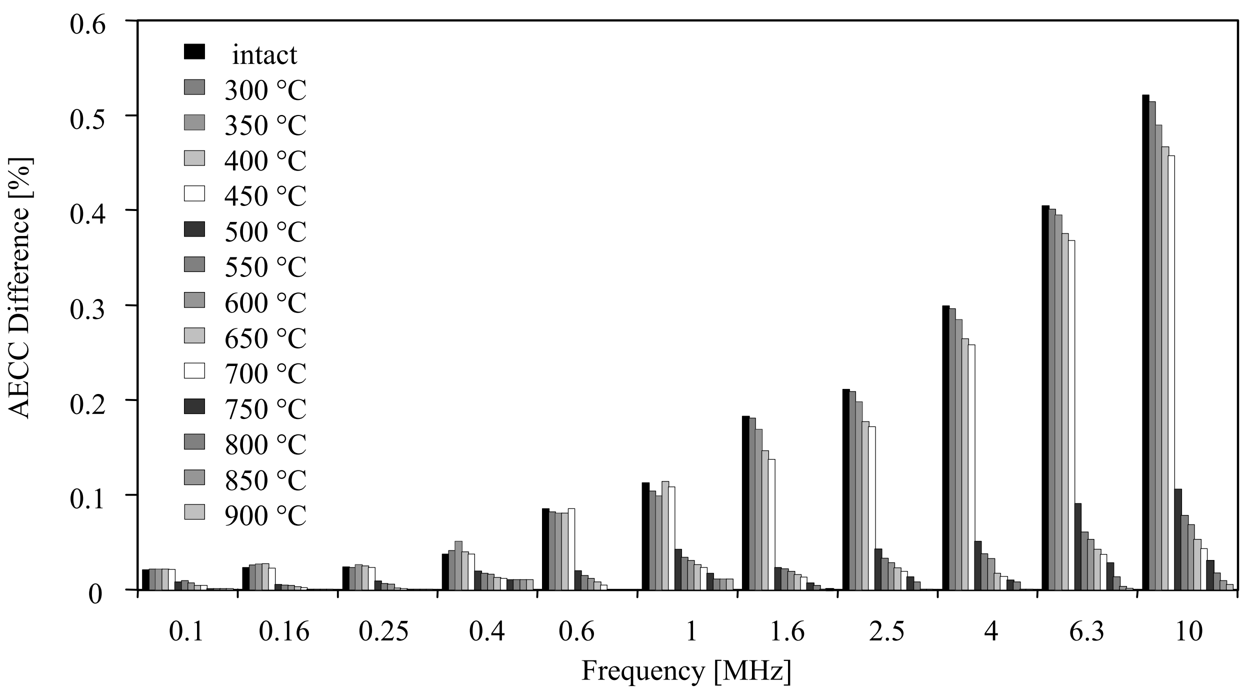

Figure 4 The decay of AECC difference between the peened and unpeened parts of a Waspaloy specimen of Almen 8A peening intensity during gradual thermal relaxation.

