Scripta Materialia 157 (2018) 44–48

Contents lists available at ScienceDirect

Scripta Materialia

journal homepage: www.elsevier.com/locate/scriptamat

Regular article

Rapid measurement of volumetric texture using resonant ultrasound spectroscopy

Bo Lan[a,*], Michael A. Carpenter[b], Weimin Gan[c], Michael Hofmann[d], Fionn P.E. Dunne[e], Michael J.S. Lowe[a]

[a]Department of Mechanical Engineering, Imperial College London, UK
[b]Department of Earth Sciences, University of Cambridge, UK
[c]German Engineering Materials Science Centre at MLZ, Helmholtz-Centre Geesthacht, Germany
[d]Heinz Maier-Leibnitz Zentrum (MLZ), Technische Universität München, Germany
[e]Department of Materials, Imperial College London, UK

ARTICLE INFO

Article history:
Received 19 May 2018
Received in revised form 20 July 2018
Accepted 21 July 2018
Available online xxxx

Keywords:
Crystallographic texture
Resonant ultrasound spectroscopy
Non-destructive evaluation

ABSTRACT

This paper presents a non-destructive evaluation method of volumetric texture using resonant ultrasound spectroscopy (RUS). It is based on a general theoretical platform that links the directional wave speeds of a polycrystalline aggregate to its texture through a simple convolution relationship, and RUS is employed to obtain the speeds by measuring the elastic constants, where well-established experimental and post-processing procedures are followed. Important lower-truncation-order textures of representative hexagonal and cubic metal samples with orthorhombic sample symmetries are extracted, and are validated against independent immersion ultrasound and neutron tests. The successful deployment of RUS indicates broader applications of the general methodology.

Crystallographic texture refers to the preferred orientation distributions in polycrystalline aggregates that are often formed during the thermal-mechanical processing procedures [1]. It dominates macroscopic physical properties [1,2], such as strength, thermal expansion and fatigue lives, hence is of great importance for various industrial applications. Unfortunately, despite texture being a volumetric concept, existing lab-based techniques (e.g. X-ray [3], electron back-scattered diffraction [4] and surface acoustic wave-based [5] methods) are confined to surface or near-surface inspections, and the bulk texture can only be obtained at large-scale neutron or X-ray synchrotron facilities with limited access [6].

Ultrasound presents an attractive option for non-destructive evaluation of volumetric texture, given its high penetration power and wide availability. Early developments in this direction (e.g. [7-9]) mainly focussed on guided (not bulk) waves in rolled plates, but the inversion involved highly cumbersome iterative least-square fitting processes, which could also lead to inaccurate and non-unique solutions. A general theoretical platform proposed by the authors [10, 11] gave a viable solution to obtaining texture using direction-dependent bulk compressional wave speeds, where high accuracy and uniqueness could be simultaneously achieved via a simple deconvolution process. It has been comprehensively validated against neutron diffraction experimentally using a conventional immersion ultrasonic system [12]. However, that particular setup requires relatively large samples to be immersed in water for sophisticated directional speed measurements. Since the theories are general and independent of the specific experimental technique, resonant ultrasound spectroscopy (RUS) provides an alternative way to extracting texture while circumventing those limitations.

RUS is an established technique for measuring elastic constants, and has been attempted for texture inversions before [13,14]. Instead of directly fitting the elastic constants, those authors explicitly expressed them in terms of orientation distribution coefficients (ODCs) through complicated homogenisation methods (most commonly the Voigt average), and iteratively fitted the ODCs using a customised protocol. Here we show that by introducing the convolution platform, the extraction of texture can be done after the elastic constants are obtained, so that the standard RUS experimental and data post-processing procedures can remain untouched, and one only needs to solve the classic wave equation to obtain the required speeds for texture, all achieved directly without iterations. Thus this approach greatly reduces the complexity of the inversion process,

* Corresponding author.
E-mail address: bo.lan@imperial.ac.uk (B. Lan).

https://doi.org/10.1016/j.scriptamat.2018.07.029

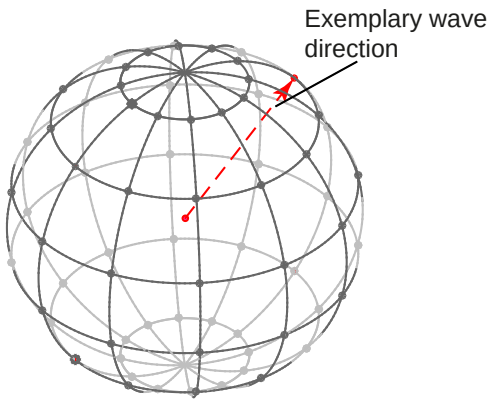

Fig. 1. 6×12 discrete directions needed for numerical integration of V_{lm} when $N = 6$ [12]. Note that the reciprocity of wave speeds reduces the number by half.

and is in a better position to take advantage of the latest technical advancement on RUS (e.g. on laser excitation [14]).

