Basic Investigations to Establish an Ultrasonic Stress Evaluation Technique for Aero Engine Materials


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Abstract. To satisfy the high demands in view of technical reliability, weight, power, economic efficiency and lifetime of modern aero engines, it is essential to benefit from the full potential of the employed materials. In this respect, residual stresses in the bulk of components are of considerable importance as they have e.g. a strong influence on component distortions during the whole manufacturing process and therefore also on the efficiency of these processes. The measurement of residual stresses using ultrasound in the bulk of materials is a fast and nondestructive method, already well-established for steel components. Thus, the aim of our research was to test whether the ultrasonic stress measurement method is also applicable for nickel- and titanium-based alloys used in aero engine manufacturing. In this contribution we report on basic investigations performed with regard to the achievable measuring effects. In uniaxial tensile tests we determined the time-of-flight sensitivity of different ultrasonic waves in dependence of the applied stresses. Based on these results we have calculated weighting factors describing the correlation between the change in stresses and the change in the velocities of longitudinal waves and of shear waves with different polarization directions with respect to the applied stresses. The test specimens were taken from different regions of a single forging made of Inconel 718. To investigate the effect of texture on the measurement results, some of the samples have been subjected to heat treatments. In our contribution we give a short overview over the basic principles of the ultrasonic method, we illustrate the modification and assembly of a high-precision ultrasound time-of-flight measurement system and we analyse the results with respect to future work.

1. Introduction

The development of next generation aero engines is a challenging task containing many influencing factors [1]. Optimizing the design of engine components with consideration of technical reliability, weight, power, economic efficiency and lifetime, it is of great interest to employ improved production techniques and materials and benefit from the full potential of these measures. In this respect, residual stresses in the bulk of materials can play an important role in the process of optimization. On the one hand, residual stresses have varying influence on component distortions during the manufacturing process and therefore on its efficiency. On the other hand, a known final residual stress state in the machined part can help to predict the lifetime or restrict the maximum load for individual components.
There exist multiple techniques to measure residual stresses, like x-ray, eddy-current or hole-drilling, but only ultrasound is capable to nondestructively determine the stresses in the bulk of materials with limited effort [2]. The ultrasonic stress measurement method is already well-established for steel components [3,4] and has been tested for several alloys [4]. The intention of this contribution thus was to identify whether the ultrasonic stress measurement method is also applicable for typical materials used in aero engine manufacturing like nickel-based alloys. This means we had to quantify the measuring effects for representative specimens.

After a brief introduction into the basic principles of the ultrasonic method, we present the modification and the assembly of a high-precision ultrasound time-of-flight measurement system. The performed measurements contain tensile tests at a selection of specimens as well as further investigations concerning the influence of texture, performed at specially treated cuboids.

2. Ultrasonic Method to Determine Residual Stresses

Residual stress measurement using ultrasound is an indirect method which is already well-established for certain materials like steel and extensively described in several papers [3,4]. The essential quantity to be measured is the ultrasound velocity. In knowledge of the Second and Third Order Elastic Constants one can calculate the stress state from the velocity values. Regarding the isotropic case, the Second Order Elastic Constants (SOEC) are reduced to the Lamé constants \( \lambda \) and \( \mu \) or, respectively, Young’s modulus \( E \) and Poisson’s ratio \( \nu \). These parameters can be calculated from the velocities of the longitudinal and the shear bulk waves in a strainless sample using Equations (1-2) or mechanically determined during tensile tests. The velocities without applied stress are named \( v_L \) for the longitudinal wave and \( v_S \) for the shear wave, \( \rho \) is the mass density.

\[
\rho v_L^2 = \lambda + 2\mu = E(1-\nu)/(1+\nu)(1-2\nu) \quad (1)
\]
\[
\rho v_S^2 = \mu = G = E/2(1+\nu) \quad (2)
\]

