NEAR-SURFACE RESIDUAL STRESS-PROFILING WITH HIGH FREQUENCY EDDY CURRENT CONDUCTIVITY MEASUREMENT

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ABSTRACT. The lifetime of aero engine components can be extended by applying an additional strain to the material. Typical aero engine-alloys like Nickel-Base superalloys or Titanium alloys can be surface-treated by use of shot peening to induce the compressive strain near the surface. However, in order to use the additional life for critical aero engine components, a quantitative determination of strain gradients near the surface has to be carried out periodically. We propose to measure the depth-profile of residual stresses non-destructively by use of high frequency eddy current techniques. This paper presents results obtained with an experimental set-up based on a high precision impedance analyzer. Test samples prepared from IN718 by shot peening of different intensities can be easily distinguished. By sweeping the frequency from 100 kHz up to 100 MHz a depth profile for the electrical conductivity from 50 µm to 500 µm can be obtained. The measured conductivity profile is a resultant from residual stresses, cold work, surface roughness and the texture of the material. In addition, first results for strain profiling obtained with industry applicable NDE instrument will be presented.

Keywords: High Frequency Eddy Current, Residual Stress Profiling
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INTRODUCTION

Non-destructive detection of residual stresses at different depths of stressed aero engine components is an important topic for aero engine life-time prediction. In this paper results obtained for stressed Nickelbase-Superalloys from high frequency eddy current conductivity measurements are discussed.

BACKGROUND AND PHYSICAL ASPECTS

Aero engines are extremely powerful machines that must be precisely engineered. The materials used for the engine construction have to face a very harsh environment, high temperatures, extreme centrifugal forces and vibrations. That is why the highest quality level of the materials is necessary to guarantee a safe and long life [1]. The materials used for disks in aero engines are titanium and nickelbase-superalloys. The surfaces of these alloys are shot peened to induce a strain in the direction that is opposite to the direction of the strain created during turbine operation [2]. Thereby, the total maximum forces acting on the engine components and their lifetime can be extended. However, the influence of the shot peening process cannot be evaluated due to the lack of appropriate nondestructive measurement technique [3].

Shot peening increases the lifetime of the engine components. This treatment causes three effects: the surface gets rough, and a residual stress profile and cold work are inserted in the surface layer. The problem is that the compressive stress can disappear because of thermal relaxation occurring during the service. That is why NDT methods are needed to monitor the residual stress states during the device life time.

The studied materials are non-ferromagnetic materials with low electrical conductivity of about 1.6 %IACS and the desired residual stress extends in the very top layers of the sample, about 50 – 500µm below the surface [4]. Due to the material parameters a frequency range from 100kHz to 100 MHz is required for a near surface depth profile.

SAMPLE PREPARATION AND CHARACTERIZATION

The samples were prepared by the MTU Aero Engines GmbH in Munich. They were cut from Inconel 718 - a forged material that obtained a complex heat treatment with solution annealing and precipitation hardening. The surfaces of the samples were shot peened with intensities of 5A and 13A (Almen). For reference, the residual stress profile was measured destructively first by a hole drilling and second by X-Ray diffraction with electrochemical etching.

MEASUREMENTS AND RESULTS

The first experiments were performed with a precision impedance analyzer under the guidance of Prof. Nagy from the University of Cincinnati [5]. Special coils on solid substrates were developed by using technology for printed circuit boards. These coils were directly connected to the impedance analyzer for measuring at the specimen. In the first step an eddy-current conductivity depth-profile was measured by sweeping the frequency range from 100 kHz to 100 MHz. The results on Inconel 718 shot peened with different intensities are shown in the Fig. 1.

