High-frequency eddy current conductivity spectroscopy for residual stress profiling in surface-treated nickel-base superalloys

Bassam A. Abu-Nabah, Peter B. Nagy*

Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, OH 45221-0070, USA

Received 24 August 2006; received in revised form 2 January 2007; accepted 21 January 2007

Available online 11 February 2007

Abstract

Recent research results indicated that eddy current conductivity measurements can be exploited for nondestructive evaluation of subsurface residual stresses in surface-treated nickel-base superalloy components. Most of the previous experimental studies were conducted on highly peened (Almen 10-16A) specimens that exhibited harmful cold work in excess of 30% plastic strain. Such high level of cold work causes thermo-mechanical relaxation at relatively modest operational temperatures; therefore the obtained results were not directly relevant to engine manufacturers and end users. The main reason for choosing peening intensities in excess of recommended normal levels was that in low-conductivity engine alloys the eddy current penetration depth could not be forced below 0.2 mm without expanding the measurements above 10 MHz which is beyond the operational range of most commercial eddy current instruments. In this paper we report the development of a new high-frequency eddy current conductivity measuring system that offers an extended inspection frequency range up to 50 MHz with a single spiral coil. In addition to its extended frequency range, the new system offers better reproducibility, accuracy, and measurement speed than the previously used conventional system.

Keywords: Eddy current; Spectroscopy; Shot peening; Residual stress

1. Introduction

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. In shot-peened components near-surface compressive residual stresses can counterbalance applied tensile loads in a shallow depth of about 50–200 μm below the surface, which improves fatigue resistance. This method can be applied on fracture-critical components of irregular shapes such as shafts, gears, springs and jet-engine turbine blades. Unfortunately, at high peening intensity levels, the accompanying cold work can reach up to 30–40% equivalent plastic strain, which substantially decreases the thermo-mechanical stability of the microstructure at elevated operating temperatures and leads to accelerated relaxation of the beneficial residual stresses [1]. Applying SP at relatively low intensity levels limits the cold work and hence improves the thermo-mechanical stability of the shot-peened component. Nevertheless, it is still beneficial to monitor the remaining residual stress profile during scheduled inspection periods to reliably assess the remaining life of the component.

The most common near-surface residual stress assessment method is based on X-ray diffraction (XRD), which measures the elastic strain in the crystal lattice and then calculates the prevailing stress distribution assuming linear elasticity. Unfortunately, depending on the operating intensity level and wavelength, XRD measurements offer only 5–20 μm penetration depth [2–5], which is one order of magnitude lower than the typical compressive residual stress penetration depth produced by most surface enhancement methods. In order to evaluate the whole compressive part of the residual stress profile using XRD measurements, successive layer removal has to be applied,

*Corresponding author. Tel.: +1 513 556 3353; fax: +1 513 556 5038. E-mail address: peter.nagy@uc.edu (P.B. Nagy).
which requires some numerical corrections to account for the stress release during this process. More importantly, this method is inherently destructive since it leaves a deep hole on the surface of interest, therefore it is not practical for maintenance purposes. There are only two known ways to avoid this limitation of XRD measurements, namely increasing the incident beam intensity and/or reducing the wavelength, which reduces the X-ray absorption coefficient of the material to get better penetration. It should be mentioned that using either synchrotron radiation or neutron diffraction can increase the penetration depth to a few centimeters [5–7], which would be more than sufficient for surface-treated materials and high enough even for many bulk residual stress assessment applications. On the negative side, the spatial resolution of these techniques is not very good. The reason for this is that a minimum diffraction volume has to be maintained to get sufficient sensitivity and that translates into a depth resolution on the order of 100 \( \mu m \). That could be still sufficient, although barely for shot-peened components which exhibit rather shallow compressive residual stress layers. Of course, it is a major disadvantage of these techniques that they require access to a synchrotron accelerator or a nuclear reactor. Because of these limitations, the NDE community needs to develop additional indirect techniques to assess residual stress profiles in surface-treated engine components.

In the past few years, eddy current NDE was found to offer great potential for near-surface residual stress assessment due its frequency-dependent penetration depth [8–18]. This approach is based on the piezoresistivity of the material, i.e., on the characteristic dependence of the electric conductivity on stress, which can be exploited for residual stress profiling in certain materials. Fig. 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, nonmagnetic, smooth, and flat specimen that would produce the same complex electric coil impedance as the inhomogeneous specimen under study [17]. If spurious material (magnetic permeability) and geometric (surface roughness) variations can be neglected, the frequency-dependent AECC can be inverted for the depth-dependent electric conductivity profile, and then, using the known piezoresistivity of the material for the sought residual stress profile (this principal path is highlighted in Fig. 1).

