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Beta-Stabilized Ti-5Al-5Mo-5V-3Cr Primary and Secondary Phase Characterization using Ultrasonic Attenuation

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ABSTRACT

Ti-5Al-5Mo-5V-3Cr (Ti-5553) is a beta-stabilized titanium alloy being evaluated for its use in additive manufacturing. The development of effective nondestructive characterization tools will be critical for successful insertion of Ti-5553 into applications. The microstructure of Ti-5553 can be modified significantly, through heat treatments alone, to produce single β-phase microstructure or dual α-β microstructure with variations on the types and quantities of the α phase in a β matrix. In this work, a set of heat treatments was chosen to obtain a range of microstructures, followed by an investigation of the ultrasonic response to gauge the degree to which these variations could be detected. Ultrasonic attenuation was selected because of its ability to detect differences in grain size and, potentially, the existence and limited details of secondary phases . Initial results show a very distinctive difference in attenuation between the single phase β and the α+β microstructures, and smaller, but still significant, differences among the α+β microstructures indicating that this approach merits further development.

Keywords: ultrasonic attenuation, Ti-5Al-5Mo-5V-3Cr, heat treatment, ultrasonic characterization

INTRODUCTION

In recent years, β-stabilized titanium (β-Ti) alloys have been studied extensively because of their excellent chemical resistance, oxidation resistance, and remarkably wide variation in mechanical properties with heat treatments [1]. These alloys have had limited use in the past due to cost, but with the growing popularity of additive manufacturing, there is a renewed interest [2,3]. Since β-Ti alloys are less mature than other more traditional Ti-based alloys, new or existing non-destructive testing (NDT) methods should be explored to determine their effectiveness to identify defects or, ideally to characterize the microstructure for this material. One such technique is ultrasonic attenuation. Attenuation is widely believed to be attributed primarily to grain boundary scattering, but this assumption does not account for secondary phases in a microstructure. However, since the secondary phases correspond to a large change in mechanical properties, it seems reasonable to expect that they may also correspond to a change in attenuation. Ultrasonic attenuation can be evaluated using a modified version of the standard amplitude-based formula that accounts for the reflection and transmission coefficients ($\boldsymbol{T_{WS}, R_{SW}, T_{SW}}$) and the diffraction correction coefficient ($\boldsymbol{D}$) derived by Rogers and Van Buren [4]. In addition, the water attenuation coefficient ($\boldsymbol{\alpha_w}$), signal amplitude ($\boldsymbol{A}$), and distance traveled in water and the sample ($\boldsymbol{x_{[w,s]}}$) must also be computed to accurately determine the ultrasonic attenuation coefficient ($\boldsymbol{\alpha_s}$), $\boldsymbol{A_0}$ is inconsequential because it cancels out when $\boldsymbol{\alpha_s}$ is computed:

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$$A = A_0 e^{-2\alpha_w x_w} T_{WS} R_{SW} T_{SW} e^{-2\alpha_s x_s} D \quad \textbf{(Eq. 1)}$$

For the case of the β-Ti alloy Ti-5553, the secondary phase, α has a different crystal structure (*hcp*) to the parent phase, β (*bcc*) and can nucleate from either β grain boundaries or more homogeneously within the grains, suggesting that type and quantity of α may alter grain boundary scattering. As mentioned previously, heat treatments modify the microstructure, and thus the mechanical properties of β alloys, making Ti-5553 an interesting candidate for testing models of ultrasonic attenuation since measurements can be made for a variety of material states (i.e., single β phase, or with the parent β phase and different types, sizes and fractions of the secondary α phase).

The focus of this study is to generate a representative range of the microstructures that involve differences in the nucleation and growth of α precipitates within the β-Ti alloy Ti-5Al-5Mo-5V-3Cr, obtain microstructural information (phases present, phase fractions, etc.), calculate the ultrasonic attenuation coefficient ($\boldsymbol{\alpha_s}$) with use of Eq. 1, and obtain a relationship between the attenuation coefficient and the microstructure to evaluate the effectiveness of this NDT technique for AM Ti-5553.

EXPERIMENTAL METHODS

The samples used in this experiment were cut from a billet of wrought Ti-5553 into discs of 1.25 in. (25.4 mm) in diameter by 0.25 in. (6.35 mm) tall, from the same radial position of the billet. The heat treatment plan, developed with the help of the Time Temperature and Transfomation (TTT) curve from Cotton [5] and outcome, is described in Table 1. Three samples remained in the as-received condition with an undisclosed commercial heat treatment so the commercially available heat treatment could be compared to the microstructural variations created using the heat treatment plan. The remaining discs were heated to 900°C to solutionize the as-received material into a uniform β microstructure. Samples were metallographically prepared using traditional grinding and polishing techniques followed by a final polishing step using 0.04 µm colloidal silica. Backscattered electron micrographs of the samples were taken using an FEI Inspect F450 scanning electron microscope (SEM) using a voltage of 10 kV and a spot size of 4.5. Attenuation measurements were made using 5 MHz and 20 MHz broadband transducers in an immersion ultrasonic test setup using a Utex UT340 pulser-receiver. Finally, mechanical performance was evaluated by averaging 25 Vickers hardness measurements per sample, collected using a loading of 0.3 kg with a dwell time of 15s with a Zwick Roell ZHU2.5 hardness indenter.