The theoretical basis of the convolution method is that in a directionally homogeneous polycrystal, the three-dimensional wave speed variations can be approximated, to excellent precision, by a spherical convolution between single crystal wave speeds and texture [10, 11]:

$$V_{lm} = \sum_{n=-l}^{l} W_{lmn} K_{ln} \tag{1}$$

where V_{lm} and K_{ln} are the series expansion coefficients of the poly- and single crystal wave speeds with respect to spherical harmonics $Y_{lm}(\theta_i, \phi_j)$, while W_{lmn} are the coefficients of the orientation distribution function (ODF) $w(\psi, \theta, \phi)$ expanded on Wigner-D functions. In the special case of hexagonal materials, where only the c-axis texture affects wave speeds (due to the elastic transverse isotropy of the single crystals), the convolution relationship can be further simplified as [10]:

$$V_{lm} = W_{lm0} K_{l0}. \tag{2}$$

The three variables in Eqs. (1) and (2) are linked by simple, pointwise multiplications of expansion coefficients that can be deployed in both forward and inverse studies. The correspondences between coefficients are unique, and applying the equations in either direction does not involve any fitting [10]. The limitation of this technique, however, is that only the ODF coefficients up to the 4th order can be reliably retrieved from elastic waves (or elasticity in general). This is because the 4th-rank elastic tensor - which intrinsically possesses 4-fold rotation symmetry - has only minimal physical coupling with the higher-order expansion bases of higher symmetries [11,15].

Of the variables, the single crystal speeds can be calculated from available elastic constants, so the key to inversely retrieving texture (as ODF coefficients W_{lmn}) is to obtain V_{lm}. This can be achieved via numerical integration of polycrystal velocities $v(\theta_i, \phi_j)$ in discrete directions [10]:

$$V_{lm} = \frac{\pi}{N} \sum_{j=0}^{2N-1} \sum_{i=0}^{N-1} v(\theta_i, \phi_j) Y^*_{lm}(\theta_i, \phi_j) \omega_N(i) \tag{3}$$

This integration scheme prescribes the discrete directions corresponding to the Gaussian-Legendre quadrature, as shown in Fig. 1, which will be determined from elastic constants measured by RUS.

Industry-relevant metal samples of hexagonal and cubic crystal symmetries are examined to demonstrate the texture inversion, including commercially pure titanium (CP Ti) and Ti-6Al-4 V (both hexagonal, though Ti-6Al-4 V contains ~10% of cubic beta-phase and is intended as a challenging case), which are used extensively in the aerospace industry; and 304 stainless steel (cubic) found in a wide range of civil engineering applications.

The samples are all cut from rolled plates or sheets along the principal sample axes (hence all have orthorhombic sample symmetry), into rectangular parallelepipeds of ~3 × 4 × 5mm^3. The RUS

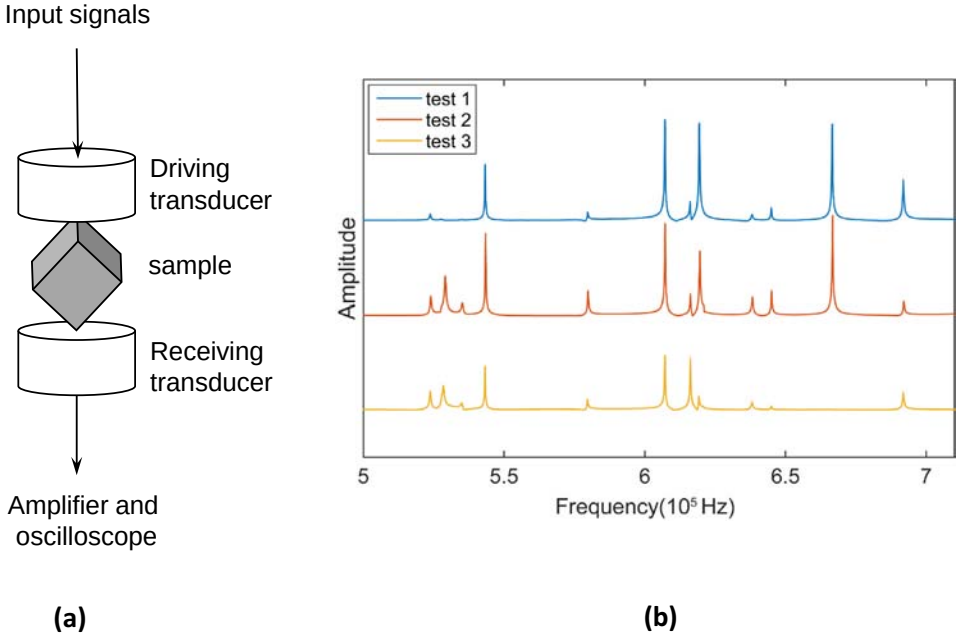

Fig. 2. (a) Schematics of the RUS setup; (b) The frequency-amplitude spectra obtained in different mounting positions (shown by different colours with artificial vertical shifts) help identify all natural vibrational modes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: (Source: This figure is reproduced from [18].)