Unfortunately, the measured complex electric coil impedance, and therefore also the inferred AECC, is

![Fig. 1. A schematic representation of physics-based eddy current residual stress profiling in surface-treated components (the principal path is highlighted).](image-url)
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 stresses 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. 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. 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 [19–22].

In paramagnetic materials, the electric conductivity 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 [13–17]. Fig. 2 illustrates that, in sharp contrast with most other materials, intact (solid symbols) shot-peened nickel-base superalloys exhibit a relative increase in AECC both with increasing peening intensity as well as with increasing inspection frequency [17]. From the point of view of nondestructive residual stress assessment, it is also very promising that the excess AECC completely vanishes upon full thermal relaxation (empty symbols) in spite of the fact that some remnant cold work is still present in the specimens. These results also illustrate that, as expected, in nickel-base superalloys the slight surface roughness produced by SP does not cause a perceivable drop of AECC up to at least 10 MHz [17,19–23].

There is, however, a significant problem with the otherwise very promising eddy current results shown in Fig. 2. Based on the independently measured piezoresistivity effect of the material, the observed AECC increase is significantly higher than it should be if the effect were solely due to the residual stress (elastic strain) contribution. It was found that this overestimation is mainly due to the uncorrected effect of cold work (plastic strain) that also increases the electric conductivity in
severely peened components [23]. Because of the previously mentioned reduced thermo-mechanical stability of the near-surface residual stress in the presence of excessive cold work, engine manufacturers refrain from using peening intensities above Almen 8A anyway, therefore the overestimation caused by excessive cold work is of limited concern. However, if the Almen 12A and 16A peening intensities were removed from Fig. 2, the remaining AECC effect would be almost buried in experimental uncertainties, which clearly indicates that lower peening intensities cannot be properly characterized without increasing the inspection frequency above 10 MHz.

In order to translate the measured frequency-dependent AECC into a depth-dependent electric conductivity profile in a nonmagnetic medium, first a simplistic inversion technique was developed [24], which was recently followed by the development of a highly convergent iterative inversion technique [25]. 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.

Knowing the electric conductivity of the intact material and the approximate depth of the near-surface conductivity profile allows us to determine the inspection frequency range required to retrieve the depth-dependent electric conductivity profile from the measured frequency-dependent AECC spectrum. In particular, to capture the near-surface hook of the residual stress profile in shot-peened nickel-base superalloys; the frequency range of inspection has to be extended far beyond 10 MHz, where the effective inspection depth is only ≈ 100 µm, as it is illustrated by the vertical dashed line in Fig. 2. The main reason for choosing peening intensities in excess of typical levels recommended by engine manufacturers in our previous studies was that the eddy current penetration depth could not be sufficiently decreased without extending the frequency range above 10 MHz, i.e., beyond the operational range of most commercially available eddy current instruments. In this paper we will report the development of a new high-frequency eddy current conductivity measuring system that offers an extended inspection frequency range up to 80 MHz with a single spiral coil. In addition, we will show that the new system offers better reproducibility, accuracy, and measurement speed than the previously used commercial systems.

2. AECC spectroscopy using a precision impedance analyzer

Most practical problems in eddy current nondestructive evaluation of materials require inspection frequencies below 10 MHz. Accordingly, most commercially available eddy current instruments work up to 10 MHz only. In contrast, in the special case of eddy current residual stress profiling in shot-peened nickel-base superalloys, the inspection frequency has to be extended to at least 50 MHz to capture the important part of the near-surface residual stress profile. In this research we adapted an Agilent 4294A high-precision impedance analyzer to eddy current conductivity spectroscopy. This instrument covers a wide impedance range between 3 mΩ and 500 MΩ at a frequency range from 40 Hz to 110 MHz. The excitation current can be adjusted from 200 µA to 20 mA, and the excitation voltage can be limited between 5 mV and 1 V. We will illustrate in this paper that the new computer-controlled eddy current system based on this instrument offers better stability, reproducibility, and measurement speed than the formerly used commercial eddy current instruments. Nevertheless, the small but not quite negligible self-capacitance and thermal instability the probe coil and adverse cabling and lift-off effects make it rather difficult to conduct sufficiently accurate eddy current conductivity measurements beyond 20 MHz.

