MATEC Web of Conferences **321**, 12035 (2020)
The 14th World Conference on Titanium
https://doi.org/10.1051/matecconf/202032112035

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

Feixiao Han, Fengqi Hou, Xiaoping Sun, Zhixia Liu, Yonggang He, KaixuanWang

Western Superconducting Technologies Co., Ltd, Xi’an, 710018, China

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℃, 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

Element	Al	V	C	Fe	O	N	H	Ti
Nominal composition/%	6.50~6.60	4.28~4.32	＜0.08	0.15	＜0.12	＜0.05	0.001	Balance

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).

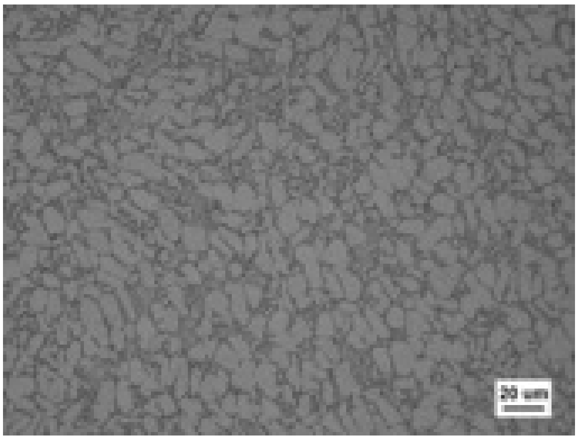

Fig 1. Original microstructure of Ti6Al4V Ti-alloy

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.

Fig 2. CL400 ultrasonic pulse reflector

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℃, ageing temperature of 500-600℃, 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℃/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 α_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 ℃, 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 α_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.

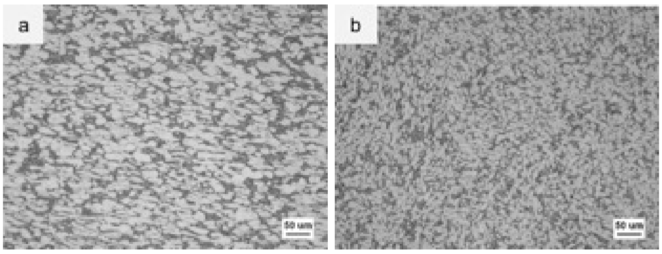

Fig 3. Microstructure in different directions of the original dia.95mm bar: (a) L direction; (b) T direction

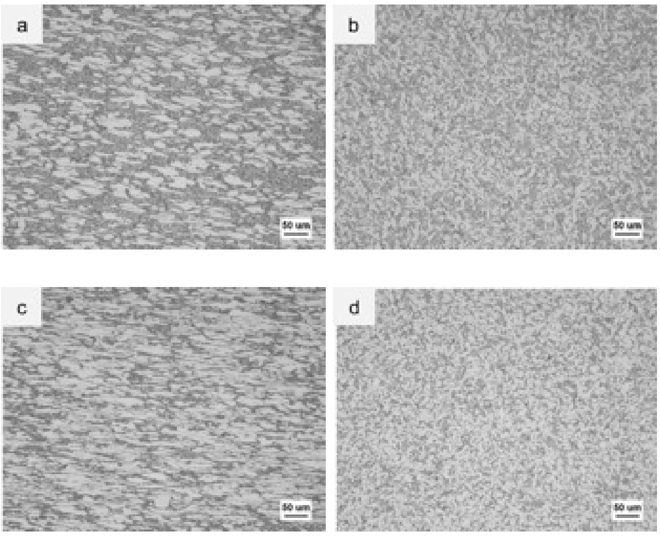

Fig 4. Microstructure of dia. 45.0mm and dia. 30.0mm bars in different directions after forging：

(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 2. Transverse and longitudinal velocity under different forging degrees

Heating temperature ℃	Diameter mm	Forging degrees %	Transverse velocity m/s	Longitudinal velocity m/s
/	Φ95	0	6230	6120
940	Φ45	75	6255	6100
	Φ30	90	6305	6080

