1.3.4 Task 4 – Nondestructive Characterization of Residual Stress Distributions

Recent research efforts sponsored by the NDE Branch of AFRL showed that eddy current conductivity measurements can be exploited for nondestructive subsurface residual stress evaluation in surface-treated nickel-base superalloys. According to this approach, first the depth dependent electric conductivity profile is calculated from the measured frequency-dependent apparent eddy current conductivity (AEEC) spectrum. Then, the residual stress depth profile is calculated from the conductivity profile based on the piezoresistivity coefficient of the material, which is determined separately from calibration measurements using known external applied stresses. It was found that broadband (0.1-100 MHz) eddy current conductivity spectroscopy can reliably and accurately map the depth profile of the electric conductivity in surface-treated metals, and the measured near-surface conductivity change correlates well with both the initial residual stress magnitude and penetration depth as well as with their subsequent changes during thermo-mechanical relaxation. However, the interpretation of the measured conductivity depth profiles separately in terms of residual stress (elastic strain) contribution and cold work (plastic strain) contribution requires better understanding of the underlying physical mechanisms. Numerous materials effects, especially that of precipitation hardening, have not been studied in depth yet and are presently not properly understood.

1.3.4.1 Research Objectives

The main goal of this research effort is to better understand the underlying physics behind the recently developed eddy current nondestructive evaluation method for subsurface residual stress characterization in surface-treated engine components in order to further improve its accuracy and reliability. Recently, a physics-based inversion procedure has been suggested for the evaluation of the subsurface residual stress profiles from the measured AECC spectra. Although this direct method has been found to be very successful in some cases, it leads to 40-50% over- or underestimation in some other cases. The demonstrated sensitivity and reproducibility of eddy current inspection is unique among alternative nondestructive inspection methods, but systematic errors related to uncorrected materials effects, if left uncorrected, would prevent the use of this method in quantitative life prognostics. Therefore, further scientific investigation is required to improve the quantitative predictive power of this very promising residual stress profiling method.

The proposed project is a broad effort to answer the most important material-related questions in eddy current residual stress characterization. These include the following problems: (i) how does the microstructure, especially precipitation hardening, affect the electric conductivity and piezoresistivity of the material, (ii) how does the electric conductivity and piezoresistivity change with thermal ageing, (iii) how does the electric conductivity and piezoresistivity change with plastic deformation, (iv) what are the different features of cold work that affect X-ray-diffraction (XRD) and AECC measurements in a distinctly different manner, (v) are these processes driven by the formation of dislocations and slip bands, which are easily detected by XRD, or by precipitates, which are not, (vi) what is the role of changing short-range and long-range ordering, and (vii) how does the ratio between residual stress (elastic strain) and cold work (plastic strain) contributions in the measured AECC signature change with different types of surface treatment (shot peening, laser shock peening, low-plasticity burnishing, etc.) and with different levels of thermo-mechanical relaxation? These specific goals are all aimed at increasing the accuracy and reliability needed to achieve our ultimate goal of enabling the practical implementation of eddy current residual stress characterization in quality control during manufacturing and maintenance as a deterministic life prediction tool.

1.3.4.2 Background

Nondestructive residual stress assessment in fracture-critical components is one of the most promising opportunities as well as one of the most difficult challenges we face in the NDE community today. Residual stress assessment is important because there is mounting evidence that it is not possible to reliably and accurately predict the remaining service life of such components without properly accounting for the presence of residual stresses. Unfortunately, both the absolute level and spatial distribution of the residual stress are rather uncertain partly because the stress profile is highly susceptible to variations in the manufacturing process and partly because subsequently it tends to undergo thermo-mechanical relaxation at high operating temperatures. Therefore, the only reliable way to establish the actual profile of the prevailing residual stress is by measuring it. Unfortunately, the only currently available NDE method for residual stress assessment is based on X-ray diffraction (XRD) measurement that is limited to an extremely thin (less than 20 μm deep) surface layer, though parallel research efforts are currently underway to develop high-energy XRD methods with sufficient penetration depth for subsurface residual stress profiling.

Surface enhancement methods, such as shot peening (SP), laser shock peening (LSP), and low-plasticity burnishing (LPB), significantly improve the fatigue resistance and foreign object damage tolerance of metallic components by introducing beneficial near-surface compressive residual stresses. Moreover, the surface is slightly strengthened and hardened by the cold-working process. By far the most common way to produce protective surface layers of compressive residual stress is shot peening, though it is probably also the worst technique from the point of view of damaging cold work which substantially decreases the thermo-mechanical stability of the microstructure at elevated operating temperatures and leads to accelerated relaxation of the beneficial residual stresses. Although LSP and LPB produce significantly deeper compressive residual stress than SP, their main advantage over SP is that they produce much less cold work on the order of 5-15% equivalent plastic strain.

Because of the above discussed limitations, the NDE community has been looking for alternative nondestructive methods of characterizing residual stress profiles in surface-treated engine components for many years and eddy current conductivity spectroscopy emerged as one of the leading candidates [1-18]. Eddy current residual stress profiling is based on the piezoresistivity of the material, i.e., on the characteristic dependence of the electric conductivity on stress. Figure 1 shows a schematic representation of physics-based eddy current residual stress profiling in surface-treated components. In order to remove the influence of the measurement system (coil size, shape, etc.) the actually measured complex electric impedance of the probe coil is first transformed into a so-called apparent eddy current conductivity (AECC) parameter. At a given inspection frequency, the AECC is defined as the electric conductivity of an equivalent homogeneous, non-magnetic, smooth, and flat specimen that would produce the same complex electric coil impedance as the inhomogeneous specimen under study [9].