Eddy current probes typically have either single or separate transmit/receive coils. Fig. 3 illustrates the main differences between these two approaches. The coil is made of a highly conductive material, like copper, in which the resistance is usually a strong function of temperature. This effect makes the resistive part of the complex coil impedance of a single probe coil strongly temperature dependent. In comparison, the temperature coefficient of the electric resistance of low-conductivity metals, like nickel-base superalloys, is relatively low therefore the thermal stability of the measurements can be significantly improved using separate transmit and receive coils in the configuration shown in Fig. 3(b) where the measured transfer impedance depends only on the mutual inductance of the coils, but not on their (temperature-dependent) resistance. Another critical issue in probe design is related to the self-capacitance of the coil. The stray capacitance between the turns of the coil and between the coil and the material to be inspected has been an issue of great concern since the early development of eddy current NDE techniques [26]. A single-coil eddy current probe can be built in a cylindrical or a spiral form, where the spiral coil has a relatively high self-resonance frequency, therefore it is particularly well suited for high-frequency inspection [27]. In order to maximize the thermal stability and self-resonance frequency of the coil, custom-made spiral probes consisting of separate transmit and receive coils were used in this study. The common topology of these coils is illustrated schematically in Fig. 3(c). Results obtained with different turn densities will be presented later to illustrate the main difficulties faced above 10 MHz. The accuracy of the obtained AECC spectrum will be analyzed assuming a given level of relative impedance measurement error. In addition, the sensitivity of the AECC spectrum to lift-off variations will be investigated.
2.1. Absolute and relative impedance accuracy

In the present study, custom-made spiral coils of three different turn density (50, 100, and 200 µm) were considered. The turn density is defined as the separation distance between neighboring transmit and receive turns. For example, in the case of 100-µm turn density, both transmit and receive coils had a pitch of 400 µm, while the number of turns was determined by the outer diameter of the spiral coil (the inner diameter was always half of the outer diameter). Although other probe sizes were also tested, in the presented results the outer diameter is always 8 mm. Fig. 4 shows the impedance magnitude spectra for the three spiral coils of different turn density used in this study. The impedance of the probes was measured over a homogenous Waspaloy specimen of nominal conductivity of 1.55 %IACS in a temperature controlled environment over a frequency range from 0.1 to 100 MHz. We will illustrate that probe coil optimization is rendered especially difficult by the fact that improvements in essentially all important aspects of coil performance (higher self-resonance frequency, lower lift-off sensitivity, better spatial resolution, wider bandwidth) will all lead to lower coil impedance. Unfortunately, the absolute magnitude of the electric transfer impedance for the best probe coils is significantly lower than the optimum impedance range (≈0.1–1 kΩ) of the 4294A [28]. Moreover, decreasing the coil density by a factor of 2 causes a reduction in the absolute coil impedance by a factor of ≈3.5, which in turn significantly reduces the absolute accuracy of the impedance measurement, especially at low frequencies. This might seem to be a setback since self-calibrating eddy current residual stress assessment is based on the measured AECC variation between low and high frequencies. However, because of the standard four-point instrument calibration used in these measurements, what really matters is the reproducibility or relative accuracy of the impedance measurement over time, i.e., the short- and long-term stability of the measurement.

In order to evaluate the relative accuracy of impedance measurements using the Agilent system, the impedance of the three probe coils over a Waspaloy reference specimen (1.55 %IACS) was recorded every 5 min for 3 h at different frequencies using the highest precision (lowest bandwidth and measurement speed) available on the Agilent 4294A. In this case, 80 frequency points between 0.1 and 100 MHz could be measured in logarithmic steps in 3.5 min. Every data point represented an average of 4 consecutive measurements and 4 repeated scans throughout the entire frequency range, i.e., an average of 16 measurements. Fig. 5 illustrates the long-term drift (a, b) and 30-min reproducibility (c, d) of the relative impedance accuracy using 8-mm spiral coils of three different densities. The charts on the left (a, c) show the time history of the overall deviation averaged from 100 kHz to 80 MHz, while the charts on the right (b, d) show the frequency spectra of the
Fig. 5. Long-term drift (a, b) and 30-min reproducibility (c, d) analysis of the relative impedance accuracy using 8-mm spiral coils of three different densities. The charts on the left (a, c) show the time history of the overall deviation averaged from 100 kHz to 80 MHz while the charts on the right (b, d) show the frequency spectra of the overall slopes averaged over 3 h.

Before each actual AECC measurement the instrument must be calibrated using the standard four-point calibration method [17]. In addition to measurements on the specimen to be characterized, the coil impedance must be also measured on two homogenous calibration blocks with and without lift-off. It takes approximately 18 min to measure all five impedance spectra needed to determine the AECC spectrum of the specimen using the Agilent 4294A with the previously described high precision and additional averaging. Because of this relatively high measurement speed, the long-term drift shown in Fig. 5(a) and (b) is overly conservative and characteristic of the relative reproducibility of the impedance measurements only when the calibration is repeated in every 3 h. More realistically, the calibration could be repeated in, let us say, every 30 min and the AECC spectrum could be evaluated using the interpolated value of the two closest calibration measurements, which also increases the overall throughput of the measurement. In order to simulate this process, we applied a 30-min running average to the previously shown data and subtracted this slowly changing smooth base-line from the instantaneous measurement. As shown in Fig. 5(c) and (d), there is almost one order of magnitude improvement in the relative impedance accuracy when the more relevant 30-min reproducibility is considered instead of the long-term drift. These results indicate that there is enough time between calibrations to measure 4–5 inhomogeneous specimens with the same high level of relative impedance accuracy. Undoubtedly, even better results could be obtained by changing the probe coil parameters (size and/or density) over the very wide, almost three decades, frequency range. However, in the interest of overall measurement speed and simplicity, this option was
not exploited and it was determined that the Agilent 4294A reaches its best relative impedance accuracy over the whole frequency range of interest when used in combination with the medium-density spiral coil of 8 mm outer diameter.

