RAYLEIGH WAVE VELOCITY DISPERSION FOR CHARACTERIZATION OF SURFACE TREATED AERO ENGINE ALLOYS

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ABSTRACT. In aero engines mechanically high stressed components made of high-strength alloys like IN718 and Ti6Al4V are usually surface treated by shot-peening. Other methods, e.g. laser-peening, deep rolling and low plasticity burnishing are also available. All methods introduce compressive residual stress desired for minimizing sensitivity to fatigue or stress corrosion failure mechanisms, resulting in improved performance and increased lifetime of components. Beside that, also cold work is introduced in an amount varying from method to method. To determine the remaining life time of critical aero engine components like compressor and turbine discs, a quantitative non-destructive determination of compressive stresses is required. The opportunity to estimate residual stress in surface treated aero engine alloys by SAW phase velocity measurements has been re-examined. For that, original engine relevant material IN718 has been used. Contrary to other publications a significant effect of the surface treatment to the ultrasonic wave velocity was observed which disappeared after thermal treatment. Also preliminary measurements of the acousto-elastic coefficient fit into this picture.

INTRODUCTION

Materials used for discs in aero engines are titanium and nickelbase-superalloys. The components of these alloys are surface treated to induce compressive stress which adds to the tensile stress created during turbine operation [1], [2]. Thereby, the total maximum tensile stress in the critical surface regions of the engine components is limited, leading to a longer lifetime. There are several methods available to introduce these stresses. The most common ones are shot peening (SP), low plasticity burnishing (LPB) and laser peening (LP). All these treatments cause at least three effects to a different degree: the surface gets rough, a residual stress profile is introduced and cold work is inserted into the surface layer. While not the best from the point of generation of deep compressive stresses with sparse side effects, for economical reasons SP is one of the mostly applied methods. We will concentrate onto this.

Unfortunately, today the advantages of the surface treating cannot be considered in the components' lifetime estimation because the compressive stress may disappear by thermal relaxation during operation. Strong cold work as introduced by shot peening is known to accelerate the relaxation. That is why NDT methods are strongly needed to monitor the residual stress states at maintenance intervals during the entire disc life time.

In a recent publication [3] the potential NDT methods for residual stress measurements in aero engine components are reviewed. The relevant range of the residual stress depth profile is between 50 µm and 500 µm [4]. So, common X-ray techniques are not applicable. Ultrasonic, eddy current and thermoelectric methods are all estimated to be sensitive enough for measurements of the residual stress [3]. But these methods sense also cold work to various degrees. So the real problem is not the sensitivity but the selectivity of the measurement against various additional influences. Contrary to ultrasonic surface acoustic (Rayleigh) waves (SAW) measurements, eddy current measurements are assessed to be less influenced by cold work. Indeed, at least for the aero engine material IN718 very good eddy current results could be obtained [3]. But later, for the same type of material contradicting results turned up [5]. The inconsistence was caused by a different hardening of the samples used for the investigations. This was confirmed by recent studies [6] with systematic variation of the sample hardness. So today, it is incontestable that for properly hardened IN718 the advantage of eddy current measurements is not given.

There are some studies about the influence of uniaxial stress to SAW velocity in the direction of the stress. They give a positive acoustoelastic constant (increasing speed with increasing compressive stress) [7]. Surface treated material (formerly homogeneous) has a stress distribution which is isotropic in the surface. By analogy to shear wave birefringence, where normal and parallel polarization usually have acousto-elastic constants of different sign and approximately equal magnitude, it was concluded, that the effect nearly cancels out [3]. But to the best of our knowledge the effect of stress perpendicular to the propagation direction was not yet measured for SAW.

The relative contribution of stress and cold work to a measurement result can be estimated by releasing the stresses with a careful thermal treatment. If the stress is released and the cold work is not, the influence of the cold work can be measured independently. It was observed that the SAW velocity does not change significantly due to such a thermal treatment [7]. The authors concluded that the change in SAW velocity is produced mainly by cold work. This conclusion was confirmed by a decrease of SAW velocity induced by shot peening, while an increase was expected ([3], [7]). While this is true for most materials, there are exceptions. So, e.g. the steel type EI702 has the opposite sign at its shear wave acousto-elastic constant [8].

