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Effect of Different Solution Treatment Temperatures on the Microstructures of Ti-6Al-4V Alloy

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Abstract

Ti-6Al-4V alloy is a (α+β) titanium alloy which composed of Al and V where the first element is a strong α-stabilizer and latter is a β-stabilizer. Based on the allotropic transformation at β-transus temperature, permutation microstructures of this alloy can be manipulated through heat treatment. This work aims to investigate the effect of varying the temperatures of solution treatment followed by annealing on the microstructures of Ti-6Al-4V alloy. Solution treatment processes were applied on six samples at different temperatures of 900, 950 and 1000°C in a vacuum furnace for 1 h, then air cooled. After that annealing, at 600°C for 4 h, air cooling, was applied to three samples, which subjected to the previous solution treatments at 900, 950 and 1000°C. The initial microstructure of this alloy was a typical lamellar microstructure, which was converted to bi-modal microstructure by applying of solution treatment at temperatures of 900 to 950°C, followed by annealing at 600°C. Bi-modal structure was evolved gradually from lamellar structure at solution treatment stage by initiation of nucleation sites of fine equiaxed α-phase, which were grown progressively at the annealing stage. The lamellar structure was re-produced with finer lamellae compared to the initial microstructure from bi-modal structure by heating the alloy just above the β-transus temperature.

Keywords: *Ti-6Al-4V alloy, β-transus, Solution Treatment, Annealing, Bi-modal, Lamellar microstructure.*

1. Introduction

Titanium alloys can be classified according to the dominant phase(s) in their microstructures as the followings; a mono-phase structure which includes alpha (α) or beta (β), and a dual-phase structure (α+β), depending on the amount of elements that act as stabilizers of either alpha (α) or beta (β). A dual-phase (α+β) alloy consists of α and retained or partially transformed β [1, 2]. The main compositions that found wide interest were based on Ti-xAl-yV and Ti-xAl-yFe systems, where aluminium is a strong α-stabilizer and vanadium and iron are β-stabilizers. The existence of the β-phase in the microstructure enhances the potential of heat treatment that increase the chances of improving of the mechanical properties [3 - 7].

Ti–6Al–4V alloy is a dual phase (α+β) material which possesses possible series and complex microstructures. The features of Ti-6Al-4V alloy are greatly affected by features of each individual phase (α and β) which constitute the microstructure, their amount (volume fraction), and their distribution [8]. Consequently, the allotropic transformation that occurs at β-transus temperature is responsible on manipulating and producing variety of microstructural permutations and combinations such as bi-modal, fully lamellar, and equiaxed microstructure. Controlling of this transformation by selecting of heat treatment parameters leads to a high understanding of alloy's behaviour based on microstructure - properties relations at different conditions [2, 9]. For example, the α-phase has lower density than the β phase due to the fact that the predominant element aluminium (Al) in α-phase has lower density than the predominant elements molybdenum (Mo) or vanadium (V) in β phase. In addition, the fine microstructures increase strength and ductility, and hinder crack nucleation. While coarse microstructures are more resistant to creep and fatigue crack growth. Equiaxed microstructures often have high ductility and fatigue strength and are ideal for super plastic deformation, whereas lamellar structures have high fracture toughness and show superior resistance to creep and fatigue crack growth [10]. Bi-modal microstructures combine the advantages of lamellar and equiaxed structures, which results in a well-balanced property profiles [8]. Also, it has been reported by many authors that bi-modal microstructure is superior to other two structures in term of the high cycle fatigue (HCF) strength [10, 11, 12]. Furthermore, Wu et al (2013), recommended to choosing the bi-modal microstructure with volume fraction of primary α-phase ranging from 30% to 50% and α - size as small as possible for applications need strict fatigue properties [6]. Therefore, it is very crucial to study in-depth understanding about microstructure of Ti-6Al-4V [13]. Generally, the solution treating temperature determines the volume fraction of the primary α-phase with temperatures just below the β-transus leading to duplex structures in which equiaxed α-phase is dispersed in an α+β lamellar matrix [14]. The volume fractions of the two phases α and β is another factor which has direct impact on the mechanical properties of Ti-6Al-4V alloys, should be taken into account during the heat treatment. Wang, Y. C and et al (2013), concluded that the volume fractions of α and β-phases of Ti-6Al-4V alloy had impact on the hardness. Vickers microhardness value of 295 and 305 were reported for specimens that contained of ~ 85% and ~ 48% for the equiaxed α-phase of bi-modal microstructure Ti-6Al-4V alloys [15]. Many worldwide researchers and research institutions have involved to understanding the metallurgy principles and the applications of titanium alloys which become their main concern. Therefore, sufficient understanding of a specific side of titanium alloy design and evolution should be explained [16]. A deep understanding of the microstructural modifications occurring during manufacturing processes are thus required allowing the improvement of the mechanical performances [17]. This research work is focusing on microstructural examinations of Ti-6Al-4V that subjected to different heat treatment conditions.