2.2. Influence of impedance measurement errors on AECC accuracy

The relative error or reproducibility of the impedance measurement will ultimately determine the accuracy of the obtained AECC spectrum. In order to simulate this effect on the Agilent system with the custom-made spiral coils, two homogenous heat-treated calibration blocks were used, namely a Waspaloy calibration block of 1.55 %IACS conductivity and an IN100 calibration block of 1.36 %IACS conductivity. For calibration purposes, the complex transfer impedance of the probe coil was measured on these two calibration blocks with \( l = 25.4 \mu m \) and without \( l = 0 \) lift-off. Then, the average of these four calibration impedances was calculated for all three coils throughout the entire frequency range to simulate measurements on a hypothetical homogeneous specimen. Since our simple four-point calibration method uses linear interpolation, without added noise, the AECC and apparent lift-off values obtained for the hypothetical “average” specimen from the simulated data are constant at 1.46 %IACS and 12.7 \( \mu m \), respectively. To assess the influence of a certain level of relative impedance error on the accuracy of the resulting AECC spectrum, 0.1% rms random variation was added to both the real and the imaginary parts of the coil impedance of the hypothetical specimen. Then, the AECC spectrum was calculated using linear four-point interpolation at 130 repetitions based on the calibrated probe impedances.

Fig. 6 shows the results of this simulation for all three spiral coils at 80 frequency points between 0.1 and 100 MHz. In all three coils, the best AECC accuracy of 0.3–0.4% is achieved between 1 and 10 MHz and then it starts diverging up to 2% or more outside that frequency range. This variation of the AECC accuracy is related to the coil sensitivity as will be illustrated in the next section. Earlier work available in the literature showed that AECC measurements can be performed with \( \pm 0.1\text{--}0.2\% \) accuracy using a commercially available Nortec 2000S eddy current instrument with three separate probes to cover the frequency range between 0.1 and 10 MHz [17]. Since the

![Fig. 6. Numerical simulation of the influence of \( \pm 0.1\% \) impedance measurement variation on the accuracy of the reproduced AECC spectra without averaging.](image)
Agilent impedance analyzer can conduct impedance measurements at a very fast rate and the nature of the measurement noise was found to be essentially incoherent, the measurement variation can be further reduced by additional averaging. To simulate this, the earlier shown 130 repetitions can be presented as 5 sets of 26 repetitions per set. In addition, a three-point running average is applied throughout the entire spectrum since it is well populated with 80 points and the AECC spectra to be measured are not expected to exhibit any sharp spectral features. Due to these measures, the AECC accuracy improves by almost one order of magnitude as shown in Fig. 7. The best accuracy of 0.05% is achieved between 1 and 10 MHz where the broadband coil has the highest sensitivity. In the case of the high-density coil, the AECC accuracy beyond 50 MHz is the worst due to the increase of the capacitive influence on the measured coil impedance. Other than that, in the case of 0.1% relative impedance error the worst AECC error is about 0.3%. Previously, it was illustrated in the 30-min reproducibility analysis that the relative accuracy of the Agilent impedance analyzer is sufficient over the whole 0.1–80 MHz frequency range to reach the AECC precision required for near-surface residual stress assessment.

2.3. Spiral coils sensitivity

It was illustrated in the previous section that the AECC accuracy changes significantly with inspection frequency and the best accuracy was achieved between 1 and 10 MHz. This variation in the AECC accuracy can be easily understood based on the relative sensitivity of the probe coil to conductivity variation, which is called the gage factor $F$ and is defined as follows:

$$ F = \frac{|\Delta Z_\perp|/|Z|}{\Delta \sigma/\sigma}, $$

where $\Delta Z_\perp$ is the impedance change normal to the lift-off direction due to a small conductivity variation $\Delta \sigma$, and $Z$ is the coil impedance for the base-line conductivity $\sigma$ of the material.

This definition of a unitless gage factor to characterize the frequency-dependent coil sensitivity is in line with the
simple four-point instrument calibration procedure and can be easily measured. For this purpose, the same two calibration blocks were used as in the previous section with and without a 25.4-μm-thick plastic polymer shim. Phase rotation was applied on the four impedance calibration points at every frequency to make the prevailing lift-off direction horizontal for better separation from conductivity variations that also have a strong vertical component.