Despite these negative results in the open literature we started to have an additional look at the SAW velocity. The seemingly contradictory eddy current results ([3] vs. [5]) show that - to avoid surprises - exactly the material relevant for the application has to be investigated. Even the hardening state can and will be of influence. Therefore in this work the SAW velocity dispersion is studied on shot peened Ti6V4Al and IN718 in exactly the material state used for discs in jet engines.

MEASUREMENT PRINCIPLES AND REALIZATION

The effect of surface treatment on the SAW velocity is very small, usually below 1 %. So, reliable and precise measurements are necessary. Several approaches have been reported for precise measurements. Among others, knife edge techniques [9], scanning acoustic microscopy, and laser acoustics were applied. The latter is particularly well suited because it is contactless either on the excitation [10, 11] or on the detection side. We use the optical detection technique similar to that of [12], and apply a commercial laser interferometer to pick up the surface vibration at several detection points (see Figure 1).

For excitation of the SAW three commercial transducers were used. Transducer “MUWB4” is a variable angle beam transducer with a center frequency of 4 MHz and a relatively narrow bandwidth. The two others have center frequencies of 5 and 10 MHz, a large bandwidth. Their element diameter is 10 mm. They are adapted on plastic wedges for SAW excitation at steel. For better matching the SAW velocity of IN718, the angle of one wedge was slightly enlarged by mechanical grinding. This leads to an obvious increase in the signal amplitude. For titanium alloy the wedges have a good matching a priori.

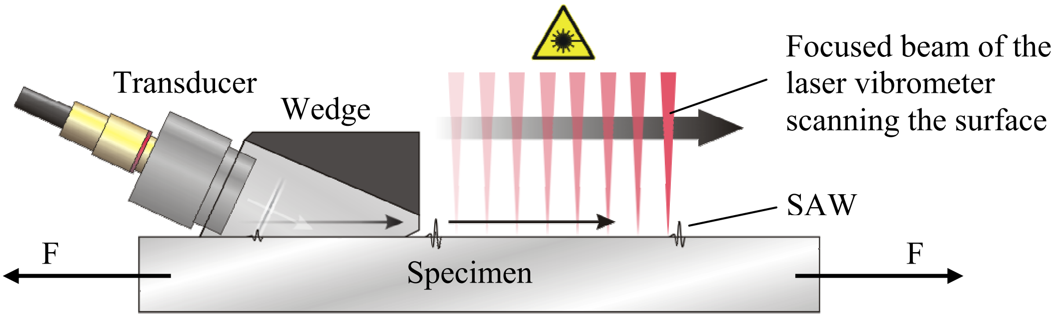

FIGURE 1. Scheme of the set up for SAW velocity dispersion measurement. For the determination of the acousto-elastic coefficients K in a tensile test machine direction of tensile force is indicated by arrows.

The software for data evaluation calculates the surface wave velocity in dependence of the frequency (phase velocity dispersion). The developed algorithm and its implementation was tested by comparison between numerical generated data and well known analytical calculations. So, it is proved that the algorithm gives accurate results [14].

The relation between the stress and the change in the acoustic velocity is given by the acousto-elastic constants. For shot peened materials, the stress is transversally isotropic in the surface and zero perpendicular to it. Let us have a coordinate system with x_1- and x_2-axis in the surface as well as x_3-axis normal to the surface. For in plane isotropic stress, the tensor σ_{ij} fulfils the conditions

$$\sigma_{i3} = \sigma_{3j} = 0 \ \text{ for } i, j = \{1,2,3\} \tag{1}$$

$$\sigma_{12} = \sigma_{21} = 0 \qquad \sigma_{11} = \sigma_{22} = \sigma \tag{2}$$

Acousto-elastic constants relate the relative change of a sound velocity $\tilde{v}$ to stress.

$$\tilde{v} = \frac{v - v_0}{v_0} = \frac{\Delta v}{v_0}$$

They can be defined in various ways. Usually they are defined for pressure waves and shear waves. In our context it is appropriate to use a definition directly for Rayleigh SAW. Supposing (1) (no stress normal to the surface) and restricting the range of indices to 1 and 2 we define:

$$(\tilde{v})_l = K_{lmn}\sigma_{mn}$$

Considering (2) as well as a sound propagation in the x_1-direction, it reduces to

$$(\tilde{v})_1 = K_{\parallel}\sigma_{11} + K_{\perp}\sigma_{22} = K\sigma \tag{3}$$

with $K_{\parallel} = K_{111}$ and $K_{\perp} = K_{122}$ and $K = K_{\parallel} + K_{11}$. K is relevant for transversally isotropic surface treated materials. Equation (3) shows that K can be determined by two uniaxial tensile experiments, where we measure $K_{\parallel}$ and $K_{\perp}$ separately.

