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ARTICLE

Phase Precipitation Behavior of TB17 Titanium Alloy During Isothermal Aging Process

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Abstract: The precipitation phase evolution and the aging response of TB17 titanium alloy, a new titanium alloy with ultra-high strength and toughness, were studied by X-ray diffraction, scanning electron microscope, transmission electron microscope, and Vickers hardness tests during isothermal aging process. The results show that $\beta \rightarrow \beta+\omega$ phase transformation mainly happens at 350 °C, and the precipitated phase ω is the shape of fine granular. After aging treatment at 450 °C, the α phase is nucleated through the assistance nucleation of ω phase. The phase transformation of $\beta \rightarrow \beta+\alpha$ occurs at 550 and 650 °C and the α phase exhibits lamellar structure. However, there are two types of α phase precipitated after aging at 550 and 650 °C for long time: the Burgers α (Type 1α) phase which satisfies the Burgers orientation relationship and the Type 2α phase which does not satisfy the Burgers orientation relationship. The Type 2α phase is a twin crystal phase nucleated on the $\{10\bar{1}2\}$ twin plane inside the Burgers α phase. The aging characteristic of TB17 titanium alloy is similar to that of most β type titanium alloys. The aging response of TB17 titanium alloy is fast. The Vickers hardness of TB17 titanium alloy is increased firstly, reaching the maximum value at 450 °C, and then decreased with increasing the aging temperatures.

Key words: TB17 titanium alloy; isothermal aging; phase transformation; two types of α phase; aging response

Titanium alloys are widely used in aviation, aerospace, marine, and chemical industries due to their excellent properties, such as low density, high specific strength, and good corrosion resistance. In order to meet the design requirements of long life and high mass reduction for the new generation aircraft and high-performance aero-engine, the higher requirements are put forward for the lightweight materials with high strength[1-7]. Because β titanium alloys have more complex phase transformation characteristics, they can be strengthened by heat treatment due to the presence of more β-stabilized elements.

The near β titanium alloy has a very complicated phase transformation process during heat treatment, and its mechanical properties are closely related to the type, morphology, and size of the precipitated phase. Researches showed that the orthorhombic martensite α'' is formed in some β titanium alloys through isothermal aging or by stress-inducing, namely stress-induced martensite (SIM)[8,9]. While the athermal ω phase and isothermal ω phase can simultaneously form in some alloys, such as Ti-5Al-5Mo-5V-3Cr[10] and Ti-4.5Fe-6.8Mo-1.5Al[11]. The ω phase has different morphologies in different alloy systems. In the high mismatch alloy system, the morphology of ω phase is cuboidal in shape, such as Ti-Fe, Ti-V, and other binary alloy systems. While the ω phase is ellipsoidal in shape in the low mismatch alloys, such as Ti-Mo and Ti-Nb binary alloy systems[12]. As for titanium alloys, the uniform and fine α phase can significantly improve the mechanical properties of titanium alloys[13]. The ω phase is a metastable phase, which can assist the nucleation of transformation phase of α phase to acquire a more uniform, more diffused, and finer secondary α phase, and solve the problem of non-uniform precipitation of titanium alloy to improve the mechanical properties of the alloy[14-17]. The matching of strength and toughness is an important factor

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affecting the development of ultra-high strength and high toughness titanium alloys. The mechanical properties of near β titanium alloys depend on the volume fraction, morphology, size, and the distribution of α precipitates in the β matrix[18]. In order to achieve the matching of ultra-high strength and high toughness of titanium alloys (ultimate tensile strength UTS> 1400 MPa; plane fracture toughness>50 MPa·$m^{1/2}$), it is necessary to investigate the phase transformation behavior under different aging conditions of near β titanium alloys.

TB17 titanium alloy is a novel metastable β-type alloy, which can achieve superior mechanical properties after solution and aging treatment: larger elongation (increased by 7%), higher tensile strength (1350 MPa), and better fracture toughness (50 MPa·$m^{1/2}$)[19]. Wang et al[20,21] studied the phase transformation behavior of TB17 titanium alloy during isothermal aging, and analyzed the relationship between the morphology of the secondary α phase and the aging temperature/time in the single-phase region. However, the phase transformation behavior under different aging conditions is still indistinct. In this research, the phase transformation behavior of TB17 titanium alloy was investigated by X-ray diffraction (XRD), scanning electron microscope (SEM), transmission electron microscope (TEM), optical microscope (OM), and Vickers hardness tester, providing an effective theoretical basis for the development and application of TB17 alloy.

1 Experiment

The TB17 titanium alloy specimens had a nominal mass composition of Ti-4.5Al-6.5Mo-2Cr-2.6Nb-2Zr-1Sn with the size of Φ10 mm×15 mm. The raw ingots of TB17 alloy were prepared by vacuum arc melting. The β phase transformation temperature of the alloy was 845 °C, which was measured by the metallographic method[22]. The initial microstructure of the alloy is shown in Fig.1. It can be seen that a large amount of globular primary α phase and lamellar secondary α phase is uniformly distributed over the β matrix.

Solution and aging treatments were conducted in the air atmosphere, according to the schematic process shown in Fig. 2. The specimens were firstly solution-treated at 870 °C for 1 h, and then air-cooled to obtain the single β phase. The β-quenched specimens were continuously heated from room temperature to different temperatures (350, 450, 550, and 650 °C), and then water-quenched to retain the microstructures. The aging time was 1 min~50 h.

