Microstructural characterization of Ti-6Al-4V using ultrasonic attenuation and its correlation with mechanical behavior

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Abstract

Ultrasonic examinations have been carried out at room temperature to correlate the microstructural variation of Ti-6Al-4V alloy with that of ultrasonic parameters. Microstructural variation in terms of different volume fractions of primary alpha phase of Ti-6Al-4V alloy has been introduced as a result of solution annealing at different temperatures followed by thermal ageing. Attenuation coefficient has been found to decrease from the content of 10% primary alpha phase to 20% primary alpha phase and then the same is increasing from the content of 20% primary alpha phase to 30% primary alpha phase. Ultrasonic attenuation coefficient strongly depends on both beta grain size effect and alloy element partitioning effect; which has been found to be the lowest at the content of 20% primary alpha phase.
Keywords: Primary alpha phase, Mechanical behavior, Ultrasonic examination, Attenuation coefficient, Beta grain size, Alloy element partitioning.

1. Introduction

Titanium alloys are widely used in aerospace applications because of their high specific strength, stiffness and fracture toughness, excellent corrosion and erosion resistance as well as its unique capability to withstand both high and low temperatures. Many critical components of air craft such as compressor disks, compressor blades, vanes and housings of modern jet-engines are made out of Ti-6Al-4V alloy and considered as a workhorse for the aerospace industries. Various microstructures namely lamellar, bimodal and equiaxed can be obtained in titanium alloys as a result of different heat treatment procedures. In 1998, Lutjering reported that a bimodal microstructure should be exploited in most of the applications of titanium alloys for their better performance in service [1]. Extensive research work has been carried out on various titanium alloys in order to correlate the effect of volume fractions of primary alpha phase on various mechanical properties i.e. creep, fracture toughness, and fatigue, etc. and described in details elsewhere [2]. All the previous work has been carried out on larger volume of materials with standard mechanical characterization techniques. As relatively large specimens need to be machined from the real components for the evaluation, standard mechanical characterization is always destructive in nature. Hence, it is necessary to know the effect of these microstructural variables on the mechanical behavior of these components in a non-invasive way without affecting service worthiness and structural integrity. Ultrasonic measurement has the potential to evaluate service worthiness and structural integrity of components and hence, is becoming a more widely used and important technique for remaining life assessment of costly and critical components like compressor shaft, disk, blade, casing etc. in recent days.

To the best of author's knowledge, correlation between volume fraction of primary alpha phase and parameters of ultrasonic measurement in titanium alloys is not yet reported. In the present investigation, therefore, an attempt has been made to correlate the microstructural variation in terms of different volume fractions of primary alpha phase of Ti-6Al-4V alloy with the parameters of ultrasonic measurement. Results indicate that ultrasonic measurement could be successfully used to assess the microstructural variation of Ti-6Al-4V alloy resulted due to solution annealing at different temperatures followed by thermal ageing.

2. Experimental methods

The beta transus temperature of the investigated Ti-6Al-4V alloy has been experimentally found to be 995^{0}C [2]. It is well documented that bimodal microstructure in Ti-6Al-4V alloy could be obtained through solution annealing (below the beta transus temperature) followed by air cooling up to room temperature and then subsequently ageing below 700^{0}C followed by air cooling [2]. The rods of Ti-6Al-4V alloy have been subjected to solution treatment at different temperatures i.e. 980, 965 and 940 ^{0}C for 2 hours followed by air cooling to room temperature and subsequently ageing at 675 ^{0}C for 2 hours followed by air cooling to room temperature. After metallographic preparation, Kroll's chemical reagent is used in order to reveal the microstructure of heat treated samples of Ti-6Al-4V alloy. Both optical and scanning electron microscopy is used to characterize the primary alpha phase and the transformed beta matrix of the bimodal microstructure in the heat treated samples of Ti-6Al-4V alloy. Nano-indentation tests were performed on metallographycally polished samples of heat treated Ti-6Al-4V alloy using a UMIS Nano-indentation system (Fisher-Cripps, Australia) at 10 mN load with a diamond Berkovich indenter (face angle 65.3^0) of tip radius 150 nm. Young's modulus and hardness values were calculated using the load-displacement curves using Oliver-Pharr analysis. Each test was carried out on individual phases more than five times and the average values were calculated in order to eliminate the errors. Cylindrical samples of 20 mm diameter have been cut from the heat treated rods using electric discharge machining. For the purpose of precise ultrasonic attenuation measurements, all the samples were ground uniformly to 58 mm thickness and the opposite faces were made plane parallel to within ± 3μm. Ultrasonic tests were accomplished by the contact pulse-echo method in Modsonic instrument using 5 MHz longitudinal wave probe at room temperature. A constant pressure was maintained between the transducer and the specimen during the contact measurements. SAE 15W40 lube oil was used as couplant. A constant velocity of 6100 ms^{-1} was applied to the samples to measure attenuation coefficient of Ti-6Al-4V alloy consisting of various volume fractions of primary alpha phase.