The Third Order Elastic Constants (TOEC) follow from the Acousto-Elastic Constants (AEC) of different wave types, which express the dependence between strain \( \varepsilon \) and velocity. This dependence is measured by recording the change in ultrasound velocities during uniaxial tensile tests. Returning to mind that we treat the isotropic case, three different waves are used to determine the three independent TOEC \((l,m,n)\). Due to geometrical restrictions in the measurement setup, a vertical insonification and therefore a wave propagation direction vertical to the direction of tension is recommended. This leads to the pulse-echo method, analysing the vertically insonified longitudinal wave and both vertically insonified shear waves, one polarized parallel and one perpendicular to the direction of tension. The ultrasound velocities are characterized by two indices. The first one specifies the direction of propagation, the second one represents the direction of polarisation. In a Cartesian coordinate system, with \( i, j, k \) naming the axis directions, respectively the direction of principal stresses, the AEC for waves propagating in \( i \)-direction and a tensile force in \( j \)-direction are expressed by Equations (3-5).

\[
AEC_{ii} = \frac{(v_{ij} - v_{jk})/v_L}{\varepsilon} \quad (3)
\]
\[
AEC_{jj} = \frac{(v_{ij} - v_{jk})/v_S}{\varepsilon} \quad (4)
\]
\[
AEC_{ik} = \frac{(v_{ij} - v_{jk})/v_S}{\varepsilon} \quad (5)
\]
The AEC correspond to the slopes in Figure 1, a generic illustration of the velocity-strain dependencies in the investigated Inconel 718. Transformations of Equations (1-5) and expressions of TOEC [4] result in:

\[
\frac{v_{ij} - v_L}{v_L} = \frac{A}{C} \cdot \sigma_i + \frac{B}{C} \cdot (\sigma_j + \sigma_k)
\]

(6)

\[
\frac{v_{ij} - v_T}{v_T} = \frac{D}{K} \cdot \sigma_i + \frac{H}{K} \cdot \sigma_j + \frac{F}{K} \cdot \sigma_k
\]

(7)

\[
\frac{v_{ik} - v_T}{v_T} = \frac{D}{K} \cdot \sigma_i + \frac{F}{K} \cdot \sigma_j + \frac{H}{K} \cdot \sigma_k
\]

(8)

The variables A, B, C, D, H, F, K include combinations of the elastic constants, whereas \(\sigma_{i,j,k}\) describe the stress components. The reciprocal coefficients - e.g. C/A - are very descriptive because they indicate the change in stress which is necessary to cause a relative change in the ultrasonic velocity by \(10^{-3}\).

3. Time-of-Flight Measurement System

The decisive variable for ultrasonic stress measurements is the ultrasonic velocity. In consequence of the very small measuring effect - the absolute variation in velocity amounts to a few m/s which corresponds to a relative change of the order \(10^{-3}\) - the temporal resolution of the system is strongly affecting the achievable results. To realize a high temporal resolution a transient recorder with a sampling frequency \(f_s\) of 1 GHz is responsible for data acquisition in the measurement system. The recorded rf-signals include several backwall echoes. Based on the distance between corresponding zero-crossings in several consecutive echoes, which is schematically shown in Figure 2, the ultrasound velocity can be determined. The velocity is computed according to the relation

\[
\text{Velocity} = \frac{\text{Propagation path length}}{\text{Distance between zero-crossings}} \cdot \text{Sampling frequency}
\]
The changes in propagation path length caused from necking during tensile tests is taken into account in our analysis algorithm by the factor \(1 - \nu \cdot \varepsilon\). Furthermore, a statistical noise reduction is applied to increase the accuracy, as each velocity displays the mean value determined from 32 single shots. The error bars, e.g. in Figure 1, indicate the statistical error of the measurements.

4. Specimens

Before the start of the measurements a sophisticated selection of samples has to be composed. This selection should cover a number of potential factors of influence on critical material parameters. The aim of the executed measurements is to identify those factors, that have a significant influence on the propagation behaviour of the employed ultrasonic waves. The samples are extracted from a larger forging in a raw state, meaning, there has no further machining taken place yet. The cross section of this workpiece made of Inconel 718 is illustrated in Figure 3. It contains two factors of influence: the position as well as the orientation of the samples in the component.
In the following chapters, the generic indices i, j, k, which describe the directions of propagation and polarisation of the ultrasonic waves, are substituted by a(xial), r(adial) and t(angential), the orientation relative to the axis of symmetry of our forging. The third criterion, that is involved in the investigations, is the heat treatment of the samples. After the extraction some of the tensile specimens as well as some cuboids have been heat-treated under different conditions. In Table 1 and 2 the specifications of all specimens are listed. Different heat treatments are sorted by their maximum annealing temperature of 955°C in treatment 1, over 1060°C to 1150°C in treatment 3. The occurrence of texture effects result from the estimated flow lines, proceeding from the forging process.