Table 1: Heat Treatment

Solutionizing Temp(°C)	Solutionizing Time (hours)	Temp 2 (°C)	Time (hr)	Temp 3 (°C)	Time (hr)	Expected Microstructure
900	0.5					β
900	0.5	700	8			Coarse α
900	0.5	550	8			Fine α
900	0.5	700	4	550	4	Bimodal
NA	NA	NA	NA	NA	NA	As-Received

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RESULTS AND DISCUSSION

Figure 1 shows the microstructures of the four samples containing secondary α. The β-phase sample is not shown because at this magnification, there are no details to analyze. A detailed discussion of the microstructural analysis is beyond the scope of this paper, but the resulting microstructures did match the experimental intention.

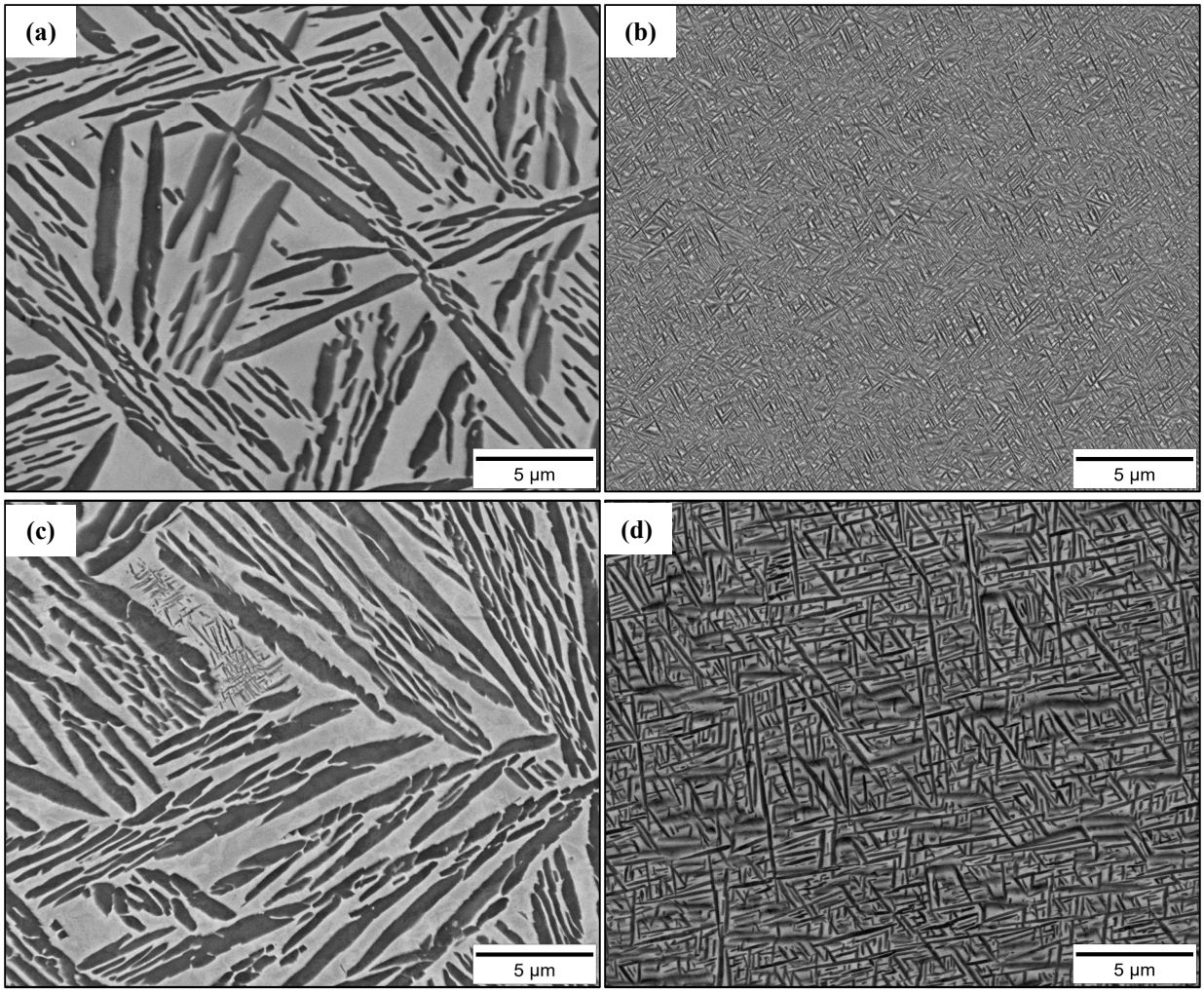

Figure 1: Micrographs of samples showing coarse α in a β matrix (a), fine α in a β matrix (b), bimodal coarse and fine α in a β matrix (c), and as-received (d). The β-phase sample is not shown.

