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ARTICLE

Effects of B and Y Additions on the Microstructure and Tensile Behaviour of High-Nb TiAl Alloys

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Abstract: The influence of B and Y on the microstructure, microsegregation, and tensile behaviour of the Ti45Al8Nb0.2W0.25Cr (at%) alloy was investigated. The β-stabilizer elements in the high-Nb TiAl alloy promote the formation of the γ phase in the microsegregation region and lead to the formation of large blocky microsegregation areas. The large blocky microsegregation regions with low specific surface areas reduce the nucleation rate of cavities and cracks at the interfaces of the microsegregation, which are harmful to colony boundary strengthening and decrease tensile resistance. The addition of B and Y affords an obvious refinement in the lamellar colony, renders an increasing opportunity for cavity nucleation at the colony boundary, and thus improves the tensile resistance. The tensile mechanisms of the alloys before and after (B, Y) addition were also compared and analysed.

Key words: TiAl; microsegregation; tension; microstructure

TiAl alloys have gained great interest for research on aerospace applications due to their low density and high specific strength in recent years[1-4]. However, the insufficient high-temperature strength restricts the application and development of TiAl alloys[5]. High-Nb TiAl alloys have been developed based on the traditional γ-TiAl alloys for this problem[6]. Recent results have shown that the ductility and strength of high-Nb TiAl alloys can be significantly improved by refining grains and the addition of alloying elements[7-10]. It has been reported that the addition of the β-stabilizer elements such as W, Cr to the high-Nb TiAl alloys can improve their room-temperature ductility and elevated temperature strength, so they show great potential in controlling and stabilizing the microstructure[11-14].

It is recognized that the as-cast high-Nb TiAl alloy, which possesses a good balance in mechanical properties, needs to be refined by the addition of refining elements such as B and Y[7,8,15]. B can effectively refine grains and reduce segregation[16]. In addition to refining the as-cast structure, rare earth element Y can also solve the problem of long-term insufficient oxidation resistance of high niobium TiAl alloy and improve the adhesion of the oxide film[15,17]. However, the effect of alloying elements on the microstructure and properties of high-Nb TiAl alloy is not a simple superposition of alloying elements in quantity. Therefore, the microstructure and mechanical properties require further research in the refined high-Nb TiAl alloys. In this study, the effect of B and Y additions on the microstructure, microsegregation, and mechanical properties of Ti45Al8Nb0.2W0.25Cr alloys was investigated with attention paid to the mechanical mechanisms.

1 Experiment

Based on a high-Nb TiAl alloy, the nominal composition of investigated alloys in this study was Ti45Al8Nb0.2W0.25Cr (TWC), and Ti45Al8Nb0.2W0.25Cr0.2B0.02Y (TWC-BY). The materials used in this investigation were produced by a vacuum induction suspension melting technique. Suspension duration was 100 s for homogenization. The size of ingots was about Φ100 mm×150 mm. The tensile test samples were cut from the as-cast ingots. The chemical compositions of investigated alloys were measured by the spectrofluorometry method, which are summarized in Table 1. The B and Y concentrations are approximate values, as they cannot be

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Table 1 Actual chemical composition of investigated alloys (at%)

Alloy	Al	Nb	W	Cr	B	Y
TWC	44.98	8.03	0.20	0.25	-	-
TWC-BY	44.95	8.01	0.20	0.25	0.20	0.02

accurately measured by the used method.

Specimens for room temperature tensile tests, with a gauge section of 1 mm×4 mm×10 mm, were sampled from the core of the alloys. The room-temperature tensile tests were carried out on Instron 5569 universal material testing machine with an initial strain rate of 2.5×10^{-4} s^{-1}. Microstructural observations were carried out via scanning electron microscope (SEM, FEI, Quanta 200FEG) equipped with electron back-scattered diffraction (EBSD, EDAX, TLS-OIM) system, and transmission electron microscopy (TEM, JEM2010) operated at 300 kV. Specimens for SEM observation were mechanically polished to 3000# grit, and subsequently electrolytically polished by a solution composed of 60vol% methanol, 34vol% butyl alcohol and 6vol% perchloric acid at -30 °C for 30 s.

