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Ultrasonic Characterization of Microstructural Inhomogeneity in Additively Manufactured Metals

Junfei Tai[1] *and Zheng Fan*[1]
[1]*School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore*
zfan@ntu.edu.sg

Abstract: Non-destructive evaluation (NDE) of additively manufactured (AM) metals is particularly challenging due to their textured and irregular microstructures, which are intimately linked to their mechanical properties. Ultrasound, with its high sensitivity to microstructural features, offers a powerful non-destructive method for characterizing these materials. While conventional metals typically exhibit a direct, monotonic relationship between ultrasonic scattering and grain size, this correlation becomes ambiguous in AM metals where multiple microstructural features coexist. In this study, we introduce a parameterization approach to quantify microstructural inhomogeneity and examine its correlation with ultrasonic scattering-induced attenuation. Finite element simulations of elastic wave propagation are employed to provide a detailed microscale description of the elastic energy distribution and the degree of microstructural inhomogeneity. Our findings indicate that the proposed parameter effectively captures grain-scale variations, including textures and grain sizes, and demonstrates a monotonic relationship with ultrasonic scattering. Specifically, an increase in microstructural inhomogeneity enhances elastic wave scattering. Moreover, the cumulative effect of scattering leads to ultrasonic attenuation, shows a positive correlation with characteristic length–weighted microstructural inhomogeneity. Importantly, this parameter exhibits a consistent monotonic correlation with ultrasonic attenuation across materials with diverse crystal systems. These results elucidate the fundamental mechanisms linking ultrasonic responses to grain-scale microstructural inhomogeneity and underscore the potential of ultrasound-based NDE for the advanced characterization of AM materials.

Keywords: Ultrasonic scattering, Microstructural inhomogeneity, Additive manufacturing.

Introduction

Additive Manufacturing (AM) has demonstrated great potential for tailoring material microstructures to achieve the mechanical properties required in critical engineering components [1]. As AM technologies continue to advance and find broader application in the fabrication of load-bearing structural parts, ensuring the structural integrity and reliability of these components has become increasingly important. The mechanical performance and ultrasonic response of AM components are primarily governed by their microstructures. Due to the inherently rapid and non-equilibrium solidification processes in AM [2], the resulting microstructures differ significantly from those produced by conventional manufacturing methods. This makes it particularly challenging to apply existing microstructural knowledge to the ultrasonic characterization of AM materials. Given the high-dimensional nature of microstructural parameters in AM, ultrasonic characterization becomes an underdetermined problem, where the coupling effects of multiple features on wave propagation lead to an ill-posed inverse problem.

To address these challenges, this study identifies key microstructural features that influence ultrasonic responses. Special attention is given to grain-scale microstructural inhomogeneity, which strongly affects ultrasonic scattering in the Rayleigh regime. To quantify this effect, a newly formulated microstructural parameter is proposed. A polycrystalline modeling framework incorporating various microstructural features is developed, and the characteristics of the proposed inhomogeneity metric are systematically analyzed. Numerical simulations reveal a monotonic relationship between microstructural inhomogeneity and ultrasonic scattering attenuation. Furthermore, the general applicability of the proposed parameter is validated across multiple materials with different crystallographic systems.

Methodology

To develop a general method for quantitatively characterizing microstructural inhomogeneity across different microstructures, this study first investigates polycrystalline modeling techniques that incorporate a range of microstructural features, particularly grain size and texture intensity. Equiaxed polycrystalline models with varying average grain sizes (from 50 to 150 m) are generated using the Neper software package [3], serving as the baseline for constructing additional models. The grain orientations in the Neper-generated microstructures follow a random distribution by default. To systematically vary the texture strength along the $\langle 100 \rangle$ direction, the distribution width of grain Euler angles is adjusted for each model. Thus, texture strength is controlled by the spread of grain orientations. Additionally, elongated grain structures are produced by applying geometric transformations—specifically compression and rotation—on the equiaxed models. Microstructures extracted from Electron Backscatter Diffraction (EBSD) measurements of actual AM samples are also incorporated into the study to enrich the diversity of the dataset. The resulting collection of microstructures, as illustrated in Figure 1, covers a wide range of relevant features for the analysis.

