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Effect of texture and grain shape on ultrasonic backscattering in polycrystals

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ABSTRACT

An ultrasonic backscattering model is developed for textured polycrystalline materials with orthotropic or trigonal grains of ellipsoidal shape. The model allows us to simulate realistic microstructures and orthotropic macroscopic material textures resulting from thermomechanical processing for a broad variety of material symmetries. The 3-D texture is described by a modified Gaussian orientation distribution function (ODF) of the crystallographic orientation of the grains along the macroscopic texture direction. The preferred texture directions are arbitrary relative to the axes of the ellipsoidal grains. The averaged elastic covariance and the directional anisotropy of the backscattering coefficient are obtained for a wave propagation direction arbitrary relative to the texture and grain elongation directions. One particular application of this analysis is the backscattering solution for cubic crystallites with common textures such as Cube, Goss, Brass and Copper. In our analysis, in the texture-defined coordinates the matrix of elastic constants for cubic crystallites takes the form of orthotropic or trigonal symmetry. Numerical results are presented, discussed and compared to the experimental data available in the literature illustrating the dependence of the backscattering coefficient on texture and grain shape.

1. Introduction

Ultrasonic waves are recognized as a major experimental modality for characterization of homogeneous and nonhomogeneous anisotropic media [1–3]. Bernard Hosten, to whom this special issue is dedicated, did pioneering work in many facets of this field. One type of randomly nonhomogeneous anisotropic media is a textured polycrystalline medium. When an ultrasonic wave propagates through polycrystalline materials it scatters on grain boundaries due to grain anisotropy and misorientation. This scattering may provide nondestructively information on material microstructures that is critical to performance in service. Scattering-induced ultrasonic attenuation has been used experimentally for a long time to study microstructure. More recently it has been realized that ultrasonic backscattering is simpler and more practically advantageous for microstructure characterization. Inverse determination of microstructure characteristics from ultrasonic scattering experiments is challenging and requires robust models relating ultrasonic scattering to microstructure. In recent years a significant number of modeling and experimental studies have been devoted to this subject and the reader is referred to reviews of the subject by different authors [4–8].

As a result of thermomechanical processing, grains in polycrystalline materials are usually nonequiaxed and exhibit preferred crystallographic orientation (texture) [3,9]. Also, due to heat gradients, textured columnar structures may develop during solidification in welds or castings. After rolling or forging the textures are three-dimensional which results in macroscopic elastic anisotropy. After extrusion the polycrystalline material may be considered to have axisymmetrical macroscopic texture and be of hexagonal symmetry. Texture leads to macroscopic anisotropy and can be determined by measuring ultrasonic velocities in different propagation directions; this is well developed and reported [3]. Several studies were devoted to ultrasonic attenuation in textured polycrystals with equiaxed grains [10–14]. However, ultrasonic backscattering in textured polycrystals is poorly understood especially in realistic cases of nonequiaxed grains and practically relevant textures. To our knowledge only a few studies have been performed in this area. Ultrasonic backscattering in materials with highly oriented, columnar cubic grains was discussed by Ahmed and Thompson [15]. They studied an idealized texture with perfect alignment of cubic grains along the [001] axis; for this case scattering is absent in the preferred texture direction. Recently Yang and Rokhlin [16] have developed a model for backscattering coefficients in textured polycrystalline materials with elongated cubic symmetry grains and axisymmetrical distribution of grain preferred orientations. In their model the texture, grain elongation and wave

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propagation directions were arbitrary; however they considered axisymmetrical (1-D) macroscopic Cube texture and assumed Gaussian distribution of grain orientations in this direction (such media exhibit hexagonal macroscopic symmetry). They found reasonable agreement between their prediction for backscattering and attenuation in different directions and the experiment reported in Ref. [17] on an extruded aluminum sample. The limitation of their model is that it is only applicable to one type of texture ("Cube texture") and extruded materials [16] and does not describe ultrasonic scattering and velocities in rolled materials with orthotropic macroscopic symmetry.

In this paper a new general ultrasonic backscatter model for a polycrystal with orthotropic and trigonal ellipsoidal grains and three-dimensional orthotropic macroscopic texture is developed. Such reduction of grain symmetry allows applicability of the model to a broad scope of materials with different crystallographic symmetries of grains and different macroscopic textures. In this paper the model is applied for scattering analysis of most practical textures for cubic polycrystals: Cube, Goss, Brass and Copper, which were inaccessible for analysis by previous models. The general model allows us to demonstrate the applicability of the axisymmetrical approximation to the 3D textures with orthorhombic symmetry grains (suitable to Cube and Goss textures); this approximation is used to obtain an explicit solution for the backscattering coefficient for a wave propagating in an arbitrary direction to the texture. Finally the model is applied to ultrasonic backscattering and velocity experimental data obtained from a rolled aluminum sample [17], with dominantly Brass texture, demonstrating reasonable agreement between the model and the experiment. While most examples shown are for aluminum alloys our results are applicable to other cubic polycrystals such as steel, nickel-based superalloys and others, and to hexagonal alloys such as titanium.