SAMPLE PREPARATION AND ALTERNATIVE CHARACTERIZATION

The samples were prepared by MTU Aero Engines GmbH in Munich. The ones for SAW dispersion measurement were made of Ti6Al4V and Inconel 718 as shown in Figure 3, but we concentrate only on IN718 here. The surface of the sample has been partially shot peened with intensities of 5A and 13A (Almen). For reference, the residual stress profile was measured destructively by both borehole method and X-ray diffraction with successive electrochemical etching.

Figure 2 illustrates the results of the destructive stress measurements. The general agreement between both methods is rather good. The maximum compressive stress is obtained a bit below the surface. It is also known, that with higher shot peening intensities the peak value of the compressive stress does not break through a certain value near the yield point stress. In our case this peak value is about -1000 MPa. But, the depth of maximum stress deepens with increasing peening intensity (here from 40 µm for 5A to 70 µm for 13A). Also the depth, where the stress crosses zero again is roughly twice as much (from 150 µm to 300 µm). The stress values in x and y direction are nearly equal showing, that the stress introduced by shot peening is isotropic in the x-y plane (parallel to the surface).

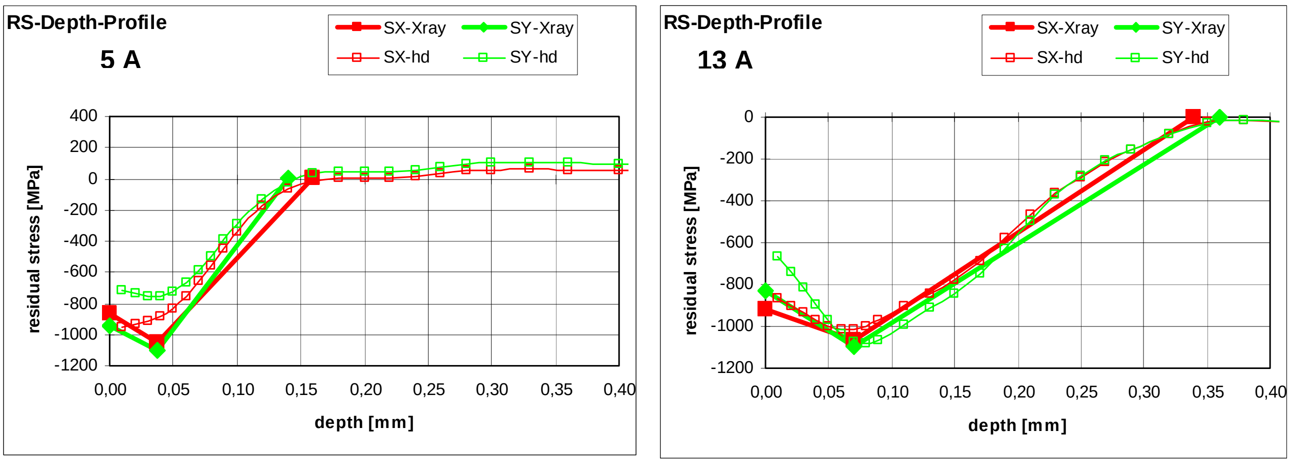

FIGURE 2. Residual stress profile of the sample material determined by X-ray diffraction (solid dots) and by borehole method (empty squares) for two peening intensities (5 A left Figure and 13 A right Figure). The stress was determined in all measurements for two orthogonal directions x and y.

Also the tensile specimens were made by MTU. They are shown in Figure 3. Here the materials Ti6246 and IN718 were deployed. For determining $K_{\parallel}$ dog bone specimens with a gage area of 70 x 16 mm^2 and a thickness of 5 mm were used. Transducer and wedge were attached at one end next to the holding jaw and the remaining gage area was used for scanning.