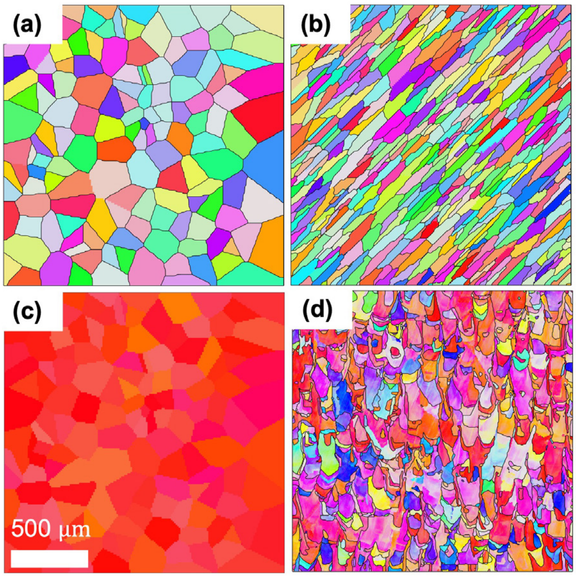

Fig. 1: Illustration of different types of microstructures with various feature.

The inhomogeneity of the microstructure is a key factor causing scattering [4, 5]. The impact of microstructural inhomogeneity at the grain-level leads to uneven distribution of stiffness across the microstructure. This, in turn, results in strain localization under loading, thereby making certain regions of the material more susceptible to the damage initiation. Therefore, an approach to integrate the stiffness inhomogeneity from microstructure features is proposed to correlate the ultrasonic scattering response in this work. In single-phase polycrystalline materials with constant density, the inhomogeneity of the microstructure induced by grains and their orientations leads to variations in the elastic tensors C_{ijkl}, which can be mathematically represented as the perturbation of the local elastic tensors based on the global [5, 6]:

$$C_{ijkl}(x,y) = C^0_{ijkl} + \delta C_{ijkl}(x,y) \tag{1}$$

where $C_{ijkl}(x,y)$ is the fourth rank elastic tensor in the spatial location (x,y). C^0_{ijkl} denotes the expectation of the global elastic tensors with given Euler angles and $\delta C_{ijkl}(x,y)$ signifies the local perturbation of elastic tensors compared with expectation. When Euler angles are assigned globally, the covariance between local elastic tensors and the average of global elastic tensors offers a parametric elucidation of spatial microstructural inhomogeneity.

$$\Xi = \mathbf{E}[C^0_{ijkl}C_{ijkl}(x,y)] - \mathbf{E}[C^0_{ijkl}]\mathbf{E}[C_{ijkl}(x,y)] \tag{2}$$

The scalar Ξ quantifies the deviation of the local elastic tensors within an inhomogeneous microstructure from the global average C^0_{ijkl} with $\mathbf{E}[\cdot]$ denoting averaging over all tensor components. In this work, we apply elastodynamic loading to generate longitudinal wave propagation and tensile loading along the *y*-axis:

$$\Xi_{22} = \mathbf{E}\left[C^0_{22kl}C_{22kl}(x,y)\right] - \mathbf{E}\left[C^0_{22kl}\right]\mathbf{E}\left[C_{22kl}(x,y)\right] \tag{3}$$

The covariance tensor is subsequently normalized by the variance of the expectation to quantitatively define the local deviation of the elastic tensors.

$$\delta(x,y) = \Xi_{22}/(\mathbf{E}\left[(C^0_{22kl})^2\right] - (\mathbf{E}\left[C^0_{22kl}\right])^2) \tag{4}$$

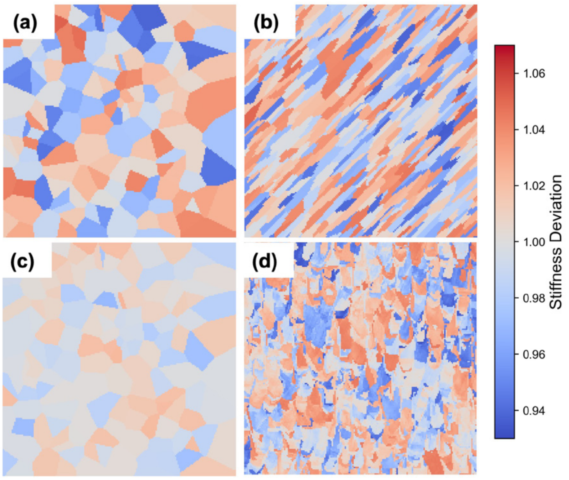

Fig. 2: The stiffness deviation maps of different microstructures.