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), ρ is the medium density (kg/m^3), and σ is the poisson's ratio. For solids, the σ 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℃/1h, AC, 950℃/1h, AC+730℃/1h, AC and 950℃/1h, AC+730℃/1h, AC+550℃/2h, AC heat treatment, the corresponding ultrasonic velocity was shown in Table 3. It can be found that after 730 ℃/1h, AC common annealing, the longitudinal microstructure did not change obviously compared to the original thermal-forging state (R state) , the orientation of microstructure and α-β ratio changed little as shown in Fig. 5(a, b). The ultrasonic velocity was consistent with the R state. However, after 950 ℃/1h, AC+730 ℃/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_p decreased significantly as well as the orientation due to the α→β phase transformation and recrystallization at 950 ℃ high temperature, as shown in Fig. 5(c). After 950 ℃/1h, AC+730 ℃/1h, AC+550 ℃/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_s 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.

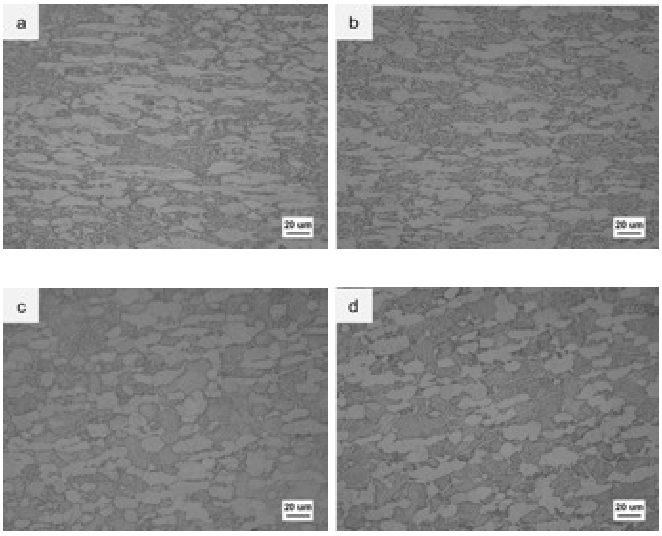

Fig 5. Microstructure of dia. 45.0mm bar after heated at different heat treatments：(a) Original microstructure;

(b) 730℃/1h,AC; (c) 950℃/1h,AC+730℃/1h,AC; (d) 950℃/1h,AC+730℃/1h,AC+550℃/2h,AC

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

No.	Heat treatment	Longitudinal velocity /(m/s)
1	Thermal-forging state (R state)	6110
2	730℃/1h,AC	6115
3	950℃/1h,AC+730℃/1h,AC	6165
4	950℃/1h,AC+730℃/1h,AC+550℃/2h,AC	6175

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℃,960℃and 970℃and subsequent 730℃/1h, AC+550℃/2h, AC heat treatment, the corresponding ultrasonic velocity was 6175m/s, 6190m/s and 6208m/s respectively. As the solution temperature increasing from 950 ℃ to 960 ℃, equiaxed α_p will 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_p 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_p decreased, that of lamellar α_s will increase [9]. Thus the ultrasonic velocity increased further, from 6190m/s to 6208m/s.

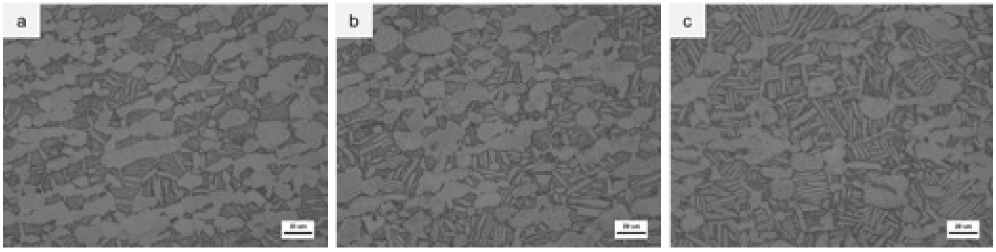

Fig 6. Microstructure after heated at different solution temperatures and 730℃/1h,AC+550℃/2h,AC：

(a)950℃/1h/AC; (b) 960℃/1h/AC; (c) 970℃/1h/AC

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℃/1h, AC+730℃/1h, AC and different ageing temperatures of 500℃,550℃and 600℃ 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 α_S 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.

