Influence of Isothermal Forging Temperature on Microstructure and Mechanical Properties of Ti-6Al-2Sn-2Zr-3Mo-1Cr-2Nb-Si Titanium Alloy

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Abstract. The influence of isothermal forging temperature on microstructure and mechanical properties of the Ti-6Al-2Sn-2Zr-3Mo-1Cr-2Nb-Si alloy was investigated with the constant strain rate of $1 \times 10^{-3} \text{s}^{-1}$ and deformation degree of 60%. The results indicate that the microstructure is mainly made up of coarse original $\beta$ grains at all temperatures, and a slight of fine equiaxed $\alpha$ phases exist in the microstructure only forged below the transus. The basket weave $\alpha$ lath distributed throughout the original $\beta$ grains uniformly. The mechanical properties of TC21 titanium alloy are not sensitive to the forging temperature. Compared to other temperatures, the combination property was optimized when forged at 970°C slightly.

Keywords: Ti-6Al-2Sn-2Zr-3Mo-1Cr-2Nb-Si alloy, isothermal forging, microstructure, mechanical properties

1. Introduction

Due to the low density, high specific strength, excellent corrosion and heating resistance as well as weldable characteristics etc., titanium alloys have been widely applied in the field of aircraft engine and structure part. With the change of the aircraft structure design concept, the high damage-tolerant titanium alloys are developed. Ti-6Al-4V (ELI), Ti-6-22-22S, and Ti-1023 are the frequently-used damage-tolerant titanium alloys at the present. Ti-6Al-2Sn-2Zr-3Mo-1Cr-2Nb-Si (TC21 alloy), a new high damage-tolerant alpha-beta titanium alloy, is a good choice of the aircraft structure materials owing to the perfect matching balance of the strength, the ductility, the fracture toughness and the crack propagation rate.10

Isothermal forging is a precisely controlled forging technology, in which the temperature of the billet is the same as that of the die consistently. Isothermal forging can overcome the chill of the forging die, bring down the metal flow stress, reduce the equipment tonnage, obtain the uniform deformation, and realize the near net-shape of the complex forgings. The bi-modal microstructure consisting of equiaxed primary $\alpha$ phase and basket weave $\alpha$ lath is obtained when the titanium alloy is forged at the temperature below the transus, and has advantages in terms of ductility because of the equiaxed $\alpha$ phase. On the contrary, Widmannstatten or basket weave microstructure will be gained when forged above the transus temperature, and these microstructures contributed to improving the strength and fracture toughness and reducing the crack propagation rate.10

In the present paper, the influence of the isothermal forging temperature near the transus on the microstructure and properties of TC21 titanium alloy is researched, aiming to supply experimental data for isothermal forging technology of TC21 titanium alloy heavy forging.

2. Materials and Experiment

The TC21 titanium alloy used in the experiment was rolled in $\alpha+\beta$ two-phase field. The original microstructure (Figure 1) consisted of equiaxed primary $\alpha$ phase and transformed $\beta$ matrix with equiaxed primary $\alpha$ phase distributed. The isothermal forging experiment was carried out in the four-column hydraulic press whose nominal pressure was 6300KN. The die for isothermal forging and the heating equipment for the die were self-made. The heating equipment for the sample was the SX-7-13 resistance-heated furnace. There were two types of samples for fracture toughness($40 \times 40 \times 60 \text{mm}$) and tensile properties($60 \times 30 \times 14 \text{mm}$) respectively. The soaking time of samples was calculated according to 0.8min/mm. The temperatures of 950°C, 970°C, 980°C (10°C below and 10°C above the transus respectively) were selected, and the constant strain rate of $1 \times 10^{-2} \text{s}^{-1}$ and the deformation degree of 60% were chosen. The heat treatment (900°C/1h, AC+590°C/4h, AC) was applied for each forging after forging. Finally the property tests were carried out and the microstructure and fracture surface morphology were observed using optical microscope and scanning electron microscope respectively.

![Figure 1. Micrographs of the as-received TC21 alloy](image)

3. Result and Analysis

3.1 Microstructure

Figure 2 shows the microstructures of the TC21 alloy after isothermal forging followed by heat treatment. As seen in Figure 2(a), the coarse original $\beta$ grains (the average diameter is about 450$\mu$m) can be
found in the microstructure after forged at 950°C (10°C below the transus). The β grain boundaries are very fine, even parts of them are discontinuous and not clear. It is noteworthy that a spot of fine equiaxed α phases distributed in the coarse original β grains uniformly, and this phenomenon can ascribe to the fact that the forging temperature below the transus. Figure 2(b) and (c) show the microstructures of the TC21 alloy isothermally forged at 970°C, 980°C, which are above the transus of 10°C, 20°C respectively. Due to the forging temperatures beyond the transus, the equiaxed α phases completely disappear and the original β grain boundaries become clear. The size of the original β grains increases with the increasing of the isothermal forging temperature, and the average diameters reach to about 540μm and 600μm, respectively. Theoretically, the equiaxed α phases will restrain the growth of the β grains, and the grain size below the transus is far less than that above the transus. But the size of the grains at 950°C is large in this paper. The higher forging temperature led to this phenomenon. The forging temperature was so close to the transus that the quantity of equiaxed α phases was very little, and the resistance of grain growth was reduced.

