Orientation Characterisation of Aerospace Materials by Spatially Resolved Acoustic Spectroscopy

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Abstract
Material characteristics such as strength, stiffness and fracture resistance are strongly related to the underlying microstructure. In order to predict the mechanical behaviour of materials relevant to the aerospace sector such as titanium, nickel and their alloys, detailed knowledge about their texture is required. A robust measurement tool is introduced which can be used to determine the crystallographic orientation of a material. This is achieved by using a laser ultrasonic technique – spatially resolved acoustic spectroscopy (SRAS) combined with a numerical surface acoustic wave (SAW) velocity model. SRAS is used to measure the SAW velocity of a material in a number of different propagation directions. The model predicts the SAW velocity from the material’s elastic constants; a search algorithm termed the overlap function is used to compare the SRAS data to the model to determine the crystallographic orientation. We examined a range of materials commonly used for aircraft components. Comparisons between SRAS and electron backscattered diffraction are presented. This is an innovative and all-purpose NDT technique for aerospace materials manufacture monitoring and quality control.

Keywords: Ultrasonic Testing (UT), orientation, ultrasonics, SAW, crystallography, microstructure

1. Introduction

Material characteristics such as strength, stiffness and fracture resistance are strongly related to the underlying microstructure. In order to predict the mechanical behaviour of materials relevant to the aerospace sector such as titanium, nickel and their alloys, detailed knowledge about their texture is required. SRAS – spatially resolved acoustic spectroscopy – is a non-destructive laser ultrasound method which can image surface microstructure, using the local surface acoustic wave (SAW) velocity as a contrast mechanism. Furthermore, the orientation of grains can be determined by comparing the SAW velocities on multiple directions to a precalculated SAW velocity model.

Crystal orientation can also be evaluated by other methods such as electron backscatter diffraction (EBSD), or in principle, by scanning acoustic microscopy [1] by analysing the phase shift of a narrow band SAW signal. Although the spatial resolution of SRAS cannot compete with EBSD, SRAS has advantages such as being non-contact, having no restriction on sample size and easier surface preparation requirements.

A search algorithm for solving the inverse problem to find the crystal orientation from velocity measurements has been developed. Crystallographic orientation images obtained from SRAS using this algorithm are presented as a velocity vector map for a titanium alloy sample, and inverse pole figures (IPF) for Inconel and aluminium alloy samples. IPFs for nickel-based supperalloy (CMSX 4) samples are presented derived from both SRAS and EBSD data for comparison.
2. Spatially resolved acoustic spectroscopy (SRAS)

The SRAS technique can be used to obtain SAW velocity information on the local area where the waves are generated. There are two ways to implement the technique; in both methods the SAW excitation pattern is generated by projecting a grating pattern of laser light. By varying the grating period from a fixed frequency pulsed laser (k-SRAS) [2, 3], or by varying the frequency by using a broadband (e.g. Q-switched) laser in combination with a fixed grating (f-SRAS) [3, 4], the local velocity \( v \) can be calculated, through \( v = f \lambda \) where \( f \) is the frequency and \( \lambda \) is the grating period. The presented data in this paper were collected by the latter method hence we explain the technique based on the f-SRAS approach.

The system setup of f-SRAS is illustrated in Figure 1; a Q-switched laser is indicated as the excitation source and the pulsed laser beam passes through an optical mask consisting of a set of stripes. The unblocked light produces SAWs when it is imaged onto the sample surface. The SAWs are detected by a knife-edge detector and sent to the oscilloscope and computer. The images that are produced by the instrument – called velocity maps – will be shown in section 4 where examples of measurements on titanium alloy are presented.

3. Determining the orientation from SRAS

Determining the velocity from known orientation and an elasticity matrix analytically is straightforward, as is obtaining the elasticity matrix from a known orientation and velocity. However obtaining the orientation from the measured velocity and elasticity matrix is difficult because it is very ill-conditioned and there is no analytical solution. For solving this inverse problem we have developed a search technique. It finds the orientation by matching the measured velocity at many different propagation directions to the analytically determined velocity from a given elasticity matrix.
3.1 Determining the velocity from the elasticity matrix

Farnell [5] provides a good description of a method to calculate SAW and pseudo-SAW velocities on different crystallographic structures by using iterative search procedures from known material elastic constants. We have made slight modifications to the approach described by Farnell in order to perform the current calculations [3, 6].

Due to the inherent symmetries in different crystal structures there are a number of solutions which are equivalent, this allows us to restrict the range over which the model needs to be calculated, for example in cubic crystals the planes (h k l) are equivalent to (-l k h) and have mirror symmetry with the plans (k h l). Hence the calculated model does not include redundant information and so saves calculation time; the orientation results are all in the first octant and other possible solutions can be recovered by the knowledge of the crystal symmetry.