If spurious material (e.g., magnetic permeability) and geometric (e.g., surface roughness, oxidization, etc.) variations can be neglected, the frequency-dependent AECC can be inverted for the depth-dependent electric conductivity profile (this principal path is highlighted in Fig. 1). Then, using the known piezoresistivity of the material, the sought residual stress profile can be calculated. Unfortunately, the measured complex electric coil impedance, and therefore also the inferred AECC, is affected by the presence of cold work and surface roughness as well as by the sought near-surface residual stress. The electric conductivity variation due to residual stress is usually weak (≈1%) and rather difficult to separate from these accompanying spurious effects. In certain materials, such as austenitic stainless steels, cold work might also cause significant magnetic permeability variation which affects the measured coil impedance. Fortunately, nickel-base superalloys do not exhibit such ferromagnetic transition from their paramagnetic state [12]. In addition, because of their significant hardness, shot-peened nickel-base superalloy components exhibit only rather limited surface roughness (≈2-3 μm rms), therefore the influence of geometrical irregularities is also limited up to about 30 MHz. Still, as the inspection frequency increases the eddy current loop becomes squeezed closer to the rough surface, which creates a more tortuous, therefore longer, path and might lead to a perceivable drop of AECC above 30 MHz [19-21].

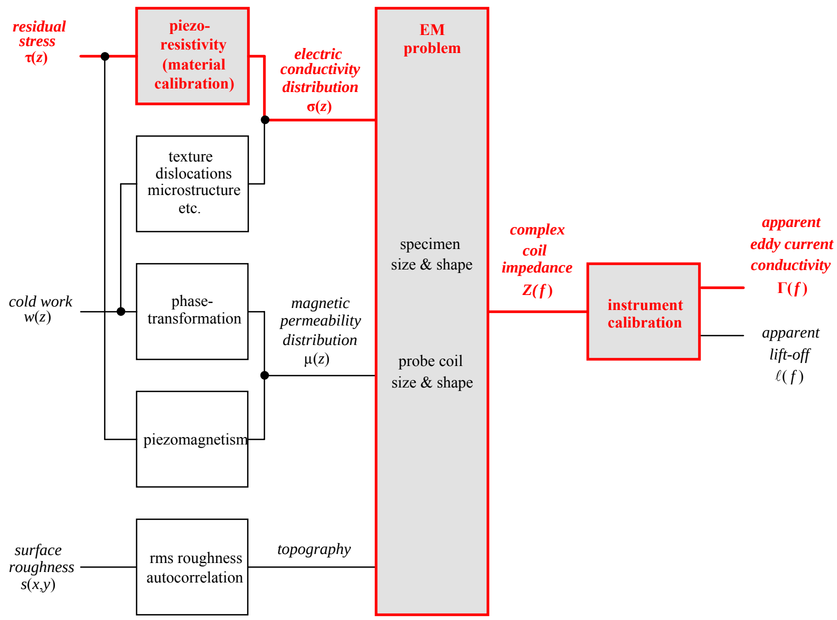

Figure 1 A schematic representation of physics-based eddy current residual stress profiling in surface-treated components (the principal path is highlighted).

Material Calibration

In the presence of elastic stress the electrical conductivity tensor of an otherwise isotropic conductor becomes slightly anisotropic. In general, the stress-dependence of the electrical resistivity can be described by a fourth-order piezoresistivity tensor. In direct analogy to the well-known acoustoelastic coefficient, a widely used NDE terminology for the stress coefficient of the acoustic velocity, the stress coefficient of the electrical conductivity is referred to as the electroelastic coefficient. During materials calibration, directional racetrack [22] or meandering [23] probe coils can be used to measure separately the parallel and normal electroelastic coefficients. In the case of shot-peened and most otherwise surface-treated materials, essentially isotropic plane stress condition prevails at the surface. Then, regardless whether conventional non-directional circular or directional probes are used, the effective electroelastic coefficient is the sum of the parallel and normal electroelastic coefficients.

In order to quantitatively assess the prevailing residual stress from eddy current conductivity measurements, the electroelastic coefficient of the material must be first determined using known external applied stress. These calibration measurements are usually conducted on a reference specimen of the same material using cyclic uniaxial loads between 0.1 and 10 Hz, which is fast enough to produce adiabatic conditions. It was shown that such dynamic calibration measurements should be corrected for the thermoelastic effect, which is always positive, i.e., it increases the conductivity in tension, when the material cools down, and reduces it in compression, when the material heats up [11]. In paramagnetic materials, the electric conductivity usually increases by approximately 1 % under a maximum biaxial compressive stress equal to the yield strength of the material. Still, it was found that in shot-peened aluminum and titanium alloy specimens the measured AECC typically decreases as much as 1-2 % with increasing peening intensity, which indicates that cold work and surface roughness effects dominate the observed phenomenon [7, 9].

