Ultrasonic velocity variation of Ti6Al4V Ti-alloy bars under conventional forging combined with triple heat treatment

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Abstract: In this paper, the microstructure evolution and ultrasonic velocity variation of Ti6Al4V Ti-alloy bars under different conventional forging deformation degrees and triple heat treatment were investigated, it was found that the the orientation of microstructure is the main factor influencing the ultrasonic velocity. Meanwhile, taking the ultrasonic velocity as target, the ultrasonic velocity variation under given conventional forging process combined with different triple heat treatment conditions (heating temperatures, holding time) were revealed, it was found that the α-β phase ratio, the volume fraction and morphology of equiaxed α_p and lamellar α_s are also influencing the ultrasonic velocity.

Keywords: Ti6Al4V Ti-alloy, Conventional forging, Triple heat treatment, Ultrasonic velocity

1. Introduction

Ti6Al4V alloy is a typical (α+β) titanium alloy, possessing excellent comprehensive properties such as high strength, high specific strength and good creep performance at high temperature, is extensively used to manufacture structural components in aerospace field, such as joints and frames[1]. As a conventional nondestructive testing method, ultrasonic testing applies a variety of physical and chemical phenomena to test without damaging the materials, so as to evaluate the physical properties, state and internal structure of the materials, and to determine whether or not they are qualified. By measuring the ultrasonic velocity of the material, the microstructure and properties of the material can be detected and evaluated[2-3].

Ultrasonic velocity is a basic physical quantity describing the propagation characteristics of ultrasonic wave in the medium, which is closely related to the material and the bonding force between material atoms and the atomic spacing. Meanwhile, to some extent, the properties of the material are determined by the microstructure of the alloy, so there is a certain relationship between the ultrasonic velocity value and the microstructure [4-7]. The purpose of the present paper is to investigate the microstructure evolution and ultrasonic velocity variation of Ti6Al4V Ti-alloy bars under different conventional forging deformation degrees, and to reveal the effect of triple heat treatment conditions on the ultrasonic velocity variation.

2. Materials and methods

2.1 Starting materials

The Ti6Al4V Ti-alloy used in the experiments was from Western Superconducting Technologies Co., Ltd with a transus β temperature of 985-990°C, its chemical composition is listed in Table 1. The microstructure of as-received material consists of above 60% equiaxed α_p and transformation β matrix, as shown in Fig. 1.

Table 1. Chemical composition of Ti6Al4V Ti-alloy

<table>
<thead>
<tr>
<th>Element</th>
<th>Al</th>
<th>V</th>
<th>C</th>
<th>Fe</th>
<th>O</th>
<th>N</th>
<th>H</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal composition/</td>
<td>6.50–6.60</td>
<td>4.28–4.32</td>
<td>&lt;0.08</td>
<td>0.15</td>
<td>&lt;0.12</td>
<td>&lt;0.05</td>
<td>0.001</td>
<td>Balance</td>
</tr>
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</table>
2.2 Experimental procedure

The bars with a diameter of 95.0mm were cut from the as-received bars. The conventional forging process was conducted on a GFM precision forging machine. The ultrasonic velocity was measured on a CL400 ultrasonic pulse reflector, as shown in Fig. 2.

In conventional forging process, forging deformation degree of 75% and 90% was considered. In subsequent triple heat treatment two heat treatment conditions (heating temperature, holding time) were considered, in detail, solution temperature of 950-970°C, ageing temperature of 500-600°C, ageing holding time of 1-3h. The ultrasonic velocity value was taken as evaluation index to investigate the effect of conventional forging deformation degree and heat treatment conditions, so as to reveal which factor affecting the ultrasonic velocity most.

The bars were heated to the conventional forging temperature at a heating rate of 10°C/min and held for 70 min to achieve thermal equilibrium and then forged. A section of 85.0mm specimen was cut off from the conventional forging bar, and then turned two end faces. The ultrasonic velocity was measured on the end faces with three times and the average values are taken, the measurement uncertainty on velocity value is 0.2%. The specimens were axially sectioned and prepared for metallographic observation by an optical microscope.