2. Experimental procedure

2.1 Materials Production

The material used in this study is a Ti-6Al-4V alloy that was melted in induction vacuum furnace using skull melting technique. The melt was casted in a ceramic mould prepared by lost wax technique. The ingot was then hot rolled at 850°C.

2.2 Heat Treatment

Different heat treatment procedures were used for evaluating the effect of the temperatures of solution treatment on the microstructure and identifying of the microstructural evolution when the solution treatment followed by annealing. Figure 1 shows a diagram of the heat treatment processes used in this study. The β-transus temperature for Ti-6Al-4V is about 995°C [18, 19].

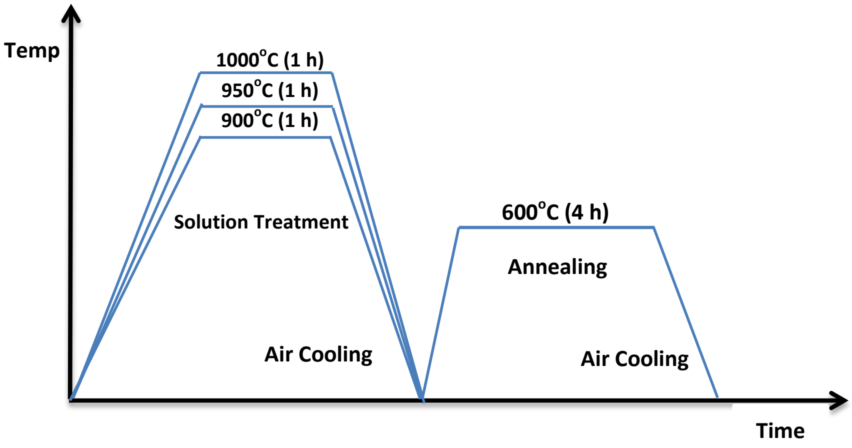

Fig. 1 Heat treatment procedures for Ti-6Al-4V specimens.

Six samples were subjected to solution treatments at different temperatures of 900, 950 and 1000°C in a vacuum furnace for 1 h, air cooled to room temperature. Three of them were followed by annealing at 600°C for 4 h and air cooling. A quartz tube connected to vacuum pump was used to protect the specimen from being oxidized. The Specimens were subjected to 900 and 950°C which represent α+β phases and 1000°C to represent β-phase region. Table 1 illustrates the designation of each specimen and its respective heat treatment procedure.

Table 1: Specimens designation and heat treatment procedures

No.	Specimen Designation	Heat Treatment
1	1S	Un-treated (hot rolled)
2	2S	Solution treatment (900°C, 1h, AC).
3	2SA	Solution treatment (900°C, 1h, AC) + Annealing (600°C, 4h, AC).
4	3S	Solution treatment (950°C, 1h, AC).
5	3SA	Solution treatment (950°C, 1h, AC) + Annealing (600°C, 4h, AC).
6	4S	Solution treatment (1000°C, 1h, AC).
7	4SA	Solution treatment (1000°C, 1h, AC) + Annealing (600°C, 4h, AC).

2.3 Microstructural Examination

All the heat treated specimens were cut, grinded, polished, and etched for an observation of their microstructure using an optical microscope and scanning electron microscope. A mixed hydrofluoric/nitric acid solution “kroll solution” of 5 ml HF, 10 ml HNO_3, and 92 ml H_2O was used as etching reagent for the microscopic examination. Time for etching is only several seconds. Optical microscopy (Nikon) and high vacuum SEM (Philips XL 40) were used to observe the microstructures of Ti-6Al-4V alloy. OLYMPUS Stream Image Analysis Software was used to measure the lamellae size and equiaxed grain.

3. Results and Discussion

The initial microstructure of as-received, un-treated, Ti-6Al-4V alloy (1S) can be simply described as a basket weave like structure which is well known as a typical lamellar microstructure of α-plates in β-matrix *(Widmanstatten structure)* as presented in Figure 2, where the size of the α-lamellae ranging from 6.59 to 14.75 μm and average size of 10.78 μm. The microstructure of the specimen (2S) shows the lamellar microstructure which is similar to that of (1S) specimen with larger size of lamellae α-phase with average size of 11.26 μm and contains few nucleation sites that taken a globular shape to form potential equiaxed grains of α-phase with an average grain size of 12.99 μm as shown in Figure 3.