Instrument Calibration

Most eddy current inspections are conducted in one of two basic modes of operation, namely in "impedance" or "conductivity" modes. In the so-called conductivity mode, which is most often used for alloy sorting and quantitative characterization of metals, the measured probe coil impedance is evaluated for an "apparent" eddy current conductivity and "apparent" lift-off distance by assuming that the specimen is a sufficiently large homogeneous non-magnetic conductor [9]. Of course, the intrinsic electrical conductivity of the material is independent of frequency. In the case of layered or otherwise inhomogeneous specimens the observed frequency-dependence of the AECC is due to the depth-dependence of the electrical conductivity (or magnetic permeability) and the frequency-dependence of the eddy current penetration depth.

The measured frequency-dependent complex electric impedance of the coil is first translated into an AECC spectrum as it was shown schematically in Fig. 1, which is then inverted into a frequency-independent depth profile of the electric conductivity as it will be described in the next section. The main advantage of this two-step approach is that it effectively eliminates the influence of the measurement system on the actually measured coil impedance, therefore AECC spectra taken with different equipments and different probe coils can be directly compared. To illustrate the robustness of this instrument calibration method, Fig. 2 shows the AECC spectra measured by four different instruments (Nortec 2000S, Agilent 4294A, Stanford Research SR844, and UniWest US-450) on three IN718 specimens of different peening intensities. In the overlapping frequency ranges the agreement between the AECC spectra obtained by different instruments is within the respective estimated errors of the instruments. This comparison illustrates how effectively the four-point instrument calibration procedure separates the sought material effects associated with shot peening from different measurement system parameters that also influence the measured probe coil impedance. Up to 10 MHz, commercially available absolute pancake and pencil probes can be used for AECC measurements. The frequency bandwidth of such probes is limited to typically less than one decade because of the very high sensitivity and stability requirements of eddy current residual stress profiling. Above 10 MHz, flexible spiral coils can be used to minimize the adverse self- and stray-capacitance effects [15, 16]. The spiral coils used in our study had separate transmit and receive coils that increases their thermal stability by eliminating the temperature-dependent wire resistance from the measured complex transfer impedance so that a single probe can be used in a wide frequency range extending well over more than two decades.

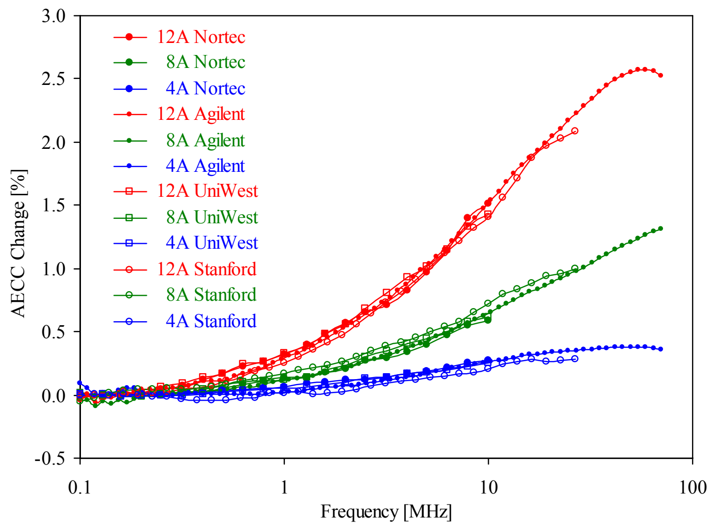

Figure 2 AECC change measured by four different instruments on three IN718 specimens of different peening intensities.

AECC Inversion

In order to translate the measured frequency-dependent AECC spectra into depth-dependent electric conductivity profiles, first a simplistic inversion technique was developed [10], which was recently followed by the development of a highly convergent iterative inversion technique [14]. Both techniques indicated that at any given frequency the measured AECC corresponds roughly to the actual electric conductivity at half of the standard penetration depth assuming that (i) the electric conductivity variation is limited to a shallow surface region of depth much less than the probe coil diameter, (ii) the relative change in electric conductivity is less than a few percents, and (iii) the electric conductivity depth profile is continuous and fairly smooth. Alternatively, best fitting of the measured electric coil impedance with the known analytical solution can be used assuming that the conductivity profile can be characterized by a small number of independent parameters [17]. Finally, the sought residual stress profile is calculated from the electric conductivity profile based on the piezoresistivity coefficient of the material, which is determined separately from material calibration measurements using known external applied stresses.

1.3.4.2 Material Limitations

The main limitation of residual stress profiling by eddy current conductivity spectroscopy is that the feasibility of this technique seems to be limited to nickel-base superalloys, though some beneficial information, e.g., on increasing hardness, could be also obtained by this technique on titanium and aluminum alloys. Unfortunately, even in the case of nickel-base superalloys, there exist some serious limitations that adversely influence the applicability of the eddy current method. The main scientific goal of the proposed research effort is to better understand and compensate for these spurious effects.