The transformation of Euler angles into stiffness deviations in the specific dimension effectively preserves crucial spatial information, as demonstrated in Figures 2. Microstructures characterized by random crystalline orientations are observed to exhibit notably larger stiffness deviations. We describe the overall microstructural inhomogeneity as the dispersion degree of local stiffness deviations by accurately parameterizing these deviations from the normalized global value.

$$\Delta_A = \frac{1}{A} \iint_A |\delta(x, y) - 1| dxdy \tag{5}$$

where A denotes the area of the two-dimensional microstructure. The microstructural inhomogeneity Δ_A quantifies the average absolute deviation in stiffness relative to the reference plane. Hence, a lower Δ_A value suggests a more homogeneous stiffness space, and vice versa. However, the spatial integration and averaging processes in Eq. ((5)) result in the decoupling of effective grain size. Therefore, the characteristic length is used to assess the cumulative effects of microstructural inhomogeneity, namely the grain projection length L_P, which describes the lengths of the platforms illustrated in Figures 3. The average grain projection length ($\overline{L}_P$) of a specific microstructure can be expressed as:

$$\overline{L}_P = \frac{1}{N} \sum_{i=1}^{N} L_{Pi} \tag{6}$$

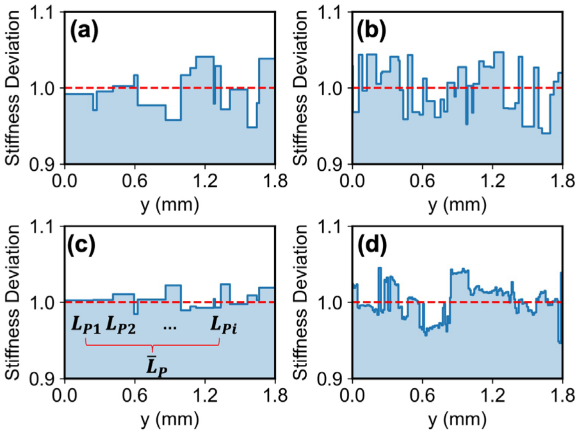

Fig. 3: Cross-sectional profiles of corresponding four types of microstructures.

We employ a series of simulated microstructures with preset grain sizes and texture intensity to investigate the characteristics of the proposed microstructural inhomogeneity. The microstructural inhomogeneity Δ_A along with its product with the average grain projection length $\overline{L}_P$ is calculated and normalized across the dataset of these 50 microstructures, as illustrated in the heat maps in Figures 4(a) and Figures 4(b), respectively. Figures 4(a) supports that Δ_A is independent of the grain size, and it only increases as texture intensity decreases.

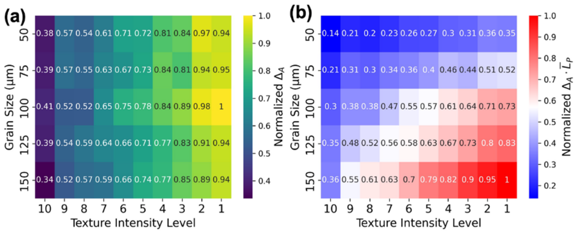

Fig. 4: Heat map of Δ_A and $\Delta_A{\cdot}\overline{L}_P$ for fifty equiaxed grain models with different grain sizes and texture intensities.

The product of Δ_A and $\overline{L}_P$ mathematically combines the effects of texture intensity and grain size into a single parameter. Physically, this product represents the cumulative effect of texture-induced inhomogeneity over a characteristic length. Specifically, it means that an inhomogeneous event of magnitude Δ_A occurs over the average grain projection length $\overline{L}_P$. As shown in Figures 4(b), a microstructure with strongly textured large grains may have the similar cumulative inhomogeneity effect as a microstructure with weakly textured small grains. This combined metric is capable of indicating the overall influence of these two independent factors derived from the principal characteristics of the microstructure. The proposed parameterization approach to microstructural features offers a valuable perspective for exploring the relationship between microstructural features and ultrasonic responses.