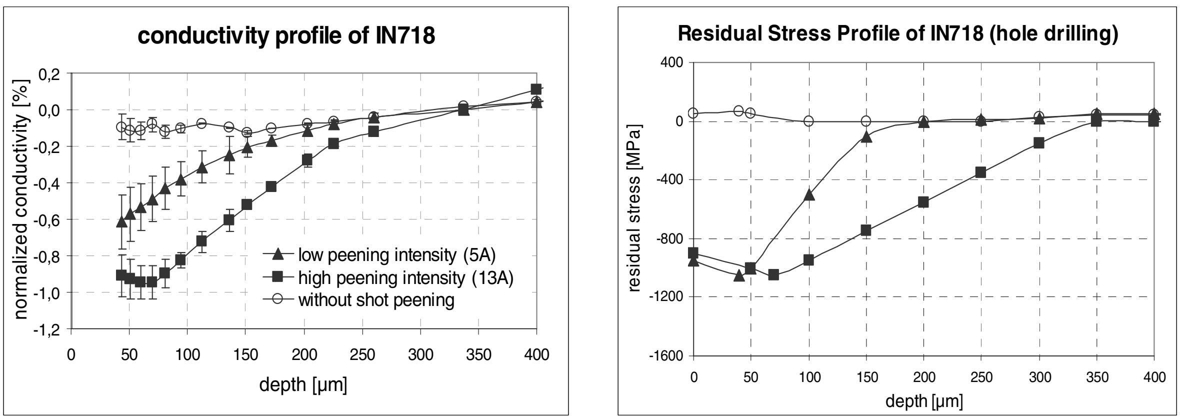

FIGURE 1. Left: A plot of an eddy current conductivity profile as a function of the depth, measured for 3 samples of Inconel 718, and right: a plot of destructively measured residual stress profile, measured by the use of hole drilling for the same IN718-samples.

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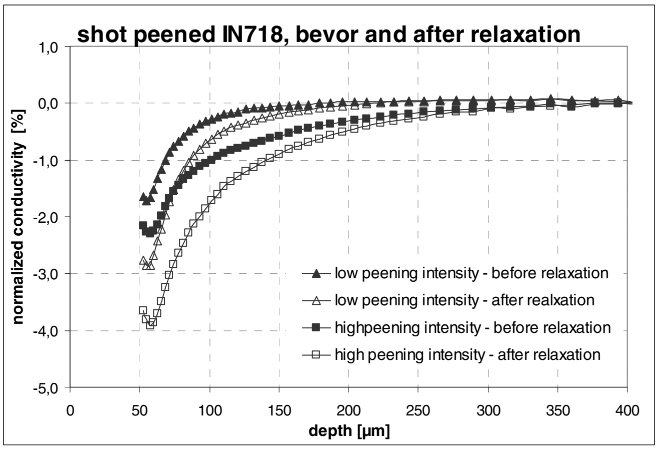


FIGURE 2. A plot of an eddy current conductivity profile as a function of the depth, measured before and after thermal relaxation at 2 samples of Inconel 718: a sample with low peening intensity before relaxation (solid triangles) and after relaxation (open rectangles) and a sample with high peening intensity before relaxation (solid rectangles) and after relaxation (open rectangles).

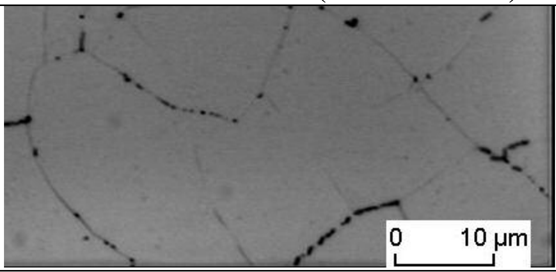
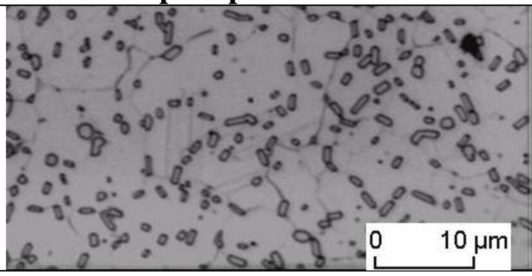
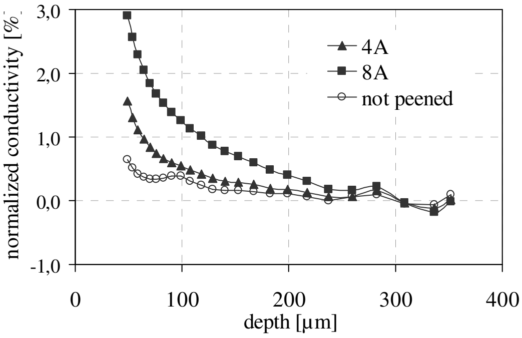
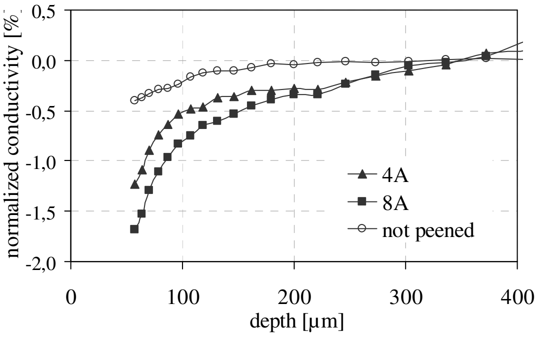
There is clear separation combined with high grade reproducibility in the eddy current conductivity between the three samples. The results of reference measurement yielded a maximum of stress of around -1000 MPa at a depth of 50 to 70µm below the surface. With increasing depth the stress converges to zero in the bulk material, as can be seen in the right-handed diagram in Fig. 1. For the 5A sample the stress disappears at a depth of around 150 µm, as compared to the 13A sample where the stress field extends up to 350 µm from the surface. From the analysis of the two diagrams, one can observe that the eddy-current conductivity shows very similar dependence on the sample depth to that of the residual stress measured by the reference methods.