Measuring $K_{\perp}$ in a tensile test machine is a bit more difficult because the SAW's propagation direction must be perpendicular to the stress direction. For reliable measurements, a SAW propagation way of some 10 mm is needed as well as additional space for coupling the transducer. This would require at least about 6 cm wide specimens. The specimens' thickness also must be a few millimeters. Otherwise the Rayleigh SAW will become a Lamb wave effectively. So, a cross-section area of a few hundred square millimeters is reached quickly. Then a very strong tensile test machine is needed to reach stresses of 1000 MPa and more. Hence, the arrangement of Figure 4 was chosen. The transducer is coupled to the backside of the specimen. The sides of the specimen are rounded to guide the Rayleigh waves around to the front side without too much damping and distortion. So, nearly the entire width of the specimen remains as scan range.

FIGURE 3. left picture: shot peened specimens made of IN718 (upper) and Ti6Al4V (below); right picture: tensile test specimen for measuring SAW parallel and perpendicular to stress direction

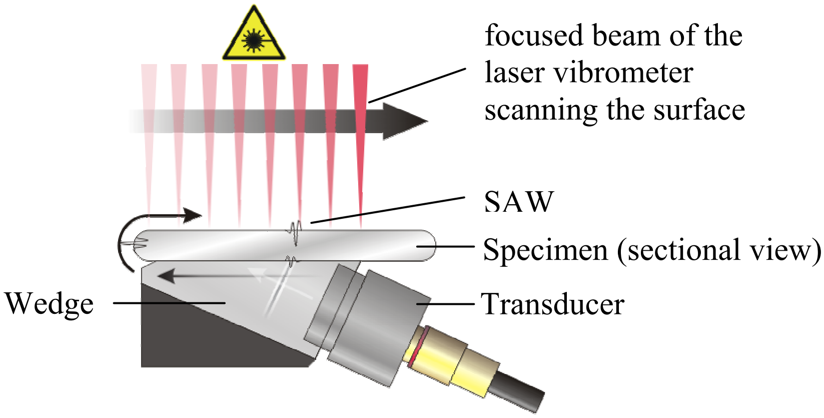

FIGURE 4. Arrangement for SAW velocity measurements perpendicular to the stress direction in a tensile test machine. The direction of tensile force is perpendicular to the drawing plane.

MEASUREMENTS AND RESULTS

Due to have an additional check of the measurement results' consistency, all three transducers mentioned above were used for exciting the SAW in the dispersion measurements at the shot peened specimens. Figure 5 shows that in the transducers' common frequency range the measurements yield coinciding results. The 10 MHz transducer covers the frequency of both other transducers and can be used solely.

A small dispersion also remains at the unpeened areas (0A). There are several possible reasons for this behavior; one is apparent dispersion due to sound field effects [12].

The decrease in the phase velocity at higher frequencies shows, that the upper layer has changed its elastic properties. A rough indication about the thickness of that layer can be obtained by considering the penetration depth of the Rayleigh SAW for a given frequency. There are two characteristic lengths $1/\alpha$ and $1/\beta$ controlling the exponential decay of the displacement amplitude over depth (Equ. (7.4) in [13]), which involve the bulk pressure wave and shear wave velocities. The scale involving the shear velocity

$$\frac{1}{\beta} = \frac{\boldsymbol{c}}{\omega \sqrt[2]{1 - \boldsymbol{c}^2 / \boldsymbol{c_p}^2}} \tag{2}$$

is assumed to be more relevant than 1/α to SAW velocity changes. Plotting the phase velocity over that length instead of the frequency give a rough estimation of the depth where the changes occur. It is interesting to compare the phase velocity over penetration depth diagram with the stress depth distribution as obtained by the borehole method. This is done in Figure 6 for 5A and 13A peening intensity and at least the main behaviors of the graphs agree. Closely below the surface, the stress magnitude of the 13A sample is smaller than the maximum stress value. This is not reproduced by the phase velocity. Apparently, this is attributed to the upper frequency limit of 12 MHz, which is even too low to see the weaker compressive stress near the surface.