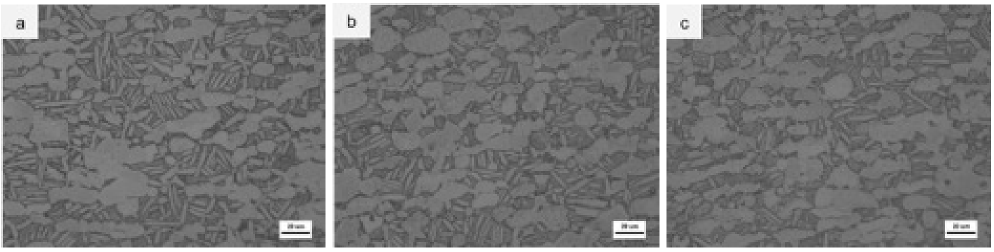

Fig 7. Microstructure after heated at 960℃/1h,AC+730℃/1h,AC and different ageing temperatures heat treatment: (a)500℃/2h/AC; (b) 550℃/2h/AC; (c) 600℃/2h/AC

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℃/1h, AC+730℃/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 α_S precipitated from β transformed matrix gradually, leading to an increase in the volume fraction and thickness of α_S, the ultrasonic velocity increased from 6186m/s to 6195m/s, but the extent of increase was modest.

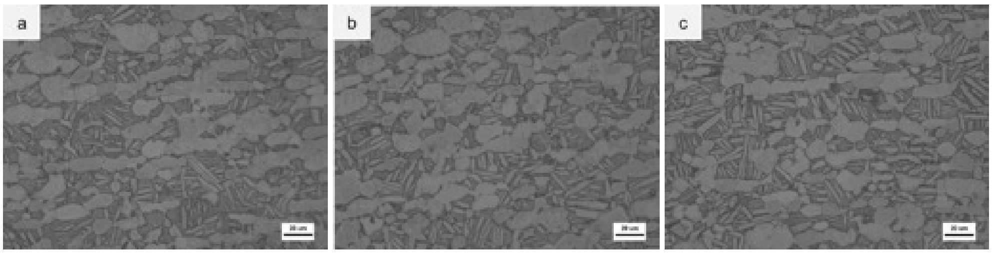

Fig 8. Microstructure after heated at 960℃/1h,AC+730℃/1h,AC and different ageing holding time heat treatment: (a) 550℃/1h/AC; (b) 550℃/2h/AC; (c) 550℃/3h/AC

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.

(3) The processing orientation of microstructure is the main factor influencing the ultrasonic velocity. As the solution temperature increasing, the volume fraction of equiaxed α_p decreased while that of lamellar α_s 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.

(4) 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

[1] Zhang Xiyan, Zhao Yongqing, Bai Chengguang. Titanium alloys and applications [M]. Beijing：Chemical industry press, 2005.

[2] Shi Yiwei. Analysis of standards and specifications on the ultrasonic inspection of titanium alloy bars [J]. Journal of Materials Enginerring, 6 (2002) 46-50.

[3] Su yong, Lin Weizheng. Measurements of material’s acoustic velocity and attenuation by signal analysis [J]. Journal of Building Materials, 4 (2001) 65-69.

[4] Xu Zhidong, Fan Ziliang. A phenomenological explanation of the variation of elastic modulus with temperature for metallic materials [J]. Journal of Southwest Jiaotong University, 2 (1993) 87-92.

[5] Hu Zongshi. Relationship of clutter and microstructure in titanium ultrasonic inspection [J]. Titanium Industry Progress, 6 (2002) 31-34.

[6] Wang Guohong. Ultrosonic studies of phase transitions of titanium and titanium alloys [J]. Rare Metals Letters, 10 (2002) 8-9.

[7] Shan S L, Shen J Y, Wang X Z. Transformation textures in a $\alpha+\beta$ titanium alloy thin sheet [J]. Materials Science and Engineering: A, 360 (2002) 58-64.

[8] Zhang Zhihui, Wang Xizhe, Shang Shunli, Bai Kewu, Shen Jianyun. Influence of processing on elastic modulus for a titanium alloy with high strength and high elastic modulus. [J]. Chinese journal of Rare Metals, 25 (2001) 19-22.

[9] Z.C.Sun, F.X.Han, H.L.Wu, H. Yang. Tri-modal microstructure evolution of TA15 Ti-alloy under conventional forging combined with given subsequent heat treatment. [J]. Journal of Materials Processing Technology, 229 (2016) 72-81.