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Effect of minor boron addition on mechanical properties of wrought TiAl alloy①

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Abstract: The effect of minor boron(1.0%, mole fraction) addition on tensile properties of wrought Ti-47-2Mn-2Nb alloy was investigated within the temperature range from 77 K to 1 373 K and the strain rate range from 10^{-5} s^{-1} to 10^{-1} s^{-1}. It was found that the minor addition of boron effectively refines the nearly lamellar microstructure of the alloy, significantly improves its strength, as well as its ductility. Although to a less degree, below its brittle-to-ductile transition temperature (T_{BD}), it does not harm its strength above its T_{BD}, and is therefore proved to be an potentially effective way to improve comprehensive properties of wrought TiAl alloy. The B addition was also found to produce no obvious change in the fracture mode except for the cases around T_{BD}.

Key words: titanium aluminide; intermetallics; boron **Document code:** A

1 INTRODUCTION

The γ-TiAl based intermetallic alloys have recently received more and more attention because of their potential as advanced high-temperature structural materials. Microstructure has been found to have a considerable effect on mechanical properties of TiAl alloys, while duplex microstructure has better room temperature ductility but poorer toughness and creep resistance, fully lamellar (FL) or nearly lamellar (NL) microstructure has higher toughness and creep resistance but lower ductility[1], which is partly attributed to their larger grains (lamellar colonies, LCs) in FL or NL microstructure. The refinement of FL or NL microstructure was expected to improve the room temperature ductility without decreasing the toughness and creep resistance. The expectation was preliminarily confirmed by recent discoveries made by Larsen et al[2] and London et al[3] in cast TiAl alloys that a minor addition of boron effectively refined grains and improved their strength and ductility. Kim[1] found a similar microstructure refinement caused by a minor boron addition to wrought TiAl alloys.

Unfortunately, the effect of minor boron addition on mechanical properties has been investigated only in cast TiAl alloys but not in the wrought TiAl alloys. In this paper, the effects of a minor boron (1%, mole fraction) addition are reported on the tensile properties of a wrought TiAl within a wide range of temperature (77 ~ 1 373 K) and strain rate (10^{-5} ~ 10^{-1} s^{-1}).

2 EXPERIMENTAL

The production of the investigated alloys, Ti-47%Al-2%Mn-2%Nb (TiAlMnNb) (mole fraction) and Ti-46.5%Al-2%Mn-2%Nb-1%B (TiAlMnNbB) (mole fraction), was accounted for elsewhere[4]. Boron was added to TiAlMnNbB alloy by XD (Exothermic Dispersion) technique, which resulted in 0.8% TiB_2(volume fraction) in TiAlMnNbB alloy. Initial microstructures of the two alloys were observed using optical microscope and transmission electron microscope (TEM)[5].

Plate tensile specimens with a gauge section of 15.0 mm × 3.5 mm × 1.8 mm were used. Tensile tests were conducted on a Shimadzu AG-100kNA material testing machine at 77, 180, 285, 398, 523, 598, 673, 773, 873, 973, 1 073, 1 173 and 1 373 K, and strain rates of 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2} and 10^{-1} s^{-1}, respectively. For cryogenic testing, the tested specimens were immersed in liquid nitrogen and the mixture of liquid nitrogen and fresh alcohol to keep the testing temperature at 77 and 180 K, respectively. For testing temperature above 1 073 K, the samples were covered with oxidation-resistant ceramic mud, which was sintered during heating prior to testing and insulated the samples from the ambient atmosphere. Fracture surfaces of the tested specimen were observed using S520 Scanning electron microscopy (SEM) operating at 20 kV.

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3 RESULTS

Metallography analysis revealed that both alloys possess NL microstructure and that the addition of 1.0 %B reduces the average LC size from 500 μm in TiAlMnNb alloy (as shown in Fig.1(a)) to 90 μm in TiAlMnNbB alloy (shown as in Fig.1(b)). However, TEM observation revealed that the thickness of γ and α_2 laths within LC is not obviously affected by the addition of boron, because of in both alloys, the thickness of γ laths varies from 0.03 to 1.25 μm while the thickness of α_2 laths varies from 0.01 to 0.15 μm[5].

The results of tensile testing showed that the strength of both alloys levels off and their ductility increases slightly from room temperature to several hundred Kelvin degree. However, above a high enough temperature, the strengths (yield strength $\sigma_{0.2}$ and ultimate tensile strength σ_b) of both alloys decrease severely and their elongation δ increases drastically, manifesting brittle-to-ductile transition[4]. As the strength decreases and ductility increases more rapidly in TiAlMnNbB alloy than in TiAlMnNb alloy, boron addition was found to decrease brittle-to-ductile transition temperature (T_{BD}) by 100 K or so[4]. The B addition significantly improves tensile strength, and although to a less efficient degree, ductility below T_{BD}, does not cause much change to the tensile strength above T_{BD}. The above-mentioned trend manifested not only under the strain rate of $10^{-4}s^{-1}$ (Fig.2), but also under other strain rates (Fig.3 and Fig.4).

SEM observation revealed that for both alloys, transgranular cleavage is the predominant fracture mode and intergranular failure is the minor fracture mode below T_{BD} (Fig.5(a),(b)) while dimple fracture is the fracture mode above T_{BD} (Fig.5(e),(f)). The minor intergranular failure in both alloys below T_{BD} suggests that grain boundary cohesion is not very weak and the boron addition does not strengthen the cohesion substantially. The effect of B addition on fracture mode is exhibited between the T_{BD}s of the two alloys, where a considerable number of dimples emerge on the fracture surface of TiAlMnNbB alloy (Fig.5(d)) but not on that of TiAlMnNb alloy (Fig.5(c)). Nevertheless, considering that the B addition increases the T_{BD}, it does not produce obvious change in fracture mode, giving the same difference between testing temperatures T and the respective T_{BD} values of the two alloys, or $T-T_{BD}$ value.