Fig. 8 shows the thereby measured gage factor for three 8-mm-diameter spiral coils of different densities. The gage factor is changing in the range of $F \approx 0.05$–0.15, i.e., 1% impedance measurement error causes as much as 6–20% AECC uncertainty. Unfortunately, maximum sensitivity is reached at medium frequencies, which happen to be less important than the low and high frequencies where the base-line conductivity of the material and the peak residual stress are calculated, respectively. Although this spectral response is less than optimal, it is a necessary consequence of using a single coil for measurements over almost three frequency decades. Except at the highest frequencies (above 80 MHz), the highest sensitivity is achieved by the high-density coil and the lowest sensitivity is exhibited by the low-density coil. However, the overall performance of the probe coil depends not only on its gage factor, but also on other effects such as its self-capacitance, which becomes increasingly important above 10 MHz, as indicated by the sharp drop in the sensitivity of the high-density coil in Fig. 8. In addition, we will illustrate later that the spurious capacitance effect also increases the sensitivity of the coil to lift-off variations, therefore it should be minimized even if that causes a substantial reduction in the gage factor. The easiest way to reduce the capacitive effect on the impedance measurement is by decreasing the coil density or coil diameter, which both reduce the absolute impedance of the coil. Because of the limited capability of the Agilent 4294A impedance analyzer to measure very low impedances, this issue will not be further investigated in the present study.

### 2.4. Lift-off sensitivity

Increasing the inspection frequency also increases the spurious capacitive effect between the turns of the eddy current coil and between the coil and the specimen being tested. The adverse influence of this capacitive effect on precision impedance measurements presents a formidable problem at elevated inspection frequencies. On a homogeneous specimen, the measured coil impedance can be corrected to eliminate the capacitive effect of the coil even at relatively high frequencies [26]. In the case of an inhomogeneous specimen, it is rather difficult, if not impossible, to correct for the capacitance effect in the measured coil impedance, which in turn causes significant errors in the calculated AECC spectra. The main problem at high inspection frequencies is that, even in the case of relatively low self-capacitance, the stray capacitance between the turns of the individual coils as well as between the transmit and receive coils via the conducting specimen causes a spurious sensitivity to lift-off variations that is far worse than the typical lift-off variation caused by the inhomogeneity of the magnetic field produced by finite-diameter probe coils.

To illustrate this effect on the measured AECC spectra, a homogenous IN100 block was tested at carefully controlled lift-off distances. Following the earlier proposed measurement procedure with the Agilent system, first a four-point calibration was completed by measuring the coil impedance on two homogenous calibration blocks (1.36 and 1.55% IACS) with and without a 25.4-μm-thick polymer shim. Fig. 9(a) illustrates the measured AECC on the IN100 specimen at different controlled lift-off distances ranging between 0 and 63.5-μm using the 8-mm medium-density spiral coil. Changing the lift-off distance causes a wide variation in the measured AECC values, especially above 20 MHz, after which the results measured at different lift-off distances start deviating more than ±1% from the true AECC. Moreover, measuring the specimen to be characterized at a lift-off higher than the lift-off used in the instrument calibration (25.4 μm) will change the measured AECC to the opposite direction. Clearly, the lift-off trajectory becomes very much curved at high frequencies, therefore the linear interpolation used in our four-point calibration procedure becomes insufficient to eliminate the influence of lift-off variation on the measured AECC. Although a more sophisticated nonlinear interpolation method could mitigate, if not completely eliminate, this adverse effect, these results indicate that the 8-mm medium-density coil does not offer sufficient tolerance to lift-off variations above 20 MHz.

One way to reduce the influence of the spurious capacitive effect on AECC measurements is to increase the separation distance between the turns, which decreases the stray capacitance both between the turns of the coil and between the specimen and the coil. Fig. 9(b) shows that decreasing the coil density while keeping the rest of the coil parameters fixed indeed reduces the lift-off sensitivity.
earlier in Fig. 8. of the coil to conductivity variations as we illustrated decreasing the coil density will also decrease the sensitivity throughout the entire frequency range. Unfortunately, decreasing the coil density will also decrease the sensitivity of the coil to conductivity variations as we illustrated earlier in Fig. 8.

