Influence of Microstructure on Fatigue Crack Propagation and Fracture Toughness of Large Ti-6Al-4V Cast Structure

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Abstract The study is part of research activities for EU-China FP7 collaborative project **(FP7-AAT-2010-RTD-CHINA)**: Casting of Large Ti Structures (COLTS) and has been carried out in order to investigate the influence of microstructure of cast Ti-6Al-4V large thin wall structure on fatigue crack propagation and fracture toughness. Some samples were post HIPped (hot isostatic pressed). The effects of grain morphology on fracture and fatigue crack propagation mechanism have also been studied. The fracture surface has been examined using scanning electron microscopy (SEM). The relationships between microstructure and fatigue crack propagation rate and fracture toughness were established and comparison has been made between the as-cast and post HIPped conditions.

Keywords Ti-6Al-4V alloy, Hot isostatic pressing, Fracture toughness, Fatigue crack growth

1. Introduction

Ti-6Al-4V alloy has been widely used in aerospace industry due to its low density, high specific strength, excellent combination of strength and toughness, and resistance to creep up to moderately high temperature. While Ti-6Al-4V alloy is mostly wrought processed, near-net-shape methods such as centrifugal investment casting are increasingly used, because the desired castings require no machining except the removal of flash around edges and possible drilling and tapping holes, which shortens the process and reduces the cost. The key issues associated with centrifugal investment casting are poor reliability and reduction in mechanical properties due to the formation of cavity and porosity during casting. These defects control the mechanical properties such as fatigue and fracture because of large stress concentration. The probability of failure due to stress concentration has been modeled by the Weibull distribution [1]. In an attempt to improve the fatigue life, the cast components usually were hot isostatically pressed (HIPped) [2], which is an effective compaction technique for the removal of internal defects such as porosity, shrinkage, and inter-dendritic cracks.

Fatigue crack growth resistance and fracture toughness are important properties for aerospace applications and have been studied extensively [3]. Since HIPing plays a noticeable role in the improvement of fatigue properties, in the current study fatigue crack growth resistance and fracture toughness were investigated on both the as-cast and post-HIPped Ti-6Al-4V alloy. The obtained results were compared and the effect of post-HIPping was discussed to gain a better understanding of the influence of post-HIPping on fatigue crack growth resistance and fracture toughness of this alloy.

2. Materials and experimental methods

The material examined in this study was Ti-6Al-4V and the cast cylinders were as shown in Figure 1, including one as-cast cylinder and the other which was post HIPped. The as-cast material have a yield stress averaged at 750MPa， the ultimate tensile stress is about 840 MPa and the elongation is about 4%. After HIPping, the yield stress is increased to 735MPa，the ultimate tensile stress is about 870MPa and the elongation is up to 8%. The Microstructures in thin sections before and after HIPping were examined by optical microscopy after polishing and etching with 1% HF + 3%HNO_3+ H_2O solution.

The fracture toughness tests using compact tension were carried out on a MTS servo-hydraulic testing system in accordance with ASTM standard E399 [4] for damage tolerance testing. Samples with the dimension of 36 mm ×37.5 mm × 15 mm were cut by electrodischarge machining (EDM) and all surfaces of each slice were ground and polished. In this testing method, a fatigue pre-cracked sample was loaded to induce crack extension while continuously measuring force versus displacement. A 3D image of the fracture surface was obtained by VHX-1000. The fracture surfaces of specific samples were examined using SEM.

The fatigue crack-growth (FCG) experiments were performed using the compact-tension samples prepared according to ASTM Standard E647-99 [5]. Fatigue crack growth testing was carried out using a RUMUL fatigue machine. Samples were cut from the thin section of the structure for FCG examination. A fatigue pre-crack was first introduced at the root of the centre notch of the sample. The crack length was measured using a crack-opening-displacement (COD) gauge using the compliance method. The fatigue crack growth tests were performed in laboratory air at a stress ratio, $R=K_{min}:K_{max}$, of 0.5. Optical microscope was used to observe the relationships between the crack path and the microstructure. Fatigue surfaces of specific samples after failure were examined by scanning electron microscopy (SEM).