2. General formulation of the backscatter model

2.1. Model assumptions for the polycrystalline medium

We consider a polycrystalline medium with anisotropic crystallites (grains) with the results specified for orthotropic (orthorhombic) and trigonal crystallite symmetries. A polycrystalline material is fully densely packed with general ellipsoid shape grains, Fig. 1a, and is described by distributions of grain sizes and crystallographic orientations. The density is assumed constant over the whole volume. The ellipsoid axes of the grains are oriented in the same direction for all grains. The grain size distribution (ellipsoid radii) is defined by a two-point correlation function which is a generalized Poisson's function. It is assumed that due to plastic deformation the material has a preferred crystallographic grain orientation, described by three dimensional (3-D) texture, and as a result is macroscopically anisotropic. Those macroscopic anisotropic elastic properties are specified in a texture coordinate system T_x, T_y, T_z (Fig. 1b). In our model the ellipsoidal grain axes a_x, a_y and a_z, given in coordinates X, Y, Z (Fig. 1a), do not coincide in general with the texture directions T_x, T_y, T_z. The direction of wave propagation **p** (Fig. 1a and b) is arbitrary to both texture and grain axes directions. In addition to 3-D texture axisymmetrical texture will be considered, where T_z is the direction of axisymmetric texture. For such texture, in the plane orthogonal to T_z, grain orientation is isotropic (i.e. in this plane the material is macroscopically isotropic); thus, for this case the material macroscopically has hexagonal symmetry.

For a given crystallite we will define the orientation of its crystallographic system x, y, z, Fig. 1c, relative to the coordinate system associated with the texture directions T_x, T_y, T_z. As will be defined later, the crystallographic orientation of the grains is described by the orientation distribution function (ODF) in the Euler coordinate system Fig. 1c. Due to grain elongation and macroscopic texture the ultrasonic backscattering exhibits complicated anisotropic behavior with propagation direction.

A propagating ultrasonic wave scatters on grain boundaries due to crystallographic misorientations of neighboring grains and the scattering over the acoustic path is determined by the relative average misorientations between the grains. We consider a statistically homogeneous and, due to texture, macroscopically anisotropic medium whose moduli are assumed to be spatially microheterogeneous

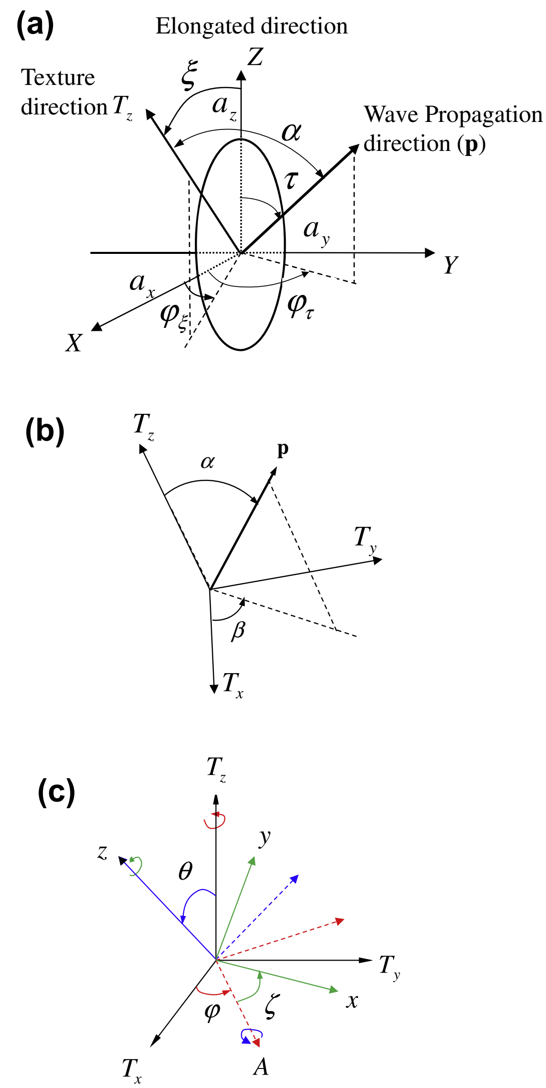

Fig. 1. (a) Geometry of ellipsoidal grains with the axes a_x, a_y and a_z in global geometry coordinate system (X, Y, Z). The arbitrary direction $\mathbf{p}(\sin\tau\cos\varphi_\tau, \sin\tau\sin\varphi_\tau, \cos\tau)$ is defined as the wave propagation direction; the texture coordinate system (T_x, T_y, T_z) is given in (b) and only the axis $T_z(\sin\xi\cos\varphi_\xi, \sin\xi\sin\varphi_\xi, \cos\xi)$ is shown in (a) for simplicity. In the axisymmetric texture model T_z is also the axial direction; angle α is the angle between wave propagation direction and texture direction. (b) Texture coordinate system (T_x, T_y, T_z) showing the wave propagation direction relative to the preferred texture direction. The global geometry coordinate system is shown in (a), in which the arbitrary wave propagation direction (**p**) and preferred texture direction (T_x, T_y, T_z) are defined independently. (c) Local crystallite crystallographic system (x, y, z) defined by Euler angles (φ, θ, ζ) in a coordinate system of an orientation cluster with texture directions T_x, T_y, T_z. The rotation sequence of the Euler angles is first rotating about axis T_z by angle φ, second rotating about axis A by angle θ and third rotating about axis z by angle ζ. Euler angles are specified by a Gaussian distribution function (20) of crystallite orientations in the cluster.