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Influence of microstructure features on wear behavior of Ti-6Al4V alloy

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Abstract

The transition from mild to severe wear mechanism of Ti-6Al4V alloy was investigated. Microstructure and wear micro-mechanisms were also investigated. The as-cast samples were subjected to hot swaging at 900°C, followed by two separate solution treatments on the swaged samples. The first treatment was applied at a temperature of 850 °C (below the β-transus temperature) for getting a bimodal structure (α+β), while the second treatment was performed at 1050 °C (above the β-transus) for getting a lamellar structure (β). The solution-treated lamellar structure resulted in an ultimate strength of 1335 MPa and a hardness of 440 HV_{20} which are significantly superior to the bimodal structure. The wear behavior of the studied Ti64 alloy was investigated at different sliding speeds in the range of 0.5 to 2.5 m/s with 0.5 m/s interval. The transition from mild to severe wear mechanism was obtained at 1.5 m/s. The lowest wear rate was reported for the samples solution treated at 1050 °C due to their fine lamellae (α+β) structure and the high hardness. SEM was used to evaluate the worn surfaces of some samples to determine the wear micro-mechanisms.

Keywords: Ti-6Al4V; Solution treatment; Microstructure; Wear; Micro-mechanisms.

1. Introduction

Three types of titanium alloys are classified based on the composition of the alloy constituents as well as the phases existing at ambient temperature. These alloy types include α and near-α alloys, α+β alloys, and β-alloys [1-3]. At ambient temperature, α+β titanium alloys consist of hexagonal α-phase and body-centered cubic β-phase [4]. The dual-phase (α+β) Ti-6Al4V alloy is the most extensively used titanium alloy today, accounting for more than half of all titanium components. [5, 6]. It is extensively used in manufacturing some components in aerospace and automotive applications, due to its good combination of tensile properties, fatigue strength, and fracture toughness [7]. During applications of such alloys, titanium structures are often subjected to shear stress [8]. One of the main elements regulating both tensile and wear properties of titanium alloy is its microstructure [9]. The effect of cooling rate on phase transformation of the phases existing in the structure affects the characteristics of α+β titanium alloys. At a high cooling rate (water quenching) from temperatures above T_β (β-transus temperature), martensitic reaction can happen [10]. At a low cooling rate (air cooling), α-phase will be formed at grain boundaries. At moderate cooling rates, the shape of the α-phase will be changed dramatically [11, 12].

Many researchers have studied the tribological characteristics of α and α+β titanium alloys thoroughly [13, 14]. When sliding against other materials, these Ti-alloys have insufficient tribological performance due to their high friction coefficients, severe adhesive wear with a strong tendency to seize, and low abrasion resistance [15]. Because of their low work hardening coefficient, low shear strength, and inadequate protection provided by their thin and brittle surface oxides, titanium alloys are known to have poor wear resistance [16, 17]. However, the creation of tribologically protective oxide layers has been shown to improve wear under particular sliding conditions (load, speed, and temperature). Hence, the usage of titanium in friction parts is problematic. Budinski [18] studied the tribological characteristics of titanium alloys extensively and concluded that Ti6Al4V had low abrasion resistance. Surface hardening treatments can be applied over titanium surface components for improving the wear resistance; however, they often compromise the fatigue strength. Full hardening can on the other hand enhance both fatigue strength and wear resistance [19].

Due to the discrepancy in the wear results for the Ti-6Al4V alloy, this work aims at studying the effect of solution treatment temperature on Ti-6Al4V samples either above or below beta transus temperature (T_β) on microstructure feature and consequently on wear behavior. The wear micro-mechanisms were also determined by examining the samples' worn surfaces using scanning electron microscopy (SEM).

2. Experimental work

Samples with a chemical analysis of Ti-6.3Al-4.17V-0.16Fe-0.02C-0.13O-0.013N-0.0052H were cast in a vacuum induction furnace as rods with a diameter of 30 mm and 300 mm long. 2.5 mm was removed from the surface of the cast rods to reduce residual stress caused by the casting process. The cast rods were dimensionally finalized into a diameter of 25 mm and a length of 250 mm, which were adequate for the hot swaging process. Swaging was used to reduce the diameter of the cast rods from 25 to 9 mm in 11 steps at 900 °C.