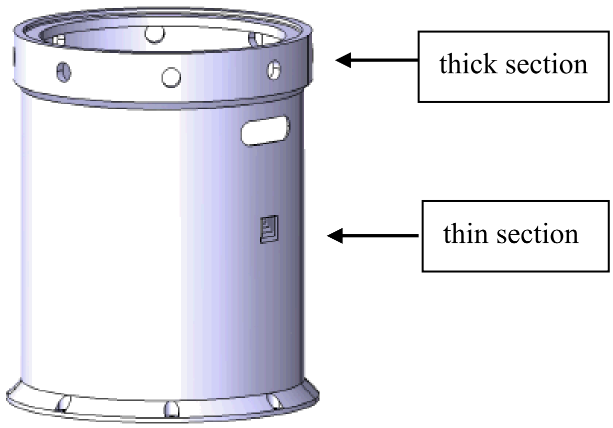

Figure 1. Ti64 component for COLTS project.

3. Results and Discussion

3.1. Microstructure

Analysis on microstructures of as-cast and post-HIPped Ti-6Al-4V showed that both samples have the lamellar colony structure and alpha film was found along beta grain boundaries. The microstructure of as-cast samples is characterized by grain size of about 2-3 mm, alpha platelet thickness of about 1.5 μm while post-HIPped samples by grain size of about 2-3 mm, alpha platelet thickness of about 4.5 μm. The grain size and the alpha platelet thickness increased after post-HIPping due to heating for a long time during HIPping.

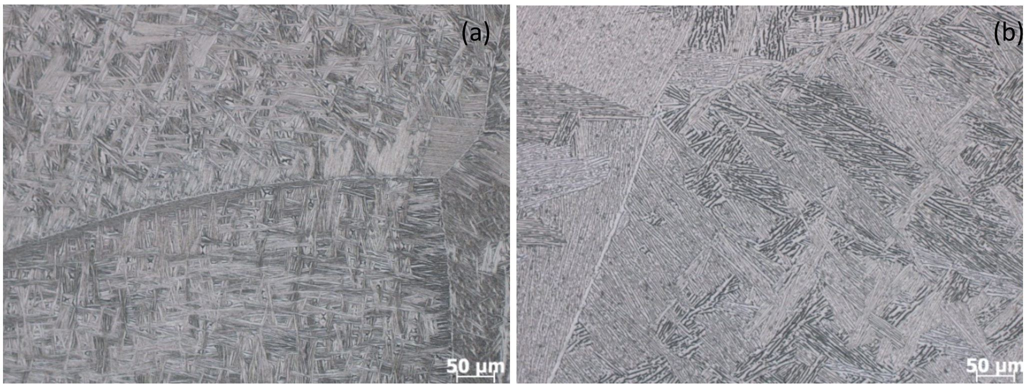

Figure 2. Optical images of microstructures in thin sections: (a) as-cast, (b) post-HIPped.

3.2. Fracture toughness

The fracture toughness sample conditions do not meet all the validity requirements ($B \geq 2.5(K_{IC}/\sigma_y)^2$), thus the testing results are considered to be an estimate of the fracture toughness. The measured fracture toughness values are 86, 83, 85 MPa $m^{1/2}$ for as-cast samples which are lower than that of post-HIPped samples (95, 97, 93 MPa $m^{1/2}$)which means the toughness was increased with increasing alpha platelet thickness. N.L. Richards also reported that the toughness obey straight-line relationships against the distance between the platelets i.e., the thickness of the alpha platelets[6].

