

Effect of volume fraction of alpha and transformed beta on the high cycle fatigue properties of bimodal Ti6Al4V alloy

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Abstract. The present study was performed to investigate the effect of volume fraction of alpha and transformed beta phase on the high-cycle fatigue (HCF) properties of the bimodal titanium Ti6Al4V alloy. The effect of such morphology on mechanical properties was studied using tensile and rotating bending fatigue test as per ASTM standards. Microstructures and fractography of the specimens were studied using optical and scanning electron microscopy (SEM) respectively. Ti6Al4V alloy samples were heat treated to have three distinctive volume fractions of alpha and transformed beta phase. With an increase in quench delay from 30, 50 and 70 sec during quenching after solutionizing temperature of 967°C, the volume fraction of alpha was found to be increased from 20% to 67%. Tests on tensile and rotating bending fatigue showed that the specimen with 20% volume fraction of alpha phase exhibited the highest tensile and fatigue strength, however the properties get deteriorate with increase in volume fraction of alpha.

1. Introduction

Due to the excellent properties (high specific strength, high fatigue strength, good corrosion resistance, etc.), titanium components (particularly Ti-6Al-4V) are often used for manufacturing critical systems such as airfoils, undercarriage components, and airframes instead of heavy steel components. During these applications titanium structures are often exposed to fatigue loading [1]. Fatigue fracture is an important failure mode for these structures. Ti-alloys are categorized into three groups; alpha (α)- alloy, β (beta)-alloy, and α - β (alpha-beta) alloy systems. The composition of α and β can be adjusted in such a way that the optimum combination of creep, fatigue, and yield strength can be achieved based upon the component and its application. The microstructure and, therefore, the mechanical properties of $\alpha + \beta$ titanium (Ti) alloys can be tailored for specific applications by carefully choosing a sequence of thermomechanical processes and heat treatments to obtain certain morphologies and spatial distributions of the α phase [2-5].

Till date, cold-end components of a gas turbine engine are dominated by Ti-alloys. Ti-6Al-4V is widely used $\alpha - \beta$ alloy in the aerospace industry (50 per cent market share for various aero applications). Gas turbine disk is subjected to high centrifugal loading cycle to increase the compressibility of fan and compressor. Hence Ti-6Al-4V can be tailor-made to impart optimum combination of yield strength and fatigue property [3]. As per the stringent airworthiness certification requirements, any rotating component needs to be forged to improve the better properties and structural integrity of the components at critical operating conditions. Normally Ti-6Al-4V forging is carried out in $\alpha - \beta$ condition below β transus temperature. The final microstructure of the forging is dictated by the volume fraction of α and β , which decides the mechanical property of Ti-6Al-4V [2-7].



Much of the research centered on improving the microstructure and attaining appropriate mechanical properties [1-10]. Earlier work has shown that the initial microstructure such as the fraction of α and β phases, the morphology and thickness of α -lathes as well as the size of α colonies (i.e. the geometrical arrangement of α and β -phases) have significant effects on the mechanical properties of the Ti6Al4V alloy [11-12]. Although there are many investigations reporting the relationship between the HCF and strength of titanium alloy, however the relationship between the HCF, strength and volume fraction in bimodal microstructure has rarely been investigated. Therefore, in the present study, the specimens with three different volume fractions of alpha and transformed beta were prepared and their HCF properties were investigated.

2. Experimental work

The material used in this study was Ti-6Al-4V alloy rod of size Ø85 mm x 210 mm. Material was supplied by the TIMET Metal Corporation. The Material received (VAR - Vacuum Arc Remelted) was in rolled condition. The β transition temperature for the material was 995°C as given by supplier considering top, bottom and middle portion of the ingot. The chemical composition of the input material is given in table 1. As received material was deformed at a temperature of 935°C (1 Hr. soaked) to a size of 202x189x31mm. To achieve different volume fraction of alpha and transformed beta phase, the deformed specimens were undergone to Solutionize at 967°C and then quenched with quench delay of 30, 50 and 70 sec, in water followed by aging at 730°C. In this study laboratory-scale muffle furnace was used. The uniformity achieved inside the furnace was ± 3 °C. It was a temperature controlled furnace heated by electric coils and could achieve a maximum of 1200 °C and having facility of varying the heating rate up to max. 12 °C /min.