2 Results and Discussion

2.1 Microstructure characteristics

Fig. 1 shows the initial microstructures of the two investigated alloys. The average sizes of the lamellar colony (here equivalent to the grain size) of the TWC and TWC-BY alloys are about 250 and 90 μm, respectively, which are repeatedly measured by the linear intercept method. And there are many areas of blocky B2+γ precipitated phase microsegregation in the matrix, which results from the β-stabilizing elements. Chen et al[18] reported that the β-segregation at the colony boundary is formed by the incomplete phase transformation of $\beta\rightarrow\alpha$ during cooling, and α-segregation is formed in the lamellar structures due to the phase transformation of $\alpha\rightarrow\alpha_2+\beta+\gamma$ in the high-Nb TiAl alloy.

Fig.1a shows microstructures of the TWC alloy. The colony boundary is distinguished. The large block β-segregation and α-segregation regions can be observed in the matrix, and the magnified microstructure of α-segregation in the lamellar structure is shown in the inset of Fig. 1a. The B and Y additions provide an obvious refinement for the lamellar colony compared with the TWC alloy and the average size of the precipitated phase is much smaller than that of the TWC alloy, as shown in Fig. 1b. The SEM microstructure of the TWC-BY alloy shows that small blocky α-segregation and β-segregation regions are observed in the matrix.

Analysis of EDS spectrum data (Table 2) shows that the bright white filamentous object is rich in B and Ti, and the atomic ratio of B to Ti is about 2:1, which is inferred as TiB_2 (position 1 in Fig. 1c). A very small amount of bright white granular object is distributed inside the lamella. The atomic ratio of O and Y is about 3:2 by spectroscopic analysis, which is inferred to be yttrium oxide Y_2O_3 (position 2 in Fig.1c). The EDS spectrum data of positions 1 and 2 are shown in Table 2.

TEM images in Fig. 2 show that both alloys are composed of α_2/γ laminations and a small amount of β phase. B and Y lead to the obvious refinement of the laminations, and the lamination spacing decreases from 600 nm to 300 nm, which is taken from the same zone axis. The corresponding β-phase and γ-phase diffraction spots in the alloy are the same, as shown in Fig. 2c and 2d. The Y-containing phase and the B-containing phase in Fig. 1 are not found by the transmission electron microscope, probably because the phase content is small.

It can be seen from the liquid phase projection diagram of the Ti-Al-B ternary phase diagram[19] that the primary phase of the alloy solidified from the liquid phase is the β phase, and the β phase after solidification will be transformed in the order of $\beta\rightarrow\alpha\rightarrow\alpha+\gamma\rightarrow(\alpha_2+\gamma)$. During the solidification of the alloy, two-phase transformation processes of L$\rightarrow\beta+TiB_2$ and L+$\beta\rightarrow\alpha+TiB_2$ may occur while B is added. A small amount of TiB_2 phase nuclei are formed from the liquid during the L$\rightarrow\beta+TiB_2$ reaction, while most of the TiB_2 phase is formed by the reaction of L+$\beta\rightarrow\alpha+TiB_2$, and it grows as a secondary phase.

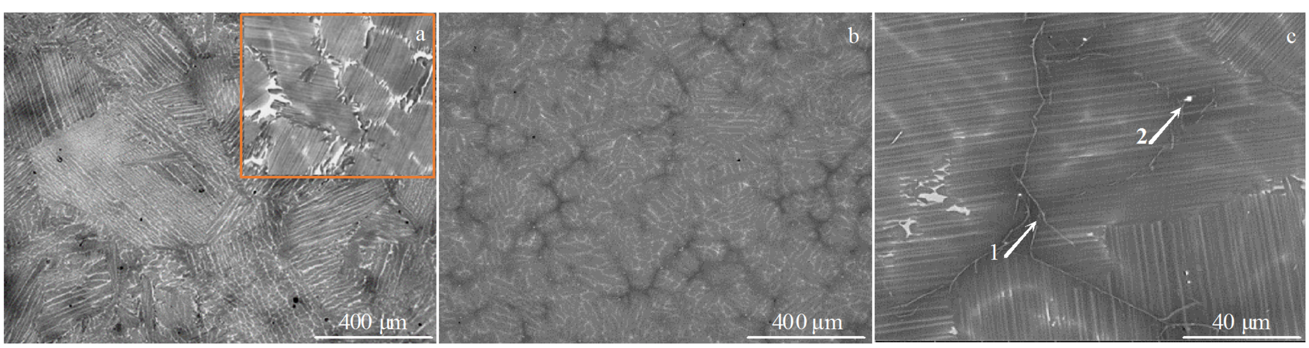

Fig.1 SEM images of initial microstructures of TWC (a) and TWC-BY (b, c) alloys

Table 2 Chemical composition of different positions marked in Fig.1c (at%)

