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ARTICLE

Effect of Y Addition on the Microstructure and Mechanical Properties of the As-cast Ti-6Al-4V Alloy

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Abstract: The effects of yttrium (Y) addition on microstructures and properties of the as-cast Ti-6Al-4V alloys were studied. The microstructure and mechanical properties were characterized by optical microscopy (OM), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and tensile testing. The results show that Ti-6Al-4V alloy exhibits typical Widmanstatten structure. With Y addition, Y_2O_3 particles form and primarily distribute along the prior-β grain boundaries, and it induces the formation of special paralleled α/β lamellas on either side of the prior-β grain boundaries. While alternate α/β lamellas are observed inside the grains of Ti-6Al-4V-0.3Y alloys. Compared with Ti-6Al-4V, the Y addition improves the strength slightly. Both the paralleled α/β lamellas and Y_2O_3 cause the transformation from cleavage fracture to intergranular fracture and the significant decrease in elongation. Therefore, the variation of the microstructure of Ti matrix caused by Y_2O_3 also plays an important role in the ductility of the alloys.

Key words: Ti-6Al-4V-0.3Y alloys; Y_2O_3 particles; α/β lamellar structure; mechanical properties; fracture behavior

Ti-6Al-4V alloy, especially its wrought alloy, has been widely applied in the fields of aerospace, automotive industry and medical implants devices, due to the excellent mechanical properties, corrosion resistance and biocompatibility[1-3]. By comparison, the as-cast alloy exhibits the advantages in cost reduction and product complexity. The microstructure of the as-cast alloys has an important influence on its hot working processing[4]. Therefore, the as-cast Ti-6Al-4V alloy is still given much attention.

Most of the Ti alloys are prepared by vacuum arc melting. The as-cast Ti-6Al-4V alloy exhibits lamellar structure and coarse grains with size of several millimeters, resulting in poor room-temperature ductility[5-8]. Then a lot of research have paid attention to micro-alloying by B[5-8], Y[5,9-12] and La[13]. The effects of alloying elements on the microstructure, mechanical properties, fracture behavior and corrosion resistance have been studied. For the as-cast Ti-6Al-4V-Y[5] and Ti-Y[9] alloys, Y could scavenge oxygen (O) to form Y_2O_3 particles with size of several microns[2,14,15], and distributed along the prior β grain boundaries. It could retard the migration of the boundaries and refine the grain size. Y addition is effective in increasing the oxidation resistance[5]. While for the mechanical properties, with increase of Y content (<0.1 wt%), the strength of the as-cast Ti-6Al-4V-0.02B-(0~0.1)Y alloys remains almost similar , while the elongation decreases from 9% to 5% which is attributed to the intergranular fracture caused by brittle Y_2O_3 particles[5]. It means that the content of Y in Ti-6Al-4V should be less than 0.1%.

Usually, the effect of the second phases on mechanical properties depends on the volume fraction, size and orientation relationship between the second phase and matrix. For the as-cast Ti-6Al-4V-Y alloy, Y_2O_3 presents strip or fine particles, but there was no study focused on the effect of Y_2O_3

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on the morphology of α and β lamellas and their relationship with the fracture mode. In the present work, in order to obtain a brittle Y containing Ti-based alloy, Ti-6Al-4V-0.3Y alloy has been prepared to study the effect of Y addition on the microstructure of Ti matrix and thus the mechanism of embrittlement.

1 Experiment

Raw materials, commercial Ti-6Al-4V alloy bar and pure Y, were melted in a water-cooled copper crucible by induction heating. The vacuum degree was kept at 5×10^{-2} Pa. The melt was kept at 1700 °C for 15~20 min. Then the melt was cooled in the crucible to form an ingot with diameter of 250 mm. Ti-6Al-4V-0.3Y and Ti-6Al-4V alloy ingots were prepared. After the ingot was machined, then specimen was cut along the radial direction for the characterization of microstructure and mechanical properties.

The microstructures were observed via optical microscopy (OM, Leica DM2500M) and scanning electron microscopy (SEM, JEOL JSM-6460) coupled with energy dispersive spectrometer (EDS). Room-temperature tensile tests were conducted on an MTS tensile testing machine (Instron 3369) at a constant cross-head speed of 0.3 mm/min. Three tensile samples with a gauge length of 25 mm and diameter of 5 mm were tested for each alloy.

