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ARTICLE

Effects of Lamellar Microstructure Characteristics on Quasi-static and Dynamic Deformation Behavior of Ti-6Al-4V-4Zr-Mo Alloys

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Abstract: The influences of lamellar microstructure characteristics on quasi-static tensile properties and dynamic compression deformation behavior were studied for newly developed titanium alloy Ti-6Al-4V-4Zr-Mo. To tailor the microstructure characteristics, the lamellar microstructure was obtained by be solution treatment at 960 °C and underwent subsequent aging treatments at 700 and 570 °C, respectively. Results show that as the aging temperature decreases, the size of α colonies and the width of α plates present a declining trend. Correspondingly, the slip length of dislocation becomes relatively shorter, resulting in the increase of quasi-static deformation capability. Dynamic compression tests also show that the lamellar microstructure aged at 570 °C with α colonies and α plates in smaller size, which induces the propagated path of crack easily bifurcate and deflect, presents higher dynamic fracture strain, in contrast with the lamellar microstructure aged at 700 °C.

Key words: titanium alloy; microstructure; quasi-static tensile behavior; dynamic compression behavior

Titanium and titanium alloys are widely used for airplanes and fighter vehicles due to their excellent properties such as low density and high specific strength [1-3]. One of the most important aspects on the investigation of titanium alloys is microstructures, and it is known that their mechanical properties are largely affected by the microstructures, which are mainly divided into lamellar, bimodal and equiaxed ones [4, 5]. Among them, the lamellar microstructures are known to have preferable specific strength, fracture toughness, creep resistance and resistance to crack propagation, but lower ductility [6-8]. Therefore, in order to improve the ductility of lamellar microstructures and obtain desired mechanical properties, the relationship between the detailed microstructure characteristics and mechanical properties should be studied. The material used in the present study is Ti-6Al-4V-4Zr-Mo (Ti6441), a newly developed titanium alloy at Beijing Institute of Technology. Lamellar microstructures with different detailed characteristics, such as size of α colonies and thickness of α plates, are obtained by varying temperatures for aging treatment. The effects of detailed microstructure characteristics on quasi-static tensile and dynamic compression behavior were investigated.

1 Experiment

The β-transus temperature of Ti6441 alloys was determined at 945 °C. The typical microstructure of the alloys in as-received state was equiaxed, which was produced via $\alpha + \beta$ processing route, i.e. initial forging in the beta phase region and final forging in the $\alpha + \beta$ phase region. Starting from the globular as-received state, the Ti6441 alloys were heat treated in a usual heat-treatment furnace above the β-transus temperature, followed by air cooling, to obtain lamellar microstructures. Then, aging treatments at different temperatures were performed in order to obtain different detailed characteristics of formed lamellar microstructures. The detail designed heat-treatment conditions are summarized in Table 1. The typical lamellar microstructure, named L0, was obtained by the solution treatment at 960 °C for 1 h followed by air

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cooling to room temperature. Then the L0 microstructure underwent (AC) subsequent aging treatments at 700 and 570 °C, respectively, for 4 h followed by air cooling. Correspondingly, the obtained microstructures with different lamellar characteristics were named L1 and L2, respectively. The morphology analysis was made by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). For the accurate and quantitative characterization of the microstructural features, Image-Pro Plus 6.0 was used to improve the image contrast. The average size of α plates was calculated by the Image-Pro Plus 6.0.

Quasi-static tensile and dynamic compression tests of the Ti6441 specimens with different detailed microstructure characteristics were performed. Quasi-static tensile properties tests were carried out using a MTS electro-hydraulic servo tester with the axial strain rate of $10^{-4}s^{-1}$, and quasi-static tensile stress-strain curves were obtained. Dynamic compression tests using a Spilt Hopkinson Pressure Bar (SHPB) system were conducted on cylindrical specimens with a diameter of 5 mm and a height of 5 mm. By a data acquisition system, true dynamic compress stress-strain curves at a high strain rate of $10^{3}s^{-1}$ were obtained, in the principles and equations mentioned in Ref.[9]. The fracture surfaces of the specimens after quasi-static tensile tests and dynamic compression tests were observed using the SEM.