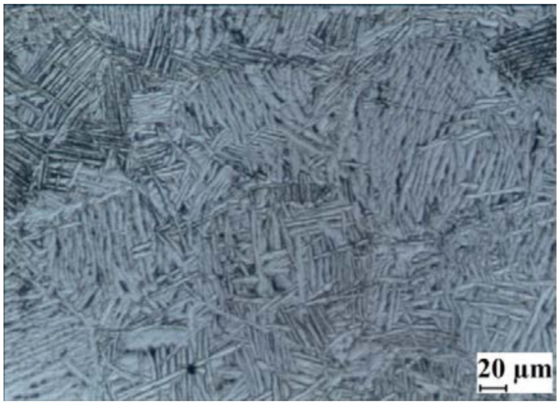

Fig. 2 The microstructure of untreated (1S) Ti-6Al-4V Alloy.

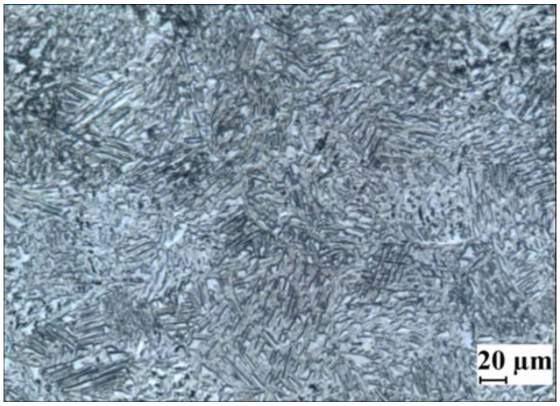

Fig. 3 The microstructure of specimen 2S.

The microstructure of the specimen (2SA) is an obvious bi-modal, as shown in Figure 4. This microstructure consists of equiaxed primary fine α-phase (white), with average size of 36.55 µm, surrounded by Widmanstatten structure, due to annealing, that was followed the solution treatment process. The average of lamellae size is about 15.66 µm which is larger than that of the sample (2S) before annealing which means that the equiaxed and lamella α phase has grown by annealing at 600^{o}C.

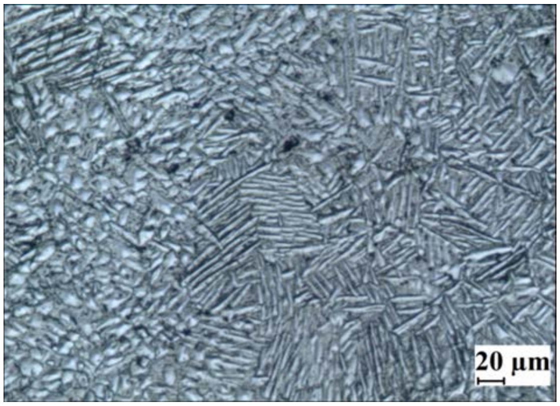

Fig. 4 The microstructure of specimen 2S.

Figure 5 shows the microstructure of the specimen 3S which was subjected to solution treatment at 950^{o}C. It is a lamellar microstructure, with average of lamellae's size of 14.79 µm, containing dispersion of many initiation sites for fine equiaxed α-phase. The average size of these sites is about 17.87 µm that appear clearly which are getting growth later to reach to 50.04 µm after annealing process (600^{o}C, 4h) to form bi-modal microstructure that offered by (3SA) specimen as displayed in Figure 6. The average lamellae size of this microstructure is 16.21 µm. It is observed by comparing of Figures 4 and 6 that varying the temperatures of solution treatment from 900^{o}C for 2SA specimen and 950^{o}C for 3SA leads to increase in the relative volume fraction of equiaxed α-phase.

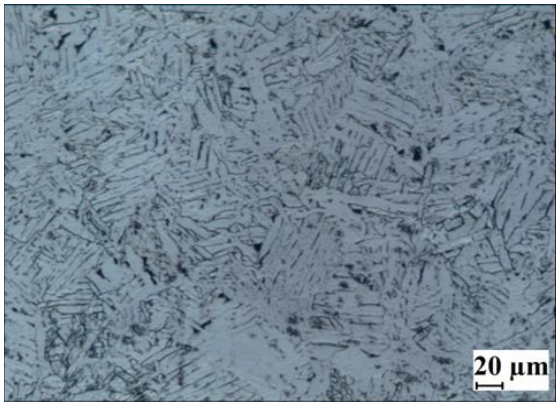

Fig. 5 The microstructure of specimen 3S.

