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TOWARDS IN-SITU DETERMINATION OF RAYLEIGH WAVE ACOUSTOELASTIC CONSTANTS FOR SURFACE TREATED MATERIALS CHARACTERIZATION

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ABSTRACT

Characterization of metal' surface treatment intensity with ultrasound requires a deep knowledge of material attributes. In particular, residual stress characterization with surface acoustic waves (Rayleigh waves) or bulk waves demands an awareness for nonlinear elastic properties. In this article several experimental works for the determination of acoustoelastic constants/third-order elastic constants (AEC/TOEC) for bulk and surface waves for Inconel 718 and Titanium 6246 alloys are compared. In addition, a new method for in-situ TOEC determination is proposed and preliminary numerical simulation are shown.

Keywords: acoustoelastic constants, third-order elastic constants, Rayleigh waves, nonlinear ultrasound, material characterization.

NOMENCLATURE

L_{ij}	acoustoelastic constant
V_{ij}	elastic wave velocity
ω_i	frequency
$\vec{k_i}$	wave vector
ε	strain in the load direction
l, m, n	TOEC in Murnaghan notation

1. INTRODUCTION

Surface engineering (treatment of the surface and near-surface regions of a material to allow the surface to perform functions that are distinct from those functions demanded from the bulk of the material, ASM Handbook) is one of the essential parts in design of high-performance components in aerospace industry. Among the variety of different methods, the shot peening, laser shot processing and low plasticity burnishing treatment allows to significantly increase the high-cycle fatigue properties and improve a foreign object damage resistance. The core of the aforementioned methods is the introduction of a compressive stress layer in the surface of structural element (i.e. leading edge of fan blades, turbine disc). Shot peening is widely used during the manufacturing and MRO (maintenance, repair, overhaul), in order to increase the fatigue performance of elements and increasing the life expectancy of an aircraft.

Currently, industrial and in-field applications are validating the intensity of treatment with series of Almen stripes measurements - treated coupons with known properties. Only the laboratory NDE methods (electron, x-ray or neutron diffraction) proved its versatility for stress/strain state evaluation for a wide range of metals. Semi-destructive (borehole drilling) and destructive (slicing) methods are also often used as reference [1]. Eager for a development of cost-effective in-field nondestructive residual stress measurement method was the motivation for the current research.

All of ultrasonic stress measurement techniques are utilizing the acoustoelastic effect - dependency of elastic wave velocity on stress level. As a prerequisite the acoustoelastic constants (AEC) have to be known, which is a nontrivial task for the surface treated materials case, due to sensitivity of AEC to the treatment (as any nonlinear parameter). Therefore, the literature AEC values, measured on untreated material, do a little contribution. Direct determination of Rayleigh wave AEC can be done in the laboratory but not in the field on large components.

The core of this work is the development of an independent method of in-situ TOEC measurement through the effect of noncollinear surface acoustic waves scattering – elastic waves interaction in a nonlinear medium. For numerical modelling of the direct problem of scattering, TOEC/AEC values for with confidence intervals have to be determined.

In the following sections the overview of current and existing bulk- and surface- wave AEC measurements for two alloys is given. As a step towards in-situ method, an approximate analytical solution has been used for elastic wave scattering intensity calculation, with use of nonlinear parameters of materials under investigation.

2. MATERIALS AND METHODS

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In this work the relative variation of ultrasonic wave propagation velocity for two high-temperature superalloys, Inconel 718 and Titanium 6246, has been examined during the tensile machine loading. In addition, numerical simulation of scattering has been performed using a commercial package.

2.1 Experimental setup for AEC measurement

During the AEC measurement with external load, two different types of samples made of In718 and Ti6246 have been tested using the tensile machine with maximal tensile stress level reaching 1000MPa and 870MPa correspondingly. Before the measurement campaign both samples have been annealed. The load was controlled with the tensile machines embedded force gauge and the actual strain was recorded with the contact extensometer. Bulk waves have been excited and recorded with commercial piezoelectric transducers, mounted with 3 possible polarizations (longitudinal wave, travelling normal to load direction (axis 1), shear wave, travelling normal to axis 1 with particle movement parallel or normal to axis 1).