In the next step the investigated samples were thermally relaxed at 700°C for 2h. The thermal relaxation was followed by a controlled cooling with a step of 10°C / min. After the thermal relaxation the eddy current conductivity measurements were repeated. The results are shown in Fig. 2. The conductivity decreases after the thermal relaxation. The difference between the curves measured before (solid symbols) and after (open symbols) relaxation is caused mainly by the thermal relaxation induced changes in the residual stresses. However, the conductivity does not converge to zero, which indicates that changes in the eddy-current conductivity may be caused by additional effects than only the electro elastic effect [6]. Residual stress and cold work may have different influence on the eddy-current conductivity: when cold work increases, the conductivity decreases and whether residual stresses increases, the conductivity increases, too.

The influence of the microstructure on the eddy current conductivity is clarified in Table 1. The left side of Table 1 shows IN718 as purchased. On the right side the condition after the precipitation hardening process is shown. The photographs show a cross-section of the materials. The corresponding normalized conductivity is shown below.

The precipitation population for the two samples is completely different. The not hardened sample has large grains and no precipitations at the grain boundary. The hardened material is twice as hard as the raw material.

TABLE 1. Comparison of IN718 as raw material (not hardened) on the left side and precipitation hardened on the right side. First raw: micrographs; second raw: Vickers hardness; third raw: eddy current conductivity of the not treated bulk material; fourth raw: conductivity profile of shot peened material

<table>
<tr><th>IN718 raw material (not hardened)</th><th>IN718 precipitation hardened</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Hardness (Vickers): 260 HV</td><td>Hardness (Vickers): > 460 HV</td></tr>
<tr><td>Bulk conductivity: $\sigma_0 = 1.48$ %IACS</td><td>Bulk conductivity: $\sigma_0 = 1.6$ %IACS</td></tr>
<tr><td>
</td><td>
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In addition, low-frequency measurements of the eddy-current conductivity showed a distinct difference in the value of σ_0 for the two samples. This bulk conductivity increases with the hardening. High-frequency eddy-current conductivity measurements were performed for raw and hardened material without shot peening and after shot peening at intensities of 4A and 8A. The results are presented in Table 1. For the raw-material specimen the conductivity increases with the shot peening intensity. For the precipitation hardened samples, the conductivity decreases with the shot peening intensity. As we can see in the diagram plotted for precipitation hardened material, the presence of the precipitations and dislocations affects strongly the character of the eddy-current conductivity.

This makes clear that a deep understanding of the microstructure is essential for stress profiling by eddy current techniques. Different states of heat treatment have a significant effect on the eddy current conductivity. Nickelbase-Superalloys receive a complex heat treatment. Because of this heat treatment and other processes occurring during service, the microstructure including precipitations and the density of dislocation changes. The eddy current conductivity is a mixed signal containing information on residual stress, microstructure and density of dislocations. To obtain information about residual stresses, the influence of the additional factors needs to be separated. The influence of different factors on the measured eddy current conductivity can be described in rough contexts with the following simplified formula (1), which shows symbolically the correlation between the individual effects.

$$\sigma(f)_{measured} = \sigma\,(f)_{residual\ stress} - \sigma\,(f)_{grain\ size} + \sigma\,(f)_{precipitations} \pm \sigma\,(f)_{dislocations\ (cold\ work)} \qquad (1)$$

Where $\sigma(f)_{measured}$ stands for the total measured conductivity at a frequency (f). The frequency can be correlated to the penetration depth of the eddy current. $\sigma\,(f)_{residual\ stress}$ describes the part of conductivity coming directly from effects caused by residual stress inside the measured volume. Comparable, the grain size $\sigma\,(f)_{grain\ size}$, the form and concentration of precipitations $\sigma\ (f)_{precipitations}$ and dislocations $\sigma\ (f)_{dislocations\ (cold\ work)}$ will influence the total conductivity. The formula describes in principal the observed effects on the conductivity. That means if the residual stress is increasing, the conductivity will increase. If the grain size is growing, the number of single grains and grain boundaries is decreasing. This results in a decreasing conductivity. The influence of dislocation or cold work can not be fixed in general. Generating a deeper understanding of all the influences will be will be the task for future work.