Different types of microstructures were obtained by using different techniques of solution treatments. The samples were divided into two batches for solution treatment (ST) and aging (A) processes. The first batch was solution treated at 1050 °C for 1 hr (above T_β, where T_β for the studied alloy was 988 °C) and then water quenched. While the second batch was solution treated at 850 °C for 1 hr (below T_β) and quenched also in water. All samples were also aged at 500 °C for 8 hrs and then air-cooled.

The analysis of the different microstructures after casting, swaging and solution treatment was achieved using SEM. The metallographic samples were therefore ground, polished, and etched according to the standard methods. To determine the β-grains size, the volume fraction of α-phase, as well as α-lamellae lath width, a micro-analysis of the microstructures, was carried out using a PC image analyzer.

The tensile properties of the investigated alloy with different microstructures were performed in accordance with ASTM E8. Tensile test was carried out on threaded cylindrical samples having a gauge length and a diameter of 30 and 6 mm, respectively. Pin-on-ring Tribometer testing machine was used for conducting adhesion wear tests. A stainless-steel ring with a 63 HRC surface hardness was used as a counterpart against a cylindrical test sample with 8 mm diameter and 12 mm length. The wear testing conditions were chosen as follows: 90 N applied force, various rotating speeds of 0.5, 1.0, 1.5, 2.0, and 2.5 m/s, and 30 minutes testing time. The wear test was done at ambient temperature in a dry environment. Before wear testing, the sample surface was ground and polished with an emery paper up to 2000 grit for getting a surface roughness within a range of 0.03 μm. The wear amount in each condition is the average wear rate for two samples. After testing, the worn surface of some selected samples was investigated using SEM for a better understanding of the wear behavior and also for determining the wear micro-mechanisms.

3. Results and discussions

3.1. Microstructure investigation

The as-cast samples of the investigated Ti-6Al-4V alloy exhibited a microstructure consisting of α+β, Fig. 1-a. It is considered a heterogeneous structure because it contains different large sizes of β-grains that ranged from 500 to 600 μm. The α-phase was located at the β-grain boundaries and also inside the β-grains. On the other hand, the swaged samples showed a very fine equiaxed α+β structure due to the high plastic deformation strain that occurred during the swaging process, Fig. 1-b. The β-grains size for the swaged equiaxed α+β structure was in the range of 40-50 μm.

The solution-treated samples revealed a microstructure that is dependent on the temperature of the solution treatment. The samples solution treated above T_β (1050 °C) showed lamellae structure, and the samples solution treated below T_β (850 °C) obtained a bimodal structure, Fig. 1 c,d. The bimodal structure of the samples treated at 850 °C revealed a distribution of interconnected equiaxed α-phases as well as lamella α+β colonies (transformed β). The overall volume fraction of the primary α-phase was in the range of 50%, and the average grain was within the range of 20 μm, Fig. 1-c. On the other side, the samples treated at 1050 °C showed a full lamellae microstructure.