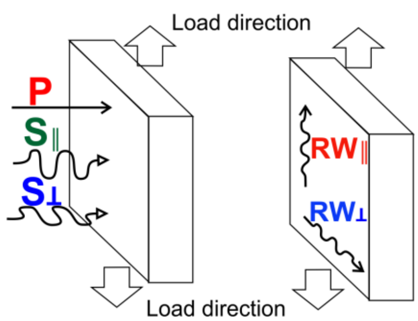

FIGURE 1: BW POLARISATION AND RW DIRECTIONS

Due to the restrained sample thicknesses (4 and 4.8 mm for different sample types) and limited velocity variation (in range of 0.05-0.5%), digital scope with high sampling rate (5GS/s for shear waves, 5 and 10GS/s for bulk waves) was used to record the multiple echoes signal variation with the load. Several velocity extraction techniques (including cross-correlation and cepstrum analysis) were used for signal processing and validation.

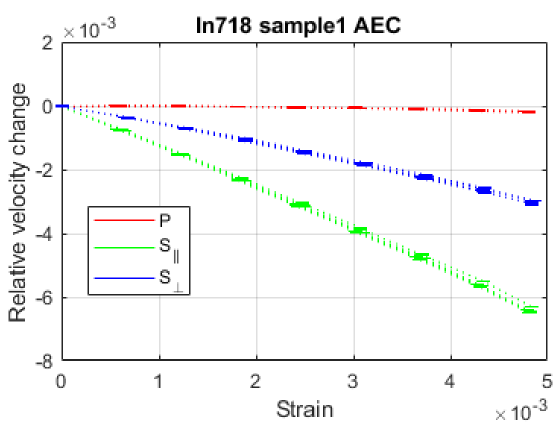

FIGURE 2: BULK WAVE AEC MEASUREMENT EXAMPLE

We used the standard bulk wave AEC definition [2]:

$$L_{ij} = \frac{dV_{ij}/V_{ij}^0}{d\varepsilon} \tag{1}$$

where the index i points on wave propagation direction, j – particle displacement direction. (1 is the load direction). Bulk wave acoustoelastic constants may be explicitly defined via third-order elastic constants (TOEC) and are normally used for the determination of the latter. In Fig. 2 an example of an AEC measurement for one of the Inconel samples is given.

For Rayleigh wave direct acoustoelastic constant measurements a three axes step scanner with mounted laser Doppler vibrometer (LDV) head was used for recording the surface wave propagation parallel and normal to the load direction.

To improve the resolution of Rayleigh wave velocity approximation the iterative parameter estimation algorithm has been used for each B-scan cross-correlation data.

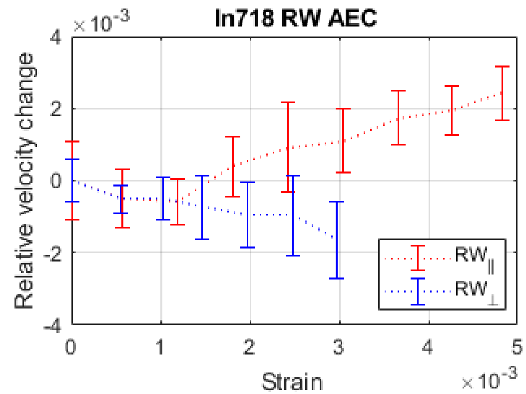

FIGURE 3: RW AEC MEASUREMENT EXAMPLE

2.2 Scattering simulation scheme

The type (longitudinal, shear, SAW) and intensity of the scattered wave depends on the types and intensities of the input waves, their frequencies, relative orientation of wave-vectors and polarization vectors, and on the material constants. Therefore, future measurements of the scattering process in a surface layer can provide the information on the TOEC, necessary for stress characterization within the acoustoelastic effect. In order to become a significant (therefore, detectable and traceable) part of a wave field, mixing intensity of nonlinear interactions of longitudinal, shear and Rayleigh waves must fulfill the phase matching (or resonance) conditions, which correspond to the energy and momentum conservation conditions in anharmonic phonon-phonon interaction [6]:

$$\begin{aligned} \omega_3 &= \omega_1 \pm \omega_2 \\ \overrightarrow{k_3} &= \overrightarrow{k_1} \pm \overrightarrow{k_2} \end{aligned} \tag{2}$$

