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Research on Three-Roll Screw Rolling Process for Ti6Al4V Titanium Alloy Bar

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Abstract: The effects of both the microstructure and the original grain size on three-roll screw rolling process of Ti6Al4V titanium alloy bar were studied in the present work. The microstructure of Ti6Al4V titanium bar had a great influence on the mechanical properties of the rolling bar. When the original size was large, the grains were apparently refined but the microstructure was uneven. But for semi-finished titanium bar composed of fine equiaxed grains, the grains after rolling were fine and uniform. During the rolling process, the Ti6Al4V titanium alloy microstructure changed from equiaxed structure to the basket-weave one. After annealing at 800°C for 1.5 hours and then cooling in air, the average tensile strength decreased from 984 MPa to 964 MPa; while after annealing at 950°C for 1.5 hours and then cooling by water, and aging at 540°C for 6 hours then cooling by air, the average tensile strength increased from 979 MPa to 1107 MPa.

Keywords: Ti6Al4V, titanium bar, screw rolling process, microstructure and mechanical properties

Introduction

Ti6Al4V titanium alloy displays an excellent combination of high strength, corrosion resistance and low density. They play an important role in modern industry and are widely used for many applications, especially in the field of aeronautics and astronautics and biomaterial [1–3]. Ti6Al4V is the most common material in this class, which is well known for its desirable mechanical properties and corrosion resistance. The mechanical properties and microstructure characteristics of Ti6Al4V depend on the variables of the microstructure of semi-finished states, hot rolling processes and post-deformation heat treatments.

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To get large deformation by the rolling process, a three-roll screw rolling system has been used to control the deformation and microstructures different from the conventional two-roll system in the early 1970s [4]. The three-roll screw rolling system has the outstanding features of high efficiency, wide size range and flexible adjustment. As so far, it has been widely used in rolling carbon steel, structural steel, spring steel, bearing steel, high alloy tool steel, heat-resistant stainless steel, nickel-chromium alloy and other metal rods and tubes [5]. Screw rolling is a type of complex unconfined volume deformation process with cyclic loading, and the research of the rolling mechanism is still in the preliminary stage. Moreover, the microstructures and mechanical properties of rolling titanium bars could not be effectively controlled and the stability and the pass percent of the rolling bars also need to be further improved [6]. Therefore, in the present study, the effects of microstructure and original grain size on the mechanical properties of three-roll screw rolling process of Ti6Al4V alloy bar with the subsequent heat treatments were investigated.

Material and experimental procedures

Material

Ti6Al4V was received as hot forged bars with Φ 60 mm, its composition (in wt%) was of 6.37 aluminum, 4.16 vanadium, 0.17 oxygen, 0.19 iron, 0.005 carbon, 0.001 hydrogen, 0.004 nitrogen and balance titanium. The beta transus-temperature was approximated 985°C measured by thermal dilation method [7].

Experimental procedures

In this study, the effects of both microstructure and the original grain size on three-roll screw rolling process of Ti6Al4V titanium alloy bar were studied. Firstly, a part of the semi-finished Ti6Al4V material was pre-heated over the beta transus-temperature 985°C for 2 hours followed

by cooling in the furnace to get the different microstructure. The rolling experiments were carried out on the three-roll screw rolling system. The semi-finished Ti6Al4V titanium alloy bars were rolled from 60 mm in diameter to 20 mm with the total deformation of 89% at the temperature of 960°C with four times continuous deformation. The work principle of the three-roll screw system is shown in Figure 1(a), compared with the conventional two-roll system shown in Figure 1(b). During rolling, three rolls in the three-roll screw system keep clockwise rotating simultaneously, while the work piece in the middle of the three-roll screw system keeps counter-clockwise screwing and forward movement [8]. The experiment schemes of the study were shown in Table 1. The pre-heated materials were prepared for TS1-TS4 schemes, while the forged one was used for TS5-TS8 schemes. Rolling samples with size of $\Phi 20$ mm were subjected to two different post-rolling heat treatments. One was annealing at 800°C for 1.5 hours and then cooling in air, while the other was solution treated at 950°C for 1.5 hours and cooled in water following with aging at 540°C for 6 hours [9–11].

Figure 1: Diagram of the three-roll screw rolling system (a) and the conventional two-roll system (b).

Table 1: Specimen number and experiment schemes of Ti6Al4V rolling.

No. of specimen	Rolling temperature/°C	No. after tolling	Details of heat treatment	No. after heat treatment
TS1	1010°C	Z1	Solution and age	H1
TS2	1010°C	Z2	Annealing	H2
TS3	930°C	Z3	Solution and age	H3
TS4	930°C	Z4	Annealing	H4
TS5	1010°C	Z5	Solution and age	H5
TS6	1010°C	Z6	Annealing	H6
TS7	930°C	Z7	Solution and age	H7
TS8	930°C	Z8	Annealing	H8

Results and discussion

Pre-heated treatment before rolling

To study the effects of the microstructure and the original grain size on three-roll screw rolling process of Ti6Al4V titanium alloy bar, the semi-finished Ti6Al4V material with $\Phi 60$ mm was pre-heated. The $\Phi 60$ mm Ti6Al4V was forged from the titanium ingot. Because of the forging process, the grain of the forged material had been broken adequately, which was fine and uniform. The macrostructure of the material with pre-heated treatment at 1150°C for 2 hours then cooling in furnace was shown in Figure 2(a), which was 165°C higher than the transus temperature. For comparison, the macrostructure without pre-heated treatment was shown in Figure 2(b), which is in forging status. When both the kinetics and thermodynamics conditions of the Ti6Al4V grain growth were feasible, only beta phase could exist at 1150°C. The cooling speed was slow enough as the furnace temperature cools from 1150°C to room temperature, thus alpha phase precipitated from beta phase and equiaxed structure was obtained. The structure was uneven and the grain size was approximately 1 mm in diameter.