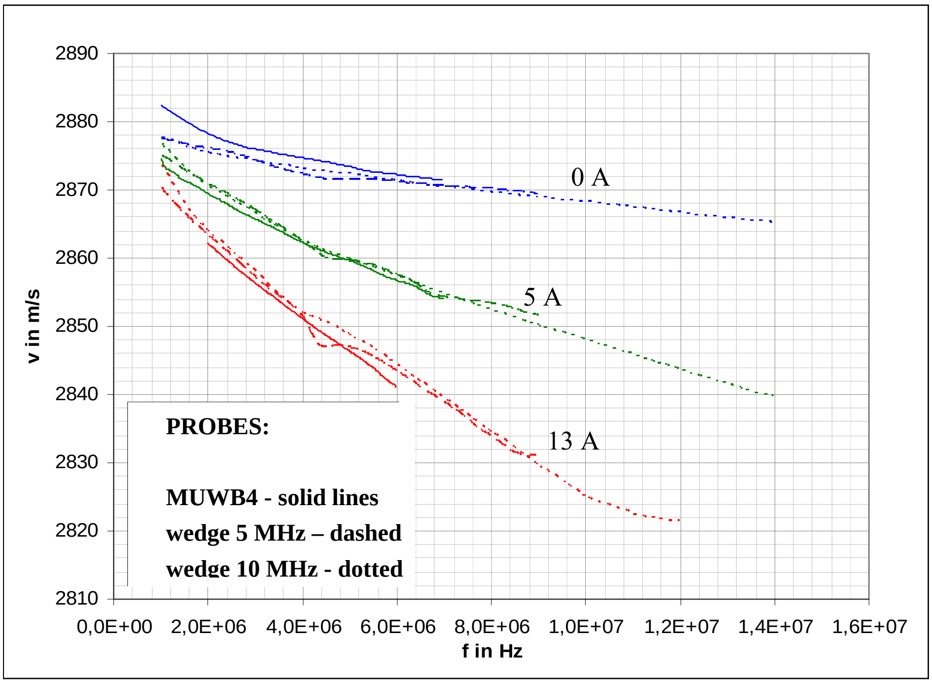

FIGURE 5. Rayleigh wave velocity results for Inconel 718 samples treated with increasing peening intensity; the values are obtained with three transducers covering different frequency ranges.

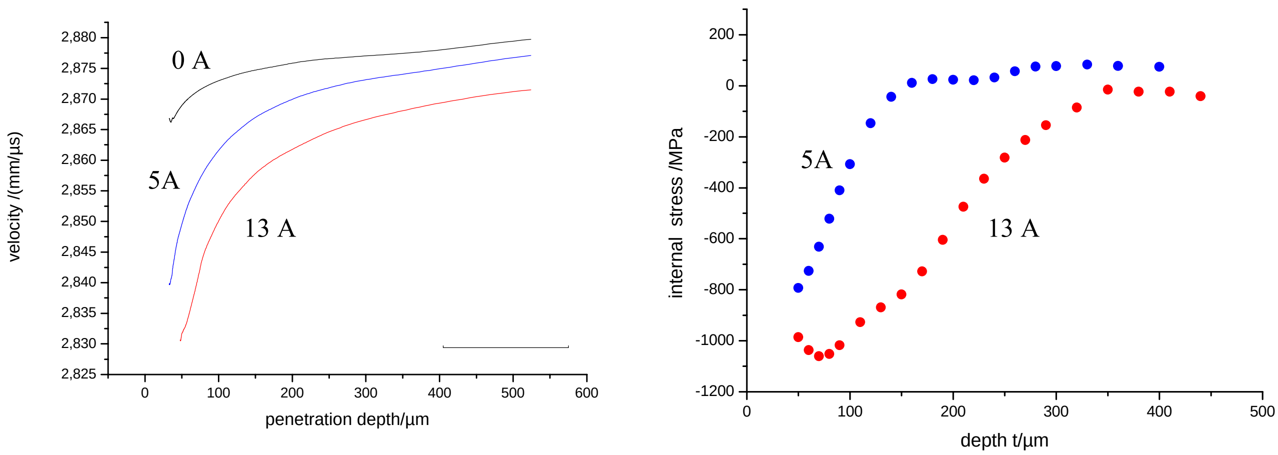

FIGURE 6. left diagram: SAW velocity versus SAW penetration depth 1/β (left Figure); right diagram: residual stress versus depth. The residual stress values are mean values for the x and y measurement represented in Figure 2.