5. Experimental Results

5.1 Tensile Tests

The procedure during the uniaxial tensile tests is the same for each sample. Starting with a measurement in the unstressed state, the applied force is increased to the predefined maximum load. Then the force is reduced in equidistant steps until it vanishes. The stresses in the samples are calculated from the tensile forces, respectively the strain, and the cross sectional area. Throughout the measurements, a significant change in velocity could be detected for different stress states. The strongest effect is observed, as can be seen in Figure 4, for the shear wave polarized parallel to the direction of tension, whereas the change in the longitudinal wave velocity is about one magnitude smaller than those of the shear waves. This corresponds to our expectations, as the shear wave with polarization into the direction of tension is the only wave, that has a component in this direction. The numeric values achieved for the AEC (Table 3) as well as the computed reciprocal coefficients (Table 4) are of the same order as those of steel [4]. In repetitive measurements from both sides of the same sample we tested the reproducibility. The AEC of the shear waves, determined from these measurements, have a maximum deviation of 8 % from the mean value, which can be treated as the accuracy of measurement.
Figure 4. Relative change in velocity in dependence of strain - determined at Sample 3 from the "front side" (3a, dashed curve) and "back side" (3b, solid curve).

Under consideration of the accuracy of measurement, the TOEC and the decisive reciprocal coefficients C/A, K/F and K/H, which are listed in Table 4, are reproducible for repetitive measurements at the same specimen. C/A represents the influence of stresses, acting in the direction of propagation, on the velocity of longitudinal waves. K/F describes the influence of stresses, acting perpendicular to the direction of propagation, on shear waves that are polarized perpendicular to the direction of stress, K/H their influence on shear waves that are polarized in the direction of stress.

Table 3. Summary of the determined AEC

<table>
<thead>
<tr>
<th>Measurement</th>
<th>1</th>
<th>2</th>
<th>3a</th>
<th>3b</th>
<th>4a</th>
<th>4b</th>
<th>4c</th>
<th>5</th>
<th>6a</th>
<th>6b</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEC_{ii} (long)</td>
<td>-0.05</td>
<td>0.04</td>
<td>-0.04</td>
<td>-0.01</td>
<td>-0.10</td>
<td>-0.08</td>
<td>-0.04</td>
<td>0.10</td>
<td>-0.07</td>
<td>-0.02</td>
</tr>
<tr>
<td>AEC_{ik} (shear \bot)</td>
<td>-0.60</td>
<td>-0.72</td>
<td>-0.50</td>
<td>-0.50</td>
<td>-0.44</td>
<td>-0.51</td>
<td>-0.51</td>
<td>-0.38</td>
<td>-0.38</td>
<td>-0.42</td>
</tr>
<tr>
<td>AEC_{ij} (shear \parallel)</td>
<td>-1.07</td>
<td>-1.32</td>
<td>-1.28</td>
<td>-1.34</td>
<td>-1.11</td>
<td>-1.18</td>
<td>-1.18</td>
<td>-1.54</td>
<td>-1.20</td>
<td>-1.11</td>
</tr>
</tbody>
</table>

Table 4. Summary of reciprocal coefficients

<table>
<thead>
<tr>
<th>Measurement</th>
<th>1</th>
<th>2</th>
<th>3a</th>
<th>3b</th>
<th>4a</th>
<th>4b</th>
<th>4c</th>
<th>5</th>
<th>6a</th>
<th>6b</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/A</td>
<td>-97</td>
<td>-73</td>
<td>-79</td>
<td>-74</td>
<td>-96</td>
<td>-87</td>
<td>-90</td>
<td>-64</td>
<td>-89</td>
<td>-100</td>
</tr>
<tr>
<td>K/F</td>
<td>-343</td>
<td>-287</td>
<td>-414</td>
<td>-411</td>
<td>-467</td>
<td>-408</td>
<td>-446</td>
<td>-406</td>
<td>-541</td>
<td>-498</td>
</tr>
</tbody>
</table>