Initial ultrasonic testing of the heat-treated alloys showed that samples consisting of a single phase β microstructure produced approximately two discernable backwall (BW) reflections while the samples with high density of the fine α phase displayed more than 14 BW reflections at a frequency of 5 MHz. This large variation in attenuation made it necessary to use two broadband transducers with central frequencies of 5 and 20 MHz. The lower frequency transducer was used for samples that displayed few BW reflections, so a minimum of two could be recorded and the higher frequency transducer was used for samples with many BW reflections so that the effects of attenuation from the material would be large enough to be measurable.

The ratios of the responses from the frontwall (FW) and two BW reflections can be used to calculate the attenuation coefficient (Eq. 1). The three combinations of ratios between the FW signal and the two BW reflections were calculated and plotted (Figure 2(a)). A linear region is identified where the three attenuation curves merged and was bounded by what would be a reasonable frequency range when considering the FFT plots of the three waveforms (Fig. 2(b)). The data from the three attenuation ratios, in the linear region, was averaged and fitted to a power law curve to represent the attenuation of each sample (Fig. 2(c)). Representative curves for the β, coarse α, fine α, bimodal and as-received samples have been plotted in Figure 3. By representing $\boldsymbol{\alpha_s}$ as a curve, attenuations at many frequencies can be reported. Finally, a preliminary correlation between attenuation and mechanical performance can be made in Table 2 using the average hardness of each microstructure (with outliers removed) and the constant of the attenuation power law equations plotted in Fig. 3.

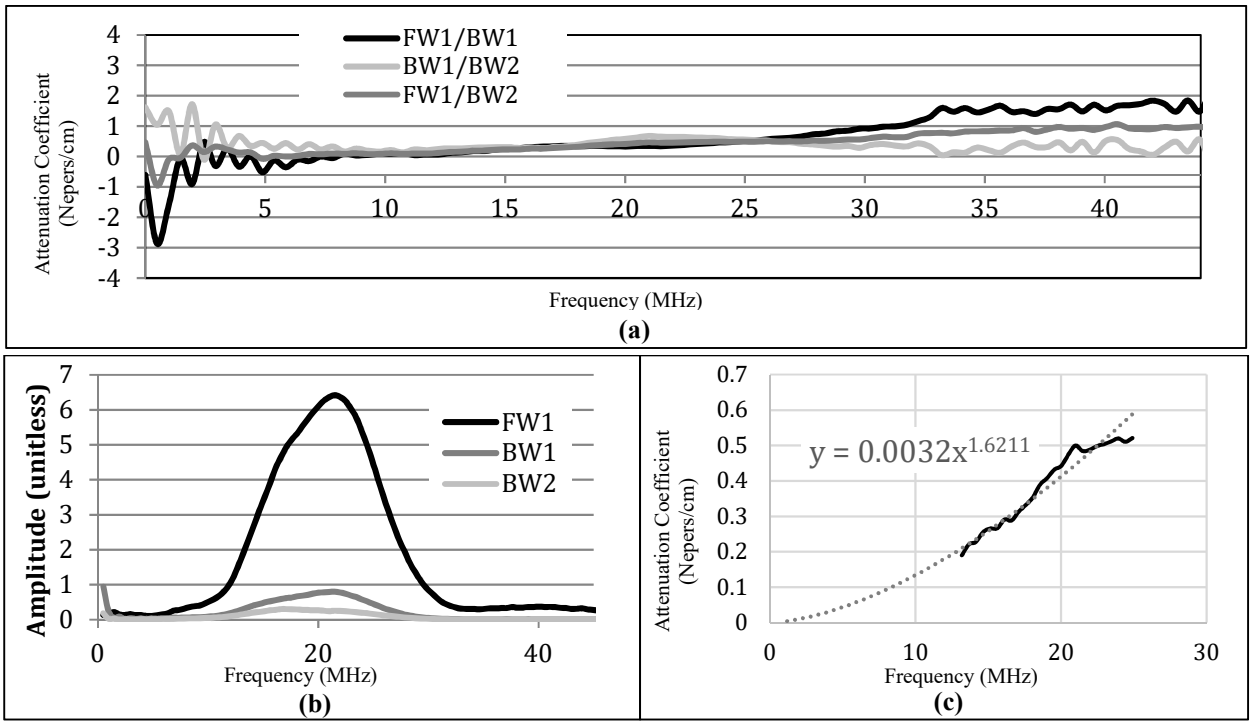

Figure 2: Process for obtaining attenuation measurements. (a) Plot the attenuation coefficients α_s obtained through taking ratios of FW1, BW1, BW2. (b) Plots of the frequency curves for each captured waveform corrected for diffraction. Frequency values in 2c are only valid for a range where both curves in the attenuation ratio are non-zero. (c) An average of the three curves in 2a is plotted and fit to a power law curve.