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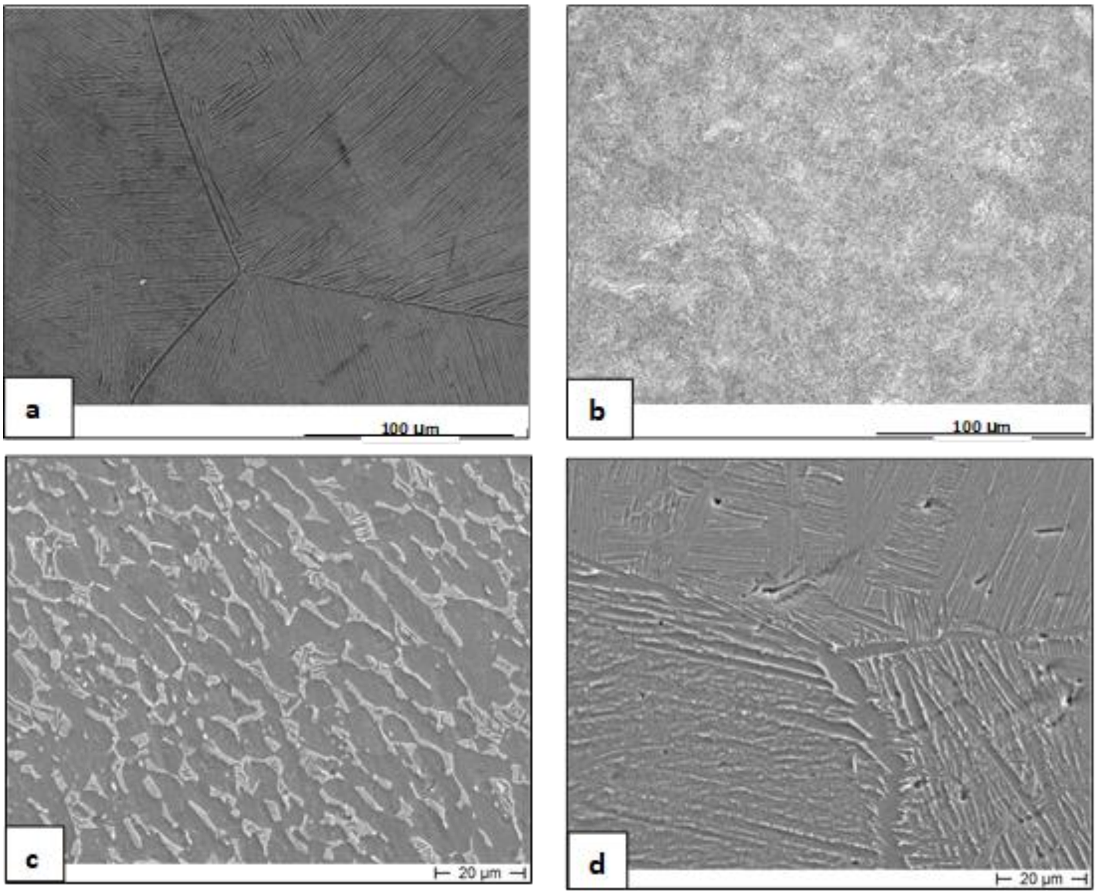

Fig. 1 Microstructure of the investigated Ti-6Al-4V alloy under different conditions (a- As-cast, b- Swaged, c- ST+A at 850 °C, d- ST+A at 1050 °C).

This microstructure had a colony size of 390 m (which is referred to as parallel orientated -lamellae) and an average prior-β grain size of 1 mm. The average α-lamellae lath width was in the range of 1-2 µm which was similar to the transformed β in bimodal microstructure, Fig. 1-d.

3.2. Mechanical properties

Heat treatment (HT) is normally used for controlling the mechanical properties of (α+β) Ti-6Al4V alloy. In such a case, the mechanical properties are correlated to the microstructure constituents. This has the benefit of allowing the production of components with a wide variety of mechanical properties. In this study, there are four types of microstructure features: i) as-cast large grains lamellae α+β structure, ii) very fine grains α+β swaged structure, iii) heat-treated (1050 °C) fine grains of lamellae α+β structure, and iv) heat-treated (850 °C) bimodal α+β structure. The correlation between these different microstructures and mechanical properties acting on hardness, yield and ultimate strengths, and wear resistance will be discussed.

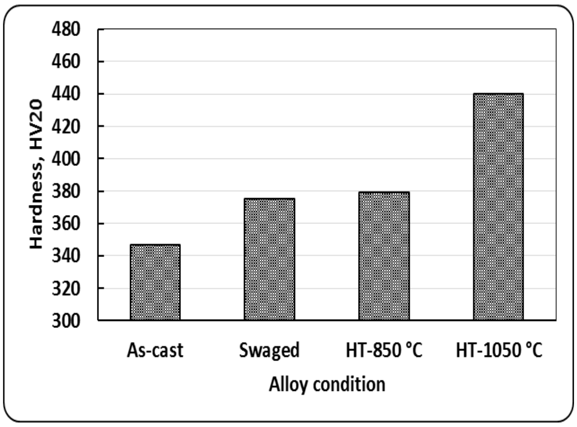

Fig. 2 The correlation between the investigated Ti-6Al4V alloy condition and hardness.