Inhomogeneity Effect

Surface-treated nickel-base superalloys exhibit an approximately 1% increase in apparent eddy current conductivity at high inspection frequencies, which can be exploited for nondestructive subsurface residual stress assessment. Unfortunately, microstructural inhomogeneity in certain as-forged and precipitation hardened nickel-base superalloys, like Waspaloy, can lead to significantly larger electrical conductivity variations of as much as 3-4%. The intrinsic electrical conductivity variation exhibited by inhomogeneous Waspaloy raises a crucial question: Can eddy current techniques detect, let alone quantitatively characterize, the weaker near-surface conductivity variations caused by surface treatment in the presence of such stronger conductivity inhomogeneity caused by microstructural variations? Eddy current conductivity images taken at different inspection frequencies indicated that low- and high-conductivity domains are essentially frequency independent due the large volumetric size of these domains [24]. This virtual frequency independence can be exploited to distinguish these inhomogeneities from near-surface residual stress and cold work effects caused by surface treatment, which, in contrast, are strongly frequency dependent. As the frequency decreases, the eddy current distribution penetrates deeper into the material and also spreads a little wider in the radial direction. Although there is some change in the AECC with frequency at most locations, on the average this frequency dependence essentially cancels out for a large number of points.

The rather weak frequency dependence of the inhomogeneity-induced AECC variation suggests that the conductivity does not vary sharply with depth, which can be exploited to separate the primary residual stress effect from the spurious material inhomogeneity using point-by-point absolute AECC measurements over a wide frequency range, followed by a comparison of the near-surface properties measured at high frequencies to those at larger depth measured at low frequencies. As an example, Fig.

3 shows the destructive residual stress profiles determined by XRD (a) and the corresponding nondestructive profiles calculated from the measured AECC (b) for highly inhomogeneous as-forged Waspaloy specimens of four different peening intensities. Solid symbols represent as-peened specimens and empty symbols represent fully relaxed specimens after 24-hour heat treatment at 900 ºC. In intact shot-peened specimens the excess AECC is roughly proportional to the peening intensity. Within the uncertainty of the eddy current measurement, the excess AECC completely vanished on fully relaxed specimens, which indicates that the eddy current method is indeed very sensitive to thermal relaxation. These results illustrate that the adverse effect of inhomogeneity can be separated from the primary residual stress effect using a self-referencing method based on the significant difference between the frequency dependences of the residual stress and inhomogeneity contributions. The inherently increased experimental uncertainty associated with AECC spectra obtained from inhomogeneous specimens relative to homogenized Waspaloy specimens necessarily reduces the feasibility of precise residual stress assessment, but does not exclude it.

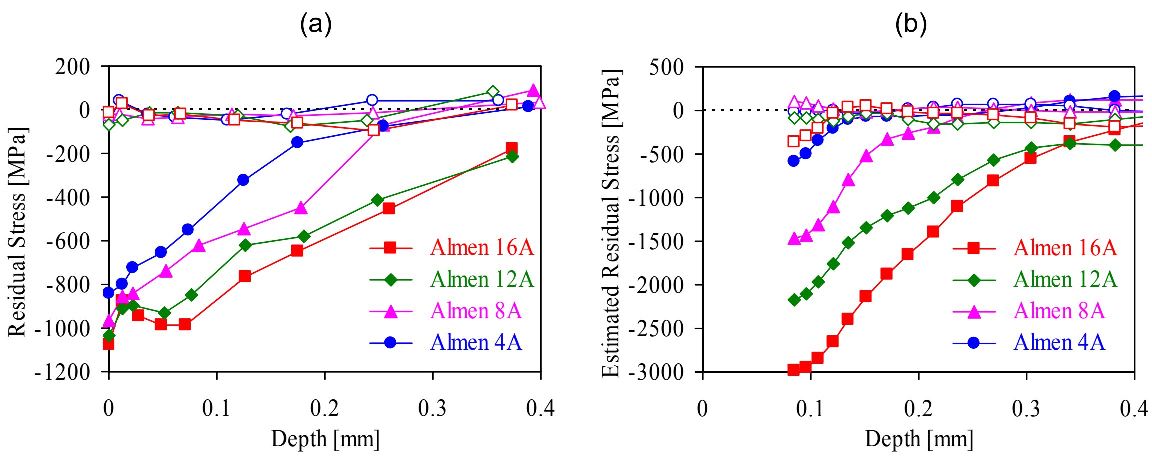

Figure 3 Comparison of destructive XRD residual stress profiles (a) and the estimated residual stress profiles (b) calculated from the measured AECC change for as-forged Waspaloy specimens of four different peening intensities (solid symbols represent as-peened specimens and empty symbols represent fully relaxed specimens after 24-hour heat treatment at 900 ºC).

Cold Work Effect

Figure 3 also indicates that in Waspaloy the piezoresistivity effect is simply not high enough to account for the observed total AECC increase. For inversion purposes we used the normalized electroelastic coefficient that was measured on a reference specimen cut from the same batch of material. A comparison of the scales in Fig. 3 reveals that the inverted eddy current residual stress profiles significantly overestimate the more reliable XRD results. It should be mentioned that the overestimation is much lower in IN718 and, especially, in IN100, as it is illustrated in Fig.4.