The heat-treated specimen was prepared by grinding and polishing for metallographic observation to ensure that the oxide layer was completely removed. The Kroll solution (volume ratio of HF:HNO_3:H_2O=1:2:7) was used for metallographic acid etching. TEM specimens were prepared by mechanical thinning, electrolytic double spray thinning, and finally twin jet electrochemical polishing at -30 °C in an electrolyte consisting of perchloric acid, methanol, and butanol with the volume ratio of 6: 34: 60. The Vickers hardness of the specimens after heat treatment was measured using an HXS-1000 digital electronic intelligent Vickers hardness tester. Each specimen was tested through 50 random points to obtain the average hardness value. The phase composition was determined by XRD analysis with Cu Kα radiation. The microstructure was observed by navo SEM 450 field emission scanning electron microscope (FE-SEM) and the JEM-2100 TEM at 200 kV. The size of the precipitated phase was measured by Image Pro 5.0 software.

2 Results and Discussion

2.1 Aging temperature and phase transformation

The XRD patterns of TB17 titanium alloy aged at 350 °C for different durations are shown in Fig. 3. The diffraction peaks of β phase are very sharp after solution treatment at 870 °C, indicating that the TB17 alloy consists of the single β phase. The intensity of diffraction peak of (211) β plane is the strongest, indicating that there is a certain preferred orientation of β grains. The peaks of β phase after aging for 2 h are still very sharp, and no other phases can be found. After aging treatment for 8 h, the width of diffraction peaks is significantly broadened, suggesting that new phases may be precipitated in these regions. It is difficult to distinguish the type of precipitation phases of TB17 titanium alloy aged at 350 °C by XRD, because the characteristic peaks of the new phases are similar to the peaks of the β phase. It is necessary to further analyze the precipitation phase of TB17 titanium alloy during the aging process at 350 °C.

Fig. 4 shows the TEM dark-field images and selected area electron diffraction (SAED) patterns of the corresponding area of TB17 titanium alloy after aging treatment at 350 °C for different durations. According to SAED patterns in Fig.4b and

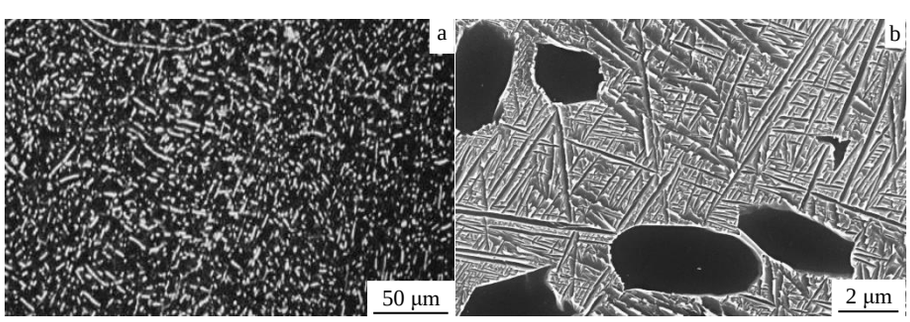

Fig.1 OM (a) and SEM (b) images of initial microstructures of TB17 titanium alloy

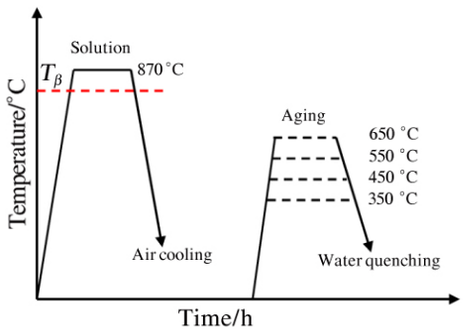

Fig.2 Schematic diagram of solution and aging treatments of TB17 titanium alloy

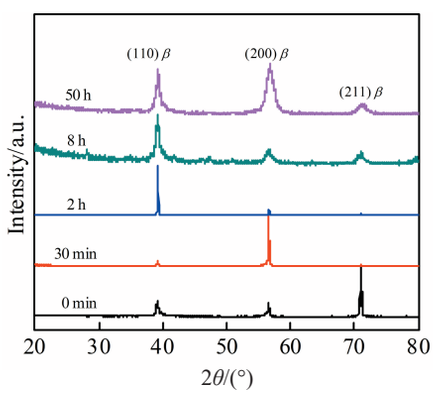

Fig.3 XRD patterns of TB17 titanium alloy after solution treatment at 870 °C and aging treatment at 350 °C for different durations

4d, it can be determined that there exists ω phase precipitation during isothermal aging at 350 °C, but no characteristic patterns of α phase can be detected. The characteristic patterns of ω phase appear at the position 1/3 and 2/3 of the way from the β diffraction spot, so it can be confirmed that only the ω phase is precipitated at 350 °C in TB17 titanium alloy. Because the amount of precipitation phase is small, the intensity of diffraction peak ω phase in TB17 alloy after aging treatment for 2 h is weak. It can be found that the dispersed fine granular ω phase is uniformly distributed in the β matrix (Fig.4a and 4c), and the size of the ω phase is less than 10 nm. Therefore, the phase transformation of TB17 titanium alloy after isothermal aging at 350 °C is $\beta \rightarrow \omega$ according to the results of TEM and XRD analyses.