2 Results and Discussion

2.1 Microstructure

Fig.1 shows the L0, L1 and L2 microstructures of Ti6441 alloys undergoing different heat treatments. As shown in Fig.1a, solution treating from the single β phase region (at 960 °C) causes a transformation occurred from high temperature β phases to lamellar α phases. The obtained coarse lamellar microstructure, named L0, is divided into α colonies, composing of lath-type α and β plates, with different orientation angels. Starting from the L0 microstructure, the Ti6441 alloy undergoes different aging treatments. It can be seen from Fig.1b and 1c that the obtained L1 and L2 microstructures are lamellar microstructures, similar to the un-aged one. However, there are some differences in the aspect of detailed microstructure characteristics, such as the size of α colonies, the width of α plates within the α colony and the length of fine acicular α precipitates within β matrix. As calculated by the Image-Pro Plus 6.0, the size of α colonies within the L1 microstructure is larger, as shown in Fig.1b, and the average length and thickness of the α plates are quantitatively measured to be 17.7 and 1.19 μm, respectively. With decreasing aging temperature, as shown in Fig.1c, the L2 microstructure, containing more close α colonies, has the length and the thickness of the α plates decreased to 12.2 and 0.85 μm, respectively. The TEM images of the L1 and L2 microstructures are shown in Fig.2, which show the fine acicular α precipitates (marked by arrows) within β matrix existing in the intersection region of lamellae colonies with different orientations more clearly. It can be seen from Fig.1 and Fig.2 that the size of fine acicular α precipitates declines from 3.58 μm to 1.36 μm, as the aging temperature decreases.

Table 1 Heat treatment parameters for the Ti6441 alloys

Sample No.	Heat treatment
L0	960 °C/1 h AC
L1	960 °C/1 h AC+700 °C/4 h AC
L2	960 °C/1 h AC+570 °C/4 h AC

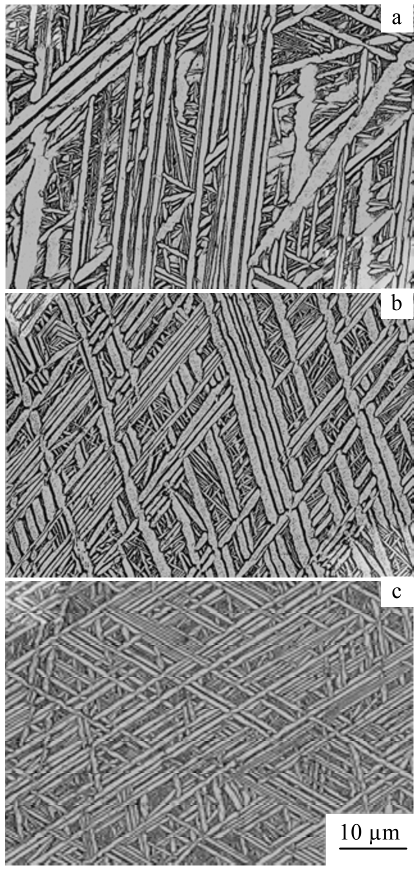

Fig.1 SEM micrographs of the (a) L0, (b) L1, and (c) L2 lamellar microstructures in Ti6441 alloy

During the warming up and holding processes of aging treatments, the α phases within L0 microstructure will transform into β phases. It's known that the equilibrium volume fraction of α phases and β phases at a certain temperature below the β-transus is determined by the equilibrium diagram for two-phase titanium alloys [10], and the volume fraction of α phases increases as the holding

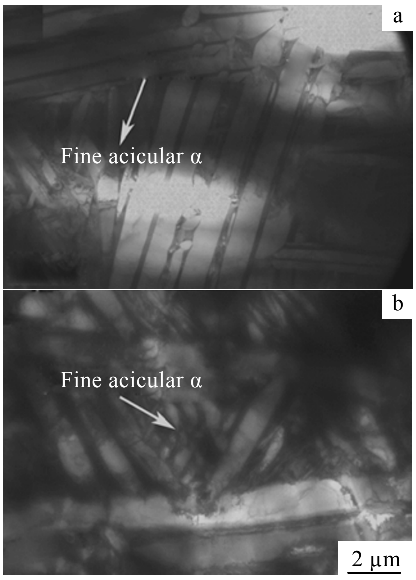

Fig.2 TEM micrographs of the L1 (a) and L2 (b) lamellar microstructures

temperature declines, and correspondingly the volume fraction of β phases decreases. Hence, in contrast with the aging treatment at 700 °C, the transformational quantities from α phases to β phases are less during the warming up and holding processes of aging at 570 °C. Correspondingly, the width of β plates within L2 microstructure at 570 °C is thinner than that within L1 microstructure at 700 °C, indicating that the lamellas' distance decreases as the aging temperature declines. Besides, the decline of aging temperature leads to the under cooling decrease during air cooling, reducing the driving force for phase transformation from β to α. Therefore, L2 microstructure exhibits thinner size of α colonies and α plates in contrast with L1 microstructure.