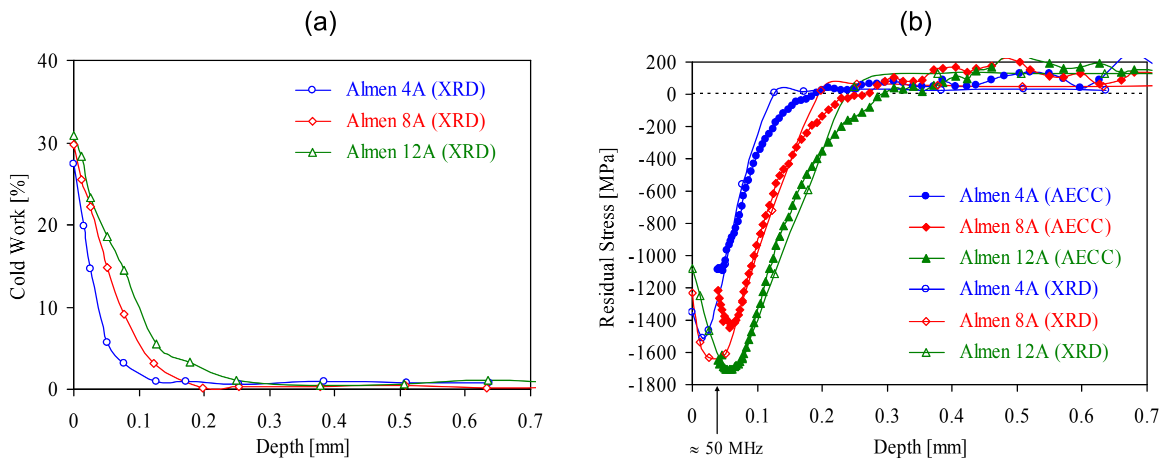

Figure 4 XRD profiling of near-surface cold work (a) and residual stress (b) profiles compared to the inverted eddy current residual stress profile in shot peened IN100 specimens of Almen 4A, 8A and 12A peening intensity levels.

The most probable reason for the observed overestimation in Fig. 3 is the material-dependent influence of cold work. In order to better understand the effects of cold work on the apparent eddy current conductivity change in shot-peened nickel-base superalloys, the effect of plastic deformation on the electrical conductivity, magnetic permeability, and electroelastic coefficient of premium grade rotor-quality nickel-base superalloys was investigated in detail [12]. The results indicated that, within the uncertainty of the measurement, the electroelastic coefficient and the magnetic permeability do not change as a result of cold work, therefore they cannot be responsible for the significant overestimation of the residual stress described above. On the other hand, the electric conductivity did show significant variation with plastic strain in cold-worked nickel-base superalloys. The substantial increase of the electrical conductivity is due to microstructural changes and could explain the observed residual stress overestimation. Of course, the cold work produced by shot peening rapidly decays away from the surface and the depth of the affected layer is typically only 30% of the thickness of the layer of compressive residual stress. Therefore, at frequencies below 10 MHz the overestimation tends to be less than what could be expected based on the sheer magnitudes of these two effects.

Cold work exerts a very convoluted effect on residual stress profiling by eddy current spectroscopic measurements and will require further research to better understand its behavior and to develop possible compensation strategies. However, it should be pointed out that the overestimation of the eddy current method due to cold work is much lower in moderately peened components, which exhibit better thermo-mechanical stability, and in LSP and LPB specimens, which offer much lower plastic deformation, and therefore also much better thermo-mechanical stability, than shot-peened ones.

Thermal Effect

As the peak temperature to which the material is cyclically heated is increased, the microstructural evolution caused by thermal exposure becomes more manifest. As an example, Fig. 5(a) shows the resistance variations in IN718 as it was exposed repeatedly to a peak temperature of 550ºC for 10-hour periods. It is clear that the material exhibits a distinct irreversible jump in resistance during the first cycle. During subsequent cycles, the resistance is still increasing, but at a gradually slower rate in every additional cycle. This observation is more obvious in Fig. 5(b) showing how the resistance varies with temperature. At this peak temperature, the instantaneous reversible temperature dependence of the electric resistivity can be readily separated from the irreversible microstructural changes that depend on both prior exposure time and temperature.

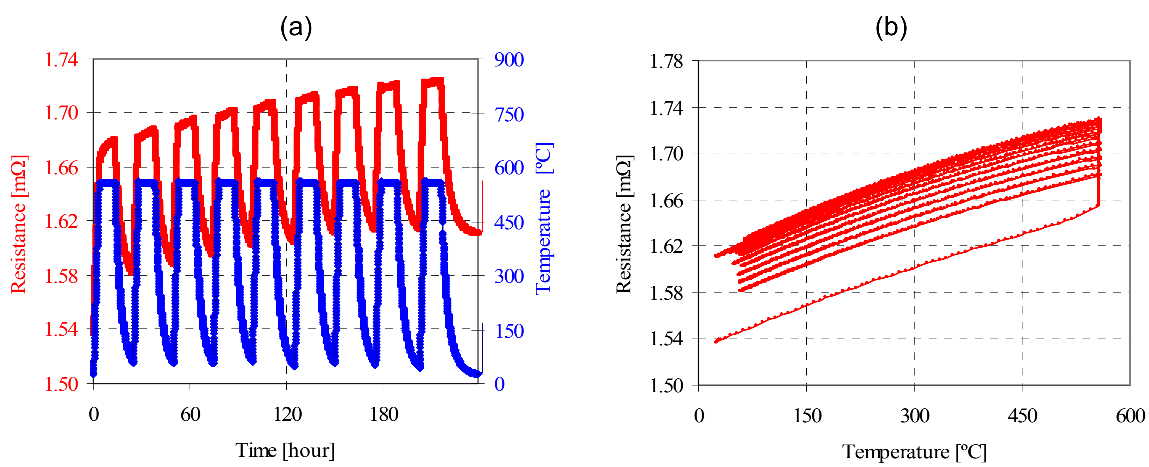

Figure 5 Variation of temperature and electric resistance in IN718 at 550ºC peak temperature.