An important check whether the SAW velocity is influenced essentially by the internal stress was done by repeating the measurements after the specimens have been thermal treated. That treatment was designed to release the stress with minimal influence to the cold work effects. So, the IN718 specimen was heated for 1 h at 700 °C in vacuum and slowly cooled down with a rate less than 10 °C per minute. In Figure 7 the SAW dispersion before and after thermal treatment are compared. The change in the curves' slope is significant and consistent with the interpretation that the stress contributes significantly to the SAW velocity. But that is true only under the assumption, that the relevant acousto-elastic constant K is positive. Measurements for the acousto elastic constant are reported in the literature only for other materials and most of all for the case of uniaxial stress. There we only found negative acousto-elastic constant values (e.g. [7]).

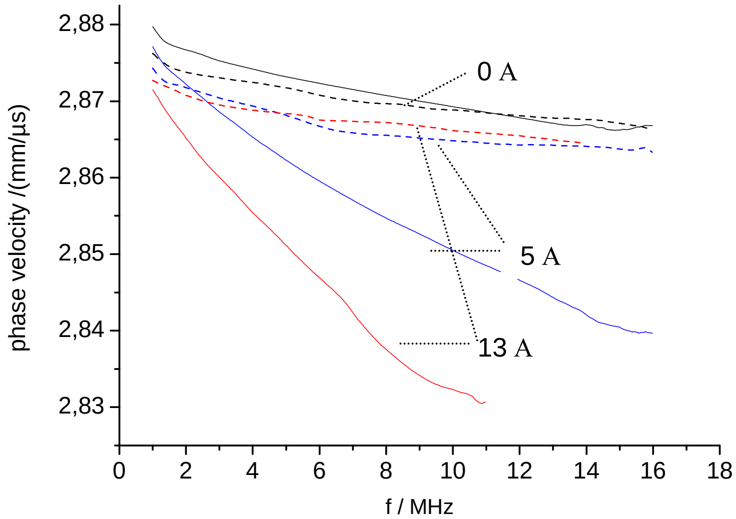

FIGURE 7. SAW velocity of shot peened IN718 before (solid lines) and after thermal treatment (dotted lines).

Due to close this gap of knowledge, we measured the SAW acousto-elastic constants for IN718 and also for Ti6246 in tensile experiments. Figures 8 and 9 give the corresponding SAW velocities parallel and perpendicular to the tensile stress. The several velocity values are mean values taken from the dispersion curves in a certain frequency range. The acousto-elastic constants are calculated from the least square fit of the velocity points and listed in Table 1.

The plots marked by empty triangles in both diagrams come from previous measurements that are already reported in [14] for the IN718 sample and stress in parallel to SAW direction. The filled squares are gained with the same samples but with a stronger tensile test machine. Both measurements agree pretty good for Ti6246, while for IN718 the new measurement gives a slight larger slope. The results of the measurement with stress perpendicular to SAW's propagation direction are denoted by filled circles.

Fortunately, the acoustoelastic constant for propagation parallel to the stress is positive for both cases contrary to the cited literature results. Unfortunately the points for SAW propagation perpendicular to the stress have a high scatter so obtained value for $\boldsymbol{K}_{\perp}$ is not very reliable. But we can certainly conclude that it is too high to compensate the positive value of. $K_{\|}$. For Ti6246, the results are indicating that the value of $\boldsymbol{K}_{\perp}$ is positive, leading to an increase of K compared to $K_{\|}$.