3. Results and Discussion

3.1 Microstructural characterization

The rods of Ti-6Al-4V alloy have been subjected to solution treatment at different temperatures i.e. 980, 965 and 940 ^{0}C for 2 hours followed by air cooling to room temperature and subsequently ageing at 675 ^{0}C for 2 hours followed by air cooling to room temperature. The optical micrographs after these heat treatments are shown in Fig.1. It has been observed that the resultant microstructures as a result of these heat treatments are bimodal in nature and consist of primary equiaxed alpha phases in a transformed beta matrix. As the Ti_3Al solvous temperature is about 550 ^{0}C for Ti-6Al-4V alloy system, thermal ageing at 675 ^{0}C will not result in the precipitation of Ti_3Al intermetallic phase in the primary alpha phase [1]. As expected, a decrease in the solution treatment temperature leads to an increase in the volume fraction of primary alpha phase. The measured average volume fraction of primary alpha phase for the 980, 965 and 940 ^{0}C solution treatments are 10, 20 and 30 percentages respectively which are shown in the

Table 1. It is also observed that prior beta grain boundaries are delineated by a thin grain boundary alpha film and the transformed beta matrix consists of lamellar structure of fine alpha laths interspersed with retained beta films. As all the specimens are air cooled after solution treatment there is no significant change in the alpha lath spacing in the transformed beta microstructure which is expected to change if different cooling methods are applied. There is a continuous decrease in the prior beta grain size with increasing volume fraction of primary alpha phase shown in the Table 1 [2]. The size of the primary alpha phase in the bimodal microstructure is found to be 7µm.

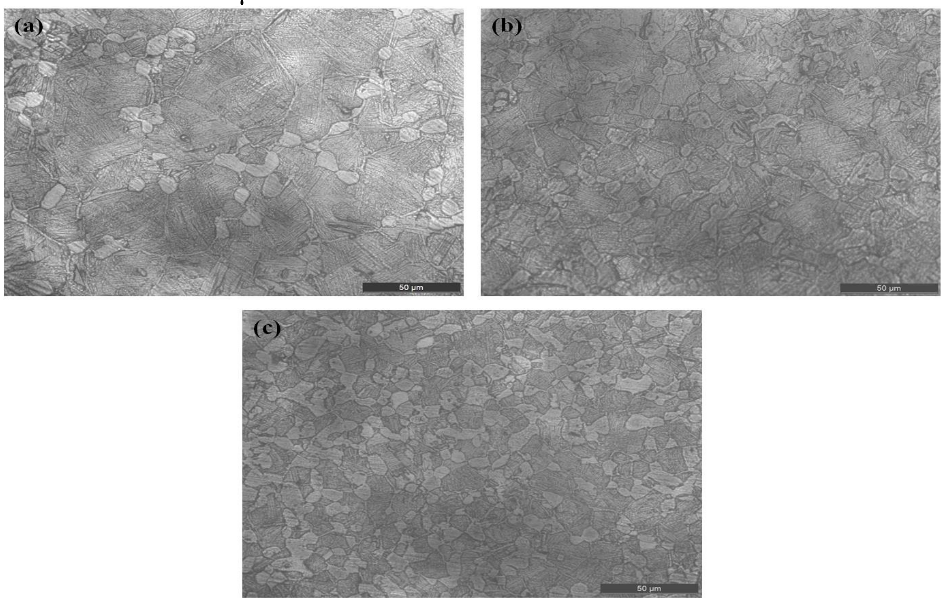

Fig.1. Bimodal microstructure of Ti-6Al-4V alloy containing various volume fractions of primary alpha phase: (a) 10%, (b) 20%, and (c) 30%

Table 1. Heat treatment procedures for Ti-6Al-4V alloy

Heat treatment	Primary alpha phase (%)	Beta grain size (µm)
980 ^{0}C + 2hr +AC +675 ^{0}C +2hr +AC	10	51
965 ^{0}C + 2hr +AC +675 ^{0}C +2hr +AC	20	23
940 ^{0}C + 2hr +AC +675 ^{0}C +2hr +AC	30	14

*AC – Air cooling

3.2 Effect of volume fraction of primary alpha phase on alloy element partitioning

Two alloying elements, i.e. Al and V are present in Ti-6Al-4V alloy system. Al is the alpha stabilizing element, although it also has significant solubility in the beta phase [1]. However, V is the beta stabilizing element and has limited solubility in the alpha phase [1]. During solution annealing at high temperature, Al tends to segregate to the alpha phase and V partitions to the beta phase.