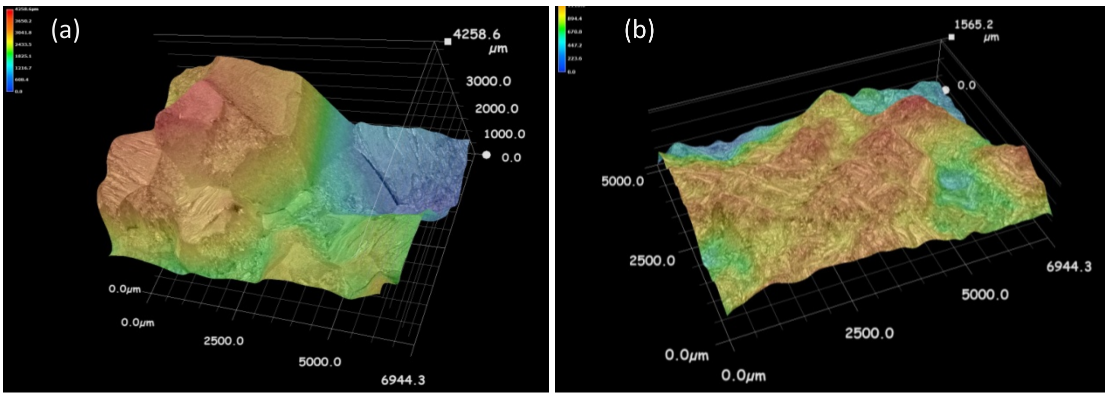

Figure 3. 3D fracture surface of Ti64 fracture toughness samples: (a) as-cast, (b) post-HIPped.

SEM fractographs for the fracture surfaces of the as-cast and post-HIPped samples are shown in

Figures 3 and 4, respectively. The fractographs show that the fracture surface changes from the intergranular-dominated fracture mode in Figure 4(a) to the transgranular fracture as shown in Figure 4(b). Figure 4(a) shows the straight edges of the grains and shiny surfaces, which indicates that the grain boundary strength is weak in some areas in the as-cast materials. The fracture surface of the post-HIPped sample is mainly transgranular, indicating improved ductility.

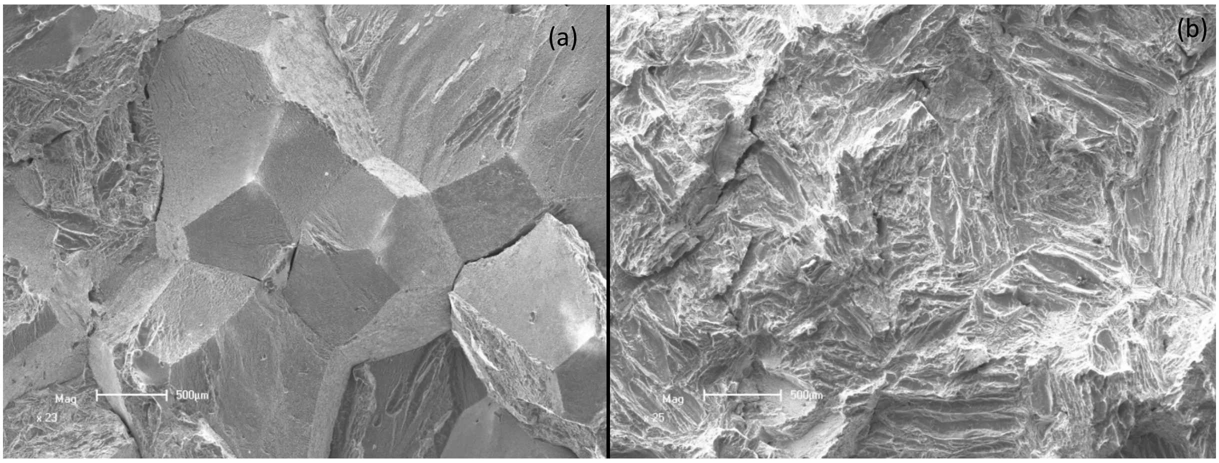

Figure 4. SEM fractographs of Ti64 fracture toughness samples: (a) as-cast, (b) post-HIPped.