Table 1. Chemical composition

Element	Al	V	Fe	Sn	O ₂	Cu	Mo	Ti
Weight[%]	6.43	4.11	0.14	<0.04	0.2	<0.04	<0.04	Balance

Vickers hardness tests were performed under a 500 g load. Tensile specimen (diameter 6.25 and gage length of 25 mm) and fatigue (gage length of 15 mm and width of 6 mm) specimens were machined parallel to the longitudinal direction as per ASTM standards. Tensile tests were performed at constant crosshead speed with an initial strain rate of 0.005 min⁻¹. Fatigue behaviour was examined in a rotating bending fatigue test according to the DIN50113 standard on the INSTRON make RBF test machine with a frequency of 50 Hz and R = -1 with a sinusoidal wave form; three samples were tested on each stress condition. Then stress-life (S-N) curves were drawn, and fatigue limits were measured when the specimens did not fail at 10⁷ cycles.

3. Results and discussion

3.1 Microstructure and tensile properties

Fig. 1a shows the as-received microstructure of the deformed condition prior to heat-treatment. It is seen that bimodal structure composed of equiaxed α embedded in transformed beta matrix. After solution treatment at 967°C for 1hr, water quenching and ageing at 730 for 2hr of the as received deformed samples, it was noted that the volume fraction of alpha and transformed beta varied with the quench delay (Fig. 1b-d) and size of alpha grains gets reduced. With the increase of quench delay from 30, 50 and 70 sec, the volume fraction of alpha increased from 20% to 67%. This is due to increasing quench delay after solution treating which allows the alpha phase to precipitate and grow, which further reduced the tensile properties.

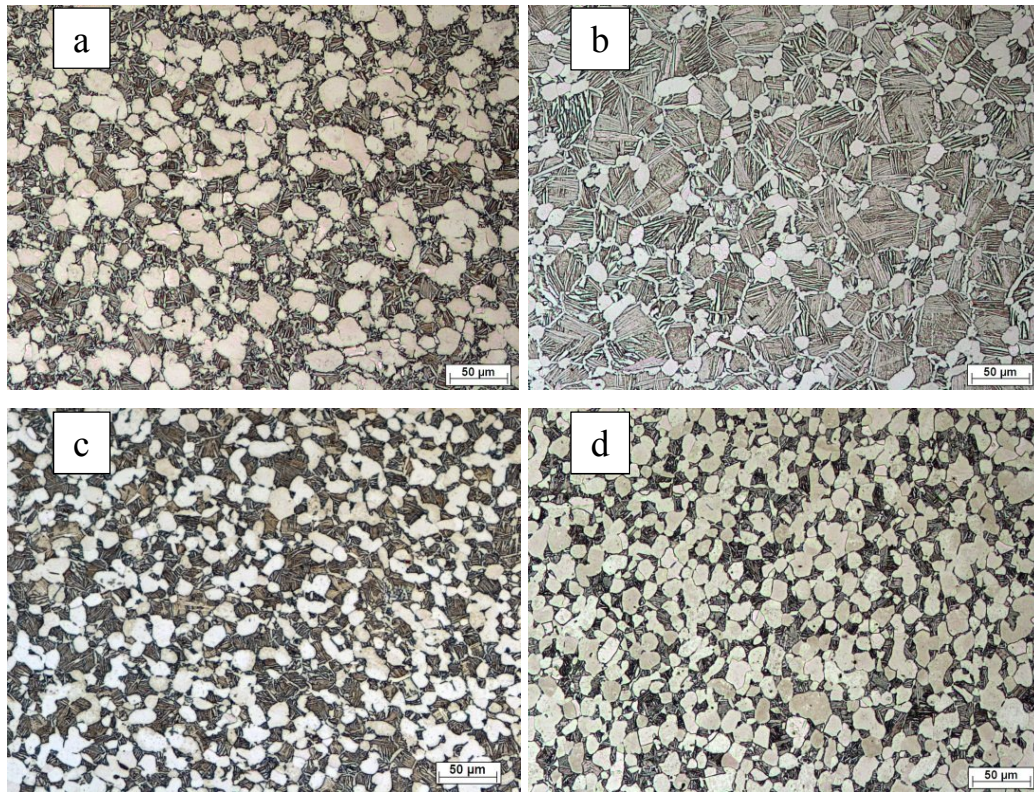


Figure.1 Optical micrograph of the specimens: (a) as-received deformed specimen (b) 30 sec quench delay (20% alpha phase) (c) 50 sec quench delay (43% alpha phase) and (d) 70 sec quench delay (67% alpha phase).