Table 2. Weight percent of Al and V in the primary alpha and transformed beta phase

Primary alpha phase (%)	Al		V	
	Primary alpha phase	Transformed beta matrix	Primary alpha phase	Transformed beta matrix
10	7.25±0.12	5.88±0.5	0.99±0.11	2.57±0.04
20	6.88±0.06	5.59±0.16	1.45±0.04	4.81±0.17
30	5.27±0.25	4.91±0.01	1.89±0.26	6.69±0.16

To determine the partitioning of Al and V elements between primary alpha and transformed beta phases, Energy Dispersive X-ray (EDX) analysis has been carried out [3]. The outcomes of the EDX analysis are presented in the Table 2 and these results correspond to the averages of four EDX spot analyses. It is observed that the presence of Al in primary alpha phase increases with decrease in volume fraction of primary alpha phase; whereas, the presence of V in transformed beta phase increases with decrease in volume fraction of transformed beta phase.

3.3 Effect of volume fraction of primary alpha phase on hardness behavior

Nano-indentation hardness testing were carried out on both the primary alpha phase and transformed beta matrix of polished samples of heat treated Ti-6Al-4V alloy consisting of various volume fractions of primary alpha phase and the results are shown in the Table 3. From Table 3, it is clearly observed that the hardness value of primary alpha phase decreases with increase in volume fractions of primary alpha phase. This observed phenomenon could possibly be attributed to the decrease in Al content in the primary alpha phase with increase in volume fraction of primary alpha phase, as Al is responsible for increasing the strength of the primary alpha phase by solid solution strengthening [4]. It is also observed that the hardness value of transformed beta matrix decreases with increase in volume fraction of primary alpha phase. This observed phenomenon could possibly be attributed to decrease in the strength of the transformed beta matrix with increase in the volume fraction of primary alpha phase due to alloy element partitioning (i.e. especially Al) [1].

Table 3. Results of Nano-indentation hardness test of Ti-6Al-4V alloy

Primary alpha phase (%)	Hardness (GPa)		Elastic Modulus (GPa)	
	Primary alpha phase	Transformed beta matrix	Primary alpha phase	Transformed beta matrix
10	2.98±0.36	4.28±0.61	149.26±9.59	190.85±20.78
20	1.99±0.14	3.76±0.56	112.29±8.13	152.15±7.93
30	1.29±0.04	2.49±0.61	85.19±1.04	120.15±9.65

3.4 Effect of volume fraction of primary alpha phase on ultrasonic attenuation behavior

Attenuation co-efficient was measured from the logarithmic decrement of amplitude (dB) between the two consecutive back wall signals and then dividing it by the total path travelled. It is expressed in terms of dB mm^{-1}. Attenuation co-efficient was calculated as

$$Attenuation\ coefficient\ (\alpha) = \frac{20\ \log\left(\frac{S_1}{S_2}\right)}{2d} \qquad \text{Equation 1}$$

where S_1 and S_2 are the amplitude of two consecutive back wall echoes and d is the thickness of the test material in mm.

Table 4. Results of ultrasonic test of Ti-6Al-4V alloy

Primary alpha phase (%)	Amplitude (dB)		Attenuation coefficient (dB mm^{-1})
	S_1	S_2	
10	24	19	0.017
20	22	20	0.007
30	24	20	0.013

Attenuation coefficient of Ti-6Al-4V alloy containing various volume fractions of primary alpha phase are presented in Table 4. It is observed that attenuation coefficient value is decreasing from the content of 10% primary alpha phase to 20% primary alpha phase and then it is increasing from the content of 20% primary alpha phase to 30% primary alpha phase.

A constant velocity of 6100 ms^{-1} was applied to the samples to measure attenuation coefficient of Ti-6Al-4V alloy consisting of various volume fractions of primary alpha phase using 5 MHz longitudinal wave transducer. In the present investigation the wave length (λ) of the ultrasonic wave is 1220 µm and the grain size (D) is less than 51 µm. Hence, the grain scattering is mainly dominated by Rayleigh scattering in which attenuation coefficient decreases with decrease in grain size [5]. If the beta grain size is the only parameter influencing the attenuation coefficient of bimodal microstructure, then the attenuation coefficient is expected to decrease continuously with increase in the volume fraction of primary alpha phase due to decrease in the size of beta grain.