As the aging temperature increases to 450 °C, the type of precipitation phase changes. According to XRD patterns in Fig. 5, the diffraction peaks of the β phase is very sharp with strong intensity after aging at 450 °C for 10 min, and no characteristic peak of the α phase appears. However, as the aging duration increases to 1 h, a weak diffraction peak of (100) α phase appears at 2θ=37°, and the diffraction peak of (110) β is significantly broadened. The intensity of the diffraction peaks of α phase continuously increases as the aging time is more than 4 h, and the diffraction peaks of the α phase are relatively wide, indicating that the size of α phase precipitated at 450 °C is small[23].

The TEM results show that the ω phase is precipitated in TB17 alloy after aging at 450 °C for 10 min (Fig.6b), and the morphology of ω phase is granular, as shown in Fig.6a. As the aging time increases to 4 h, the diffraction peaks of ω phase disappear, and those of the α phase appear at the position 1/2 of the way from the β phase, indicating that the ω phase is

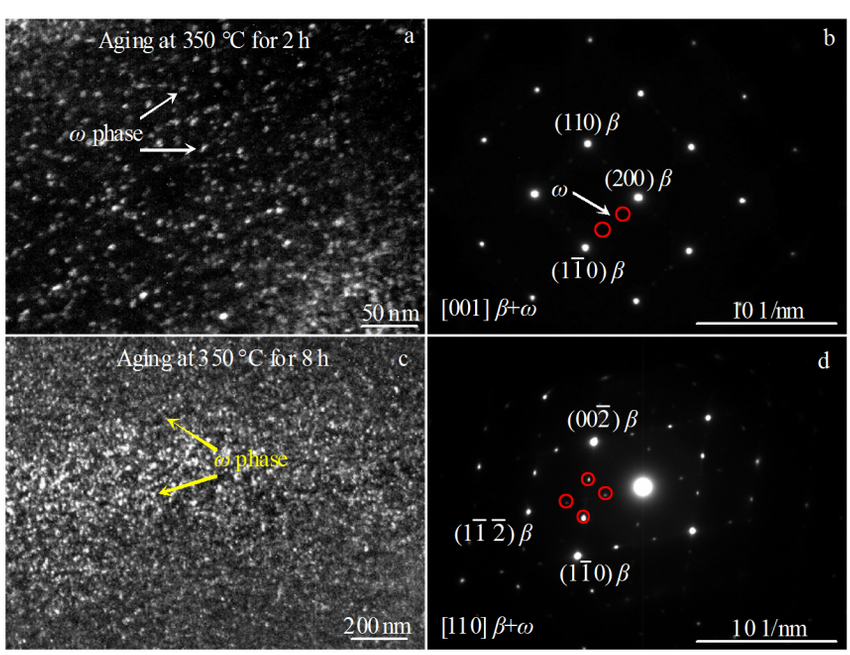

Fig.4 TEM dark-field image of ω phase (a) and SAED pattern along [001] β zone axis (b) of TB17 titanium alloys aged at 350 °C for 2 h; TEM dark-field image of ω phase (c) and SAED pattern along [110] β zone axis (d) of TB17 titanium alloys aged at 350 °C for 8 h

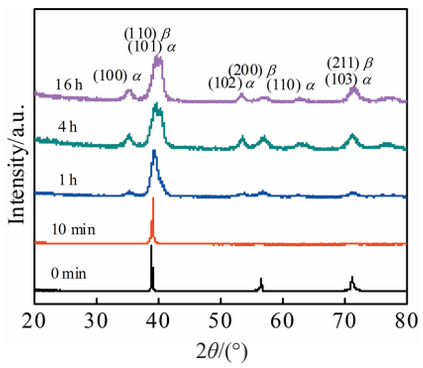

Fig.5 XRD patterns of TB17 titanium alloy after solution treatment at 870 °C and aging treatment at 450 °C for different durations

converted to the α phase as the aging duration increases (Fig. 6d). The morphology of the precipitated phase changes from granular to lamellar (Fig. 6c). According to the above analysis, the α phase is precipitated through the assistance of ω phase by nucleation at 450 °C[14], and the process of phase transformation is $\beta \rightarrow \beta+\omega \rightarrow \beta+\alpha$.

The XRD patterns of TB17 titanium alloy aged at 550 °C are shown in Fig. 7. It can be seen that the $\beta \rightarrow \alpha$ phase transformation mainly occurs at 550 °C. With prolonging the aging time, the intensity of the diffraction peaks of β phase becomes weaker, and the diffraction peaks of α phase appear and their intensity is gradually enhanced, indicating that the β phase is gradually transformed into α phase as the aging time increases.