Table.2 Mechanical properties of specimen used in this study

Specimen (Quench Delay, Sec)	Alpha Phase (%)	Transformed Beta phase (%)	Ultimate tensile Strength (MPa)	Yield Strength (MPa)	Hardness (HRC)	Fatigue Limit (MPa)
30	20	80	1073	1034	37.2	630
50	43	57	1006	998	35.6	610
70	67	33	993	950	32.5	585

Table 2 shows the mechanical properties and the volume fraction of specimen used in this study. Tensile strength and hardness values of heat-treated specimens were higher in lower alpha phase, and decrease with the increase of the volume fraction of alpha.

3.2 Fatigue properties

Fig. 2 shows the S–N data of the specimens containing various volume fraction of alpha and transformed beta. Corresponding fatigue strength values measured at 107 cycles were presented in Table 3. The specimen having the highest strength (containing 20% volume fraction of alpha) represented higher fatigue limit. For bi-modal microstructures is the alloy element partitioning effect increasing with increase in volume fraction of alpha and leading to a lower basic strength within the lamellar part of the bi-modal microstructure as compared to a fully lamellar structure [13]. Thus HCF strength is lowered with increasing volume fraction of alpha phase. The fatigue cracks are nucleated in lamellar grains of bi-modal structure. These lamellar grains are softer than alpha grains as a consequence of alloy partitioning effect. The continuous decline in HCF strength with increasing volume fraction of alpha

shows that, at lower stress amplitudes with limited slip activity over short distances, the decline in basic strength of lamellar regions (alloy element partitioning effect) is stronger than the positive contribution due to the reduced alpha colony size[13]. Despite the similar slip lengths in the equiaxed grains and α colonies, the cracks initiated consistently within primary α grains, but short crack propagation by faceted growth occurred through both α grains and α colonies. Elemental partitioning during $\alpha + \beta$ processing[13] results in a higher concentration of Al in the equiaxed α as compared to lamellar α . This causes increased slip planarity and preferential crack nucleation in the primary α grains.

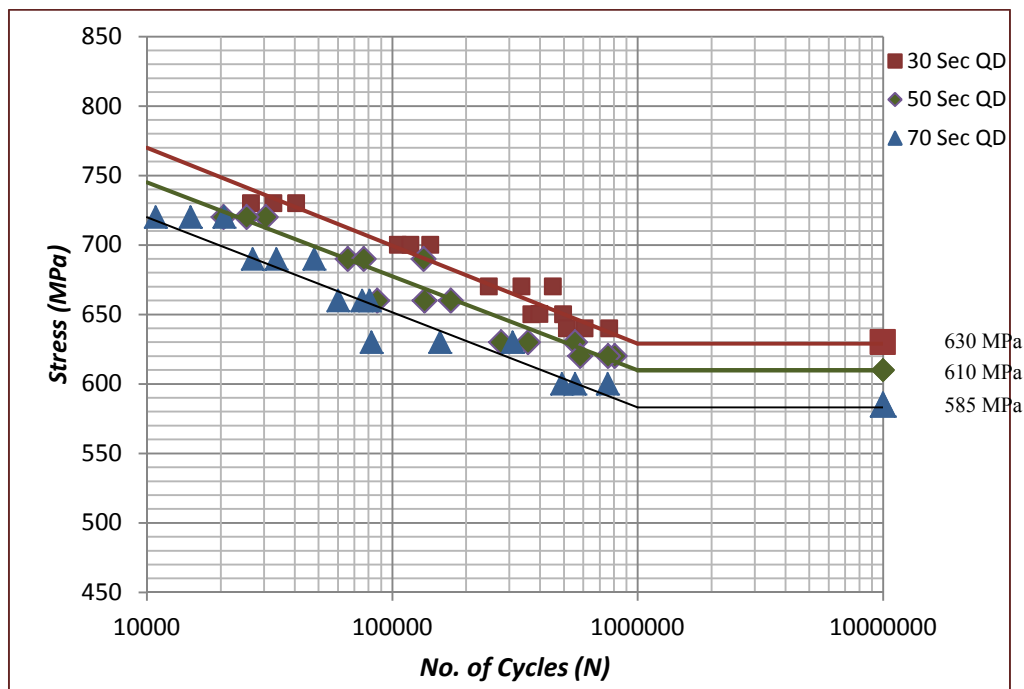


Figure.2 S–N curve for the specimens containing various volume fraction of alpha and transformed beta

