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On Comparison of Experiment and Theory for Ultrasonic Attenuation in Polycrystalline Niobium

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Abstract In this communication comparison of experimental attenuation results in polycrystalline niobium (Zeng et al., J. Nondestruct. Eval. 29:93–103, 2010) with scattering-induced attenuation models is reexamined. Reasonable agreement is found between those results and the standard Stanke and Kino model (in J. Acoust. Soc. Am. 75:665–681, 1984) contradicting the conclusions of Zeng et al.

Keywords Ultrasonic attenuation · Polycrystals · Grain scattering models · Ultrasonic microstructure characterization

Zeng et al. have recently published in this journal [1] a comprehensive experimental study of ultrasonic attenuation in polycrystalline niobium. In this study attenuation measurements were performed in the 5–30 MHz frequency range for single phase polycrystalline niobium (Nb) microstructures with varying averaged grain sizes obtained by different heat treatments. The grain size distribution was obtained by linear intercept measurements [1] from optical micrographs and by orientation imaging microscopy (OIM) characterization; the mean linear intercept length obtained is in the range 25–125 μm.

The main motivation of the study [1] was "to develop a nondestructive method of determining the grain size ... because of the well-known connections between engineering properties and grain size". To facilitate the grain size estimation from attenuation measurements it is advantageous to use theoretical attenuation models based on ultrasonic grain scattering. Thus, Zeng et al. [1] have employed Stanke and Kino's unified theory [2] to compare with their experimental results and have obtained more than an order-of-magnitude discrepancy with the model. These raise significant doubts about the applicability of the current standard model [2] even to single-phase well-characterized microstructures. In this letter we have reexamined the comparison of the results of the experiment [1] and the model [2] and Weaver's model [3] and model [4] for elongated grains (models [2, 3] are for equaixed grains). We have found reasonable agreement between the experiment and all of the models [2–4] which contradicts the results and conclusions of the comparison in [1].

The experimental results presented in [1] contain a wealth of data on ultrasonic attenuation and velocity, and images and data of carefully characterized microstructures with different grain sizes. This allows one to reexamine the applicability of the theory to their results. The measured attenuation coefficient versus frequency is presented in Fig. 1 for different grain sizes (the data are reproduced from Figs. 9 and 10 of reference [1]).

The parameter d in Fig. 1 is the mean linear intercept length obtained from micrographs [1] (the notations l or d are used by Zeng et al. [1] for this parameter). It plays an important role in the models [2–4], where it is used in a geometrical two-point correlation function [5, 6] $\exp(-\mathbf{r}/d)$ with assumption of Poisson statistics for the intercept length ($\mathbf{r}$ is a radius vector and the mean linear intercept length d is a correlation distance). The data are replotted in the standard form for nondimensional attenuation versus nondimensional frequency in Fig. 2 (similar to the data representation in Fig. 13 in [1]). The parameter $D = 2d$ is used to define [2] the effective average linear dimension of the grain and plot the normalized attenuation and frequency as shown in Fig. 2.

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Figure 2 also displays our computations using the Stanke and Kino [2] and Weaver [3] models shown together with the Rayleigh and stochastic asymptotes. For Weaver's model the computation were performed using a generalized model [4], which is applicable to cubic microstructures with elongated grains (the calculations were done for equiaxed grains with ellipsoid radii equal to each other). Weaver's model is valid below the geometric limit and is equivalent in this frequency range to the Stanke and Kino unified theory. It is seen that except in the high frequency range the two models coincide. The experimental data are in the Rayleigh-to-stochastic transition range. For calculations we used the density $\rho = 8.57\ \mathrm{g/cm^3}$ and elastic constants from the middle column of Table 2 of [1]: $C_{11} = 235$, $C_{12} = 121$ and $C_{44} = 28.2$ in GPa. (anisotropy factor $A = (C_{11} - C_{12})/2C_{44} = 2.02$). The other elastic constants presented in Table 2 of [1] were also considered; that resulted in only a slightly visible difference in the calculated attenuation. Reasonable agreement is observed between experimental and theoretical results. The calculations from the model [2] shown in Fig. 2 are strikingly different from those displayed in Fig. 13 of [1], which are about 20 times lower than the experimental data and our computations by the same model (this corresponds to about two order of magnitude shift in the nondimensional frequency). We attribute this difference to a miscalculation in [1] when using the model [2].