3. The microstructure evolution and ultrasonic velocity variation under different forging degrees.

Fig. 3 shows the microstructure of original Ti6Al4V Ti-alloy bar with a diameter of 95.0mm. It can be found that the transverse equiaxed $\alpha_p$ was small and fine, while the longitudinal microstructure has a certain orientation but was not obvious. Fig. 4 shows the microstructure in different directions of dia. 45.0mm and dia. 30.0mm bars after forging at 940 °C, the corresponding ultrasonic velocity was shown in Table 2. It was obvious that longitudinal microstructure of two specifications has processing orientation, which was growing stronger as the forging deformation degree increased from 75% of dia. 45.0mm to 90% of dia. 30.mm, the primary equiaxed $\alpha_p$ was elongated and even broken. Meanwhile, the longitudinal ultrasonic velocity decreased from 6120m/s of original dia. 95.0mm to 6080m/s of dia. 30.0mm, as shown in Fig. 4(a, c). On the contrary, the transverse ultrasonic velocity increased from 6230m/s of original dia. 95.0mm to 6305m/s of dia. 30.0mm. In addition, the difference of ultrasonic velocity between transverse and longitudinal directions increases as forging deformation degree
increasing. The original difference of dia. 95.0mm was 110m/s, however, the difference increased to 155m/s and 225m/s after the forging deformation degree increased to 75% and 90% respectively.

![Fig 3. Microstructure in different directions of the original dia.95mm bar: (a) L direction; (b) T direction](image)

![Fig 4. Microstructure of dia. 45.0mm and dia. 30.0mm bar in different directions after forging](image)

(a) dia. 45.0mm/L direction; (b) dia. 45.0mm/T direction; (c) dia. 30.0mm/L direction; (d) dia. 30.0mm/T direction

<table>
<thead>
<tr>
<th>Heating temperature</th>
<th>Diameter</th>
<th>Forging degrees</th>
<th>Transverse velocity</th>
<th>Longitudinal velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>mm</td>
<td>%</td>
<td>m/s</td>
<td>m/s</td>
</tr>
<tr>
<td>/</td>
<td>Φ95</td>
<td>0</td>
<td>6230</td>
<td>6120</td>
</tr>
<tr>
<td>940</td>
<td>Φ45</td>
<td>75</td>
<td>6255</td>
<td>6100</td>
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<tr>
<td></td>
<td>Φ30</td>
<td>90</td>
<td>6305</td>
<td>6080</td>
</tr>
</tbody>
</table>

In an infinite solid medium, the longitudinal ultrasonic velocity can be described by the following formula:

\[
v = \sqrt{\frac{E(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}}
\]

In the above formula, \(E\) is the elastic modulus (N/m\(^2\)), \(\rho\) is the medium density (kg/m\(^3\)), and \(\sigma\) is the poisson’s ratio. For solids, the \(\sigma\) is usually in the range of 0~0.5. Therefore, for Ti6Al4V Ti-alloy, when the composition was determined, the main cause for the ultrasonic velocity variation of forging bar was the change of elastic modulus caused by microstructure under different processes, while the elastic modulus was mainly affected by the plastic deformation, crystal structure and phase transformation. After large plastic deformation, obvious processing texture will emerge in metal materials. Due to the existence of processing texture, the properties of bars in different directions will be different. Meanwhile, there is a big difference in the elastic modulus between the longitudinal and transverse direction\(^8\), thus leading to a big difference in the ultrasonic velocity.

4. The microstructure evolution and ultrasonic velocity variation under triple heat treatment

Fig. 5 shows the microstructure of dia. 45.0mm forging bar after 730°C/1h, AC, 950°C/1h, AC+730°C/1h, AC and 950°C/1h, AC+730°C/1h, AC+550°C/2h, AC heat treatment, the corresponding ultrasonic velocity was shown in Table 3. It can be found that
after 730 °C/1h, AC common annealing, the longitudinal microstructure did not change obviously compared to the original thermal-forging state (R state). However, after 950 °C/1h, AC+730 °C/1h, AC two-step heat treatment, the ultrasonic velocity increased significantly, from 6110m/s in R state to 6165m/s. This was because the volume fraction of equiaxed α decreased significantly as well as the orientation due to the α→β phase transformation and recrystallization at 950 °C high temperature, as shown in Fig. 5(c). After 950 °C/1h, AC+730 °C/1h, AC+550 °C/2h, AC triple heat treatment, the ultrasonic velocity increase further to 6175m/s. The orientation of microstructure was barely changed, but the volume fraction and thickness of secondary lamellar α increased, as shown in Fig. 5(d). This was because in two-phase Ti-alloy, the atomic density of α-Ti (HCP) was higher than that of β-Ti (BCC, the atomic density was 0.68). Therefore, the elastic modulus of α phase was higher than that of β phase, the ultrasonic wave propagated faster in α phase.