3.3 Fractography

In the fatigue damage stage, cyclic stress attacks both surface and internal defects, and it is considered that the site which is selected for main crack initiation is always competitive and depends on the size of the potential sites and the stress level. SEM analysis shows similar behavior for all samples that the transition of fatigue crack initiation originates from surface to the interior. The entire fatigue fracture surface can be separated into three typical zones (see Fig. 3(a)) as crack initiation, crack propagation and final fracture. Fig3 (b) showed the image of crack initiation zone. Several facets (as marked by the arrow) usually formed in globular primary α can be commonly observed. F. Bridier et al. [12] observed such facets always formed near the basal plane and it propagated more rapidly than prismatic cracks, indicating that basal slip played an important role in crack initiation during high cycle fatigue. Fig. 3(c) showed the morphology of the steady crack propagation zone, where slow crack growth resulted in the formation of very fine striation-like features and the space expanded gradually with the increase of the distance from crack initiation area [13]. High magnification observation of this region (Fig. 3c) revealed a large amount of very fine microscopic cracks distributed parallel to the major stress axis. The fast crack growth zone was associated with dimples (Fig. 3d), which indicated the locally ductile failure mechanism. Neither inclusions nor pores were detected at the initiation site of the investigated fracture surface.

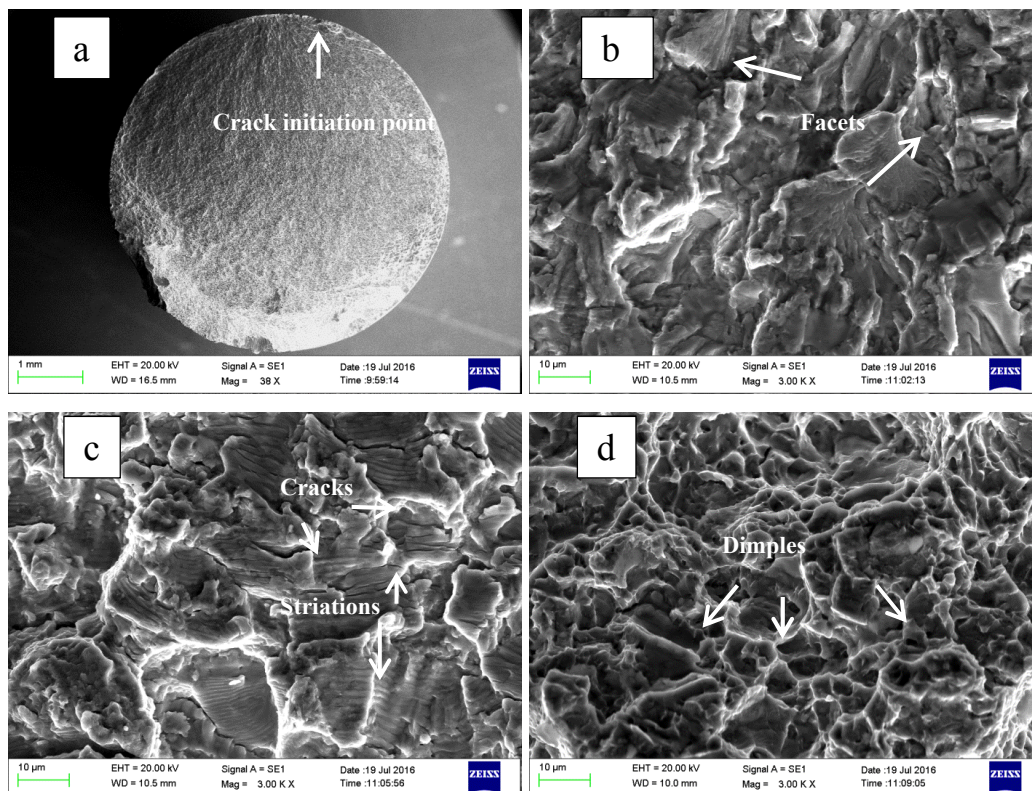


Figure.3 SEM micrographs of a) Fatigue fracture surface b) Crack initiation zone c) Crack Propagation zone d) Final fracture zone