As shown in Fig. 2, all experimental measurements are in the Rayleigh-to-stochastic transition range in the attenuation coefficient (this was also noted in [1] for some experimental data). The theoretical attenuation make a smooth transition from fourth, in the Rayleigh regime, to second power frequency dependence in the stochastic region. In the transition range the frequency dependence deviates significantly from the Rayleigh or stochastic asymptotes. The transition range for longitudinal wave attenuation is characterized by a hump [2], which is physically explained by a transition of the scattering mechanism: from longitudinal-to-transverse wave scattering in the Rayleigh region to longitudinal-to-longitudinal in the stochastic region.

The existence of the hump complicates interpretation of the experimental data. As follows from Fig. 1 the attenu-

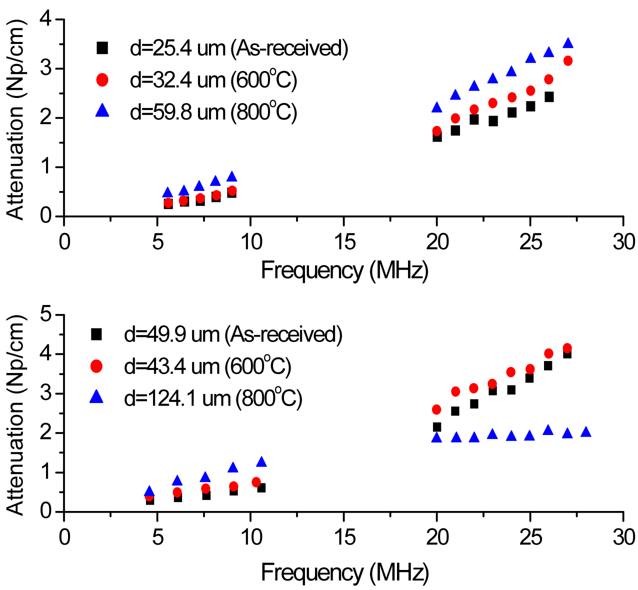

Fig. 1 Measured attenuation versus frequency (points are reproduced from Figs. 9 and 10 of reference [1])

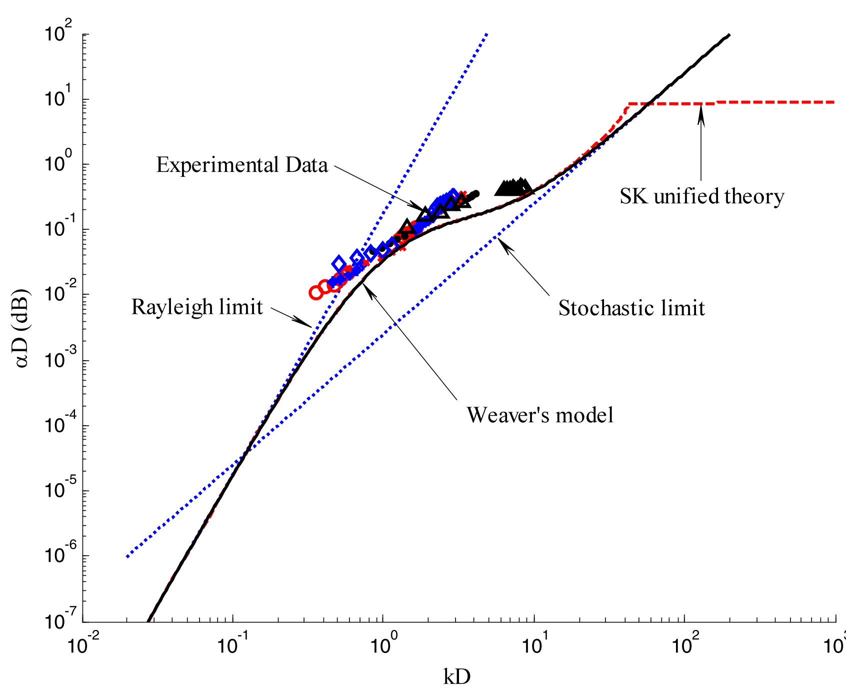

Fig. 2 Nondimensional attenuation αD versus nondimensional frequency kD (k is the wave vector and $D = 2d$ is the effective mean grain size. No adjustable parameters are used. Experimental data [1] (*points*) are replotted from Fig. 1. Calculations are for the Stanke and Kino (SK) [2] and for Weaver's [3] models; the results for the Weaver model [3] were obtained using the model described in [4] applying it to the microstructure with equiaxed grains. Weaver's and the Stanke and Kino models coincide in the Rayleigh and transition regions; Weaver's model departs from the Stanke and Kino model and is not applicable far in the stochastic and geometric regions