2.2 Quasi-static tensile deformation behavior

Fig.3 presents stress-strain curves obtained from the quasi-static tensile tests. It can be seen that the tensile strength and fracture strain both increase in the order of L1 and L2, with declining the aging temperature. That is to say the lamellar microstructure undergoing a subsequent aging treatment at a lower temperature obtains better mechanical properties with enhanced strength and improved ductility, in comparison to the lamellar microstructure aged at a higher temperature. The increase of strength is due to the continuous refinement of α colonies and α plates, as the aging temperature declines. The reason why L2 microstructure has a better ductility than L1 microstructure is that the slip length across α colonies is decreased due to the decline of colonies size, which reduces the possibility of local stress concentration.

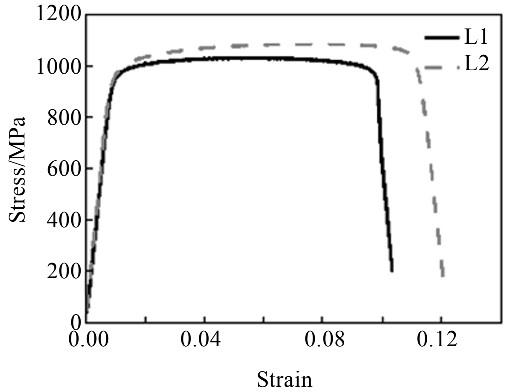

Fig.3 Stress-strain curves obtained from the quasi-static tensile tests

SEM fractographic observations of the fracture surfaces for tensile specimens with different detailed microstructure characteristics are shown in Fig.4. It can be seen that both the L1 and L2 microstructures, with a large number of dimples in the fracture surfaces, show a typical ductile fracture mode. However, in contrast with the L1 microstructure, the L2 microstructure displays larger size of dimples with some secondary cracks in their bottom and obvious tearing ridge, explaining that the L2 microstructure has better ductility.

2.3 Dynamic compression deformation behavior

The true stress-strain curves of the Ti6441 alloys with different microstructure characteristics are obtained from dynamic compression tests at the strain rate of 3000 s^{-1} (Fig.5). It can be seen from Fig.5 that the stress of the alloy with two different microstructures shows a similar varied

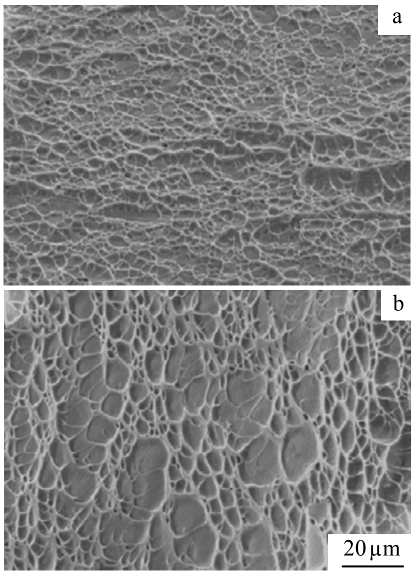

Fig.4 SEM fractographies of the fractured tensile specimens with L1 (a) and L2 (b) lamellar microstructures

tendency, as the strain increases. The maximum stress point is reached immediately after a little plastic deformation. After that, the flow stress roughly retains a certain value with the increasing strain, due to the balance of strain, strain rate hardening and thermal softening at the steady deformation stage. As the strain proceeds to increase, thermal softening, which overrides strain rate hardening and strain hardening, is sufficient to induce plastic instability and stress decreases sharply, resulting in the final adiabatic shear failure.