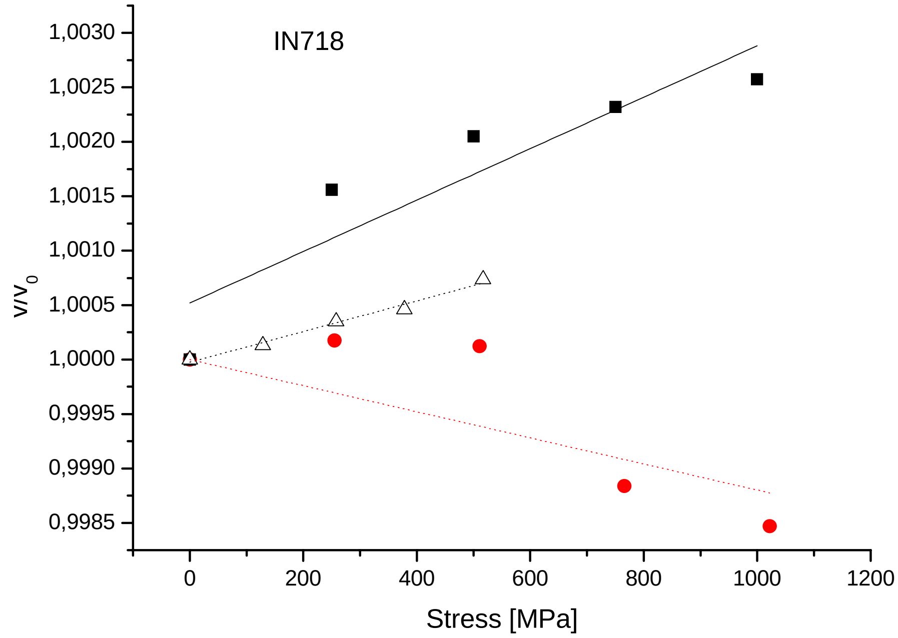

FIGURE 8. Relative SAW velocity for Inconel 718 specimens; triangles: result of first measurements on dog bone specimen (SAW propagation parallel to stress); filled squares: result of new measurements on the same specimen but with higher stress; filled circles: result of measurements perpendicular to the stress

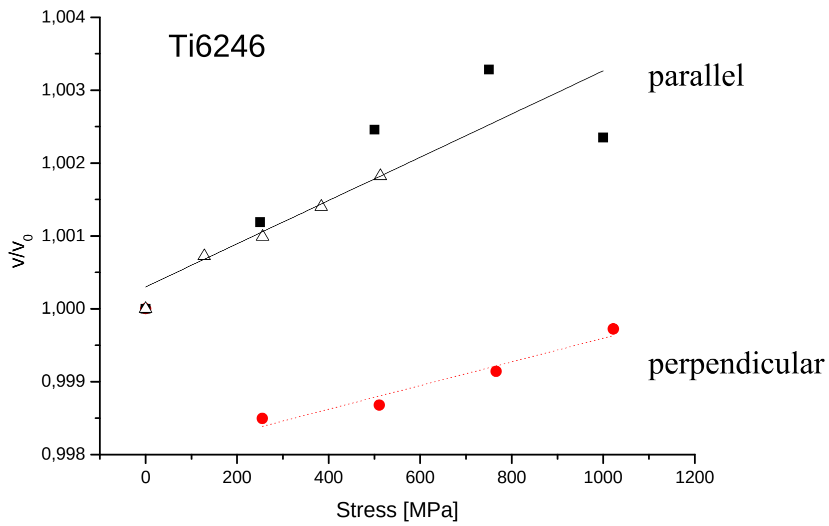

FIGURE 9. Relative SAW velocity for Ti6246 specimens; triangles: result of first measurements on dog bone specimen (SAW propagation parallel to stress); filled squares: result of new measurements on the same specimen but with higher stress; filled circles: result of measurements perpendicular to the stress

TABLE 1: Acousto-elastic constants for uniaxial stress parallel and perpendicular to SAW propagation direction as well as for calculated biaxial isotropic stress; for IN 718 the values in parentheses are taken from the previous measurements (triangles in Figure 8). In the results of the measurements on Ti6246 specimen (SAW perpendicular to stress) the first point was interpreted as a measurement error and disregarded for fitting $\boldsymbol{K}_{\perp}$. The fit including this point is given in parentheses.

Material	$K_{\parallel}$ **/(10^{-6}/MPa)**	$K_{\perp}$ **/(10^{-6}/MPa)**	**K /(10^{-6}/MPa)**	**$\Delta v/v_0$ (1 GPa) /10^{-3}**
IN718	2.36 (1.88)	-1.2	1.16 (0.68)	1.16
Ti6246	2.79	+ 1.62 (+0.038)	4.41 (2.83)	4.41 (2.83)

SUMMARY AND CONCLUSIONS

The possibility to estimate residual stress in surface treated aero engine alloys by SAW phase velocity measurements has been re-examined. For that purpose original engine relevant material IN718 was used. Contrary to other publications a significant change of the SAW velocity caused by the surface treatment was observed. The effect disappeared after thermal treatment.

An approach for measurements of both acousto-elastic constants (perpendicular and parallel to uniaxial stress) was performed. For both materials (Ti6246 and Inconell 718) the constants have been determined. The constant for in plane isotropic stress for both materials is positive (increase of velocity for tensile stress) corresponding to reduced surface velocity in case of compressive stress caused by surface treatment. While this explains some of the dispersion slope’s drop the obtained values of the acousto-elastic constants are not high enough to explain the whole change in the SAW velocity. There must also be some change in cold work.

