CHARACTERIZATION OF SOLUTION ANNEALING BEHAVIOUR IN TITANIUM ALLOYS BY ULTRASONIC VELOCITY MEASUREMENTS

Anish Kumar1, Baldev Raj1, T. Jayakumar1 and K. K. Ray2

1Metallurgy and Materials Group, Indira Gandhi Centre for Atomic Research, Kalpakkam 603102, India.
2Indian Institute of Technology, Kharagpur 721302, India.

ABSTRACT. Ultrasonic velocity measurements have been carried out in two titanium alloys, Ti-6Al-4V and Ti-4.5Al-3Mo-1V (VT14), solution annealed at different temperatures starting from 923 K to 1323 K at an interval of 50 K for 1 h followed by water quenching. In both the Ti-alloys, ultrasonic longitudinal and shear wave velocities have been found to decrease with increase in solutionizing temperature up to about 1123 K, and beyond that it is found to increase. Ultrasonic velocities have been found to be constant in the VT14 alloy specimens solution annealed at above 1223 K (β transus temperature) and in Ti-6Al-4V alloy above 1273 K (β transus temperature). The present study revealed for the first time that ultrasonic velocity measurements can be used not only for the characterization of microstructural features but also for the identification of β transus temperature in Titanium alloys. Further, it has been found that ultrasonic shear wave velocity is a better parameter for microstructural characterizations in titanium alloys.

INTRODUCTION

The combination of high strength (and rigidity) to weight ratio and superior at elevated temperature mechanical properties of titanium alloys make them the preferred materials for aerospace applications. Further, due to their excellent corrosion resistance and good compatibility with human organs, titanium alloys are also widely used for human implants. The addition of controlled amounts of beta-stabilizing alloying elements causes the beta phase to persist below the β-transus temperature, down to room temperature, resulting in a two-phase system. The β-transus temperature of the α+β titanium alloys depends upon the amount of α and β stabilizing elements in the alloy. These two-phase titanium alloys can be strengthened significantly by heat treatment consisting of a quench from some temperature in the alpha-beta range, followed by an aging cycle at a somewhat lower temperature. Solution annealed and tempered α+β titanium alloys possess better mechanical properties than α+β annealed alloys [1]. The solution annealing temperature plays an important role, as it decides the volume fraction of primary α and β phases and volume fraction of the alloying elements in different phases [2]. The amount of β stabilizing element in β phase governs the stability of the phase upon rapid cooling to room temperature and hence decides the product phase. Further, if solution annealing is carried out above β-transus temperature, the alloy loses its ductility due to the substantial increase in grain size. While elastic properties of most of the structural materials differ very marginally with heat treatments, titanium alloys can exhibit variations as high as 10 % [2].
As propagation of ultrasonic waves depend upon the elastic properties of the material, ultrasonic velocity can be a very good parameter for characterization of heat treatments and corresponding microstructures in titanium alloys.

Ultrasonic technique has been used extensively for characterization of microstructures, assessment of defects and evaluation of material properties. The use of ultrasonic measurements during fabrication and heat treatment ensures the absence of unacceptable discontinuities and presence of desired microstructure with acceptable properties [3]. Ultrasonic in-service inspection is carried out to detect any unacceptable degradation in microstructure and formation and extension of defects during the operation of a component [4]. As the ultrasonic velocity is a direct function of the modulus of the material, which in turn depends upon the volume fraction of the phases with different elastic properties present in the alloy. This property of the ultrasonic velocity has been utilized effectively by many investigators for the determination of volume fraction of different phases in different alloy systems, for example volume fraction of ferrite in various duplex Fe-Mn-Al alloy steels [5] and volume fraction of martensite in 4140 grade steel [6]. Ultrasonic velocity measurements have also been correlated with the microstructural features evolved during solutionizing [7] and ageing [8] heat treatments in ferritic steels, superalloy [9], aluminum alloy [10] and many other materials.

The present work deals with the correlation of ultrasonic velocity with various microstructural features in solution annealed titanium alloys, Ti-6Al-4V and VT 14 alloy (Ti-4.5Al-3Mo-1V). Further, it has been found for the first time that ultrasonic velocity measurements can be used for the identification of β-transus temperature in these two titanium alloys.

**EXPERIMENTAL**

Various specimens of VT14 and Ti-6Al-4V titanium alloys were solution annealed at different temperatures starting from α+β phases range (923 K) to complete β range (1323 K) at an interval of 50 K followed by water quenching. Metallographic examination was carried out to reveal the microstructures in different specimens. The etchant used was Kroll’s reagent [11]. Surface grinding of these specimens was carried out to obtain the specimens with plane parallelism to an accuracy of better than ±3 μm for accurate ultrasonic velocity measurements.