It is not possible to derive any effects of texture from the coefficients C/A and K/H, because their variation lies within the accuracy of our method. Only K/F, the less sensitive parameter, shows significant changes for the textured samples 1, 2 and 6. Regarding the plastically deformed and heat treated Specimen 5, we recognize a significant decrease for C/A and K/H, but not for K/F. Compared to Sample 4, which has the same orientation and is also supposed to be free of texture, the plastically deformed sample reacts more sensitive on changes of applied stress.
5.2 Investigations on Texture in Cuboids

For further investigations on the influence of texture and different heat treatments, we determine the ultrasonic velocities in six cuboids, extracted from the same forging as the tensile specimens are. Regarding three types of waves and three directions of propagation, we obtain nine different velocities per cuboid. Cuboid 2 is taken as reference body in order to get relative deviations. The velocities of the textured Cuboid 1, that contain axial components, deviate from the appropriate values of Cuboid 2 by at least 0.5%, as can be seen in Table 5. In case of an orthorhombic symmetry, the velocities of transposed direction of propagation and polarization - e.g. $v_{ar}$ and $v_{ra}$ - should be identical. The small differences in our data can be explained due to the accuracy of measurement and the fact that the directions of texture have not necessarily to be consistent with the edges of the cuboids.

Table 5. Relative deviation of ultrasound velocities referred to Cuboid 2

<table>
<thead>
<tr>
<th>Cuboid</th>
<th>1</th>
<th>3</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{ar}$</td>
<td>1.65</td>
<td>0.32</td>
<td>-0.07</td>
<td>-1.10</td>
<td>-1.27</td>
</tr>
<tr>
<td>$v_{ra}$</td>
<td>2.20</td>
<td>-0.02</td>
<td>0.06</td>
<td>-1.07</td>
<td>-1.54</td>
</tr>
<tr>
<td>$v_{at}$</td>
<td>-0.65</td>
<td>-0.04</td>
<td>-0.07</td>
<td>-0.90</td>
<td>-0.65</td>
</tr>
<tr>
<td>$v_{ta}$</td>
<td>-0.56</td>
<td>0.01</td>
<td>0.02</td>
<td>-0.54</td>
<td>-5.28</td>
</tr>
<tr>
<td>$v_{rt}$</td>
<td>0.24</td>
<td>-0.02</td>
<td>0.29</td>
<td>-1.34</td>
<td>-1.21</td>
</tr>
<tr>
<td>$v_{tr}$</td>
<td>0.14</td>
<td>-0.21</td>
<td>0.20</td>
<td>-1.42</td>
<td>-6.02</td>
</tr>
</tbody>
</table>

In addition, we notice a systematic decrease of all velocities of Cuboids 8 and 9, which have been heat treated at high temperatures. The obvious influence on the quality of the rf-signal by the heat treatment is illustrated in Figure 5.

5.3 Calculation of Stresses Using a Material-Specific Coefficient

To evaluate the ultrasonic stress measurement method, the last step of our investigations is the calculation of stresses in the tensile specimens by using a material-specific coefficient and the velocities $v_{ij}$ from the tensile tests. We make use of the parameter K/H, as it is sensitive and not affected by texture effects, and average over all measurements except those on Specimen 5, to get a representative coefficient. In Figure 6, the calculated stresses...
are plotted versus stresses determined during the tensile tests. The deviation for all samples, except Sample 5, is < 10 % and therefore within the accuracy of measurement.

6. Conclusion

The measurements performed at the presented selection of specimens attest a significant influence of stresses on the propagation velocities of ultrasonic waves in the material under concern. The determined reciprocal coefficients in IN718 are similar to those of steel [4], which demonstrates the potential of the ultrasonic stress measurement method for this alloy. Texture effects could be detected for the tensile specimens as well as for the cuboids. Despite these effects, we identified an appropriate material-specific coefficient, the averaged K/H, to calculate stresses in all samples. The results are within the accuracy of measurement, but could probably be improved, as we still have varying texture and microstructure due to different heat treatments and extraction positions of the specimens. Restrictions on the employed heat treatments and further investigations on a beneficial application of texture information seem to be a promising approach. In addition the coupling conditions and the necking during the tensile tests are two essential aspects concerning the accuracy of the time-of-flight measurements and should also be regarded in future works.

References