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Model-Assisted Analysis of Local Attenuation in Ti-6Al-4V Materials

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***Abstract*—The nondestructive quantification of microstructure states in polycrystalline materials is an important area of recent research. Mean grain size estimates, for example, have been successfully made in a number of instances using frequency-dependent attenuation measurements and signal inversion theory based on statistically isotropic/equiaxed microstructure states and random crystallographic orientation conditions. In order to have a greater impact on engineering analysis and remaining life predictions, however, nondestructive evaluation estimates of local microstructure state variations are needed. In the present effort, forward ultrasonic models and targeted experiments are used to study and quantify the local statistical variability of microstructure states and ultrasonic signal response behaviors in synthetically generated and realistic Ti-6Al-4V titanium materials. An extension of equiaxed grain states to include extended log-normal grain size distributions is made, where local variations in the volumetric microstructure state, ultrasonic field scattering behavior, and frequency-dependent attenuation are evaluated using model-assisted studies and pulse-echo immersion ultrasound measurements.**

Keywords—Titanium alloys, Ultrasound Attenuation, FEM

I. Introduction

The ultrasonic estimation of mean grain size in polycrystalline materials has been an important engineering problem for more than 50 years, and is still an active research area today. Beginning with the original empirical observations by Mason and McSkimin in 1947 [1] that suggested a power law dependency existed between ultrasonic attenuation measurements and polycrystalline grain sizes, an extensive and systematic effort to uncover and exploit ultrasound for polycrystalline material property estimation has occurred. Although important advances and progress have been made, the current state-of-the-art is still somewhat limited in the ability of ultrasound to quantify local material property states below millimeter length scales with high confidence and accuracy. This is in part due to the physical limitations of most ultrasound inspection methods, which involve mm to cm sized probes and ultrasound fields that typically interact with volumetric regions of a sample. In addition, the use of ultrasound signal inversion methods developed in the mid-80s [2] have primarily focused on average property estimations (e.g. mean grain size), where assumptions regarding small degrees of heterogeneity, random grain orientations, equiaxed grains, and single-phased material systems are required.

In recent years, two key advances have occurred that are providing new opportunities for ultrasound evaluations of advanced polycrystalline material states with improved spatial resolution levels and characterization opportunities. The first advance involves the development and use of modified ultrasound inspection methods that localize the ultrasound energy fields and/or probe local field responses with length scales approaching micron levels. The scanning acoustic microscopy (SAM) [3] and laser-based ultrasound sensing approaches [4,5], for example, utilize high-frequency ultrasound, near-field ultrasound focusing methods, and local focused laser beam probing to compliment traditional ultrasound sensing methods with the potential for microscopic energy field interactions. Improvements in computing power and model-assisted methods have led to a second major advance in recent years, which is providing a means for correlating realistic and synthetic polycrystalline microstructure states with simulated ultrasound sensing methods and signals. The recently reported efforts of Van Pamel [6], Ryzy [7], Liu [8], Arguelles [9], and Bostrom [10] are of particular note, where advances in non-equiaxed grain states, grain size distribution, and two-phase material system evaluations have been made using model-assistance.

In the current effort, model-assisted methods are used to guide experiments for enhanced characterization of local material state properties in Ti-6Al-4V titanium materials. The specific titanium material of interest is an important engineering alloy involving a complex, bimodal microstructure consisting of globular primary α phase grains separated by transformed β phase regions of fine lamellae and retained β phase [11]. In this effort, scanning immersion ultrasound measurements are first used to evaluate ultrasonic signal behaviors and variability for a standard planar transducer, normal incidence inspection of a Ti-6Al-4V reference standard sample. Two-dimensional model-assisted studies are then used to systematically study the ultrasound frequency-dependent signal response and local signal variability for a single-phase, equiaxed, primary-α grain synthetic microstructure system. A set of three-dimensional synthetic models are then used to study local ultrasound field property behaviors and signal variability for equiaxed and non-equiaxed (extended log-normal grain size distribution), primary-α grain cases, where increases in local signal response variability were observed for

$k_0d > 1$ conditions, and a potential direct correlative relation with local grain states was observed in the model results.