The correlation between alloy condition and hardness is shown in Fig. 2. The as-cast structure showed the lowest hardness of 347 HV_{20} due to its large β-grains and the heterogeneity existing in the α+β structure. By refining the as-cast α+β structure by applying a severe plastic deformation (hot swaging process), the hardness increased to 375 HV_{20}. Solution treatments and subsequent aging at 500 °C for 8 hrs result in a hardness increase compared to the as-cast and swaging conditions. The samples treated at 1050 °C showed the highest hardness value of 440 HV_{20} due to the fineness effect in the microstructure. However, the samples treated at 850 °C showed also higher hardness of the as-cast and swaged conditions due to the precipitation of the fine α-phase in the bimodal α+β structure. Jovanovic et al. [20] obtained in their study that the hardness of Ti-6Al-4V alloy could probably be increased due to precipitation of fine α-particles in α+β structure from the prior β-phase.

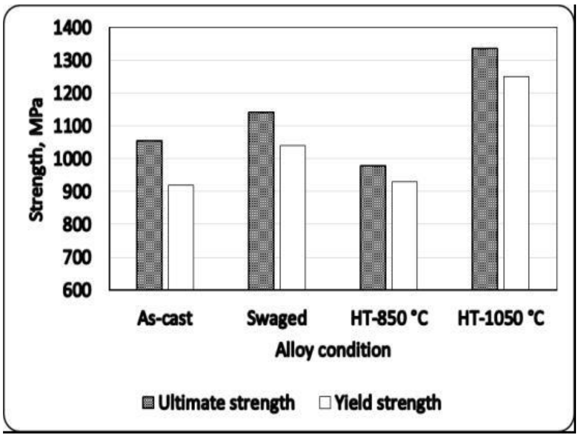

Fig. 3 The correlation between the investigated Ti-6Al4V alloy condition and strength.

The effect of microstructure features on yield and ultimate strengths is shown in Fig. 3. In this investigation, there are four different features of microstructure, where the as-cast structure obtained large grains of α+β microstructure as well as heterogeneous distribution of α+β microstructure. Of course, this heterogeneity of the α+β structure will produce low yield and ultimate strengths of 920 MPa and 1056 MPa for the as-cast structure, respectively. By decreasing the grain size of the α+β microstructure using hot swaging at 900 °C a high amount of dislocation density will be produced inside the grains which in turn will increase the values of yield and ultimate strengths. Hence, the ultimate strength for the swaged condition will be increased to 1141 MPa due to the fineness effect that happened in the microstructure as well as the existence of a high amount of dislocation density in the structure.

By applying solution treatment and aging processes of course the microstructure is changed and then the mechanical properties will be correlated to this microstructure change. The sample solution treated at 1050 °C with fine lamellae structure showed the highest values of both yield and ultimate strengths. Maximum strength of 1335 MPa was reported for the fine lamellae structure due to the homogeneity existing in the microstructure that happened by applying a solution treatment at 1050 °C and consequently aging at 500 °C for 8 hrs. Actually, such a treatment process decreases the dislocation density and increases the homogeneity in grain size which in turn improve the tensile strength in comparison to as-cast and swaged conditions. An increase in the ultimate strength of 279 MPa is noticed by applying a solution treatment (1050 °C) to the as-cast samples. This means, there is an increase in the strength of about 26.4%, or it may be said that there is an increase of more than a quarter value of the as-cast strength by applying this solution treatment above T_β. However, the sample solution treated at 850 °C, which has a bimodal structure, showed lower strength than the sample solution treated at 1050 °C. The yield and ultimate strengths of solution-treated samples at 850 °C are 930 MPa and 978 MPa, respectively.

It may be concluded here that the solution-treated lamellae structure produced higher strength compared to the bimodal one. This was obvious by comparing the strength values of solution-treated samples at 1050 °C, as-cast and swaged samples that have lamellae structure with different features, and the samples solution treated at 850 °C with bimodal structure. These observations correlating microstructure as well as properties of Ti-6Al4V alloy are in agreement with other studies [7, 21, 22].

3.3. Wear property of Ti-6Al-4V

Various strategies are used to improve the wear resistance of titanium alloys and permit their efficient usage as a sliding material. Heat treatment, composition adjustment surface modification, and matrix reinforcement with precipitates are different mechanisms for improving the wear resistance of materials [23].