4. Summary

The high cycle fatigue properties of bimodal Ti6Al4V titanium alloy were investigated in this study in relation to the volume fraction of Alpha and transformed beta. An increased in quench delay from 30sec, 50sec to 70sec during Solution Treatment process resulted into variable volume fractions of alpha and transformed beta, where alpha percentage was found to be increase to 20%, 43% and 67%, respectively. Reduction in tensile strength and hardness was recorded with an increase in quench delay and the subsequent alpha percentage. Excess increase in volume fraction of alpha in comparison with transformed beta contributed to reduced fatigue strength. The entire fatigue fracture surface can be separated into three typical zones as crack initiation, crack propagation and final fracture. There was no major difference notified on the effect of change in volume percentage of alpha on the fatigue behavior phenomenon. The transition of fatigue crack initiation was observed from surface to interior for all samples.

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6. References

- [1] G.Q. Wua, C.L. Shi, W. Sha, A.X. Sha, H.R. Jiang, Effect of microstructure on the fatigue properties of Ti–6Al–4V titanium alloys, *Materials and Design* **46** (2013) 668–674.
- [2] Anuradha Nayak Majila, D. Chandru Fernando, S.N. Narendra Babu, B.V.A. Patnaik, and N.E. Prasad, Evaluation of Tensile Properties and their Correlation with Microstructural Characteristics of a Closed Die Forging of Iso-symmetrical Aerospace Grade Ti-6Al-4V Alloy,

Defence Science Journal, Vol. **65**, No. 2, March 2015, pp. 171-178.

- [3] Babu, J.; Dutta, Abhijit; Kumar, Amit & Raghu, T. Flow behaviour of Ti-6Al-4V subjected to step temperature isothermal forging. *Int. J. Emerging Tech. Adv. Eng.*, 2012, **2**(2), 321-325.
- [4] Mithun, Kuruvilla; Srivatsan, T.S.; Petraroli, M. & Lisa, Park. An investigation of microstructure, hardness, tensile behaviour of a titanium alloy: Role of orientation. *Sadhana*, 2008, **33**(3), 235-250.
- [5] Nalla, R.K.; Boyce, B.L.; Campbell, J.P.; Peters, J.O. & Ritchie, R.O. Influence of microstructure on high-cycle fatigue of Ti-6Al-4V: bimodal vs lamellar structure. *Metallurgical Material Trans. A.*, 2002, **33**(3), pp. 899.
- [6] Whittaker, M.T.; Evans, W.J.; Lancaster, R.; Harrison, W. & Webster, P.S. The effect of microstructure and texture on material properties of Ti6-4. *Int. J. Fatigue*, 2009, **31**(11-12), 2022-30.
- [7] Filip, R.; Kubiak, K.; Ziaja, W. & Sieniawski, J. The effect of microstructure on the mechanical properties of two-phase titanium alloy. *J. Mater. Process Techno*, 2003, **133**(1-2), 84-89.
- [8] Ding, R.; Guo, Z.X. & Wilson, A. Microstructural evolution of a Ti-6Al-4V alloy during thermomechanical processing. *Mater. Sci. Eng.*, 2002, **327**(2), 233-245.
- [9] M. Janefeka, F. Novýb, P. Harcubaa, J. Stráskýa, L. Trkoc, M. Mhaeded and L. Wagnerd, The Very High Cycle Fatigue Behaviour of Ti6Al4V Alloy, *Proceedings of the International Symposium on Physics of Materials (ISPM13)*, 2015, 497-502
- [10] K. Kubiak, J. Sieniawski, Development of the microstructure and fatigue strength of two phase titanium alloys in the processes of forging and heat treatment, *Journal of Materials Processing Technology* **78** (1998) 117–121.
- [11] H. Zuoa, Z.G. Wang, E.H. Han, Effect of microstructure on ultra-high cycle fatigue behavior of Ti–6Al–4V, *Materials Science and Engineering A* **473** (2008) 147–152.
- [12] F. Bridier, P. Villechaise, J. Mendez, Slip and fatigue crack formation processes in an α/β titanium alloy in relation to crystallographic texture on different scales. *Acta Mater*, **56** (2008), 3951-3962.

Reference to a book:

- [13] G. Lutjering, J.C. Williams, *Engineering materials and processes, Titanium, second edition*, Springer Berlin Heidelberg New York.