3.2 Solving the inverse problem

The signals obtained from the experiment contain a range of acoustic frequencies and their amplitudes for each propagation direction angle \( \phi \). With knowledge of the grating spacing these frequencies are converted to velocities and a velocity surface is produced \( A(\phi, v) \), which is presented in the lower right hand side of Figure 2. The theoretical model velocities are defined as \( v(h, k, l, \theta) \), where the plane is \( (h k l) \), and \( \theta \) is the angle on the plane (plotted as stars in the bottom right of Figure 2). To compare the experiment data for a particular calculated plane we need to assess how similar the velocities are. This is achieved with the figure of merit, which is the sum of \( A(\phi, v(h, k, l, \theta)) \) at each \( (h k l) \) and \( \theta \) calculated according to Equation 1

\[
F(h, k, l, \theta) = \sum_{\phi=0}^{n-1} A(\phi, v(h, k, l, (\phi - \theta))), n = 1, 2, 3, \ldots
\]

where \( n \) represents the number of evenly spaced velocity measurements used to determine the orientation. Therefore, by repeating the calculation on all modelled planes and directions, the largest value for \( F \) can be found indicating the best match and thus the orientation and rotational angle of the plane (see figure 2 left and upper right).
Figure 2. Curve fitting procedure. The figure of merit is shown on the left as a function of planes (x and y axes) and propagation directions (z axis); the maximum value is denoted by the arrow in the top right figure, which is at the propagation direction of 21°. The bottom right figure displays the output plane on the experimental velocity spectrum; it shows the plane of a nickel sample (0.22 0 1) with 20.6° rotation from the reference direction after the interpolation on the figure of merit.

4. Experimental validation on industrial materials

We have measured a range of industrial materials, e.g. titanium, aluminium and nickel based alloys. As the materials have different crystal structures, two ways of plotting the data are used to illustrate the orientation of grains: velocity vector maps (for hexagonal crystals) and IPFs (for cubic crystals).

4.1 Hexagonal crystals: titanium based alloys

The SAW velocities are an expression of material's elastic properties; the symmetry of hexagonal crystals dictates that the slowness surface of the planes which are tilted away from the c-axis at the same angle are identical, hence the velocities from two orthogonal directions are sufficient to show how far the planes are away from the basal plane.

Figure 3 shows the SAW velocity maps in two orthogonal directions and the velocity vector map of Ti-6243, which is combined from the two velocity maps. It can be immediately seen that the SRAS method is sensitive to crystallographic orientation. The scan speed of f-SRAS instrument is approximately 1000 points per second; it takes 54 minutes to obtain each two mega-pixel velocity map.
Figure 3. The top two figures are SRAS velocity maps in two orthogonal directions of Ti-6243; SAWs propagate from left to right (top) and top to bottom (middle), pixel size is 50×60μm. The velocity vector map is on the bottom: colour blue indicates the basal plane, green and red corresponds to the grain's c-axis is pointing 3 o'clock and 6 o'clock respectively.

4.2 Cubic crystals: aluminium and nickel based alloys

We measure the SAW velocity in multiple directions over an aluminium and an Inconel 617 sample surface by SRAS. IPFs which present the orientation of grains are shown in Figure 4. These images show us the high consistency of the SRAS results and the search algorithm performance on a material with low anisotropy (aluminium) even though there are no complementary EBSD results available due to the size of the samples.
Figure 4. Crystallographic orientation maps of aluminium (top row) and Inconel 617 (bottom row) samples. The left column shows the IPFs, the right column shows the rotation angle on the plane. The pixel size of both images are 100x50μm with spatial resolution 100μm.

Figure 5 demonstrates the orientation maps of the nickel-based superalloy (CMSX4) samples measured by EBSD and SRAS and shows that the SRAS results agree well with the EBSD data. The resolution of SRAS is not competitive to EBSD, however SRAS is sufficient for the applications which have lower requirements for spatial resolution but higher demands of the sample size and examination speed.
5. Conclusion

This paper has described a general method which is used to determine crystallographic orientation from the velocity of SAWs propagating in different directions, and that the SRAS technique may be used to perform these measurements in a rapid and robust fashion. A SAW velocity model of cubic crystals has been built according to Farnell's theory and this is matched with the measured velocity measurements to recover the orientation. In the present work the effect of generation and detection efficiency is considered in a rather ad hoc fashion and in future an explicit model of generation efficiency – for SAWs excited by a pulsed laser – will allow one to match the experimentally measured displacements without additional assumptions.

We have demonstrated that the SRAS technique is capable of being employed on multigrain samples. For hexagonal crystal structure materials, the orientation information of a titanium-6243 sample has been presented in a SRAS velocity vector map. In order to establish the general applicability of the technique for cubic materials we have shown that the orientation of aluminium and Inconel 617 samples can be recovered with good precision. The SRAS technique also has been confirmed having a good agreement with EBSD by comparing results of measurements on a nickel super alloy.

Acknowledgements

This work was supported by the EPSRC Platform Grant in Advanced Ultrasonics (EP/G061661/1). We wish to thank BJ Foss and BA Shollock for EBSD data, Rolls-Royce plc for their support and to E.ON New Build & Technology Limited for the Inconel 617 sample.
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