2 Results and Discussion

2.1 Microstructure characterization

Fig.1 shows the microstructure of the as-cast Ti-6Al-4V and Ti-6Al-4V-0.3Y alloy. Both alloys show Widmanstatten structure with alternate lamellas of α-Ti (hcp) and β-Ti (bcc) within the prior β grains. As shown in Fig.1a and 1b, Ti-6Al-4V alloy exhibits straight prior β grain boundaries. While Ti-6Al-4V-0.3Y alloy exhibits curved boundaries, and the second phase distributes along the boundaries (as shown in Fig.1c~1e). The second phase could pin the grain boundaries and result in finer grains in Ti-6Al-4V-0.3Y alloy than those in Ti-6Al-4V alloy (as shown in Fig.1a and 1c). On the other hand, in Ti-6Al-4V-0.3Y alloy, paralleled α/β lamellas with length of about 20 μm form on either side of the prior-β grain boundaries as shown in Fig.1d and 1e, and the orientation of the α/β lamellas is quite different from that on the other side of grain boundary or that within grains. The paralleled α/β lamellas along grain boundaries have not been observed in Ti-6Al-4V alloy in the present work and Ti-6Al-4V alloys with B or/and Y in Ref. [5-12].

Then the second phase in Ti-6Al-4V-0.3Y alloy were observed by SEM-BSE and TEM, as shown in Fig.2. Except for the strip-like second phase along grain boundaries (Fig.1e), there are granular second phase with a size of 2~10 μm (in bright color in Fig.2a) within the grains. The TEM micrographs indicate that the second phase is of dendritic morphology, and the SAED pattern reveals that the second phase should be Y_2O_3 with a bcc structure as shown in the insert of Fig.2b. Both Ti-6Al-4V and Ti-6Al-4V-0.3Y alloys exhibit equiaxed prior-β grains. Then the β/α phase transformation occurs to form lamellar structure. The paralleled α/β lamellas are induced by Y_2O_3 along the boundaries. The Y_2O_3 particles act as nucleation site during α phase precipitation, and the α-Ti would keep specific orientation relationship with

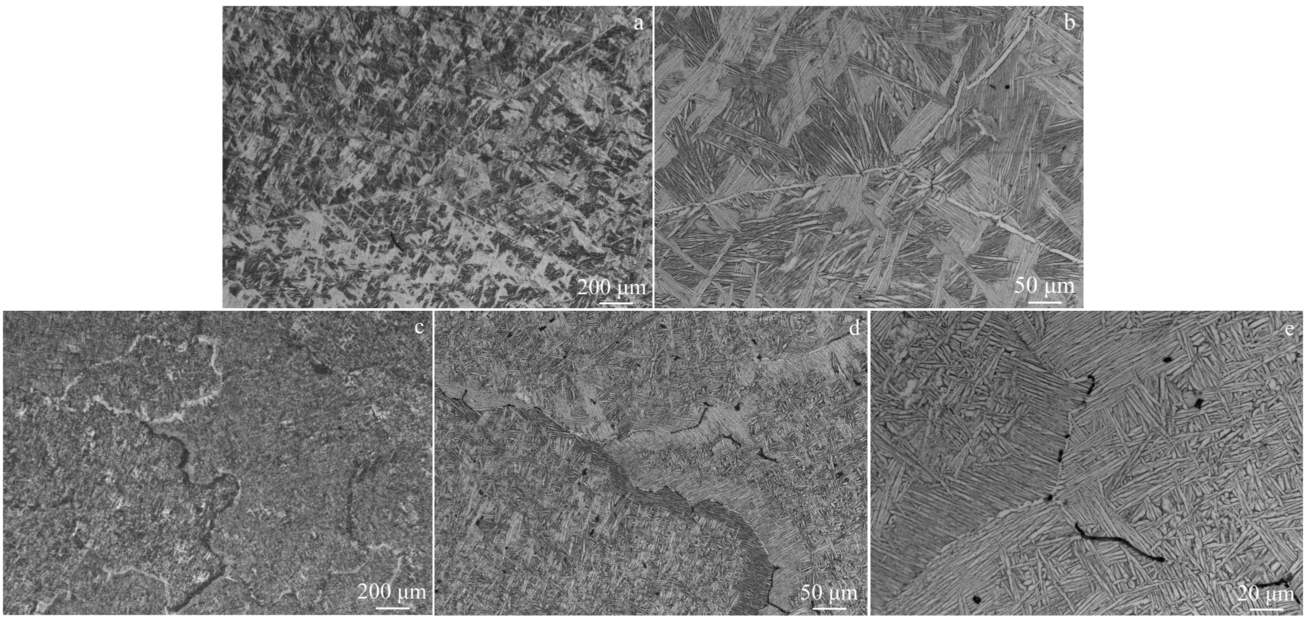

Fig.1 Optical microstructures of the as-cast Ti-6Al-4V (a, b) and Ti-6Al-4V-0.3Y (c~e) alloys