3. System verification

In the previous section, we illustrated that the Agilent 4294A impedance analyzer with a single custom-made spiral coil can be used for AECC spectrum measurements over a wide frequency range from 0.1 to 80 MHz. Subsequent measurements on different samples of the same material and surface treatment and repeated measurements on the same samples over a period of six months verified that the obtained AECC spectra were reproducible within ±0.1% relative accuracy. In this section, we will demonstrate the advantages of this system over conventional eddy current instruments to conduct broadband AECC measurements on shot-peened nickel-base superalloys. First, the results obtained by the Agilent system will be compared to those obtained by a Nortec 2000S and a UniWest US-450 instrument. The efficiency of the four-point instrument calibration procedure with simple linear interpolation will be illustrated by how effectively it separates the sought material effects associated with the specimen from size and shape effects associated with the probe coil and other instrument parameters as long as the conductivity range of interest is properly bracketed with the two carefully selected calibration blocks. Finally, the AECC spectrum will be inverted to obtain an estimated near-surface residual stress profile, which will be compared favorably to destructive XRD results.

3.1. Comparison to conventional eddy current instruments

Based on our reproducibility analysis of the Agilent system, the whole measurement cycle, that includes the calibration process and measurements on the specimen(s) to be characterized, should be done within 30 min. Using a single probe coil and computer-controlled operation, this can be achieved while as many as five specimens are measured with the previously selected operational parameters (precision 5, 4 point-average, 4 sweep-average). These parameters allow a single impedance spectrum (80 points in logarithmic increments between 0.1 and 100 MHz) to be collected in about 3.5 min. This cycle is then repeated 5 times to create a set of measurements. In this way, the average time required to finish a single set of AECC measurements on one specimen is about 30 min (i.e., 150 min for five specimens).

For the validation study, two types of nickel-base superalloys were selected, namely IN100 and IN718. First, three blocks of 102 mm × 51 mm × 13 mm were cut from both materials. These blocks were subsequently low-stress ground and then shot-peened on half of their top surface (51 mm × 51 mm) at Almen 4A, 8A, and 12A intensity levels using 100% coverage, while the other half remained un-peened so that relative AECC measurements could be made within the same block between the peened and the un-peened sides [17]. Only the medium-density coil was used in this part of the study along with the previously described pair of calibration blocks (1.55 and 1.36 %IACS). A dedicated LabView program was developed to control the Agilent impedance analyzer and to evaluate the measured data.

For comparison purposes, relative AECC measurements were also performed on the same specimens using a Nortec 2000S and a UniWest 450 eddy current instrument following the previously introduced measurement procedure [17]. Three UniWest pencil probes of 2-mm outer diameter were used to cover the frequency range between 0.1 and 10 MHz. In this case, since the pencil probe coils were relatively small in comparison to the 8-mm diameter medium-density spiral coil that was used with the Agilent system, nine clustered spots were measured and then averaged to cover roughly the same area. These relative AECC measurements were conducted at 21 frequencies in logarithmic increments between 0.1 and 10 MHz and then repeated twice to get one set of measurements in about 2 h.

Fig. 9. Uncorrected lift-off effect on AECC measurements using the 8-mm (a) medium-density and (b) low-density coils on a homogenous IN100 specimen.
Finally, in order to improve the relative AECC accuracy to the required 0.1–0.2% level, four independent sets were taken and averaged. In spite of the reduced frequency range (0.1–10 MHz versus 0.1–100 MHz) and smaller number of measurement points (21 versus 81), the total measurement time for one specimen was about 8 h versus 0.5 h with the Agilent system.

Fig. 10 shows a comparison of AECC spectra obtained on shot-peened IN718 and IN100 specimens with the new Agilent system and two commercially available eddy current instruments. In the overlapping frequency range between 0.1 and 10 MHz, the agreement between the AECC spectra obtained by these different instruments is very good within the estimated errors of the two conventional instruments (±0.1–0.2%) and the new Agilent system (±40.05–0.1%). This comparison well illustrates how effectively the applied system calibration separates the sought material effects associated with the specimen from different measurement system parameters. Therefore, we can conclude that the AECC spectrum of the specimen is more suitable for quantitative materials characterization purposes than the directly measured complex electric impedance of the probe coil, which is sensitive to both material and measurement system parameters. We can also conclude that the AECC spectra obtained by the new Agilent system were validated by the commercially available instruments, at least up to 10 MHz. For want of suitable eddy current instrumentation, further verification of the measured AECC data above 10 MHz will have to be done indirectly by comparing the inverted results to residual stress profiles obtained by destructive XRD measurements.