II. Local Attenuation Measurements and Models in Titanium Materials

A. *Immersion Ultrasound Measurememnts of Local Attenuation in Titanium Materials*

A series of normal-incidence immersion ultrasound measurements were accomplished on a representative Ti-6Al-4V reference standard with dimensions of 24 mm x 20 mm x 6.7 mm +/-0.1mm, prepared to have flat/parallel top and bottom surfaces within a +/-5 micron tolerance. Figure 1 depicts an example of the typical microstructure in the sample, where backscatter scanning electron microscopy (SEM) measurements provided size estimates for the average primary-α grains: 8.89 microns +/- 3 microns, and a bimodal α-lath spacing in the transformed β grains of 1-2 microns.

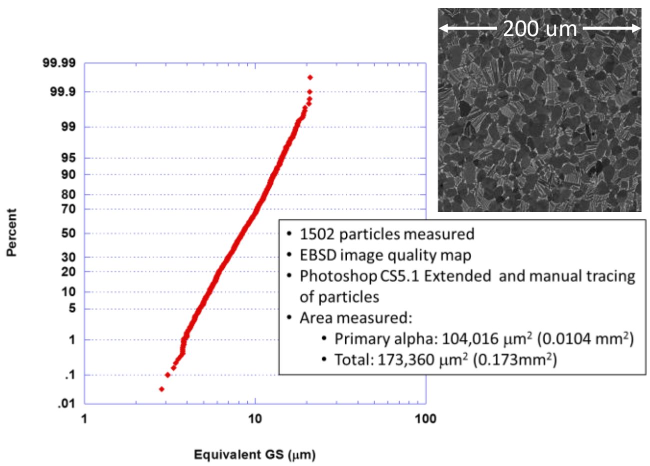

Fig. 1. As-received, forged Ti-6Al-4V material representative microstructure with prinary-a grain size characteristics (image courtesy of J Porter).

Normal incidence, pulse-echo immersion ultrasound measurements of the Ti-6Al-4V sample were accomplished with a 5 MHz, ½” diameter, planar transducer using the configuration depicted in Figure 2 (left). A representative C-scan image is also included in the figure, where a rectangular overlay of the sample position, and a circular overlay of the ½” diameter transducer beam footprint, is included in C-scan image field (right). Noticeable edge effects are observed within the C-scan image field, where a grey-level scale adjustment provides a highlight of the interior rectangular measurement area that is not impacted by the transducer-sample edge effects.

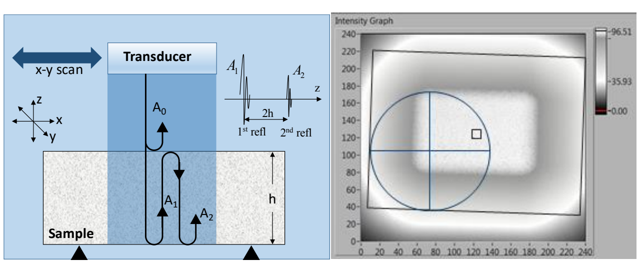

Fig. 2. Schematic diagram of pulse-echo measurement approach (left), and typical C-scan measurement (right) for 5 MHz, ½” dia., planar transducer.

Using the captured A-scan signals within the interior x,y scan region (5 mm x 5 mm region not impacted by sample edge effects), a calculation of the average and standard deviation attenuation levels were made using the 1st and 2nd backwall signals [11], respectively, where a 0.0017 dB/mm +/-0.00012 dB/mm level was measured representing a 0.7% variance within the measurement area, which is in reasonable agreement with published values for Ti-6Al-4V and ultrasound frequencies in the 5-25 MHz frequency range. The C-scan measurement involved a 24 mm x 24mm scan at 240x240 steps, corresponding to 100 micron spatial resolution steps, and spatial points in the scan representing variations of approximately 10 grains per step. Regarding signal and attenuation variance levels within the scan region, a <1% level is considered low for local grain heterogeneity analysis purposes, where higher ultrasound frequencies and spatial resolution levels are needed to improve local microstructure characterization opportunities.

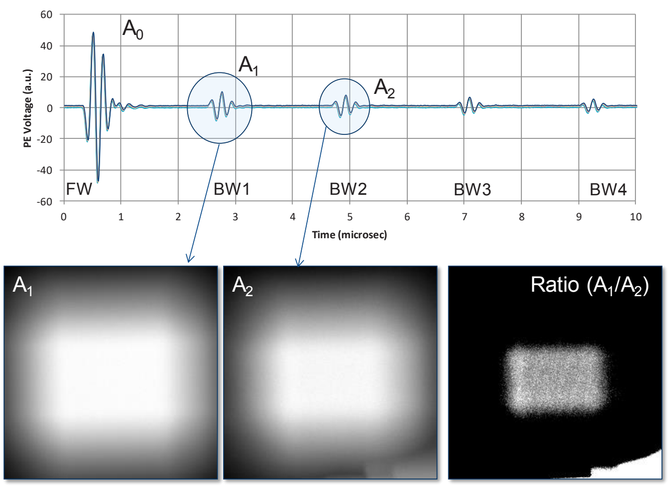

Fig. 3. A-scan signals, attenuation analysis, and backwall A1/A2 image ratio.