Such information can be extremely useful in material property and microstructure characterization (Tasks 1 and 2 of the present proposal). For example, information might be needed about the operating temperature of a given aerospace engine component. Indeed, this information can be determined from repeated electrical resistivity measurements assuming that sufficient data is accumulated regarding the component's material in its as-fabricated condition. Periodically, after known periods of exposure in the operating environment, electrical resistivity measurements are conducted. From the characteristic

Larson-Miller Parameter (LMP) vs. property plot for the particular alloy, one can then approximate the value of LMP and, knowing the exposure time, the equivalent temperature experienced at different parts of the component could be calculated. It should also be noted that with this technique, it will be possible to actually identify locations where sudden uncontrolled extreme changes in temperature have occurred since the LMP is linearly proportional to temperature but only logarithmically to exposure time [25].

Anomalous Relaxation in Waspaloy

Recent research efforts revealed a series of situations where anomalous stress-dependence and relaxation behavior were observed. This is not surprising at all in the case of an inherently indirect nondestructive method, but will certainly require further scientific investigation. One of the main questions concerning the feasibility of eddy current residual stress profiling is whether or not the AECC difference decays gradually with thermal relaxation, which is extremely important from the point of view of assessing partial relaxation. Initial experimental evidence indicated that the decay is usually monotonic and gradual, but it was noticed early on that occasionally the rate of decay was much faster than expected. For example, in one of the first such experiments a Waspaloy specimen of Almen 8A peening intensity was gradually relaxed by repeated heat treatments of 24-hour each at increasing temperatures in 50-ºC steps from 300 ºC to 900 ºC in protective nitrogen environment [9]. The results clearly indicated that the measured AECC difference gradually decreases during thermal relaxation and almost completely disappears after 24-hour heat treatment at 900 ºC. However, there was a very steep drop in the AECC difference at 450 °C, which is highly suspicious as the peening-induced residual stress is certainly more persistent in Waspaloy at such a low temperature.

Subsequent studies investigated the changing electric conductivity of nickel-base superalloys due to microstructural evolution at elevated temperatures [24]. These results suggested that spurious electric conductivity variations caused by microstructural anomalies in nickel-base superalloys interfere with eddy current residual stress assessment of subsurface residual stresses. If the conductivity variations were entirely volumetric effects, they would not cause frequency-dependent changes in the AECC spectrum, therefore they could be distinguished from near-surface residual stress and cold work effects caused by surface treatment, which, in contrast, are strongly frequency-dependent. According to the self-referencing method, the average AECC measured at sufficiently low frequencies (e.g., between 0.1 and 0.3 MHz) is subtracted from the absolute AECC measured at all frequencies, i.e., the conductivity close to the surface is compared to the conductivity at a sufficiently large depth where the material can be considered intact, i.e., unaffected by surface treatment.

Recent experimental observations indicate that the above assumption is not necessarily valid in Waspaloy specimens relaxed at around 400-450°C. Figure 6(a) illustrates schematically how the presence of cold work could reduce the transition temperature at which thermally-activated microstructural evolution takes place in the material. For example, let us assume that the typically 30-40% near-surface plastic strain caused by cold work reduces the activation temperature by about 40°C. If then the surface-treated component is exposed to moderate temperatures so that the transition occurs in the cold-worked near-surface layer, but not deeper below the surface, a significant conductivity difference will develop, as it is shown in Fig. 6(b). This effect will be detectable in the measured frequency-dependent AECC spectrum and could easily overshadow the residual stress relaxation effect that is very weak at these temperatures. Currently, experiments are underway to verify that the steep drop in AECC reported earlier [24] at around 400-450°C would actually reach below zero if the exposure time were increased. The most obvious way to mitigate this problem seems to be to expose all new the components to a carefully chosen heat treatment, e.g., 500-550°C for 24 hours. Such treatment would significantly reduce further changes in conductivity and might not be necessary at all on used components which tend to develop a uniformly high electric conductivity distribution due to their long exposure to elevated operational temperatures.