Figure 2. The coarse original β grains isothermally forged at different temperatures followed by heat treatment (a)950°C; (b)970°C; (c)980°C

Figure 3(a), (b) and (c) give the details in the original β grains of TC21 alloy after isothermally forging at 950°C, 970°C, 980°C respectively. After isothermal forging at different temperatures followed by heat treatment, the basketweave microstructure was caused in the β grains. After forging at 950°C, there are a spot of equiaxed α phases (with the average diameter smaller than 10μm) existing in the matrix of basketweave microstructure, while at 970°C and 980°C, there are no equiaxed α phases. The size, especially the width of secondary α phases forged at 950°C, is similar with that at 970°C and larger than that at 980°C.

Figure 3. The basketweave microstructure in the β grains (a)950°C; (b)970°C; (c)980°C

3.2 Mechanical Properties

Table 1 shows the room temperature mechanical properties of TC21 forgings. According to the table, little change of the mechanical properties of TC21 happens with the change of the forging temperatures.

Table 1. The fracture toughness of the TC21 titanium alloy isothermally forged at different temperatures followed by heat treatment

<table>
<thead>
<tr>
<th>Forging temperature T/°C</th>
<th>Tensile strength σ₀/MPa</th>
<th>Yield strength σ₈/MPa</th>
<th>Elongation δ/%</th>
<th>Percentage reduction of area ψ/%</th>
<th>Fracture toughness KIC/MPa·m½</th>
</tr>
</thead>
<tbody>
<tr>
<td>950</td>
<td>1255</td>
<td>1195</td>
<td>8.5</td>
<td>28, 75</td>
<td>75.1</td>
</tr>
<tr>
<td>970</td>
<td>1240</td>
<td>1170</td>
<td>9.5</td>
<td>27.75</td>
<td>75.1</td>
</tr>
<tr>
<td>980</td>
<td>1235</td>
<td>1145</td>
<td>8.5</td>
<td>20.75</td>
<td>72.5</td>
</tr>
<tr>
<td>Technical requirement</td>
<td>≥1100</td>
<td>≥1000</td>
<td>≥8.0</td>
<td>≥15.0</td>
<td>≥70.0</td>
</tr>
</tbody>
</table>

The mechanical properties of titanium alloy are determined by the microstructure, so the change of the mechanical properties can be explained by the microstructure evolution. The microstructures of the titanium alloys are divided into four basic types; the equiaxed microstructure, the bi-modal one, the bas-

ketweave one and the Widmannstatten one. The room temperature ductility of the equiaxed and bi-modal microstructures is larger than that of the basketweave and Widmannstatten microstructures, however, the room temperature strength and fracture toughness of the equiaxed and bi-modal microstructures are lower than those of the basketweave and microstructures, normally. The microstructures under three different forging temperatures in this experiment mainly consist of the coarse original β grains, in which is the basketweave microstructure, as well as few grain boundary α phases (equiaxed α phases for 950°C). But the equiaxed α phases are so few that little influence on the mechanical properties can be caused.

Figure 4 shows that the major routes through which the crack propagate in the basketweave microstructure. It can be seen that the cracks were either along the secondary α phases or across them with the equal opportunity. Therefore, the fracture toughness is mainly related to the basketweave microstructure. The test results of the fracture toughness can be explained by the thickness of the secondary α phases. The thickness of the secondary α phases at 950°C, which is similar with that at 970°C, is larger than that at 980°C. The thicker the secondary α phases which are crossed by crack, the more energy will be consumed. So the fracture toughness of the TC21 alloy with the thicker secondary α phases at 950°C and 970°C is higher than that at 980°C.

![Figure 4. The expanding route of the crack in the fracture toughness sample of the TC21 alloy isothermally forged at 950°C](image)

Figure 5 gives the SEM image of the fracture surface of the samples after fracture toughness test. The curve marked in the image is the stretch zone, whose width is linear with the fracture toughness. The left of the stretch zone is the prefabrication fatigue crack zone and the right is the plastic fracture zone. According to the dimples and tear ridges in the plastic fracture zone, it can be concluded that the fracture mechanism is the hybrid ductile rupture. The same results are found in other forging temperatures.

As seen in Table 1, there is little change on the tensile properties of TC21 alloy at different forging temperatures. The strength index, including tensile strength and yield strength, slightly decreases with the increase of the forging temperature. Even so, the values are still far higher than that of the technical requirements. And the same tendency can be found in the percentage reduction of area. The values of the elongation are very small, only larger than the technical requirement by 6% (950°C, 980°C) and 19% (970°C), respectively. The results maybe attributed to the similar microstructures under different forging temperatures. To sum up, after isothermal forging at 950°C, 970°C and 980°C, the mechanical properties of the TC21 titanium alloy satisfy the mechanical requirement. The better combination property can be obtained when forged at 970°C.

4. Conclusions

Based on the discussion above, the following conclusions can be obtained:

(1) Under all the three forging temperatures, the coarse original β grains, in which is the basketweave microstructure, can be found in the microstructure, and the size of the β grains increases with the increasing of the isothermal forging temperature. The size, especially the width of secondary α phases in the basketweave microstructure forged at 950°C, is similar with that at 970°C and larger than that at 980°C. Moreover, there are few of equiaxed α phases in the microstructure at 950°C.

(2) The mechanical properties of TC21 titanium alloys have little change with the change of isothermal forging temperatures near the transus. The tensile strength, yield strength and percentage reduction of area, a little drop with the increase of forging temperatures, are far larger than the technical requirements. The elongation and fracture toughness just satisfy the technical requirements. Compared to other temperatures, the combination property isothermally forged at 970°C is better.

REFERENCES


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