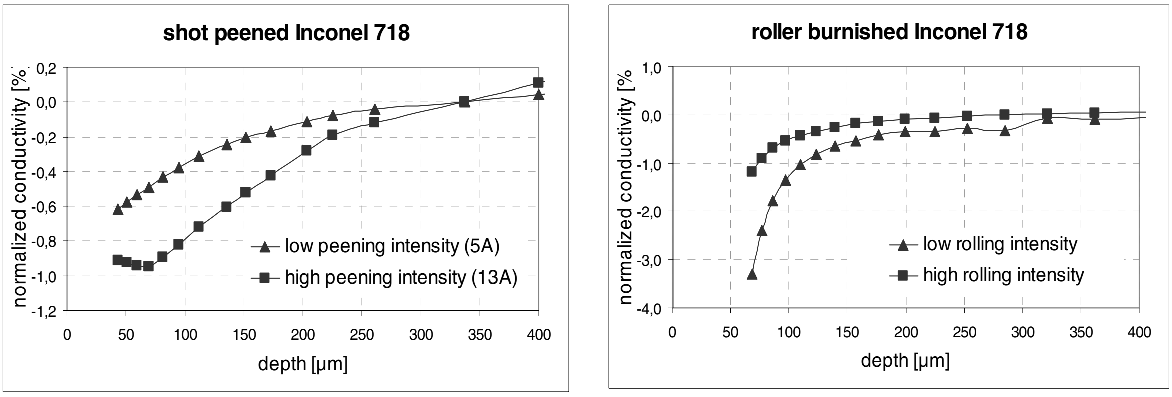

FIGURE 3. Comparison of an eddy current conductivity profile of shot peened Inconel 718 specimen in the left diagram and roller burnished Inconel 718 specimen in the right diagram.

The influence of cold work on the eddy current conductivity is also visible in some additional results, shown in Fig. 3. A comparison between shot peened Inconel 718 specimen in the left diagram and roller burnished Inconel 718 in the right diagram is shown. In contrast to the shot peened samples the roller burnished samples shows a different behavior, the low stressed sample has a lower conductivity than the high stressed sample. That is caused by the different cold work profiles of these samples and the fact, that cold work and residual stresses have a different behavior in the eddy current conductivity.

PROTOTYPE DEVICE

Fraunhofer IZFP developed a prototype device for high frequency eddy current in-service inspections, e.g. after shot peening or to measure remaining strain gradients after a longtime turbine operation to be done during the maintenance cycles. This allows performing high precise eddy current measurements with frequencies up to 100MHz without network analyzer. The device is designed for in field inspections.

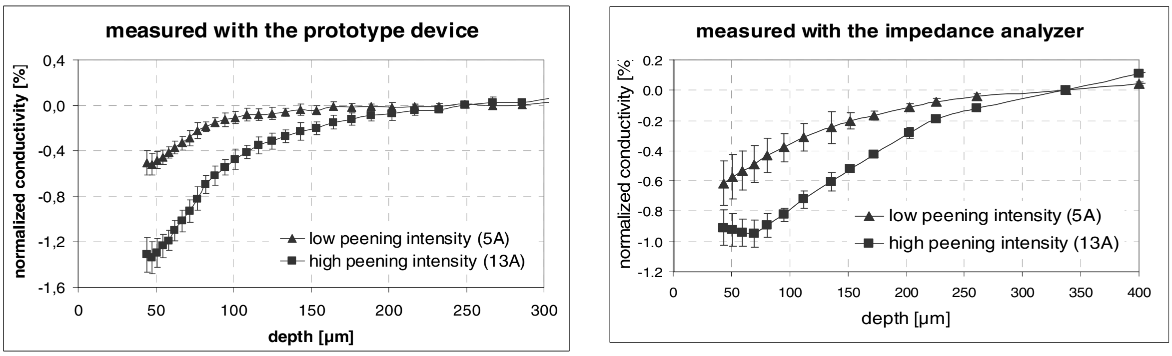

FIGURE 4. Comparison of conductivity profiles from shot peened Inconel 718 measured with the prototype device (left diagram) and the impedance analyzer (right diagram).

Figure 4 shows a comparison of eddy current conductivity profiles measured with the prototype device on the left side and performed with the measurement system with impedance analyzer on the right side.

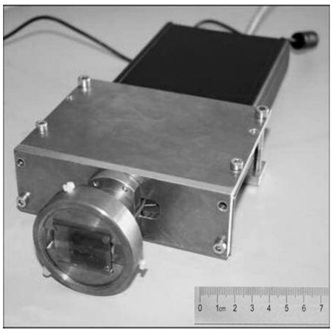

FIGURE 5. Photo of the Prototype device for characterizing the state of solidification.

The most important high frequency range is much better repeatable as compared to the impedance analyzer. Additionally it is possible to perform fast measurements, with just half of the measurement time in comparison to the impedance analyzer. The prototype device is prepared for the appliance in industrial environments for in-service inspections. A photograph of the device is shown in Fig. 5.

ACKNOWLEDGEMENTS

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