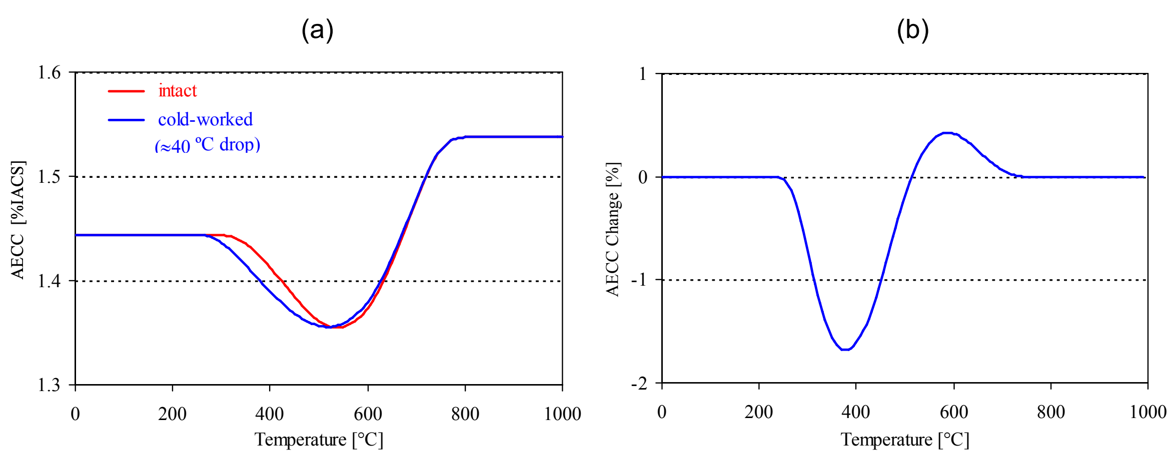

Figure 6 A schematic illustration of how the presence of cold work reduces the transition temperature at which thermally-activated microstructural evolution takes place in the material (a) and the resulting AECC change between the cold-worked surface and the intact interior (b).

Anomalous Behavior in Hardened IN718

It was recently found that special versions of the common IN718 material can also exhibit anomalous behavior that is very different from those of the commercial versions reported in the. A common feature of these precipitation hardened materials seems to be that their custom-designed thermo-mechanical processing results in both increased hardness and increased electric conductivity. In a recent test of twelve fine-grain IN718 specimens various hardness levels were produced by heat treatment (see Table 1). First, all twelve specimens were solution annealed at 1800 ºF for 30 minutes and then air fan cooled to room temperature. Then, the specimens were thermally aged in two steps. Partial aging was achieved by heating the specimens to 1300 ºF and holding them for various treatment times from 0 to 16 hours before air fan cooling to 1200 ºF for full aging. Full aging was achieved by holding the specimens at this lower temperature for a total furnace time of 18 hours and air cooling them. Figure 7 shows the bulk apparent eddy current conductivity (AECC) versus Rockwell C hardness in these twelve shot-peened IN718 specimens of Almen 4A and 6A intensity. The "bulk" AECC was defined as the average AECC between 0.6 and 1.1 MHz. The error bars represent the ±1% uncertainty of the calibration blocks and the solid lines are quadratic regressions. As expected, this bulk parameter is very susceptible to precipitation hardening, but not affected by surface treatment.

ID	treatment	HRC	HV
#1	solution	24.9	265.7
#2	solution	26.5	276.3
#3	0 minutes	31.0	309.7
#4	0 minutes	33.8	333.1
#5	6 minutes	31.9	317.0
#6	6 minutes	33.8	333.1
#7	24 minutes	35.9	352.1
#8	24 minutes	35.7	350.2
#9	2 hours	39.0	382.1
#10	2 hours	39.3	385.2
#11	16 hours	45.5	453.4
#12	16 hours	45.3	451.0

Table 1 List of fine-grain IN718 specimens of various hardness levels.

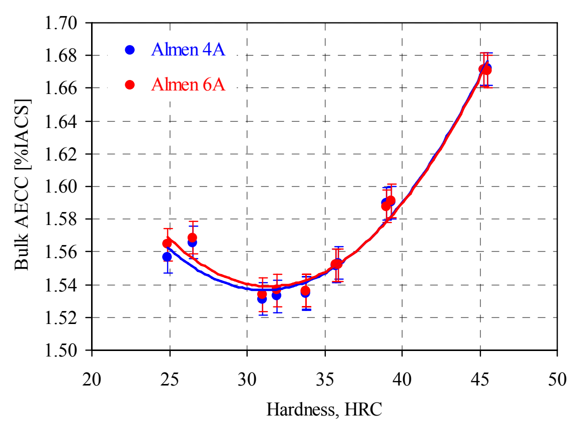

Figure 7 Bulk AECC versus Rockwell C hardness in twelve shot-peened IN718 specimens of Almen 4A and 6A intensity.

Figure 8 shows the measured apparent eddy current conductivity change (ΔAECC) spectra in the twelve shot-peened specimens. At around HV 380 (HRC 39) the "classical" positive ΔAECC changes sign. Above HV 420 (HRC 43) the negative ΔAECC is small but measurable. At the same time X-ray diffraction measurements indicated that neither the residual stress nor the cold work profiles were affected significantly by the varying hardness, therefore the observed changes in eddy current signature must have been caused by microstructural changes due to different levels of precipitation hardening.