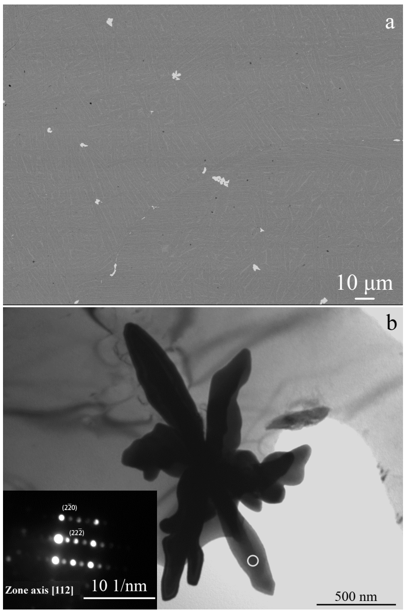

Fig.2 SEM (a) and TEM (b) images of as-cast Ti-6Al-4V-0.3Y alloys (the insert is the SAED pattern of the white circle in Fig.2b)

Y_2O_3 to reduce the distortion energy. While the α-Ti precipitates randomly within the β grains, forming alternate lamellas, which is similar to that of Ti-6Al-4V alloy.

2.2 Tensile properties and fracture behavior of the alloys

Fig.3 shows the room-temperature tensile stress-strain curves of the alloys. Ti-6Al-4V alloy exhibits tensile yield strength of 741±3 MPa, tensile strength of 823±15 MPa and elongation of 11.0%±1.0%. While Ti-6Al-4V-0.3Y alloy exhibits tensile yield strength of 773±3 MPa, tensile strength of 851±11 MPa and elongation of 2.2%±0.4%. It means that with trace addition of Y, the strengths of the alloy increase by about 30 MPa, while the elongation decreases significantly. Considering the microstructures of the two alloys, Y_2O_3 particles and finer grains in Ti-6Al-4V-0.3Y alloy play a positive role in improving strength. But the size of Y_2O_3 and grains reaches several microns and millimeters, respectively, so their contribution to the strength is very limited.

The fracture surface of the alloys is shown in Fig.4. Obvious cleavage planes and tearing ridges could be observed (as shown in Fig.4a and 4b), which means that Ti-6Al-4V exhibits a typical cleavage fracture mode. While Ti-6Al-4V-0.3Y alloy exhibits intergranular fracture. During the tensile process, Y_2O_3 particles act as crack sources due to stress concentration. Then

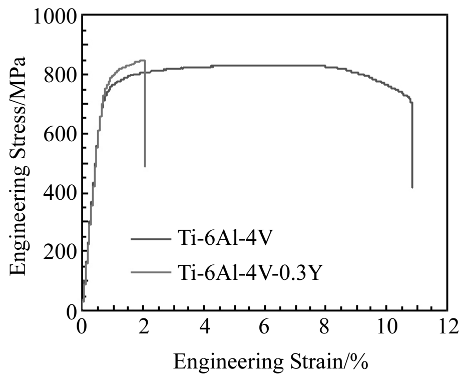

Fig.3 Room-temperature tensile stress-strain curves of the as-cast Ti-6Al-4V and Ti-6Al-4V-0.3Y alloys