B. *Forward 2D and 3D Ultrasound Model Studies*

In order to better understand ultrasound sensing opportunities for assessing local heterogeneity in a Ti-6Al-4V material system, a series of 2D/3D ultrasound sensing models were used to study the frequency-dependent local and collective ultrasound signal behaviors for variations of grain property statistics. Synthetic Ti-6Al-4V microstructures were approximated using a single phase, primary-α grain material, where the DREAM3D software package [12] was used to create the 2D and 3D grain instantiations for use in the PZflex ultrasound modeling software package [13]. An example of DREAM3D’s synthetic generator is depicted in Figure 4, where a log-normal size distribution was used to control the mean grain size (MGS) and grain size distribution (GSD) statistics of the microstructure. For the 2D set of model studies, mean grain sizes were varied from 10-100 microns, with equivalent grain size distribution ranges of +/-20%. For the 3D model cases the MGS was kept consistent, while the GSD statistics were expanded to include small and large grain cases in the same grain instantiation by extending the log-normal distribution tail. An example of one of the 2D model DREAM3D synthetic generator log-normal distributions is included in Figure 4 for a 60 micron mean grain size case.

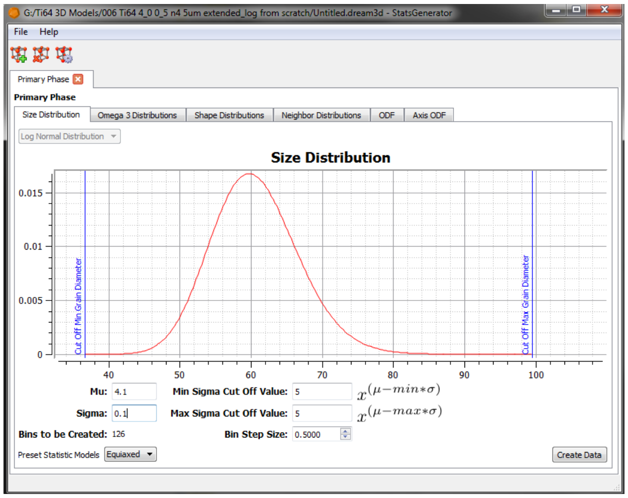

Fig. 4. Dream3D synthetic generator system used to create customized grain size distributions for PZflex finite element ultrasound sensing model studies.

The 2D finite element models used the PZflex software package [13] to propagate an idealized longitudinal wave through the material system, where local and collective displacement information was captured and analyzed to understand scattering and signal attenuation behaviors. Figure 5 depicts an example of a set of ultrasonic waves propagating through a polycrystalline microstructure with two different ultrasound frequencies. In the models, the polycrystalline MGS was varied systematically in addition to the ultrasound driving frequency to create a range of k_0d values from 0.08 to over 16 covering the Rayleigh, Stochastic, and Geometric scattering regimes. The 2D models included a 2 mm x 2 mm overall area with a 5 micron regularized grid resolution. The excitation source included a uniform pressure loading on the left side of the model, with discrete x-displacement signal levels captured on the right side for analysis. A series of overlayed signal examples are also provided in Figure 5.