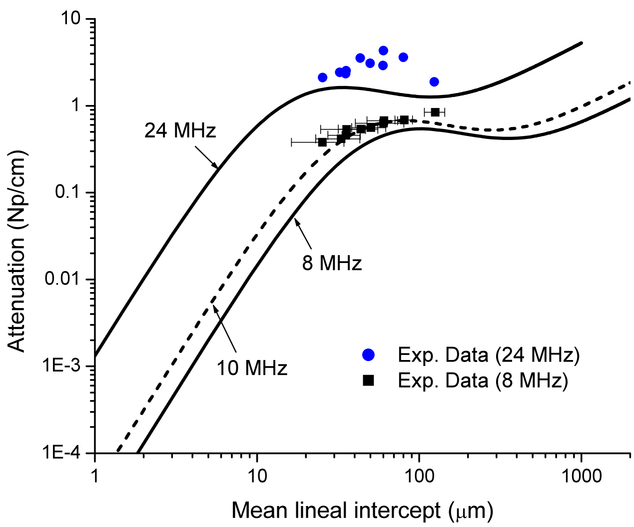

Fig. 3 Attenuation coefficient versus mean linear intercept length d; measurements-points, theory—*solid lines*; no adjustable parameters are used in the calculations. Experimental data for 8 MHz are reproduced from Fig. 11 of reference [1] and for 24 MHz are from Fig. 1. The attenuation coefficient decreases due to a hump in the Rayleigh-to-stochastic transition range

ation coefficient is frequency independent for large grains $d = 124$ μm (in the frequency range 25–30 MHz) and drops off with increase of the mean linear intercept length d. This led to the conclusion in [1] on geometrical scattering in this size/frequency range. Also, it was observed in [1] (Fig. 11) that the attenuation coefficient is nearly linearly proportional to the mean linear intercept at 8 MHz, which led them to propose that the data are in the stochastic scattering regime. However, the slope differs from that of the stochastic range. Such nearly linear behavior is characteristic for the transition range and was also observed for Ti alloys [7]. As have been already noted and follows from Fig. 2, all experimental measurements are in the Rayleigh-to-stochastic transition range. The existence of the hump in this range induces nonuniqueness in the dependences of attenuation versus frequency or grain size which complicates the scattering regime identification using the experimental data. To elucidate this point Fig. 3 shows the attenuation coefficient versus mean linear intercept length d for 8 MHz and 24 MHz (the data (points) for 8 MHz are reproduced from Fig. 11 of reference [1] and for 24 MHz from Fig. 1). Again the theory [2, 3] (lines) explains the experimental behavior including attenuation decrease due to the transitional hump. Figure 3 also shows a theoretical curve for 10 MHz which nearly perfectly matches experimental data specified at 8 MHz. This indicates that scaling with nondimensional parameters used in Fig. 2 is preferred for the experiment and model comparison.

It is difficult to expect exact coincidence of experiment and theory for attenuation in polycrystals due to experimental errors and the many simplified assumptions of realistic microstructures in the models and the nature of volumetric effects of the microstructure on the ultrasonic attenuation: (a) Due to microstructure inhomogeneities, the mean linear intercept length d obtained from limited sample cross-sections may deviate from volumetric averages related to ultrasonic measurements (the model assume uniformity of the effective grain size distribution). (b) The two-point correlation represented by Poisson's exponential function is a simplified representation for the geometrical two-point correlation function of realistic microstructures and the actual two-point correlation function is not available. (c) The model assumes absence of correlation between crystallographic orientations of neighboring grains (d) The material texture is ignored (it is relatively small in the samples studied in [1] as was shown by shear velocity measurements with different polarizations in Table 3 of [1]). (e) The models [2, 3] assume equiaxed grain shape. The aspect ratio for the grains was measured in [1] as 1.2; its effect was checked by us using a model for ellipsoidal grains [4]. The effect was small, supporting applicability of the unified theory [2] (those results are not shown in Fig. 2).

In spite of those simplifications in the models [2–4] the theory and experiment are in reasonable agreement, thus supporting the applicability of these models for estimations of attenuation in niobium alloys studied in [1].

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