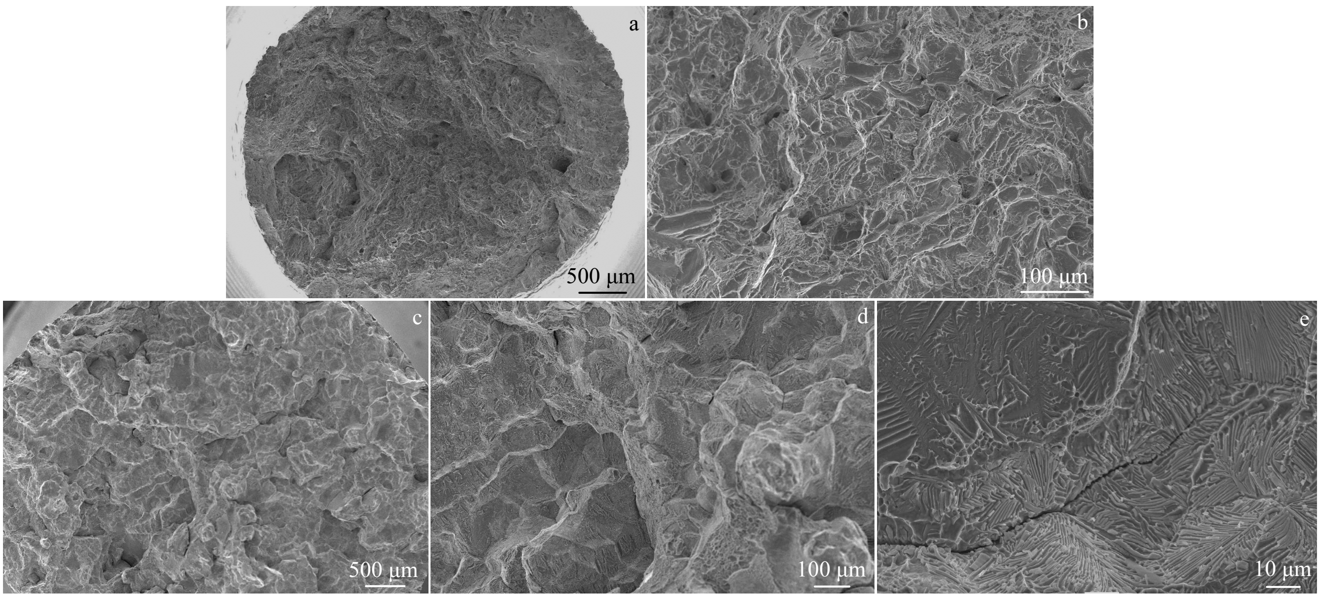

Fig.4 Fracture surface of the as-cast Ti-6Al-4V (a, b) and Ti-6Al-4V-0.3Y (c~e) alloys

the cracks propagate along the grain boundaries. Meanwhile, the lamellas are broken along the direction perpendicular to the tensile direction and promote the growth of the cracks along the grain boundaries. Finally, it results in the intergranular fracture and the morphology with paralleled lamellas on the fracture surface as shown in Fig.4c~4e. Therefore, the paralleled α/β lamellas reduce the bond between grains, cause the transformation of fracture mode from cleavage fracture to intergranular fracture, further resulting in the decrease in elongation. The paralleled α/β lamellas have negative effect on the mechanical properties and the deformation ability of the as-cast Ti alloys. For the development of Ti-based alloys containing Y, more attention should be paid to Y content and casting process to eliminate the parallel α/β lamellar structure.

3 Conclusions

1) Y as micro-alloying element distributes along the prior β grain boundaries in form of Y_2O_3. Paralleled α/β lamellas form on either side of the prior-β grain boundaries in Ti-6Al-4V-0.3Y alloy.

2) Y addition could slightly improve the strength of the as-cast alloy, but significantly reduce the elongation.

3) The paralleled α/β lamellas and Y_2O_3 around the grain boundary lead to the transformation of fracture mode from cleavage fracture to intergranular fracture, resulting in lower elongation. Therefore, the microstructure of Ti matrix also plays an important role in the ductility of the alloy.

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Y 元素对铸造 Ti-6Al-4V 合金微观组织与力学性能的影响

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摘 要：研究了 Y 元素合金化对铸造 Ti-6Al-4V 合金微观组织与力学性能的影响。铸态合金微观组织与力学性能分别利用金相显微镜、扫描电镜、透射电镜和拉伸试验进行表征。结果显示，Ti-6Al-4V 合金呈现典型的魏氏组织特征。添加 Y 元素后，合金中形成 Y_2O_3 颗粒并分布在初生 β 晶粒的晶界处，同时在晶界两侧形成平行的 α/β 层片结构，而晶粒内部形成相互交叉的 α/β 层片结构，即 Y_2O_3 明显改变了 Ti 基体片层组织形貌。相比于 Ti-6Al-4V 合金，添加 Y 元素之后，合金的屈服强度和抗拉强度稍有提高，但是平行的 α/β 层片结构和 Y_2O_3 颗粒引起合金由解理断裂向沿晶断裂转变，进而导致延伸率显著减小。所以，Ti 基体微观组织变化对合金力学性能同样具有重要作用。

关键词：Ti-6Al-4V-0.3Y 合金；Y_2O_3 颗粒；α/β 层片组织；力学性能；断裂行为

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