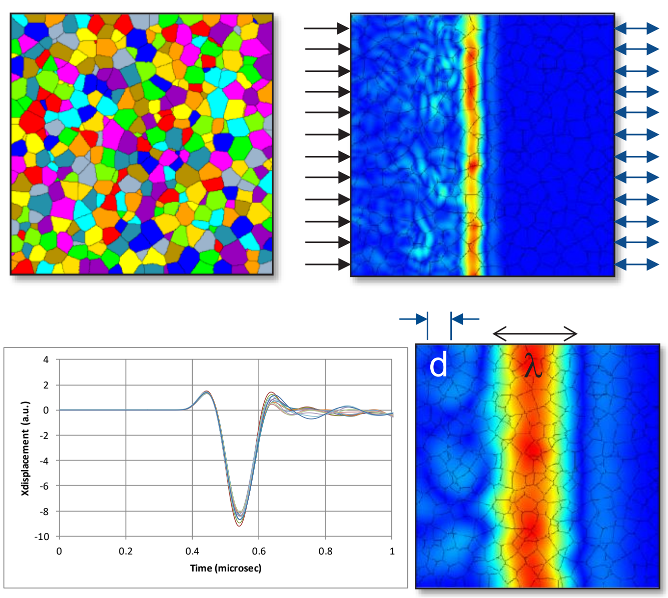

Fig. 5. 2D finite element model results depicting an example of a DREAM3D grain instantiation, and two different ultrasound wave cases.

Ultrasonic scattering and signal attenuation behaviors are typically evaluated as an average or integrated signal response, which involves measurement areas and volumes in the mm-cm ranges. In the present set of studies, an extension of these methods to include local properties and local signal variations were of interest to aid in developing more localized measurement and analysis capabilities. Finite element models provide a means for examining correlative relationships between local signal behaviors and local grain property statistics at discrete points in a model space. Figure 6 provides an example of this, where signal averages and variance levels are captured and depicted for a series of models over an extended k_0d range. Both linear and log plots are provided, which depict displacement signal attenuation behaviors captured on the right side of the model relative to the initial input levels on the left side. An increasing level of scattering behaviors is noticed as mean grain size levels, d, increase, with increasing levels of local variability also present as k_0d levels approach the 1-5 range, with the average signal attenuation level peaking at k_0d ~4. The overlayed circles in each plot highlight key transition locations in scattering and signal attenuation behaviors, where for example, maximum discrete signal variance levels approached +/-20% for k_0d > 1 levels, suggesting measurement confidence levels would be reduced.

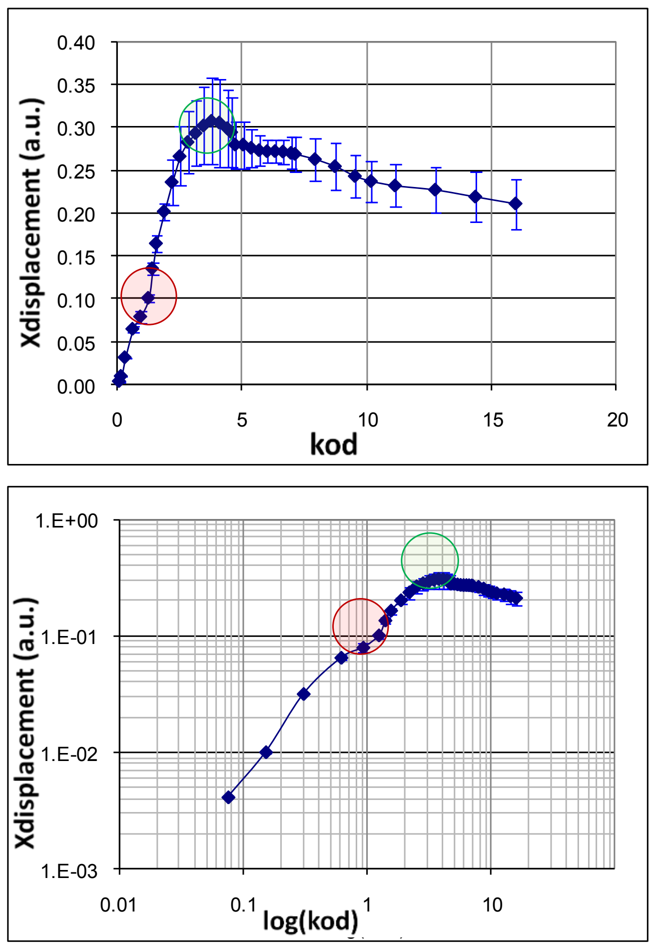

Fig. 6. Linear and log plot results for 2D finite element modles depicting x-average and discrete signal behaviors for variations in mean grain size vs ultrasound frequencies showing normalized signal loss behaviors of k_0d ranges from 0.8 to 16 levels.