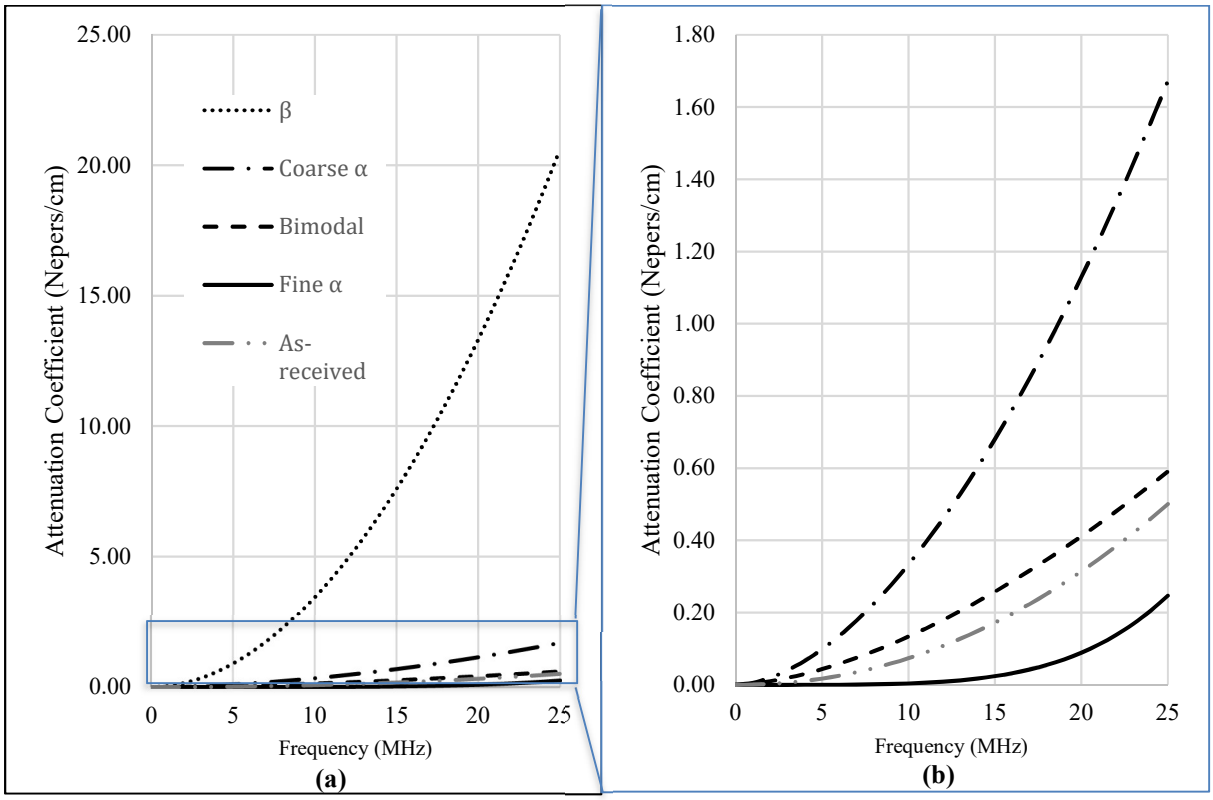

Figure 3: Power law attenuation curves for each sample where the β samples were measured with a 5 MHz transducer and the remaining samples were measured with a 20 MHz transducer. (a) All samples plotted to show the difference between β and α-β samples, and lower part of the chart magnified in (b) so the difference in attenuation by α type can be visualized.

Table 2: Hardness of each evaluated type of microstructure

Microstructure	Average Hardness (HV)	Standard deviation	Attenuation Constant (Nepers/cm)
β	284	6.26	3.8×10^{-2}
Coarse α	326	7.79	5.8×10^{-3}
Bimodal	353	18.2	3.2×10^{-3}
Fine α	446	12.8	1.0×10^{-7}

CONCLUSIONS AND FUTURE WORK

This study provides evidence that the microstructures can be controlled in Ti-5553 using specific heat treatments can be correlated to changes in attenuation. These results are significant because they indicate that an inspection technique may be able to be developed for Ti-5553 using attenuation and other ultrasonic measurements. Future work could include evaluating how the attenuation differences presented in this study fit into attenuation models such as the one presented by Stanke and Kino [6]

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