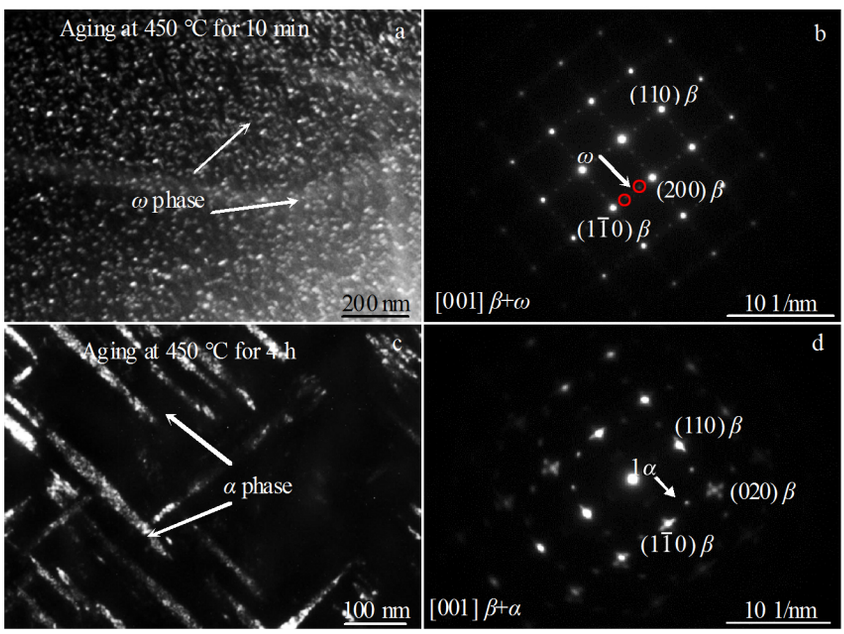

Fig.6 TEM dark-field image of ω phase (a) and SAED pattern along [001] β zone axis (b) of TB17 titanium alloys aged at 450 °C for 10 min; TEM dark-field image of α phase (c) and SAED pattern along [001] β zone axis (d) of TB17 titanium alloys aged at 450 °C for 4 h

Fig. 8 shows the TEM bright-field images and SAED patterns of TB17 titanium alloy after aging treatment at 550 °C for different durations. It can be found that after the short-time aging treatment, α phase is not completely precipitated, and the thickness of α phase layer is about 20 nm (Fig. 8a). According to the SAED pattern in Fig. 8b, a weak diffraction spot of α phase appears at 1/2 of the way from the diffraction pattern of β phase, indicating that the phase transformation of $\beta \rightarrow \beta+\alpha$ may occur at 550 °C. As the aging time increases to 4 h, the precipitated phase grows significantly, and the thickness of the α phase reaches about 80 nm (Fig. 8c). It is found that the SAED pattern of TB17 titanium alloy after aging at 550 °C for 4 h is more complicated than that of alloy aged for 3 min, and there are some additional diffraction spots in SAED pattern of α phase at 1/2 of the way from the diffraction spots of β phase (Fig. 8d). According to Ref. [24], these diffraction spots are regarded as the Type 2α phase which does not satisfy

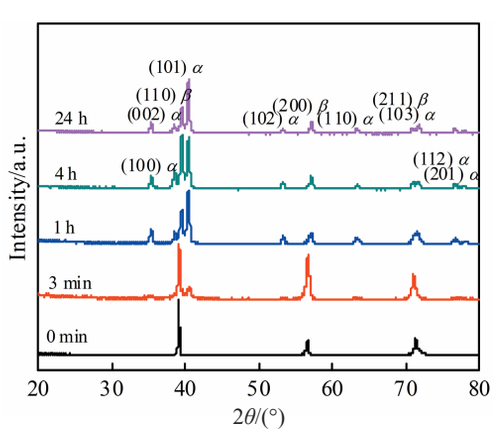

Fig.7 XRD patterns of TB17 titanium alloy after solution treatment at 870 °C and aging treatment at 550 °C for different durations

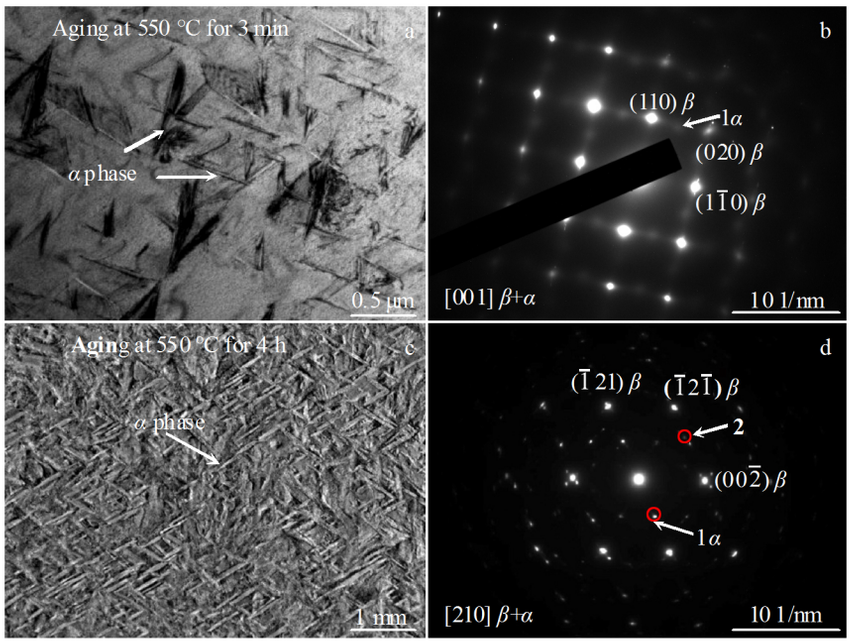

Fig.8 TEM bright-field image of α phase (a) and SAED pattern along [001] β zone axis (b) of TB17 titanium alloys aged at 550 °C for 3 min; TEM bright-field image of α phase (c) and SAED pattern along [210] β zone axis (d) of TB17 titanium alloys aged at 550 °C for 4 h

the Burgers orientation relationship.