Young's modulus values of both primary alpha phase and transformed beta matrix were obtained from the Nano-indentation experiments of Ti-6Al-4V alloy consisting of different volume fractions of primary alpha phase and are presented in Table 3. From Table 2, it is observed that the presence of Al in primary alpha phase increases with decrease in volume fraction of primary alpha phase; whereas, the presence of V in transformed beta phase increases with decrease in volume fraction of transformed beta phase. Addition of alpha stabilizing elements or lowering of beta stabilizing elements increases the young's modulus in Ti-6Al-4V alloy. Hence, young's modulus of both primary alpha phase and transformed beta phase increases with increase in solution treatment temperature. Young's modulus of a multiphase alloy is determined by the specific moduli of the phases and by their volume fractions. By applying rule of mixture, it is observed that Young's modulus of Ti-6Al-4V alloy increases with decrease in volume fractions of primary alpha phase. It is reported in literature that Young's modulus of Ti-6Al-4V alloy increases with increase in solution treatment temperature [6]. Hence, it is predominately clear that the increase in solution treatment temperature decreases the volume fraction of primary alpha phase resulting in the increase in the young's modulus value of the Ti-6Al-4V alloy. Kumar et al. reported that ultrasonic velocity decreases with increase in temperature up to about 850 ^{0}C and thereafter the same increases continuously with increase in temperature up to 1000 ^{0}C in Ti-6Al-4V alloy [7]. Ultrasonic velocity increases with increase in Young's modulus of material. The increase in ultrasonic velocity with temperature in the range of 850 to 1000 ^{0}C was attributed to the increase in both Young's modulus and hardness due to increased amount of beta phase having lesser beta stabilizing elements. Kumar et al. also reported that the variation of attenuation coefficient with solution annealing temperature exhibits opposite behavior to that of ultrasonic velocity [8]. They reported that the attenuation coefficient decreases with increase in solution treatment temperature in the range of 850 to 950 ^{0}C in VT 14 titanium alloy [8]. Hence, it is clearly demonstrated that attenuation coefficient decreases with decrease in volume fraction of primary alpha phase due to increase in young's modulus as a result of partitioning of alloying elements [8]. If the alloy element partitioning is the only parameter influencing the attenuation coefficient of bimodal microstructure, then the attenuation coefficient is expected to decrease continuously with decrease in the volume fraction of primary alpha phase due to increase in the young's modulus.

The microstructural parameters which have greater influence on attenuation coefficient of bimodal microstructure in titanium alloys are beta grain size and alloy element partitioning. Decrease in the solution treatment temperature resulted in continuous decrease in the prior beta grain size with increasing volume fraction of primary alpha phase [2]. Decrease in the beta grain size leads to decrease in attenuation coefficient. If the beta grain size is the only parameter influencing the attenuation coefficient of bimodal microstructure, then with decrease in the size of beta grain the attenuation coefficient is expected to decrease continuously. But, increase in the volume fraction of primary alpha phase resulted in increase in alloy element partitioning effect, which in turn, decreases the young's modulus of both the primary alpha phase and the lamellar part of the bimodal microstructure as they contain less alpha stabilizing and more beta stabilizing elements respectively. If the alloy element partitioning is the only parameter influencing the attenuation coefficient of bimodal microstructure, then the attenuation coefficient is expected to decrease continuously with decrease in the volume fraction of primary alpha phase due to increase in the young's modulus. It is observed that for small volume fractions of primary alpha phase the beta grain size effect dominates and that for large volume fractions of primary alpha phase there is a dominance of the alloy element partitioning effect. The attenuation behavior strongly depends on volume fraction of primary alpha phase in the bimodal microstructure of titanium alloys. As a result, the ultrasonic attenuation coefficient strongly depends on both beta grain size effect and alloy element partitioning effect; which has found to be lowest at the content of 20% primary alpha phase.

4. Conclusions

Experimental study on the effect of volume fraction of primary alpha phase on ultrasonic attenuation behavior of Ti-6Al-4V alloy leads to the following conclusions.

- Ultrasonic test has successfully been carried out to evaluate attenuation behavior of Ti-6Al-4V alloy consisting of various volume fractions of primary alpha phase.
- Ultrasonic test parameter i.e. attenuation coefficient is decreasing from the content of 10% primary alpha phase to 20% primary alpha phase and then it is increasing from the content of 20% primary alpha phase to 30% primary alpha phase.
- Attenuation coefficient strongly depends on volume fraction of primary alpha phase in the bimodal microstructure of Ti-6Al-4V alloy. This also strongly depends on both beta grain size effect and alloy element partitioning effect; which has found to be lowest at the content of 20% primary alpha phase.
- Attenuation coefficient has been identified as an important parameter indicating the suitability of this material for industrial applications.
- This identified parameter of ultrasonic test can be used as a base line data and have the potential to evaluate the degradation trend of this material while it is used in service.

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