Instead of the bulk wave interaction case, thoroughly scrutinized by different groups of authors ([7], [8]); for bulk wave - surface wave interaction in isotropic solid the only available reference is [9]. The scattering intensity was evaluated by application of theoretical model, based on small perturbation theory [3], for the allowed combinations.

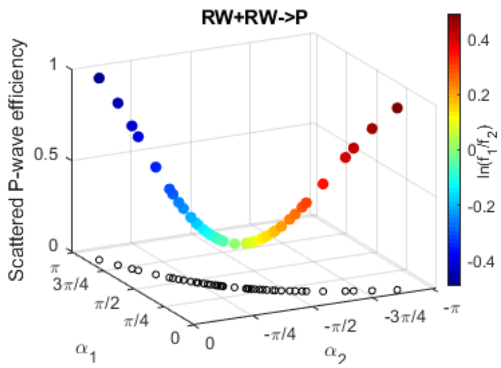

FIGURE 4: EXAMPLE OF SCATTERING EFFICIENCY SIMULATION

3. RESULTS AND DISCUSSION

3.1 Measurement results and comparison with previous AEC/TOEC measurements

Based on the AEC measurements at five points for each sample, TOEC values have been obtained.

Measured values	l, GPa	m, GPa	n, GPa
In718	-547±7.19	-613±5.99	-493±6.07
Ti6246	-258±107	-257±53	-399±44
Literature values			
In718 [10]	-524.7±4.05	-603.7±4.05	-476.3±2.3
In718 [11]	-472±18.54	-564±15.09	-489±7.11
Ti6246 [10]	-356±34.8	-389±20.6	-475±15.1

TABLE 1. BW TOEC MEASUREMENT RESULTS (SAMPLE 1)

Large deviation for Ti6246 is a result of extremely strong dependence of AEC values on measurement point position. This may be the result of microstructural properties spatial variations, which is beyond the scope of the current work.

For the surface acoustic waves (Rayleigh waves) several ways for AEC definition are available [3, 4, 5]. Table 2 gives a comparison between Rayleigh wave acoustoelastic constants for Inconel 718 (as defined in [4]) measured in this work and already stated elsewhere.

In718 RW AEC	AEC parallel to stress [10^-3/GPa]	AEC normal to stress [10^-3/GPa]
Measured values	2.86	-0.679
Köhler et al [12]	2.36	-1.2

TABLE 2: RW AEC VALUES OF THIS WORK; COMPARED WITH LITERATURE VALUES

3.2 Elastic wave scattering simulation

Among the ten considered wave scattering combinations allowed by Eq. (1), the four most efficient ones were picked (Table 3). Interactions are labeled as /first input wave/ *[scattered wave frequency sign rule]* /second input wave/ → /scattered wave/. S stands for shear wave, V for vertical polarization. In the following work these cases will be used for TOEC determination without the need for external loading.

Scattering case	Relative efficiency
SV-SV -> RW	1
RW+RW-> P	0.35
RW+SV -> P	0.31
RW + SV -> SV	0.18

TABLE 3: RESULTS OF WAVE SCATTERING SIMULATION

4. CONCLUSION

As necessary steps towards in-situ TOEC measurements through elastic waves scattering and residual stress profile extraction, reference TOEC measurements and scattering simulation have been performed. The obtained Inconel data are in reasonable accordance with the known values. With means of analytical solution modelling, the most efficient elastic wave scattering cases have been picked. The next steps include direct measurement of wave scattering as well as experimental investigation on TOEC extraction procedures sensitivity to parameter variation [5].

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