The phase transformation behavior of TB17 titanium alloy aged at 650 °C is similar to that of alloy aged at 550 °C. The phase transformation of $\beta \rightarrow \alpha$ occurs, according to the XRD patterns in Fig. 9. The TEM bright-field images and SAED patterns of TB17 titanium alloy aged at 650 °C for different durations are shown in Fig. 10. It can be found that the Type 1α phase, which satisfies the Burgers orientation relationship, is precipitated mainly after aging at 650 °C for 10 min (Fig. 10b), and the α phase shows a coarse layer with the thickness of 150 nm (Fig. 10a). When the aging time increases to 8 h, the characteristic spots of the Type 2α phase can be found according to SAED pattern in Fig. 10c, and the size of the α phase has no obvious change (Fig. 10d).

Fig. 11 shows the effect of different aging temperatures on

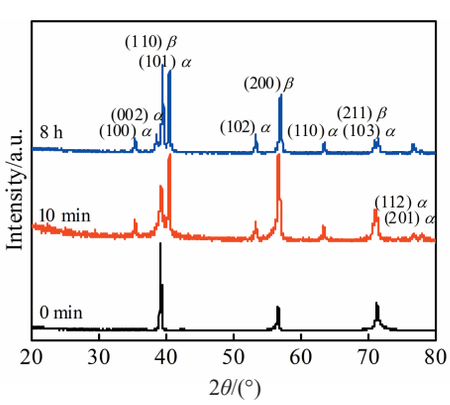

Fig.9 XRD patterns of TB17 titanium alloy after solution treatment at 870 °C and aging treatment at 650 °C for different durations

the morphologies of precipitated phases of TB17 titanium alloy. Three types of α phase can be observed, namely α_{GB}, α_{WGB}, and α_{WM}. The α_{GB} phase is the α precipitates in β/β grain boundaries; the α_{WGB} phase is the α Widmanstatten precipitates which originate from the β/β boundaries or from α_{GB} in parallel colonies; the α_{WM} phase is the α Widmanstatten precipitates in the intragranular area with a basketweave microstructure[25].

It can be seen that the aging temperature has a great influence on the precipitation position, morphology, and the size of the α phase. Continuous layer α_{GB} is precipitated along the β grain boundary and there is no α_{WGB} precipitation at 450 °C (Fig. 11a). As the aging temperature increases to 550 °C, the α_{WGB} phase is precipitated along the α_{GB} phase with a certain angle and continuously extends into the interior of β matrix, resulting in a colony structure. The length of the α_{WGB} phase increases until α_{WGB} phase contacts the α_{WM} phase (Fig. 11b). When the aging temperature further increases to 650 °C (Fig. 11c), the length of the α_{WGB} phase continues to increase, and the thickness of α_{WGB} phase is larger significantly.

The relationship between the lamella thickness of α phase and aging temperatures is shown in Fig. 12. The α phase of the TB17 titanium alloy precipitated at 450 °C is very fine with the lamella thickness of about 40 nm. The results of TEM analysis show that the α phase is precipitated through the assistance of ω phase by nucleation at 450 °C. This kind of precipitation can significantly improve the uniformity of the microstructure, and the dispersed fine α phase can significantly improve the mechanical strength of titanium alloy[9,26]. As the aging temperature increases to 550 °C, the lamella thickness of α phase increases to 80 nm. As the aging temperature further increases to 650 °C, the lamella thickness of