The SAW velocity measurement is sensitive to the surface stress but also to the cold work effects. To separate residual stress from cold work effects, further quantities have to be measured. There are hints in the literature [15] that the eccentricity of the surface point motion orbits created by travelling SAW could be the key to rise to this challenge.

ACKNOWLEDGMENTS

This work was performed by the Fraunhofer Institute for Non-destructive Testing in Dresden together with and under the support of the MTU Aero Engines GmbH Munich. The support is grateful acknowledged.

REFERENCES

1. T. Seliga, “Investigations of the Microstructural Stability of Wrought Ni-(Fe)-Based Superalloys for Steam Turbine Rotor Applications beyond 700 °C”(in German), PhD thesis 2005, Rheinisch-Westfälische Technische Hochschule Aachen.

2. P. J. Withers, “Residual Stress and its role in failure”, Reports on Progress in Physics, Vol.: 70, Issue: 12, Pages: 2211-2264, December 2007.
3. P. Nagy, "Opportunities and Challenges for Nondestructive Residual Stress Assessment", Proceedings of the Rev. of Progress in QNDE 2005, ed. by D.O. Thompson, D. E. Chimenti, Vol. 25, (2006), p.1349 ff.

4. Y. Shen, C. Lee, C. C. H. Lo, N. Nakagawa and A .M. Frishman, “Conductivity profile determination by eddy current for shot-peened superalloy surfaces toward residual stress assessment”, Journal of Applied Physics, 101 (2007) 014907.
5. S. Hillmann, H. Heuer, H.-U. Baron, J. Bamberg, A. Yashan, and N. Meyendorf, "Near-surface residual stress-profiling with high Frequency eddy current conductivity measurement", Proceedings of the Review of Progress in QNDE 2008, ed. by D.O. Thompson, D.E. Chimenti, Vol 28, p.1349 ff.
6. Bassam A. Abu-Nabah, Waled T. Hassan, Daniel Ryan, Mark P. Blodgett, and Peter B. Nagy, "The Effect of Hardness on Eddy Current Residual Stress Profiling in Shot-Peened Nickel Alloys", J. Nondestr. Eval. 60, to be published.
7. A. I. Lavrentyev, P. A. Stucky, and W. A. Veronesi, "Feasibility of Ultrasonic and Eddy current methods for measurement of residual stress in shot peend metals", Proc. of Rev. of Progress in QNDE, Ed. by D. O. Thompson and D. E. Chimenti, 19, (2000), 1621-1628.
8. A. N. Guz, F. G. Makhort, "The physical fundamentals of the ultrasonic nondestructive stress analysis of solids", International Applied Mechanics. 36 (200) 1119.
9. K. Jassby and D. Kishoni, "Experimental technique for measurement of stress-acoustic coefficients of Rayleigh waves", Experimental Mechanics 23 (1983) 74-80.
10. D. Schneider, T. Schwarz, "A photoacoustic method for characterizing thin films", Surface and Coatings Technology 91 (1997) 136-146.
11. D. Schneider T. Witke, T. Schwarz, B. Schöneich, B. Schultrich, "Testing ultra-thin films by laser-acoustics", Surface and Coatings Technology, 126 (2000) 136-141.
12. A. Ruiz, P. B. Nagy, "SAW dispersion measurements for ultrasonic characterization of surface treated metals", Instr. Meas. Metrol. 3 (2003) 59.
13. Lester W. Schmerr Jr., Sung-Jin Song "Ultrasonic Nondestructive Evaluation Systems, Models and Measurements", Springer, NY, 2007.
14. B. Koehler, M. Barth, F. Schubert, J. Bamberg, and H.-U. Baron, "Characterization of surface treated aero engine alloys by Rayleigh wave velocity dispersion". Proc. of Rev. of Progress in QNDE, Ed. by D. O. Thompson and D. E. Chimenti, **29**, (2009), (to appear).
15. M. Junge, L. J. Jacobs, J. Qu, J. Jarzynski, V. La Saponara "The measurement of applied stresses using the polarization of rayleigh surface waves". Proc. of Rev. of Progress in QNDE, Ed. by D. O. Thompson and D. E. Chimenti, **22**, (2003), 1188-1191.