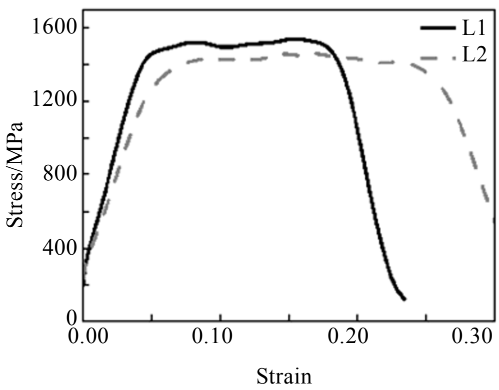

Fig.5 Stress-strain curves obtained from the dynamic compression tests

It also can be seen from Fig.5 that the dynamic strength slightly declines, but the dynamic ductility dramatically increases in the order of L1 and L2 microstructures, as the aging temperature decreases. Because the crack deflection behavior becomes severer with decreasing the size of the α colonies and α plates, which can be deduced from the Fig.1, thereby requiring much more energy and reducing the possibility of adiabatic shear failure. Hence, the L2 microstructure performs better dynamic ductility and has relatively larger deformation extent before fracture.

SEM fractographies of the Ti6441 alloys with different detailed characteristics of lamellar microstructures are shown in Fig.6. As presented in Fig.6a, the fractured compressed specimens for both the L1 and L2 lamellar microstructures show a typical adiabatic shear fracture mode [11], composed of relatively smooth shear regions and ductile dimples, but dimples are elongated in the shear direction compared with those of quasi-static tensile fractured specimens. It can be induced from the SEM image that the L2 microstructure show higher dynamic ductility than the L1, due to the following reasons: (1) voids (Fig.6b) are observed within the shear region of the L2 microstructure, explaining an additional consumption of energy [12]; (2) dimples in larger value of size are presented within the L2 microstructure, as shown in Fig.6c and 6d.

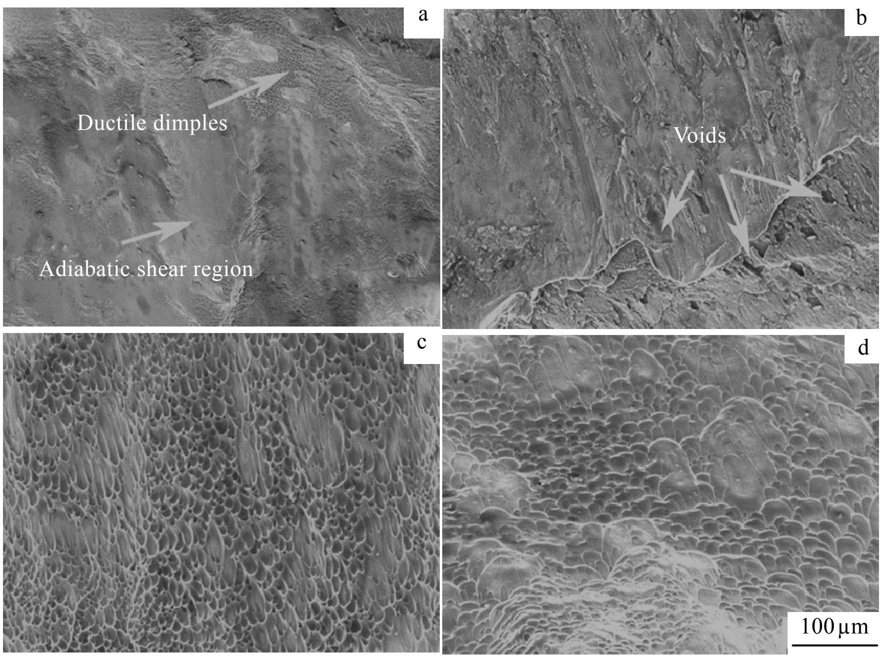

Fig.6 SEM fractographs of the dynamically fractured specimens for both the L1 and L2 lamellar microstructures: (a) the same macro-fracture, (b) the local magnified micrograph of smooth shear region of L2; and the dimples within L1 (c) and L2 (d)

3 Conclusions

1) In lamellar microstructures, α colonies, α plates and fine acicular α precipitates all decrease in size, as the aging temperature declines.

2) The fracture strain both at quasi-static and dynamic loading rates increases with declining the aging temperature.

3) The refinement of α colonies results in the diminution of effective slip length and the increase of crack propagated path. Correspondingly, the lamellar microstructure aged at 570 °C shows a better ductility.

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