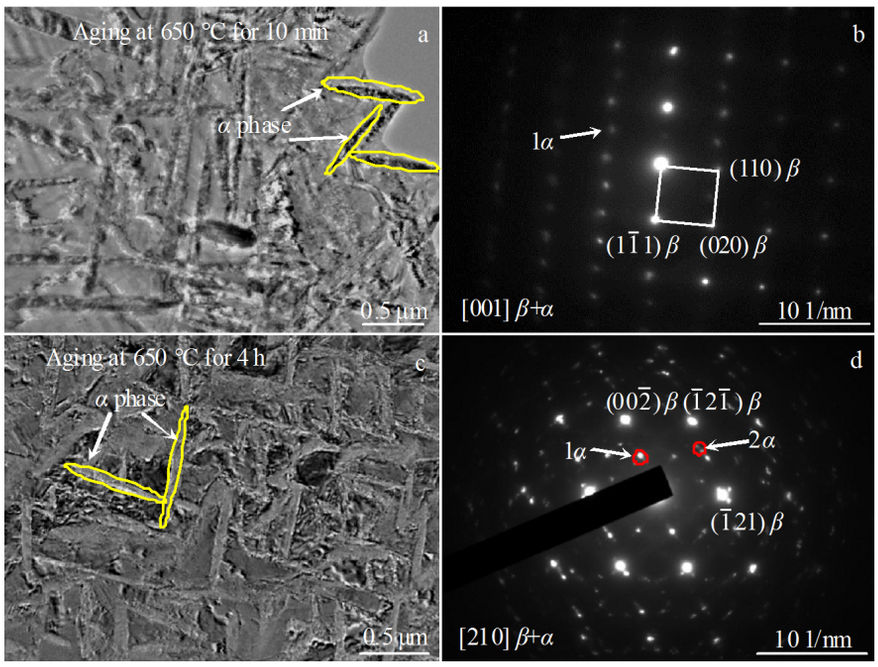

Fig.10 TEM bright-field images of α phase (a) and SAED pattern along [001] β zone axis (b) of TB17 titanium alloys aged at 650 °C for 10 min; TEM bright-field image of α phase (c) and SAED pattern along [210] β zone axis (d) of TB17 titanium alloys aged at 650 °C for 4 h

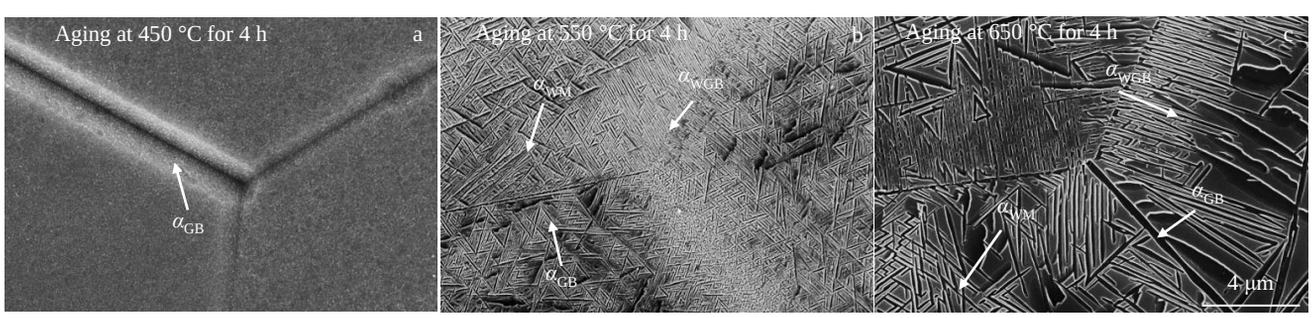

Fig.11 Microstructures of TB17 titanium alloy aged at different temperatures for 4 h: (a) 450 °C, (b) 550 °C, and (c) 650 °C

α phase further increases to 150 nm. It can be seen that the α phase is significantly coarsened with increasing the aging temperature.

According to the above results, the schematic process for the precipitation phases of TB17 alloy during solution and aging treatments is summarized in Fig. 13. The phase transformation process of TB17 titanium alloy can be divided into four fields according to different temperature ranges. During aging treatment at low temperature (Field 1: temperature <400 °C), the $\beta \rightarrow \beta+\omega$ phase transformation occurs in the TB17 titanium alloy, and the amount of ω phase is increased with prolonging the aging time. This is because the diffusion-controlled phase transformation process of $\beta \rightarrow \alpha$ is very slow when the aging temperature is too low. Therefore, the α phase cannot be formed. The $\beta \rightarrow \omega$ phase transformation is a non-diffusion phase transformation process, and the

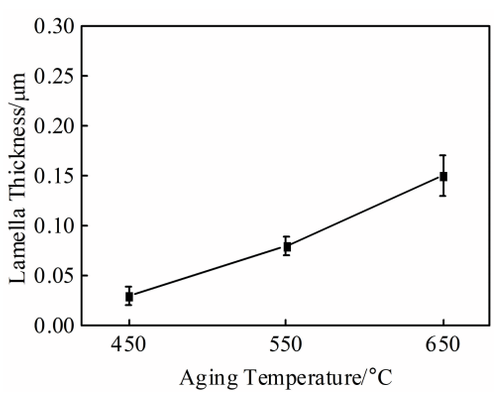

Fig.12 Relationship between lamella thickness of α phase and aging temperatures of TB17 alloy aged for 4 h

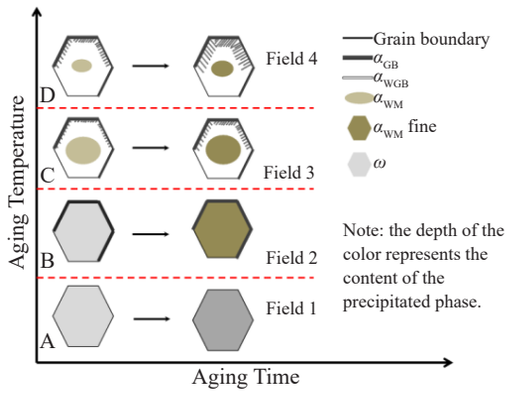

Fig.13 Schematic diagram of precipitation process of phases in TB17 alloy during solution and aging treatments