Position	Ti	Al	Nb	W	Cr	Y	B	O
1	31.49	9.47	4.71	-	-		54.33	
2	16.83	13.01	2.73	-	-	21.59		45.85

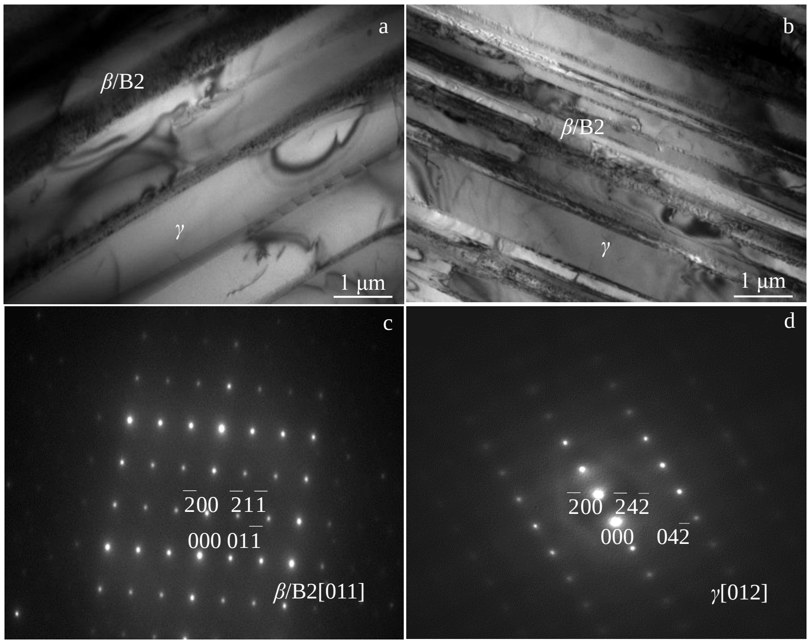

Fig.2 TEM images of lamellar microstructures of as-cast TWC (a) and TWC-BY (b) alloys; selected area electron diffraction patterns of *β*/B2 phase (c) and *γ* phase (d)

As can be seen from Fig. 1, TiB_2 is mainly distributed at the interface of the crystal colony, indicating that boride is discharged from the liquid-solid crystallization front to the liquid phase during the solidification. And with the growth of the crystal colony, it is pushed to the crystal boundary. The refinement mechanism of alloy grain is mainly the second phase which prevents the grain from growing. Additionally, a small amount of TiB_2 is distributed in the crystal, which shows that the heterogeneous nucleation mechanism of trace element B also plays a role in the grain refinement of the alloy.

Y as a surface-active element can reduce the surface tension of the liquid metal. The smaller the surface tension of the interface, the smaller the energy fluctuation required to form crystal nucleus. That is, the addition of Y reduces the nucleation of the alloy to form the critical crystal nucleus and increases the crystal nucleus. In addition, the Y element has a high activity coefficient and a strong affinity with oxygen atoms. In the early stage of solidification, Y is easily concentrated at the front edge of the solid-liquid interface, thereby forming a stable oxide Y_2O_3, inhibiting the *β* phase crystal nucleus from growing and increasing the number of *β*-phase nucleation. Also besides, the enrichment of Y at the solid-liquid interface will cause the constitutional supercooling of the crystallization front, which branches out the precipitated phase, forms grain boundary segregation, hinders the movement of the grain boundary, and reduces the growth rate of the crystal. At the same time, the dissolved Y atoms will cause elastic distortion around them and be pinned at the *α* interface, resulting in a decrease in the layering energy of the *α* phase interface, and forming a high phase interface energy. Y atoms will hinder the dislocations and step movement at the interface, which reduces the rate of lateral thickening of the *γ* phase, thereby refining the lamellar spacing.