In the present study, there is a trial to improve the tribological behavior of titanium alloy under investigation by using solution treatment either above or below the beta transus, followed by 8 hrs of aging at 500 °C for. The wear rate of the investigated Ti-

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6Al4V alloy as a function of sliding speed for various solution temperatures is depicted in Fig. 4. Duplicate tests were conducted for each condition, and the average wear rate of the tested samples are plotted. For all conditions, the calculated wear rate showed that wear rate increased with increasing sliding speed. Alam et al. [24] found that raising the sliding speed to 500 rpm increased the wear rate under a constant load of 45 N.

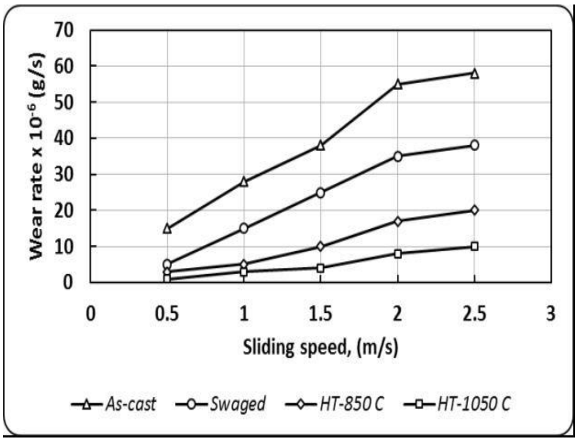

Fig. 4 Wear rat of the studied Ti-6Al-4V alloy as a function of sliding speed.

The sliding wear mechanism of Ti-6Al-4V alloy is complex because it has a complex microstructure feature. The complexity of wear mechanism of such alloy is due to the oxide layer that formed during testing and adhered to and then transformed to the counter-face surface [15, 25]. This is obvious in Fig. 4, where the wear rate is increased gradually with increasing sliding speed from 0.5 to 2.5 m/s. Hence, with increasing the sliding speed the amount of transferring layer from the titanium sample to the rotating stainless-steel ring is increased. The microstructure feature and hardness are the key factors for determining the wear severity in each alloy condition. Archard's law states that the weight loss of a material is inversely related to its hardness value [26]. This means that the harder the material, the less weight loses. The hardness values of the Ti-6Al4V alloy examined in this study fluctuate significantly depending on the conditions, therefore the experimental sliding wear results are consistent with Archard's law. Because the as-cast sample has a large grain size (500-600 μm) and low hardness (347 HV_{20}), it is reported the highest wear rate when compared to the others. The treated samples at 1050 °C with fine grain size (390 μm) and high hardness (440 HV_{20}) had the lowest wear rate.