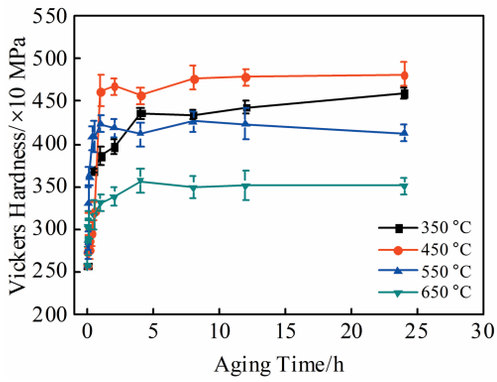

Fig.14 Vickers hardness of TB17 titanium alloys aged under different conditions

nucleation of ω phase requires only a short-range migration of atoms, so the ω phase is more easily formed at the low aging temperature[27]. The phase transformation of $\beta \rightarrow \beta+\omega \rightarrow \beta+\alpha$ occurs at the middle aging temperature (Field 2: 400~500 °C). The ω phase is precipitated at the beginning of aging and transformed into the α phase as the aging treatment proceeds, and the microstructure of alloys after aging at this condition is very fine and dispersed. During aging from the middle temperature to high temperature (Field 3: 500~600 °C), the phase transformation of $\beta \rightarrow \beta+\alpha$ occurs. The α_{GB} precipitation nucleates at the grain boundaries and grows into a continuous layer. The α_{WGB} precipitation nucleates near the α_{GB} sites and grows in lath shape towards the interior of β matrix, resulting in the formation of a colony structure. The α_{WGB} phase at the grain boundary continuously grows into the grain, while the α_{WM} phase in the grain continues to spread outward with increasing the aging time. The phase transformation of $\beta \rightarrow \beta+\alpha$ happens during aging at high temperature (Field 4: temperature>600 °C). The grain boundary as a "fast channel" for atom diffusion improves the enrichment of α-stabilized elements at the grain boundaries, thereby accelerating the growth of α_{WGB} phase. The α phase inside the grains is stable. The decrease in element content results in a decrease in the amount of α_{WM} phase precipitation.

2.2 Vickers hardness

The Vickers hardness of TB17 titanium alloys aged under different conditions is shown in Fig.14. It can be noticed that the Vickers hardness of TB17 alloys is increased rapidly at first, and then remains stable with increasing the aging time, suggesting that the aging response of TB17 titanium alloy is fast. With increasing the aging time, the content of the precipitated phases is increased, resulting in the increase of hardening effect and the Vickers hardness of the alloys. In addition, as the aging temperature increases, the Vickers hardness of the alloy increases firstly, reaching the maximum value at 450 °C, and then decreases. The size of the precipitated phase increases as the aging temperature increases (Fig. 12), and the dispersed fine precipitate phase can significantly increase the hardness of the matrix. However, when the size of the precipitated phase exceeds a certain critical value, the effect of dispersion strengthening is weakened, resulting in a lower hardness.

2.3 Discussion

Rhodes et al[24] found that there are two types of α phase (Burgers α phase and Type 2α phase) after isothermal aging of Ti-Mo β titanium alloy. The Burgers α phase and the β phase can satisfy the Burgers orientation relationship of $<11\bar{2}0>_{\alpha}//<111>_{\beta}$ and $\{0001\}_{\alpha}//\{110\}_{\beta}$, while the Type 2$\alpha$ phase cannot. In addition, there are different opinions on the cause of the formation of Type 2α phase. Rhodes et al[24] believed that the morphology of Type 2α phase is granular and the Type 2α phase grows around the lamellar Burgers α phase. However, Banerjee[28] and Cortial[29] et al indicated that the Type 2α phase exists in the interior and interface of Burgers α phase, which can no longer satisfy the Burgers orientation relationship. In addition, the Type 2α has an interface phase with face-center cubic (fcc) structure, which exists at the interface of different phases (α/β)[28] in the titanium alloy.

The high resolution TEM (HRTEM) images of TB17 titanium alloy after aging at 550 °C for 4 h are shown in Fig. 15. The black stripes are parallel to each other in the lamellar Burgers α phase (the circle in Fig.15a), and regularly form an angle of about 60° with the side stripes. According to Ref.[24], the black stripe is determined as the Type 2α phase. The SAED pattern of the square area inside the 1α phase shows a twin relationship between the Burgers α phase and Type 2α phase (Fig.15d). The calibration results indicate that the Type 2α phase has a close-packed hexagonal (hcp) crystal structure. In summary, the Type 2α phase is formed inside the Burgers α phase. The results show that there is a complete coherence between the Type 2α phase and the Burgers α phase, but there is an angle of about 14° between the $(01\bar{1}0)_{2\alpha}$ and the $(10\bar{1}1)_{1\alpha}$ crystal planes, indicating that there is a twin relationship between the Type 2α phase and the Burgers α phase.