3.3. Fatigue crack growth

The fatigue crack growth curves obtained for these two conditions are presented in Figure 5, which plots the fatigue crack growth rate, da/dN, against the applied stress intensity factor range. As shown in Figure 5, the rate of fatigue crack growth in the as-cast condition is faster than that after post-HIPping.

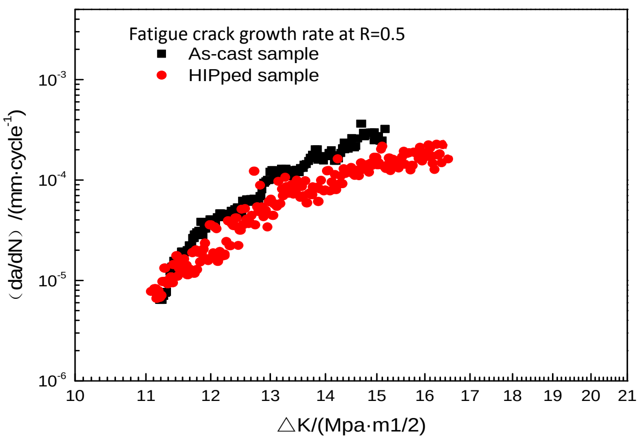

Figure 5. Fatigue crack growth resistance curves of Ti64 in both as-cast and post-HIPped state.

The crack paths in the two tested samples are shown in Figure 6. Crack deflection and branching were also found in these samples illustrated in Figure 7. The crack deflection at colony boundaries shows a zigzag path. When the crack propagated through lamellae of unfavorable orientations, it consumes more energy than a straight path, leading to a higher fatigue crack propagation resistance

[7]. The difference between the actual crack path direction and the direction of the maximal energy release varies between 2 to 15 degrees, which has been verified by Rubinstein [8]. The high magnification graphs in Figure 7(a) and (b) show that the crack deflection and branching in both samples are severe. This means that it needs more energy to proceed and enables a larger fraction of volume to contribute to stress relief by plastic deformation [9].

Fatigue fracture surface features (Figure 8) on FCG samples show a correlation to the underlying microstructure, where microstructural parameters such as the lamellar spacing and lamellar colony size appear to affect the crack propagation resistance. Chan and Kim [10] have suggested a relatively complex dependence of fatigue fracture toughness on the colony size. The thickening of alpha platelets can increase fatigue fracture toughness by contributing to crack deviation. Such improvement by alpha plate coarsening has been observed in many previous investigations [11]. It is important when the crack tip lies in a colony or the plastic zone size is similar to the thickness of platelets. The colony size can also affect the fatigue crack growth when crack propagates across colony boundaries [12]. In terms of grain boundary α, the increase in thickness of α at β grain boundary is helpful for frequent crack deviations when cracks go through the grain boundaries [13].

Fatigue striations and secondary cracks were found on fatigue fracture surfaces (Figure 8) of both samples, which indictate some ductillity of the materials. However the fatigue fracture surfaces also show that both sample conditions have similar fatigue fracture mechanisms, although, more secondary cracks were found in the as-cast Ti-6Al-4V.