3.2. Comparison to XRD

Although the ultimate goal of our present research effort is to predict the near-surface residual stress profile in the material, for the purposes of system validation, a direct comparison between AECC and XRD residual stress profiles is less than ideal because of the unknown and uncorrected contributions of cold work [23] and, to a lesser degree, possible surface roughness effects [22] to the actual electric conductivity variation. Fig. 11 shows (a) the cold work and (b) residual stress profiles obtained by destructive XRD measurements in shot-peened IN100 specimens of Almen 4A, 8A, and 12A peening intensities. One interesting feature of these results is the unexpectedly high value of the peak compressive stress at around 1700 MPa, which is much higher than the tabulated yield strength of 1050–1120 MPa of the annealed IN100. Of course near-surface cold work during SP could increase the yield point in work-hardening materials by 10–20%, but the observed ≈50–60% increase in yield strength is highly unusual. At this point, we are not entirely sure whether the observed unexpectedly high stress values are, at least in part, due to errors associated with the XRD residual stress measurement, e.g., due to best-fitting the badly distorted beam profile caused by extensive cold work, or represent actual values. Typically, the expected experimental uncertainty of these measurements, which was conducted by Lambda Research of Cincinnati, is only approximately ±5 ksi, which is all but negligible in our case. Therefore, it is assumed that the very high compressive peak stress is due to the presence of 30–50% plastic strain. It was shown that IN100 exhibits unusually high degree of work hardening that could increase the yield strength to levels consistent with the measured 1700 MPa peak residual stress [29].

For comparison purposes, Fig. 11(b) also shows the residual stress profiles reconstructed in two steps from the measured AECC spectra. Except for a sharper-than-expected near-surface “hook” observed in the Almen 8A specimen, which is most probably caused by imperfect lift-off rejection above 25 MHz, the general agreement between the AECC and XRD data is very good. In the first step, the depth-dependent electric conductivity change was

---

Fig. 10. Comparison of AECC spectra obtained on shot-peened (a) IN718 and (b) IN100 specimens with the new Agilent system and two commercially available eddy current instruments ( Agilent 4294A, Nortec 2000S and UniWest US-450).
calculated using a recently developed iterative inversion procedure [25]. Then, the sought depth profile of the residual stress was estimated by neglecting cold work and surface roughness effects. For isotropic plane-state of stress, the relative conductivity change can be calculated from the piezoresistive effect as follows [18]:

\[
\frac{\Delta \sigma}{\sigma_0} = \kappa_{ip} \frac{\tau_{ip}}{E},
\]

where \(\Delta \sigma\) is the stress-induced change in electric conductivity, \(\sigma_0\) is the intrinsic electric conductivity of the unstressed metal (\(\sigma_0 = 1.39 \text{ %IACS}\)), \(\tau_{ip}\) is the isotropic plane stress produced by SP, \(E\) is Young’s modulus (\(E = 210 \text{ GPa}\)), and \(\kappa_{ip}\) is the dimensionless isotropic electroelastic coefficient, which is simply the sum of the parallel \(\kappa_{11}\) and normal \(\kappa_{12}\) electroelastic coefficients \(\kappa_{ip} = \kappa_{11} + \kappa_{12}\).

Unfortunately, the shot-peened IN100 specimens were too small to measure their electroelastic coefficients in an MTS machine. However, based on our previous measurements in different IN100 specimens, the electroelastic coefficient of this material is expected to be \(\kappa_{ip} = -1.58 \pm 0.16\). Applying Eq. (2) on the reconstructed depth-dependent conductivity profile with this average electroelastic coefficient yields a significant underestimation in the predicted residual stress level. In order to get the good overall agreement illustrated in Fig. 11(b), we had to use \(\kappa_{ip} = -1.06\), which is 33% lower than the independently measured average value for IN100. The exact reason for the need for this “empirical” correction is currently not known and will require further investigation. However, it should be pointed out that the present underestimation of the residual stress level by the inverted AECC relative to the destructive XRD results does not seem to be physically related to the previously reported overestimation in Waspaloy and IN718 alloys due to increasing electric conductivity caused by microstructural changes under extensive cold work [23]. Since a single constant was sufficient to bring all the AECC and XRD results into good agreement with each other for all three peening intensities in spite of their different levels of cold work, the cause of this apparent underestimation by the AECC method is most probably the intrinsic variation of the electroelastic coefficient with microstructure. This assumption could be verified in the future by a new material calibration procedure that allows the measurement of the electroelastic coefficient in compression on small specimens and even on awkward shaped components, which cannot be tested in an MTS frame using the previously developed tensile procedure [18].

4. Conclusions

Due its frequency-dependent penetration depth, eddy current nondestructive evaluation showed a strong potential towards near-surface residual stress assessment. Previous experiments measured the AECC spectrum up to 10 MHz on nickel-base specimens that were shot-peened at relatively high peening intensity levels up to Almen 16A. Although the peak compressive residual stress is not affected significantly by the peening intensity, it does increase the penetration depth of the subsurface compressive layer. Therefore, highly peened components lend themselves to fairly complete residual stress profiling even below 10 MHz, which is the operational range of most commercially available eddy current instruments. Although high peening intensity levels are of insignificant interest in certain applications; due to the lack thermo-mechanical stability in excessively cold-worked components, such peening intensities are not used in high-temperature turbine engines. In the case of peening intensity levels between Almen 4A and 8A, which exhibit more moderate cold work levels and therefore offer relatively high thermo-mechanical stability, the penetration depth of the compressive layer is much smaller and the inspection frequency range necessary for residual stress profiling has to be extended from 10 MHz to at least 50–80 MHz to
capture the crucial peak compressive residual stress. An alternative solution would be to control the actual penetration depth of eddy current inspection by reducing the effective probe dimension at relatively low inspection frequencies. Although this method was not investigated in this study, it should be mentioned that the spatial-frequency approach is expected to be even more sensitive to lift-off uncertainties than the discussed temporal-frequency approach.