The experimental setup used for ultrasonic measurements is given elsewhere [7]. A broadband ultrasonic pulser-receiver (UTA-3, Aerotech Laboratories, USA) and 500 MHz digitizing oscilloscope (Tektronix TDS524) were used for the ultrasonic measurements. Ultrasonic longitudinal and shear wave velocities measurements are carried out using 15 MHz and 5 MHz transducers respectively. The gated backwall echoes from the oscilloscope were transferred to a personal computer with the help of GPIB interfacing and software developed in LabVIEW programming system. Ultrasonic velocity measurements were carried out using cross correlation based methodology, as described in an earlier publication [7]. The accuracy in ultrasonic longitudinal and shear wave velocity measurements are ± 2.5 m/s and ± 1.5 m/s respectively.

**RESULTS AND DISCUSSION**

Figure 1 Shows the micrographs of the VT14 alloy specimens solution annealed at 1173 K and 1223 K. Presence of primary α in the α' martensite matrix can be seen in the specimen solution annealed at 1173 K. Whereas, the specimen solution annealed at 1223 K
showed the presence of α' martensite only, thus indicating that the β transus (Ac₃) temperature of VT14 alloy lies between 1173 K and 1223 K. Figure 2 shows the micrographs of the Ti-6Al-4V specimens solutionized at 1223 K and 1273 K. Similar to the case of VT14 alloy, it can be seen clearly that the β transus (Ac₃) temperature of Ti-6Al-4V lies between 1223 K and 1273 K. The difference in the β transus temperature in VT14 alloy and Ti-6Al-4V can be explained on the basis of the amount of α (Al) and β (Mo, V) phase stabilizers. The amount of α phase stabilizer (Al) is more in Ti-6Al-4V, and hence the β transus temperature is also high.

**FIGURE 1.** Photomicrographs of the VT14 alloy specimens solution annealed at (a) 1173 K and (b) 1223 K followed by water quenching.

**FIGURE 2.** Photomicrographs of the Ti-6Al-4V specimens solution annealed at (a) 1173 K and (b) 1223 K followed by water quenching.
In any α+β titanium alloy, volume fraction of β phase increases with increase in temperature up to β transus temperature. But as the amount of β stabilizing elements is fixed, the volume fraction of β stabilizing elements in β phase decreases with increase in temperature. This makes the β phase unstable and hence it transforms to stable β and secondary α on cooling to room temperature, if enough time is given for the diffusion to take place. If the alloy is quenched to room temperature (diffusion is not allowed), the β phase becomes unstable and either remains as unstable β (body centered cubic), or transform to soft α′ (orthorhombic) or hard α′ (hexagonal closed packed) martensite, depending upon the solution annealing temperature [2]. The unstable β has been reported to be a soft phase having the lowest moduli and highest damping capacity among all the phases present [1, 2].

Figures 3 and 4 show the variation in ultrasonic longitudinal and shear velocities respectively with solution annealing temperature for VT14 alloy and Ti-6Al-4V. Ultrasonic velocities decrease with temperature up to about 1123 K followed by continuous increase up to 1223 K in VT14 alloy and up to 1273 K in Ti-6Al-4V. The decrease in ultrasonic velocities with increase in temperature is attributed to the increased amount of β phase.
having lesser $\beta$ stabilizing elements [2]. This decreases the elastic modulus of the $\beta$ phase [2] and hence that of the alloy soaked at higher temperatures. The minimum in ultrasonic velocities at about 1123 K is attributed to the formation of maximum amount of soft unstable $\beta$ phase with lesser $\beta$-stabilizing elements and having the lowest modulus. The increase in the velocities and hardness beyond the minima is attributed to the formation of hard $\alpha'$ martensite instead of unstable $\beta$ phase. Beyond 1223 K in VT 14 alloy and 1273 K in Ti-6Al-4V, ultrasonic velocities become constant due to formation of complete $\alpha'$ martensite, and hence similar modulus, in all the specimens solution annealed at above these temperatures. This is in agreement with the metallographic studies, which exhibited the presence of only $\alpha'$ martensite in the specimen solutionized at 1223 K for VT 14 alloy and at 1273 K for Ti-6Al-4V (Figs. 1 and 2). This indicates that ultrasonic velocity measurements can be used for the identification of $\beta$-transus temperature in titanium alloys. The maximum changes in ultrasonic longitudinal and shear wave velocities for the heat treatments considered in this study for VT14 alloy are $\sim$ 1.76 % and $\sim$ 6.9 % respectively. The corresponding values for Ti-6Al-4V are $\sim$ 1 % and $\sim$ 2 % respectively. The larger variations and better accuracy (due to lower velocity and hence higher transite time) in shear wave velocity measurements show that ultrasonic shear wave velocity is a better parameter than longitudinal wave velocity for microstructural characterization in these titanium alloys.

**CONCLUSION**

The present study revealed that ultrasonic velocity measurement can be used for the characterization of microstructures in solution annealed titanium alloys. It has been found that ultrasonic shear wave velocity is a better parameter for microstructural characterizations in titanium alloys. Further, it has also been shown for the first time that ultrasonic velocity measurements can be used for the identification of $\beta$-transus temperature in titanium alloys.

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