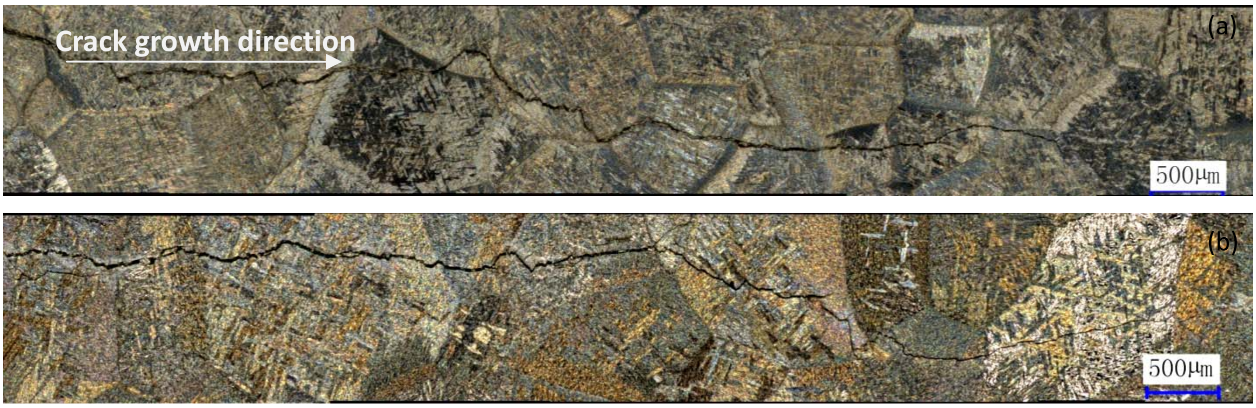

Figure 6. Crack profile of Ti64: (a) as-cast, (b) post-HIPped.

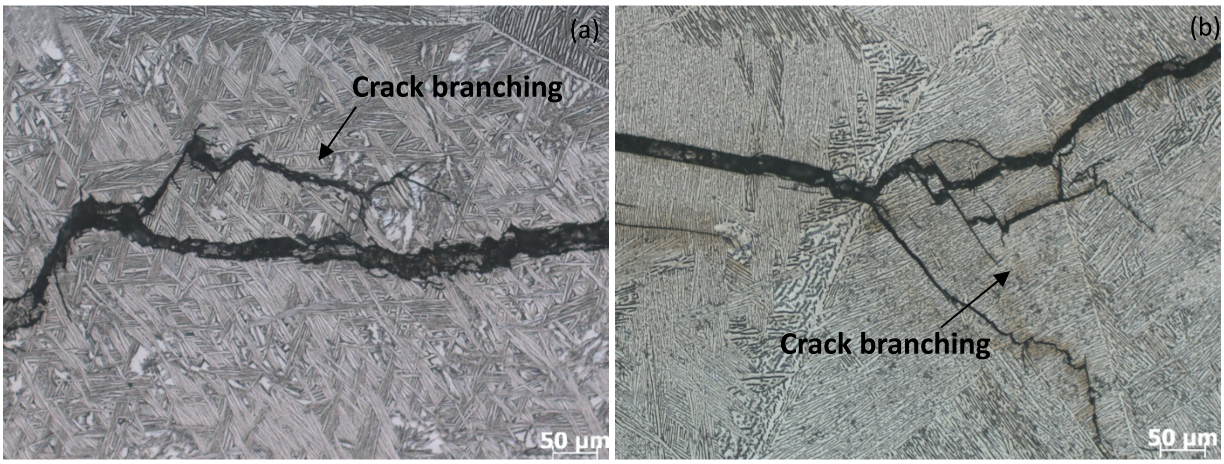

Figure 7. Crack path morphologies of Ti64: (a) as-cast, (b) post-HIPped.