An additional set of 3-dimensional model studies were accomplished to study spatial signal variations and potential correlative behaviors with local grain statistic behaviors. The same basic approach was taken that was used for the 2-dimensional models, where DREAM3D was used to create a 3-dimensional polycrystalline grain instantiation that was imported and used in the PZflex models. An idealized plane compressional wave was again used to understand local wavefront perturbations and displacement signal variations at different thru-transmission locations on the outer material/model surface after propagating thru the volumetric grain structures. An example of this is provided in Figure 7, where a 60 micron mean grain size instantiation +/-20% is depicted along with a 10 MHz compressional wave model result as the wave propagates through the 3D volume. In this set of model studies, a 2 mm x 2 mm x 2mm overall model size was used at 5 micron regularized grid spacing. Similar to the 2D model cases, an idealized, uniform pressure wave was input on the right face of the 3D material cube, with discrete x-displacement signals capture on the left for further analysis.

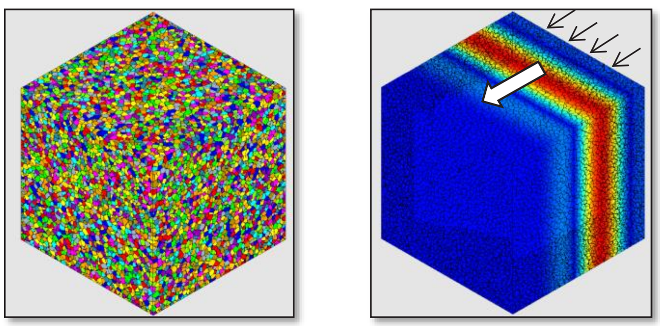

Fig. 7. 3-dimensional model results depicting DREAM3D grain instantiation (left) and 10 MHz idealized compressional wave propagating from right to left in the model (right).

Figure 8 depicts two representative 3D model result cases, where the overall 3D model is depicted in the left set of images, the thru-transmission end-face grain map is depicted in the center set of images, and a peak-to-peak x-displacement signal level plot is depicted as a grey-level map for the ultrasound field interaction result in the right set of images. In a traditional ultrasound measurement, the discrete signal information displayed in Figure 8 would be averaged or integrated to create a single response event, where the local spatial variability would not be measureable or directly evident in the signal content. The inherent variability may, however, be observed as integrated signal variability (noise) when an ultrasound sensor is scanned from position to position in a C-scan measurement. Of note in the present study, however, is a potential underlying correlative relationship of local signal levels relative to local grain states (Fig 8). Qualitatively, there is a suggested similarity between the end-face local grain states and the local ultrasound field signal levels. In addition, a measurement of the average and standard deviations of the two cases (8.905 +/-0.135 for equiaxed and 8.796 +/-0.222 for extended log-normal) indicate variations in signal amplitude and attenuation levels between the two cases even though they represent the same mean grain size levels, where the local grain size distribution has impacted the results.

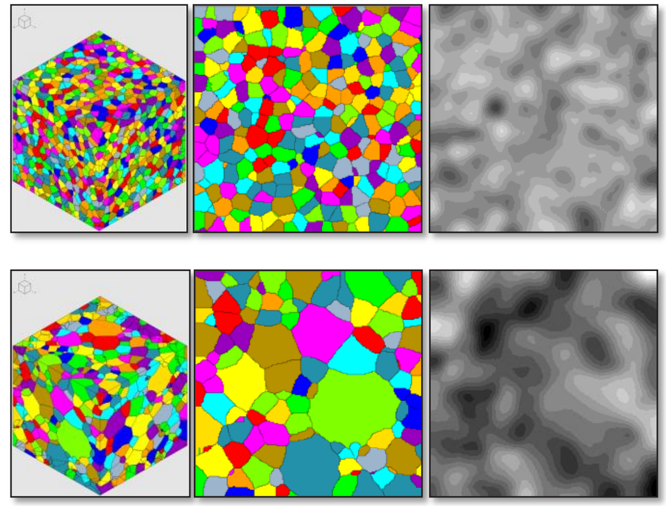

Fig. 8. 3-dimensional model results for near-equiaxed (top) and extended log-normal grain size distribution cases (bottom), with 3D model (left), end-face grains (center), and peak amplitude ultrasound signal plot (right) results.

III. Conclusions

Forward ultrasonic models were used to study and quantify the local statistical variability of microstructure states and ultrasonic signal response behaviors in synthetically generated Ti-6Al-4V titanium materials. An extension of equiaxed grain states to include an extended log-normal grain size distribution was made, where local variations in the ultrasonic field scattering behavior, and frequency-dependent attenuation were evaluated showing increased local signal variance levels for k_0d levels greater than 1, and potential spatial correlative relationships of local thru-transmission signal levels and local grain property states.

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