In order to facilitate sufficiently accurate AECC measurement at high frequencies, a new eddy current conductivity spectroscopic system was presented based on the Agilent 4294A high-precision impedance analyzer. The new system also offers better reproducibility, accuracy, and measurement speed than the previously used conventional systems. Aiming at increasing the self-resonance frequency of the eddy current probe coil at elevated inspection frequencies, three custom-made spiral coils of 8-mm-outer-diameter and different turn density have been tested. All three probes exhibited relatively low absolute impedance at the lower part of the inspection frequency range, i.e., between 0.1 and 10 MHz, considering the optimal measurement range of the Agilent impedance analyzer. However, as the coil density increases, its absolute impedance increases too, which also increases the relative accuracy of the impedance measurement. The relative accuracy of the impedance measurement showed high reproducibility within a 30-min period with maximum uncertainty of 0.1%. Based on the gage factor of our probe coils over the whole frequency range from 0.1 to 80 MHz, this 0.1% uncertainty translates into a maximum variation of 0.4% in AECC. Since the nature of this uncertainty was found entirely incoherent, repetitive averaging can further decrease this error by as much as one order of magnitude at the expense of increased measurement time.

Decreasing the coil density decreases the capacitive effects on the AECC measurements, but it also decreases the sensitivity of the probe coil to conductivity variation. The optimum configuration among the three 8-mm-diameter spiral coils tested in this study was the one with medium turn density (100 µm). The gage factor of this coil was between 0.04 and 0.12 throughout the whole frequency range; which allowed us to use a single spiral probe coil over the whole frequency range of almost three decades.

AECC measurements have been conducted on two nickel-base superalloys (IN100 and IN718) of three different peening intensities (Almen 4A, 8A, and 12A) using three different systems, namely Agilent 4294A, Nortec 2000S, and UniWest US-450. The results showed good agreement within ±0.1% between all three systems up to 10 MHz, which indicates that the applied system calibration effectively eliminated the adverse influence of measurement system parameters, such as coil size and shape. Although the Agilent system offers a frequency range up to 110 MHz, the residual stress profiles reconstructed based on the piezoresistivity of the material indicated that beyond 20 MHz the AECC spectra do not necessarily reflect the actual electric conductivity profile unless special measures are taken to eliminate the adverse effects of lift-off variations. AECC measurements taken on homogenous specimens at different lift-off distances indicated the spurious influence of capacitive coupling between the transmit and receive coils, which might cause up to 1% AECC error at high frequencies even for lift-off variations as small as 0.1 mm or less. In general, decreasing the coil density or diameter could reduce this capacitive lift-off effect on the AECC measurement, but the reducing transfer impedance of the probe coil must be compensated for by either increased excitation (the Agilent instrument uses only 20 mA driving current) or by added preamplifier gain. In addition, it is expected that an improved nonlinear interpolation during probe calibration could further reduce the effect of lift-off uncertainty by better separating it from the true conductivity contributions in the measured electric transfer impedance.

The broadband AECC spectra were inverted for near-surface residual stress profiles in IN100 specimens of three different peening intensities. These estimated residual stress profiles compared favorably to destructive XRD results. In this respect, further experimental efforts are needed that would not fit within the limited length and focus area of the present paper, therefore a follow-up paper will be published on the detailed comparison of XRD and eddy current residual stress profiles.

The ultimate applicability of the described nondestructive residual stress profiling technique for quality control by engine manufacturers and for maintenance and life prediction purposes by end users will have to be further investigated. The development of the high-frequency eddy current conductivity measurement system described in this paper represents a necessary step in this direction. Based on these result, the US Air Force is presently developing a standardized procedure for eddy current residual stress profiling in collaboration with major engine manufacturers. Further development is necessary to improve the robustness of this technique, especially to reduce the inherent lift-off sensitivity on curved surfaces at high inspection frequencies and to correct for the adverse effects of cold work, inhomogeneity, and surface roughness, before it can be adapted to depot applications.

Acknowledgments

This work was performed at the University of Cincinnati in cooperation with the Center for NDE at Iowa State University with funding from the Air Force Research Laboratory on contract FA 8650-04-C-5228. The authors would like to acknowledge valuable contributions to the reported experiments by Steve Bain, Curtis Fox, and Michael Miller.

References