Microstructure of Ti6Al4V bar

The microstructure of the Ti6Al4V bar after rolling was shown in Figure 3. The rolling temperature of both Z1 and Z5 was 1010°C. The bar was heated to beta phase formation temperature, and the end-rolling temperature was between the alpha and beta phase region. During this process, the original grain boundary was broken and finally basket-weave structure was obtained. When the rolling temperature was above the transus temperature, the microstructure of Ti6Al4V titanium bar had no influences on that of the rolling bar.

The rolling temperature for Z3 and Z7 was 930°C, which was below the Ti6Al4V transus temperature. Before rolling, the grain size of pre-heat Ti6Al4V titanium bar was large, as is shown in Figure 2(a). After rolling, the microstructure was mainly consist of lamellar alpha phase, grain boundary alpha phase and beta transfer phase, displaying apparently uneven microstructure, which was shown in Figure 3(Z3). The microsturcture of fine structure distributed forged bar after rolling was alpha and beta phase. Apparently fine and uniform microstructure was obtained, as is shown in Figure 3(Z7).

Figure 2: The macrostructure of the semi-finished Ti6Al4V material before rolling with pre-heat treatment at 1150°C for 2 h (a), the forged status without pre-heat treatment (b).

Figure 3: The microstructure of Ti6Al4V rolling bar at temperature of 1010°C (Z1&Z3), 930°C (Z5&Z7).

The microstructures of Ti6Al4V rolling bar after heat treatment were illustrated in Figure 4. H5 and H6 showed the microstructures after rolling at temperature of 1010°C in beta region, it was clearly seen that the alpha structures were highly elongated. For H5 sample, the post-deformation heat treatment was carried at 950°C for 1.5 hours and then cooled in water, where the transfer time was less than 20s from annealing oven into water. After aging at 540°C for 6 hours, the alpha structures are broken to pieces, as is shown in Figure 4(H5). When the annealing treatments was applied at 800°C for 1.5 hours, fine lamellar structure was obtained, which is different from the low temperature aging Figure 4(H6).

H7 and H8 in Figure 4 showed that the equiaxed structure was obtained after hot rolling temperature at 930°C, which was between alpha and beta region temperature. After solution treated at 950°C for 1.5 hours and cooled by water and then aging at 540°C for 6 hours, equiaxed structure was acquired, where the alpha grains percentage was approximately 40 %. After annealing at 800°C for 1.5 hours, the alpha grains percentage is approximately 80 %. According to Figure 4, it was distinct that the alpha phase spheroidization could be promoted by solution and age heat treatments, compared with annealing. In order to get the uniform and steady microstructure of the rolling bar, the recommended prior rolling temperature was at 930°C.

Figure 4: The microstructure of Ti6Al4V rolling bar at rolling temperature 1010°C (H5&H6), 930°C (H7&H8) after heat treatment at 950°C for 1.5 h followed by WC then age at 540°C for 6 h followed by AC (H5&H7), 800°C for 1.5 h followed by AC (H6&H8).

Mechanical properties of Ti6Al4V bar

Tensile tests were performed to identify the mechanical properties of the alloy bar. The effect of the post deformation heat treatment on the mechanical properties of Ti6Al4V was investigated. Figure 5 shows the strength variation of the sample after different heat treatments

after rolling. It can be found that the average tensile strength increased from 979 MPa to 1107 MPa after solution treated at 950°C for 1.5 hours and aged at 540°C for 6 hours. When annealing at 800°C for 1.5 hours, the average tensile strength decreased from 984 MPa to 964 MPa. The area reduction rate was also studied here, which is shown in Figure 6. No obvious change was found here.

Figure 5: Tensile strength of the studied rolling bar before/after heat treatment.

Figure 6: Area reduction rate of the rolling bar before/after heat treatment.

According to Figures 5 and 6, it can be reached that the heat treatments had an important influence on the tensile property of Ti6Al4V bar, but had limited impact on the area reduction rate.

Conclusions

1. When the grains of Ti6Al4V semi-finished titanium bar were large, uneven structure was obtained after rolling, whereas fine original structure can gain uniform microstructure.
2. The optimum rolling temperature for Ti6Al4V is at 930°C, where uniform microstructure can be obtained for rolled bar.
3. Post heat treatments play an important role in the microstructure and mechanical properties. Solution and age treatments can enhance the alpha-phase spheroidization as well as improve the tensile strength from 979 MPa to 1107 MPa while an decrease in tensile strength from 984 MPa to 964 MPa through annealing was observed.

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