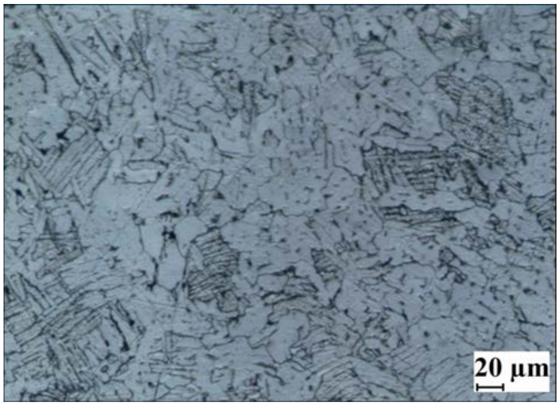

Fig. 6 The microstructure of specimen 3SA.

Figures 7 and 8 are micrographs of the resultant microstructures of specimens (4S) and (4SA) respectively, where the former subjected to solution treatment (1000^{o}C, 1h) only, while the latter followed by annealing (600^{o}C, 4h). The solution treatment has been performed at (1000^{o}C) just above the β-transus temperature (995^{o}C) that yielded to re-produce the lamellar structure with finer lamellae (6.2µm) compared to the initial microstructure whose average of lamellae size is 10.78 µm (Figure 2). The latter microstructure (Figure 8) shows lamellar structure with 8.86 µm of average lamellae size. The annealing process led to increase of lamellae size with keeping the same pattern of the microstructure.

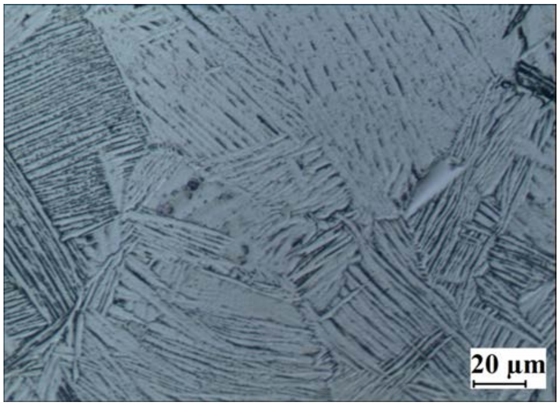

Fig. 7 The microstructure of specimen 4S.

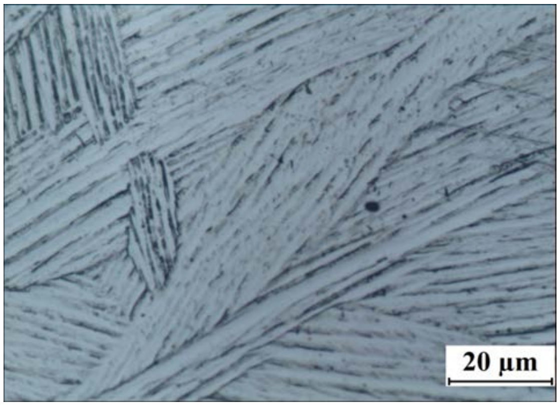

Fig. 8 The microstructure of specimen 4SA.

4. Conclusions

The heat treatment is a successful metallurgical approach used to manipulate and control Ti-6Al-4V alloy’s microstructures. The lamellar microstructure can be converted easily to bi-modal microstructure by solution treatment at either temperature of 900 or 950°C that is just below the β-transus temperature (995°C) for 1 h, then followed by annealing at 600°C. Bi-modal structure evolves gradually through the heat treatment by initiation of nucleation sites of fine equiaxed α-phase prematurely from lamellar structure at solution treatment stage. These sites develop and grow progressively to form entire equiaxed α-grains at the annealing stage. The annealing process is obviously responsible for the growth of both equiaxed and lamellae of α-phase. The relative volume fractions of equiaxed α-grain increase as the solution treatment increase from 900 to 950°C when followed with same annealing conditions. Lamellae size of α-phase is also solution treatment temperature dependent, where it increases to reach its average to 11.26 μm and 14.79 μm when Ti-6Al-4V alloy subjected to 900°C and 950°C respectively. Fine lamellar microstructure can be re-produced distinctly from bi-modal structure by heating the alloy just above the β-transus temperature.

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