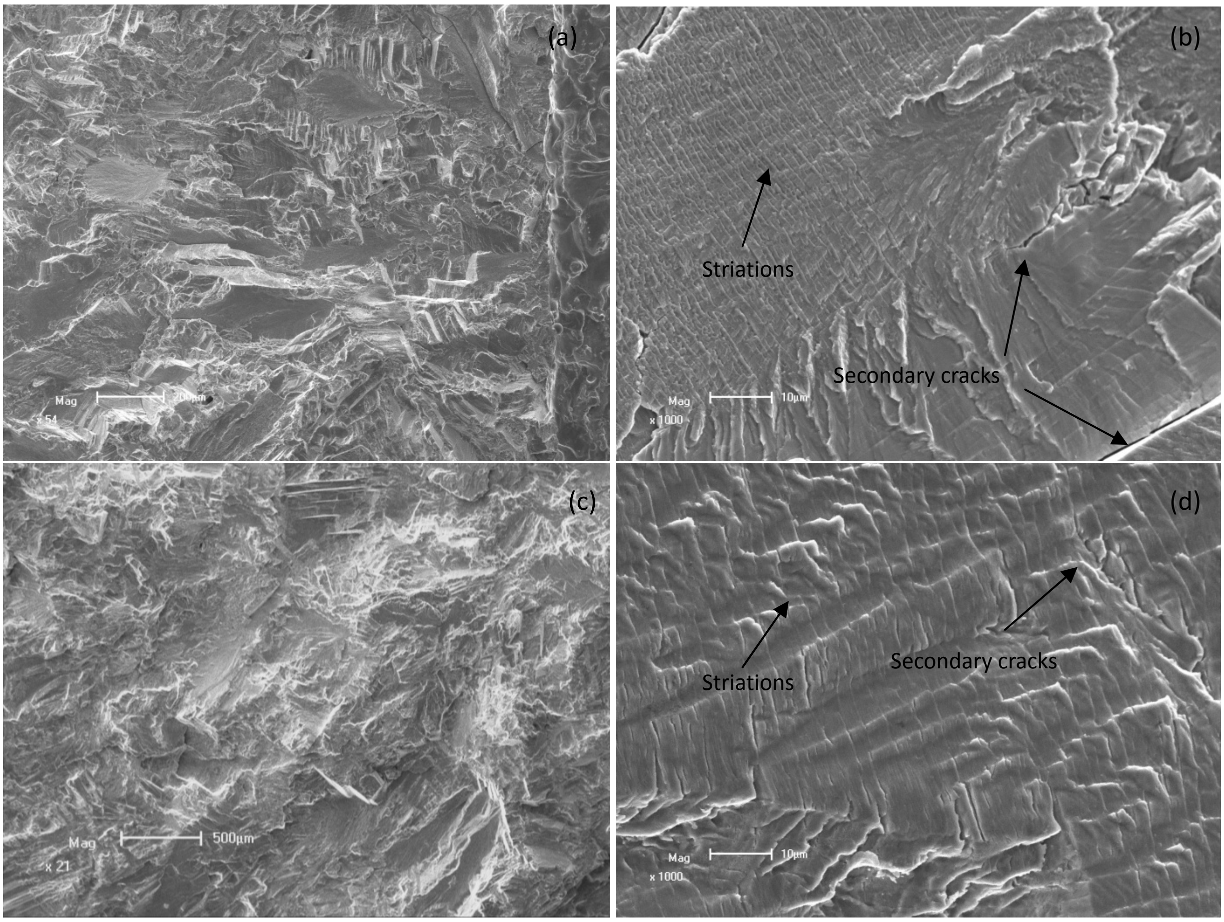

Figure 8. Scanning electron micrographs of Ti64 alloy fatigue fracture surfaces: (a) (b)as-cast, (c) (d) post-HIPped.

4. Conclusions

(1) Microstructures of Ti-6Al-4V alloy in the as-cast and post-HIPped condition were both lamellar colony structures. Following HIPping of the alloy, the thicknesses of lamellar plate and the alpha colony size both increased.
Fracture toughness of the post-HIPped samples is higher than that of the as-cast samples. This was associated with the significant reduction in the volume fraction of pores by HIPping. The fracture mode changed from the intergranular fracture into transgranular fracture.

(2) The fatigue crack growth rate of the post-HIPped sample with larger lamellar spacings was lower than that of the as-cast samples with smaller lamellar spacings. More crack deflections and branchings were found in the post-HIPped samples than in the as-cast samples, which indicates more energy was consumed in the fatigue crack propagation of the post-HIPped samples.

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