2.2 Mechanical properties

The room temperature tensile curves of the two alloys are shown in Fig. 3. It can be seen that the performance is improved with (B, Y) addition. The tensile strength and elongation of the alloy both increase. The tensile strength increases from 582 MPa to 613 MPa, and it is brittle fracture. Compared with the TWC alloy, it is found that the fracture morphology of TWC-BY alloy is still a mixed fracture of interlaminar cleavage fracture and intergranular brittle fracture, neither of which exhibit the existence of dimples, as shown in Fig.4.

The grain size and interlamellar spacing of the TWC-BY alloy are significantly refined, and the room temperature tensile properties of the alloy are also greatly improved.

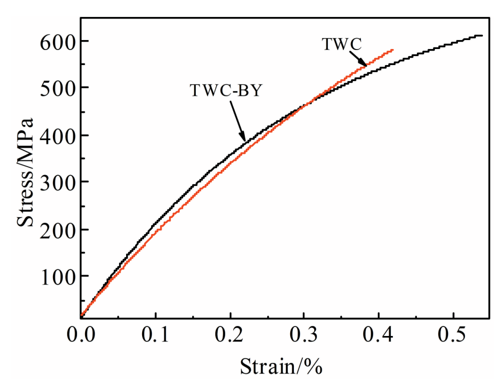

Fig.3 Room temperature stress-strain curves of alloys

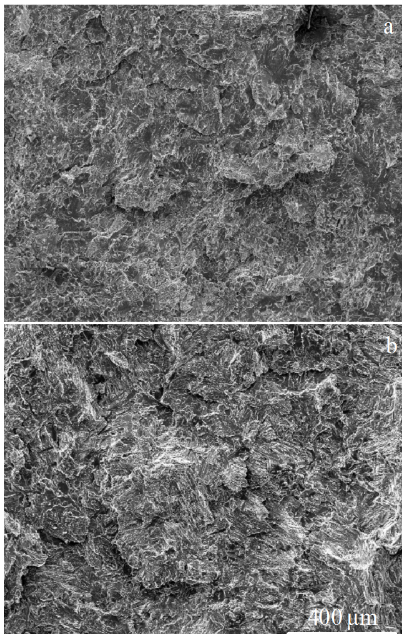

Fig.4 Tensile fracture morphologies at room temperature of TWC (a) and TWC-BY (b) alloys

However, the as-cast TWC-BY alloy still cannot satisfy the requirements for engineering applications. Moreover, β/B2 phase segregation in the as-cast structure of the alloy seriously reduces the room temperature plasticity and fracture toughness of the alloy material. Therefore, in order to optimize the alloy microstructure, improve the mechanical properties of the alloy, and accelerate the industrial application of the β-phase solidified as-cast high-Nb TiAl alloy, it is necessary to study the elimination process of β-phase segregation.

3 Conclusions

1) The β-stabilizer elements in the TWC alloy promote the formation of the γ phase in the microsegregation region and lead to the formation of large blocky microsegregation areas.

2) The large blocky microsegregation regions with low specific surface areas reduce the nucleation rate of cavities and cracks at the interfaces of the microsegregation, which are harmful to colony boundary strengthening, thus decreasing the tensile resistance.

3) The addition of B and Y in the TWC-BY alloy provides an obvious refinement in the lamellar colony, renders an increasing opportunity for cavity nucleation at the colony boundary, and thus improves the tensile resistance. The room temperature tensile properties of both alloys are brittle fracture.

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B 和 Y 对高铌 TiAl 合金组织和拉伸性能的影响

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摘　要：研究了 B 和 Y 对 Ti45Al8Nb0.2W0.25Cr (at%) 合金的微观结构、微观偏析和拉伸行为的影响。结果表明，高铌 TiAl 合金中的 β 相稳定元素促进了微观偏析区域中 γ 相以及大块状微观偏析区域的形成。具有低比表面积的大块状微偏析区域降低了微偏析界面处的空洞和裂纹的成核率，明显降低了晶界处的强度和合金的抗拉强度。B 和 Y 的添加明显的细化了片层团，增加了片层团处空洞成核的机会，从而提高了变形抗力。分析了 2 种合金的拉伸机理。

关键词：TiAl；微观偏析；拉伸；组织

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