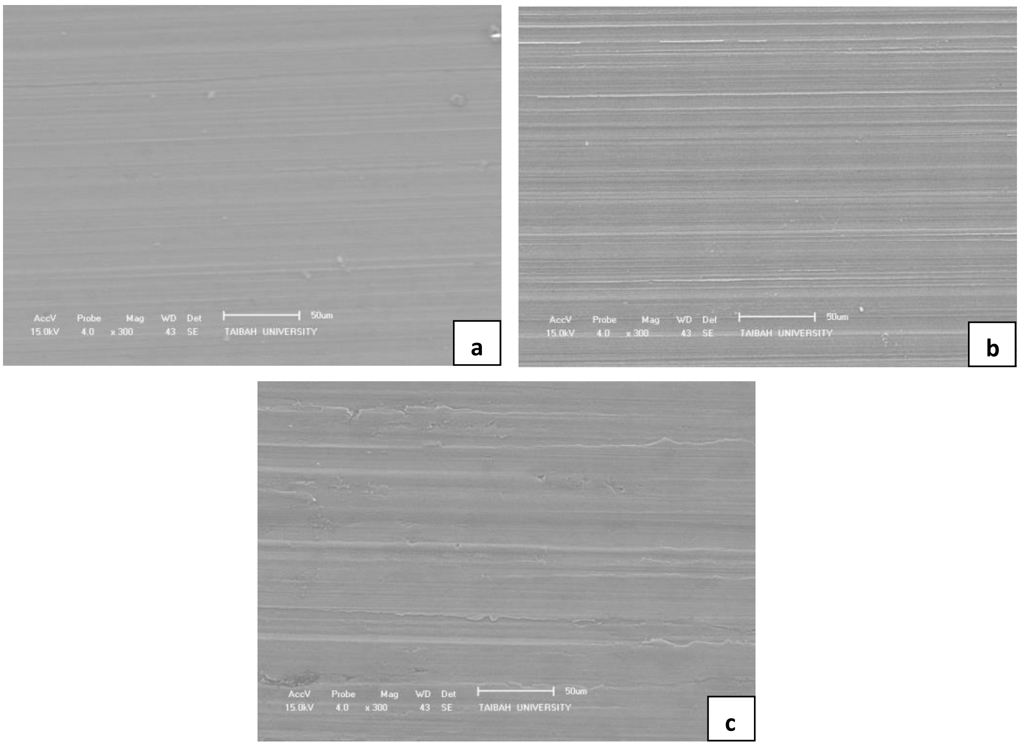

Fig. 5 SEM images of the wear track surfaces on Ti-6Al-4V samples at different sliding speeds: a- 0.5 m/s, b- 1.5 m/s, and c- 2 m/s.

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The heat-treated samples at 850 °C gave a moderate wear rate, however, they obtained the finest grain size (20 µm). Therefore, it may be concluded here that the microstructure grain size does not play an important role in determining the wear rate of Ti-6Al4V alloy. But hardness and microstructure feature (lamellae or bimodal) are considered the main factors determining the wear rate of such Ti-alloy. This finding was consistent with earlier studies [7, 9, 27, 28]. For all alloy conditions, there is a transition in wear rate with sliding speed at 1.5 m/s, where the wear rate can be classified into three different zones. Zone (I), where the wear rate is relatively increased with increasing the sliding speed from 0.5 to 1.5 m/s due to the first direct contact between the sample surface and the rotating ring. Therefore, the wear process in zone I can be defined as mild wear. Zone (II) from 1.5 to 2 m/s, where there was a high increase in wear rate due to increasing the inclination of the curve. Zone (II) can be characterized as a severe wear mechanism. Zone (III) from 2 to 2.5 m/s, where the wear rate is still severe but less severity compared to zone (II) due to existing of a good coinciding between the sample and the revolving ring. In both zones (II) & (III), the wear mechanism can be also defined as severe wear due to the high temperature generated as a result of increasing the sliding speed which will cause softening for the pin material and consequently increasing in wear rate.

The surface of wear tracks of some selected samples after being solution treated at 1050 °C because they showed the minimum wear rate at different sliding speeds (0.5, 1.5, and 2 m/s) was examined using SEM. All images in Fig. 5 for the wear track surfaces were taken at the same magnification (50 µm) in order to compare the wear mechanisms in each speed condition.

On the worn tracks, regardless of the sliding speed, evidence of ongoing sliding marks with grooves can be detected. Shallow grooves and scratching were observed on the samples surfaces in case of low sliding speed (0.5 m/s), Fig. 5 a. At medium sliding speed of 1.5 m/s, deeper sliding marks with small plastically distorted grooves can be found on wear tracks, Fig. 5 b. Ploughing or plastic deformation is observed to be higher at a sliding speed of 2 m/s due to increasing the shear stress between the rotating ring and the sample during wear test, Fig. 5 c. In addition, delamination wear mechanism can be seen with high sliding speed (2 m/s) due to increasing the plastic deformation over the worn surface [29].

4. Conclusions

- Hot swaging at 900°C breaks down as-cast coarse grains of α+β lamellar structure into a fine equiaxed structure.
- Solution treatment at 1050 °C produced a fine-β lamellar structure with an island, while 850 °C produced a bimodal structure.
- Maximum ultimate strength of 1335 MPa, hardness of 440 HV_{20}, and minimum wear rate were obtained for the sample solution treated at 1050 °C as a result of their fine lamellae structure.
- Regardless of the sliding speed, evidence of continuous sliding markings with plastically deformed grooves was found on the worn tracks. With increasing sliding speed, the plastic deformation over the worn surface increases.

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