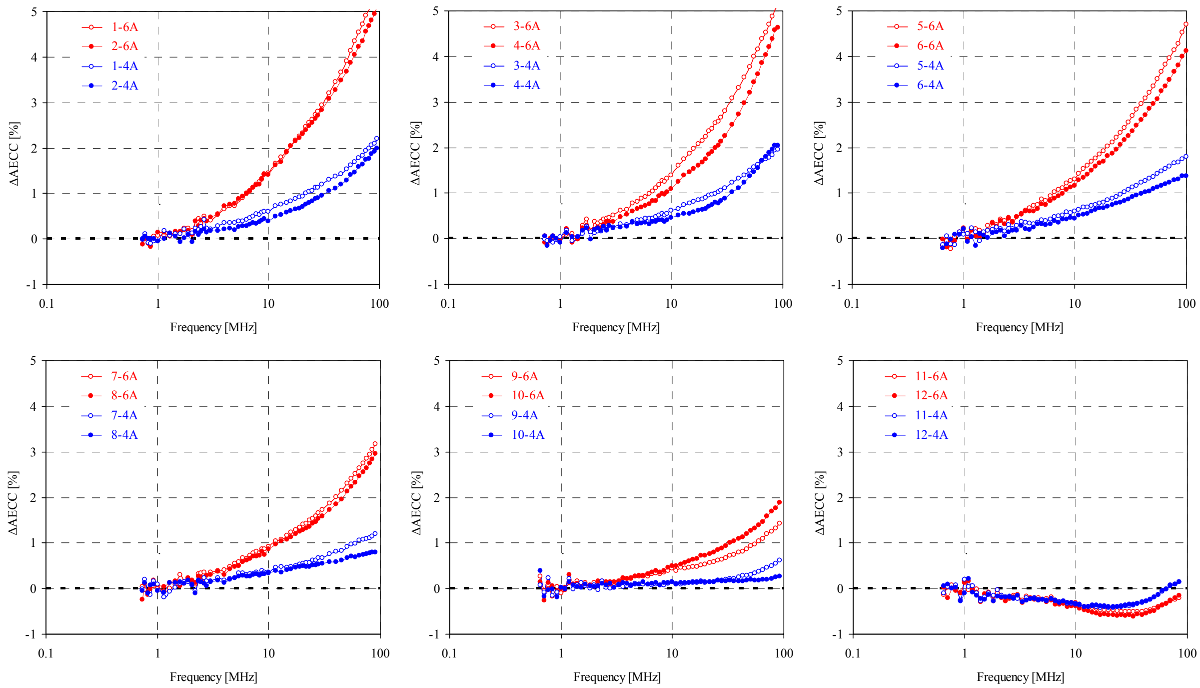

Figure 8 Apparent eddy current conductivity change in the twelve shot-peened IN718 specimens listed in Table 1.

The very significant and systematic changes observed in the AECC spectra taken from shot-peened specimens of different hardness is a material artifact that must be understood if eddy current spectroscopy were to become an effective residual stress profiling tool. These results represent an important step towards understanding the scientific issues, but numerous questions remain open. First of all, does the hardness influence the residual stress effect, the cold work effect, or both? This question could be answered by conducting electro-elastic coefficient measurements on a series of specimens of varying hardness. The likely conclusion of these tests will be that the sporadic "materials anomalies" previously observed in different nickel base superalloys are all caused by the varying influence of near-surface cold work that strongly depends on the level of hardness. It is absolutely necessary that the actual mechanisms responsible for the dominant influence of hardness be identified so that the feasibility of accounting for this crucial materials effect could be established and, hopefully, appropriate correction methods could be found.

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1.6 Capabilities and Relevant Experience

The work at UC would be conducted by a PhD student under the supervision of Professor Peter B. Nagy who has more than 25 years of experience in experimental physical acoustics, ultrasonic, electromagnetic, and thermoelectric materials characterization, nondestructive testing of aerospace materials, and residual stress assessment. A variety of state-of-the-art research equipment is available in the Department of Aerospace Engineering at the University of Cincinnati for this effort. The most relevant electromagnetic NDE instrumentations for the proposed research effort are listed below:

- Several Nortec 2000S and Nortec 2000D eddy current instrument (Staveley)
- Eddy current scanner (Staveley, Velmex)
- US-450 eddy current instrument (UniWest)
- 4294A Precision Impedance Analyzer (Agilent Technologies)
- SR720 LCR Meter (Stanford Research)

- LR700 ACPD Impedance Analyzer (Linear Research)
- Magnetoscop 1.069 magnetic susceptibility meter (Foerster Instruments)
- Feritscope MP30E-S (Fischer Technology)
- Several lock-in amplifiers, box-car averagers, etc. (Stanford Research, PAR)
- Several amplifiers, generators, etc. (Stanford Research, Agilent Technologies, LeCroy)

PART II: OFFEROR STATEMENT OF WORK

2.4 Task 4 – Nondestructive Characterization of Residual Stress Distributions

The NDE Laboratory of the Aerospace Engineering Department at the University of Cincinnati will provide expertise in eddy current-based nondestructive detection methods by which the residual stress (RS) and micro-structural state of a component can be monitored. Research is expected to include inversion methods to correlate measurements to residual stress, investigations of residual stress in nickel-base alloys and other metals, as required, and improvements in measurement techniques. Research in other aspects of NDE (besides RS) may be requested, depending on program technical requirements. University of Cincinnati will present the results of their R&D efforts at conferences and publish them in appropriate refereed journals. University of Cincinnati will provide monthly research status reports, including cost and man hours expended. It is expected that funding will be sufficient to provide for a graduate student research assistantship and technical consultation by the advising professor.

It should be emphasized that many of the problems and solutions anticipated in the work on Nondestructive Characterization of Residual Stress Distributions (Task 4) are closely related to other issues discussed in this proposal. For example, our ability to profile residual stress distributions in surface treated engine components is strongly influenced by the cold-work induced changes in material properties and microstructure (Tasks 1 and 2) and separation of spurious influences requires extensive Modeling, Simulation and Probability Analysis (Task 3). It should be also emphasized that the same electromagnetic techniques we are proposing to develop for residual stress profiling could find important applications in both property and microstructure characterization (Tasks 1 and 2).