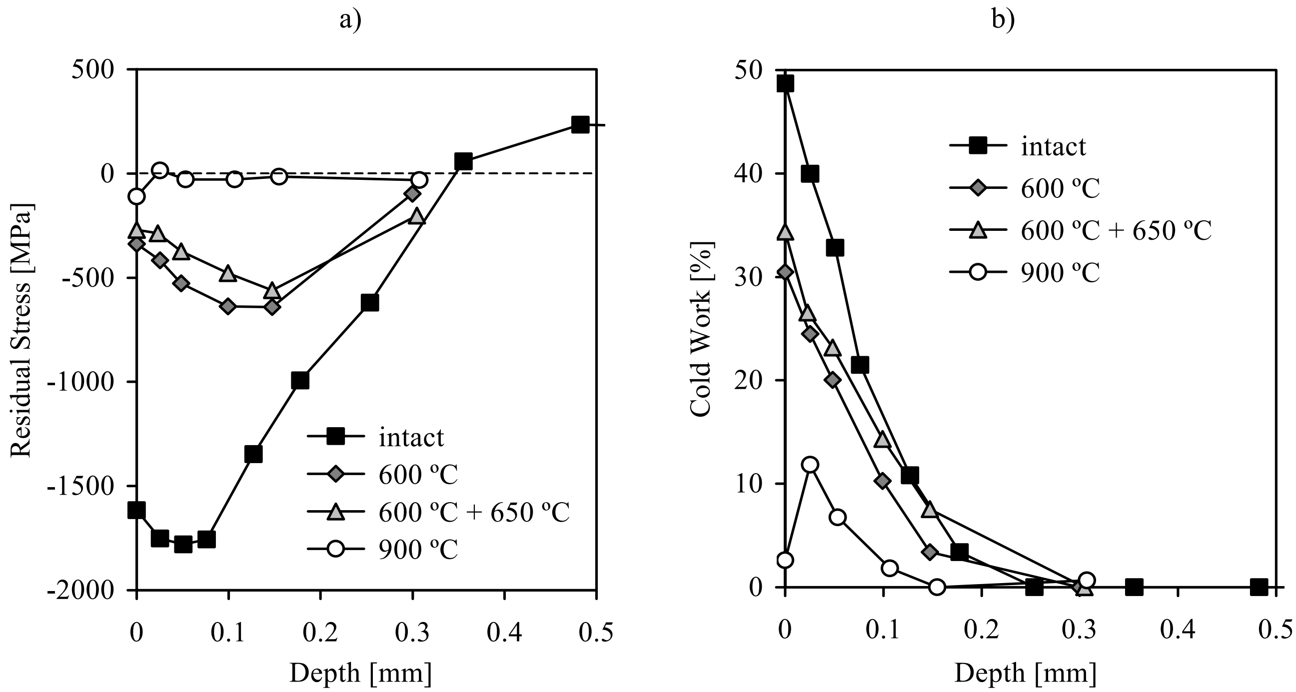

Figure 5 X-ray diffraction (a) residual stress and (b) cold work profiles in a series of Waspaloy samples of Almen 16A peening intensity after different levels of thermal relaxation.

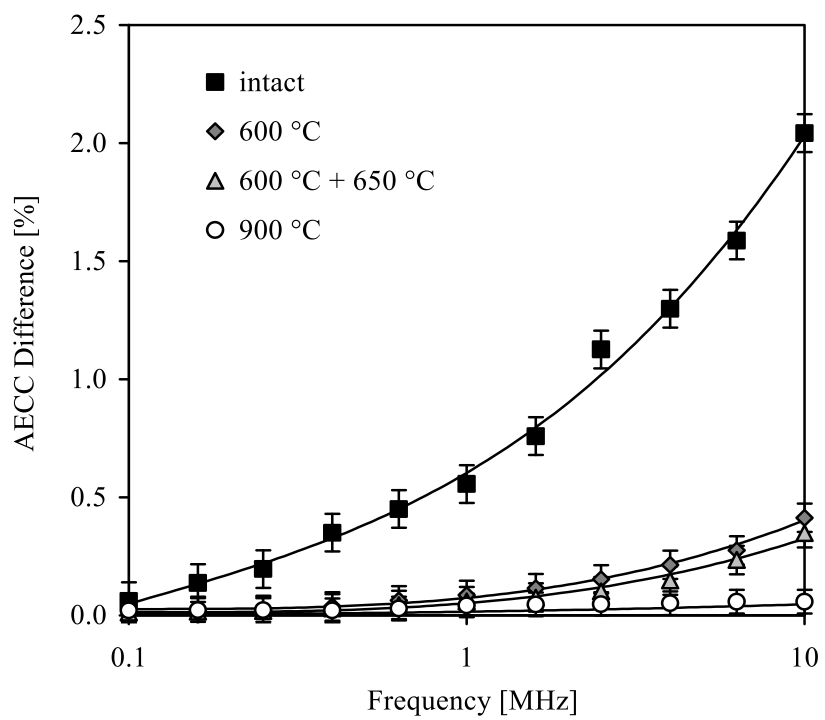

Figure 6 Eddy current conductivity measurements in shot-peened Waspaloy of Almen 16A intensity (each heat treatment was 24 hours).