![Fig 5. Microstructure of dia. 45.0mm bar after heated at different heat treatments: (a) Original microstructure; (b) 730 °C/1h, AC; (c) 950 °C/1h, AC+730 °C/1h, AC; (d) 950 °C/1h, AC+730 °C/1h, AC+550 °C/2h, AC](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Heat treatment</th>
<th>Longitudinal velocity / (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thermal-forging state (R state)</td>
<td>6110</td>
</tr>
<tr>
<td>2</td>
<td>730 °C/1h, AC</td>
<td>6115</td>
</tr>
<tr>
<td>3</td>
<td>950 °C/1h, AC+730 °C/1h, AC</td>
<td>6165</td>
</tr>
<tr>
<td>4</td>
<td>950 °C/1h, AC+730 °C/1h, AC+550 °C/2h, AC</td>
<td>6175</td>
</tr>
</tbody>
</table>

Table 3. Microstructure and velocity of dia. 45mm bar under different heat treatments

Apparently, given the conventional forging process, the ultrasonic velocity of Ti6Al4V forging bars varied significantly under different triple heat treatments. Therefore, it was necessary to study the microstructure evolution and ultrasonic velocity variation under different triple heat treatment conditions, so as to provide a reference for adjusting the ultrasonic velocity in different directions of forging bars.

4.1 The microstructure evolution and ultrasonic velocity variation under different solution temperatures.

Fig. 6 shows the microstructure of Ti6Al4V dia. 45.0mm forging bar heated at different solution temperatures of 950 °C, 960 °C and 970 °C and subsequent 730 °C/1h, AC+550 °C/2h, AC heat treatment, the corresponding ultrasonic velocity was 6175m/s, 6190m/s and 6208m/s respectively. As the solution temperature increasing from 950 °C to 960 °C, equiaxed α decreased transform into high-temperature β phase and its volume fraction will reduce. Meanwhile, the orientation of microstructure decreased because of recrystallization at high temperature, the ultrasonic increased from 6175m/s to 6190m/s. As the solution temperature increasing further, equiaxed α decreased faster, and there is basically no obvious orientation or processing texture, as shown in Fig. 6(c). However, for a given Ti-alloy the content of α stable element is certain, when the volume fraction of equiaxed α decreased, that of lamellar α will increase [9]. Thus the ultrasonic velocity increased further, from 6190m/s to 6208m/s.
4.2 The microstructure evolution and ultrasonic velocity variation under different ageing temperatures.

Fig. 7 shows the microstructure of dia. 45.0mm forging bar heated at 960°C/1h, AC+730°C/1h, AC and different ageing temperatures of 500°C, 550°C and 600°C heat treatment, the corresponding ultrasonic velocity was 6200m/s, 6190m/s and 6178m/s respectively. It can be found that as ageing temperature increasing, the orientation of microstructure changed little, but the volume fraction and thickness of secondary lamellar αₕ decreased significantly. As mentioned above, the ultrasonic wave propagated faster in α phase compared to β phase, the ultrasonic velocity decreased as the volume fraction of α phase decreased.

4.3 The microstructure evolution and ultrasonic velocity variation under different ageing holding time.

Fig. 8 shows the microstructure of dia. 45mm forging bar heated at 960°C/1h, AC+730°C/1h, AC and different ageing holding time of 1h, 2h and 3h heat treatment, the corresponding ultrasonic velocity was 6186m/s, 6190m/s and 6195m/s respectively. As the ageing holding time increasing, the lamellar αₕ precipitated from β transformed matrix gradually, leading to an increase in the volume fraction and thickness of αₕ, the ultrasonic velocity increased from 6186m/s to 6195m/s, but the extent of increase was modest.

5. Conclusion

(1) Due to the existence of processing orientation in conventional forging of Ti6Al4V Ti-alloy bar, there is a big difference in the ultrasonic velocity in the longitudinal and transverse direction, the longitudinal ultrasonic velocity decreased with the increase of forging deformation degree.

(2) The ultrasonic wave propagated faster in α phase compared to β phase, thus the ultrasonic velocity increased as the volume fraction and thickness of α phase increased.
The processing orientation of microstructure is the main factor influencing the ultrasonic velocity. As the solution temperature increasing, the volume fraction of equiaxed $\alpha$ decreased while that of lamellar $\alpha$ increased, the processing orientation decreased but the ultrasonic velocity increased significantly. With the decrease of ageing temperature and the increase of ageing holding time, the longitudinal ultrasonic velocity increased, but the effect of ageing temperature on ultrasonic velocity is more effective than that of ageing holding time.

The results would provide a guide to obtain a Ti-alloy bar with high-ultrasonic velocity through conventional forging combined with triple heat treatment process.

References