Results

Using the 50 different simulated microstructures and the microstructures obtained from EBSD analysis of LPBF-fabricated SS316L samples, The ultrasound propagation is simulated to investigate the relationship between microstructural inhomogeneity and ultrasonic responses. Their correlation with the proposed parameters $\Delta_A \cdot \overline{L}_P$ is of our interest. In the explicit elastodynamics analysis, a longitudinal plane wave with 10 MHz is applied to the microstructure along the *y*-axis in a through-transmission mode from top surface to the bottom.

The ultrasonic attenuation reflects the cumulative effect of microscale scattering and is typically related to the characteristic length of the microstructure. Figure 5 demonstrates a positive correlation between ultrasonic attenuation and grain projection length-weighted microstructural inhomogeneity ($\Delta_A \cdot \overline{L}_P$). It can be observed that microstructures with different grain sizes and textures follow the same trend in Figure 5, highlighting the ability of proposed parameter to represent diverse microstructural attributes. This indicates that the primary factor influencing ultrasonic attenuation is the cumulative effect of microstructural inhomogeneity along the grain projection length. This nearly linear correlation enables the characterization and evaluation of grain projection length-weighted microstructural inhomogeneity using ultrasonic techniques. This implies that the focus of ultrasonic characterization can shift from resolving coupled effects of grain size and texture intensity to characterizing an integrated variable, namely grain projection length-weighted microstructural inhomogeneity. However, further investigation is required to verify the universality of this correlation across different crystal systems.

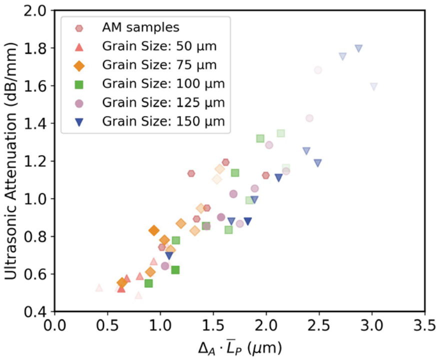

Fig. 5: Correlation between ultrasonic attenuation and $\Delta_A \cdot \overline{L}_P$ at the macroscale.

Explicit elastodynamic simulations and calculations of microstructural inhomogeneity are performed on various materials across different crystal systems. The microstructures used remain consistent with different features, while demonstrate variations in elastic constants corresponding to their distinct crystal systems. As shown in Figure 6, the fitted curves of normalized $\Delta_A \cdot \overline{L}_P$ and ultrasonic attenuation for different materials are plotted together for comparison. The results confirm that the positive correlation holds universally for all crystal systems, though the slope of the correlation differs depending on the anisotropy of each material's elastic tensor. This suggests that the proposed parameterization method has broad applicability, while the quantitative and accurate use for each material requires individual calibration.

Conclusion

This paper examines the challenges and issues associated with ultrasonic characterization of AM materials. The interactions between different microstructural features and their effects on ultrasonic scattering attenuation are mutually coupled, making it a challenging problem with indeterminate solutions. The proposed quantitative parameter of microstructural inhomogeneity from parameterization of microstructural features effectively incorporates grain-level microstructural features into the representation of microstructural inhomogeneity, demonstrating a consistent monotonic relationship with ultrasonic attenuation. This correlation is consistent across all crystal systems, indicating the universality of the proposed parameterization method.

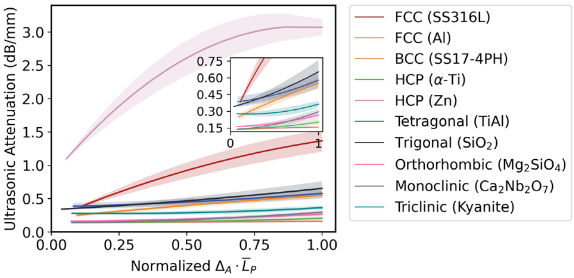

Fig. 6: Correlation between ultrasonic attenuation and $\Delta_A \cdot \overline{L}_P$ applied in multiple materials from different crystal systems.

Acknowledgments

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