This phenomenon caused by the aging process of TB17 titanium alloy can be explained as follows. TB17 titanium alloy, a new type of ultra-high strength and toughness titanium alloy, contains many kinds of alloy elements and the fine and

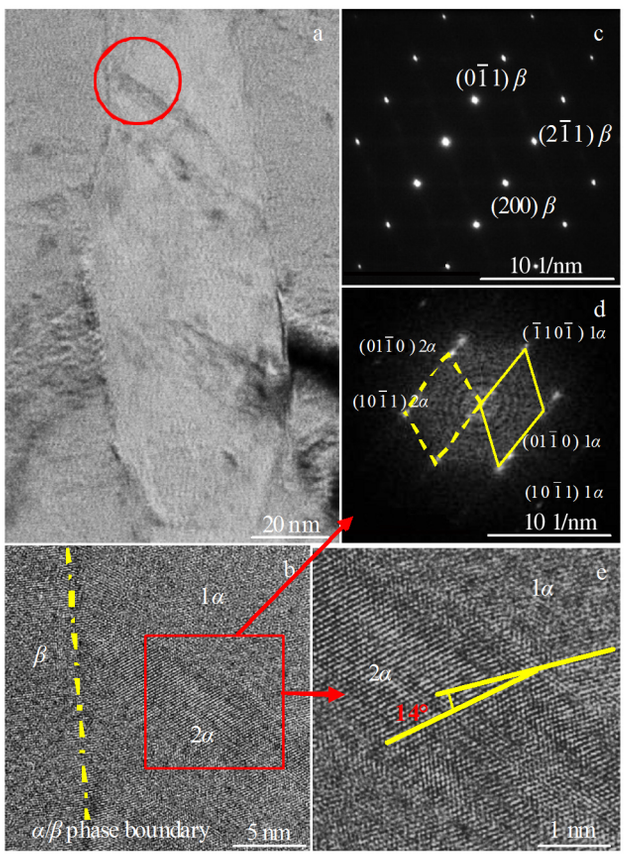

Fig.15 TEM image of Burgers α phase (a); HRTEM image of circle area in Fig. 15a (b); SAED pattern of α and β phases (c); SAED pattern (d) and HRTEM image (e) of Type 2α phase and Burgers α phase corresponding to the square area in Fig.15b

dispersed α phase can be precipitated when the alloy is fully aged[19]. The collision and extrusion between the Burgers α phases inhibit the growth and cause stress concentration. Because of the growth constraints and thermal stress, the Burgers α phase with hcp crystal structure induces twinning at the $\{10\bar{1}2\}$ crystal plane to form flaky twin crystals, and the $\{10\bar{1}2\}$ twinning has the smallest twinning shear and shows a tension twin mode[30]. This is the nucleation process of Type 2α phase. The twin boundary is continuously widened along the growth direction of the Burgers α phase and the self-growth is completed by consuming the originally precipitated Burgers α phase with increasing the aging time.

In theory, the second phase tends to nucleate at defects, such as vacancies, dislocations, grain boundaries, or phase boundaries, but the twin boundary is not an ideal nucleation site as a low-energy coherent interface[31]. Therefore, the kinetic conditions of Type 2α phase formation should be further investigated. It is certain that the dispersion of the Type 2α phase in the β matrix can significantly improve the mechanical properties of the alloys, because the formation of twins changes the crystal structure. Some of the unfavorable slip systems shift to the positions which are favorable for slippage, which stimulates the further slip and crystal deformation, and thereby improves the mechanical properties of the alloy[31].

3 Conclusions

1) The TB17 titanium alloy mainly undergoes the phase transformation of $\beta \rightarrow \omega$ during aging at 350 °C, and the ω phase is granular. During aging at 450 °C, the α phase is precipitated through the assistance of ω phase by nucleation, and the phase transformation process is $\beta \rightarrow \beta+\omega \rightarrow \beta+\alpha$. The phase transformation of $\beta \rightarrow \beta+\alpha$ mainly occurs at 550 and 650 °C.

2) The aging temperature has a great influence on the α Widmanstatten precipitates in the intragranular area with a basketweave microstructure (α_{WM}) and α Widmanstatten precipitates which originate from the β/β boundaries or from α_{GB} in parallel colonies (α_{WGB}) of TB17 titanium alloy. As the aging temperature increases, the length of α_{WGB} is increased, the amount of α_{WM} is decreased, and the α phase is obviously coarsened.

3) The aging response of TB17 titanium alloy is fast. The Vickers hardness is increased firstly, reaching the maximum value at 450 °C, and then decreased with increasing the aging temperature.

4) There are two types of α phase in TB17 titanium alloy after aging at 550 and 650 °C. The Type 2α phase is a twin crystal phase, which originates from the nucleation of the $\{10\bar{1}2\}$ twin plane inside the Burgers α phase.

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TB17钛合金在等温时效过程中的相析出行为

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摘 要：采用X射线衍射、扫描电子显微镜、透射电子显微镜和硬度测试分析了新型超高强韧钛合金TB17在等温时效过程中析出相的演变及时效响应。结果表明：该合金在350 ℃时主要发生$\beta\rightarrow\beta+\omega$相变，$\omega$相为细小的颗粒。在450 ℃下进行时效处理时，$\alpha$相通过$\omega$相辅助形核的方式形核长大。在550和650 ℃时主要发生$\beta\rightarrow\beta+\alpha$相变，$\alpha$相为片层状。在该温度范围内长时间进行时效处理的TB17合金存在2种类型α相，满足Burgers关系的1α相和不满足Burgers关系的2α相。其中2α相为孪晶α相，在1α相内部{10$\bar{1}$2}孪晶面形核，并不断消耗1α相而长大。TB17钛合金的时效特征与其他β型钛合金相似。TB17钛合金的时效响应快，显微硬度随着时效温度升高呈现出先增加后降低的趋势，在450 ℃时效处理下硬度达到最大。

关键词：TB17钛合金；等温时效；相变；2种类型α相；时效响应

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