4 DISCUSSION

There are three ways for B atoms to distribute in a wrought TiAl alloy: to be present as a solid-solution in γ-TiAl and α_2-Ti_3Al phases, to precipitate as dispersed TiB_2 particles and to segregate along grain boundaries[6]. The finer microstructure of B-doped alloy (Fig.1) may be attributed to the precipitation of TiB_2 particles and the segregation of B atoms along grain boundaries, as was pointed by Pu[6] and Larsen[7]. Accordingly, B addition is expected to influence mechanical properties of TiAl alloy through the following three ways: solid-solution strengthening, dispersion strengthening by TiB_2 precipitates, and grain refinement strengthening by TiB_2 precipitates and/or B segregate along grain boundaries[5,6]. As TiB_2 particles take up only 0.8 % volume of TiAlMnNbB alloy, their dispersion strengthening is too weak to be a main mechanism for the improvement on mechanical properties below T_{BD}. As the solubility of B is as low as 0.1 % and 0.03 % (mole fraction) in γ and α_2 phases, respectively[7], the sol-

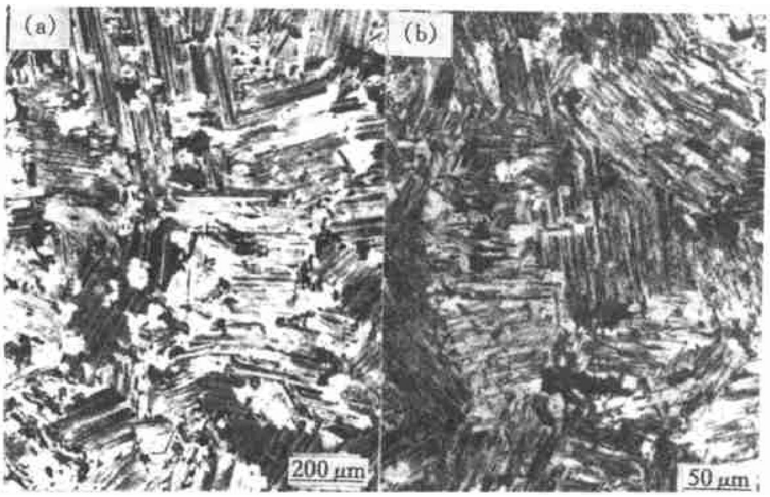

Fig.1 Initial microstructures of alloys
(a) —TiAlMnNb; (b) —TiAlMnNbB

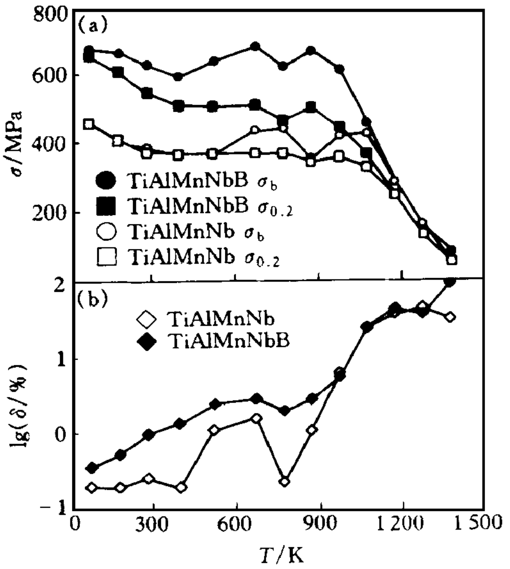

Fig.2 Difference in $\sigma_{0.2}$, σ_b(a) and δ(b) of two alloys with temperatures at strain rate of 10^{-4} s^{-1}

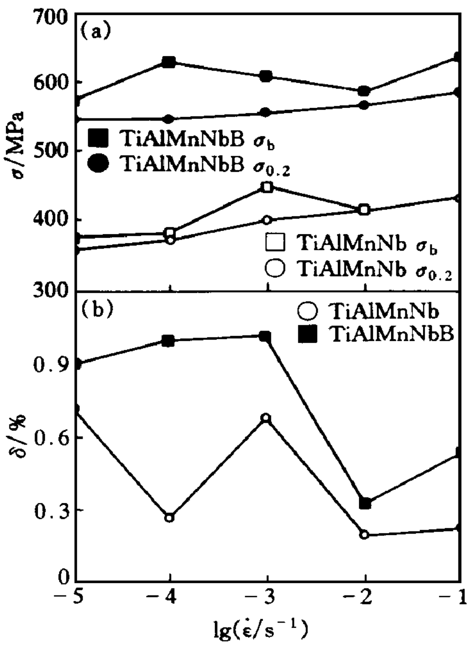

Fig.3 $\sigma_{0.2}$, σ_b(a) and δ(b) of two alloys at 285 K and different strain rates

id-solution strengthening may not be attributed for the strength improvement, either. An indirect evidence exists in the low and even negative estimated values of combined contributions to the strength from solid solute boron strengthening and microstructure refinement[8]. As microstructure refinement itself always contributes positively to the strength, the solid-solution strengthening must be weak. Thus, the strength improvement has to be attributed to the microstructure refinement. One evidence is the concurrent improvement on strength and ductility, which can be realized not by the two excluded mechanisms, but by

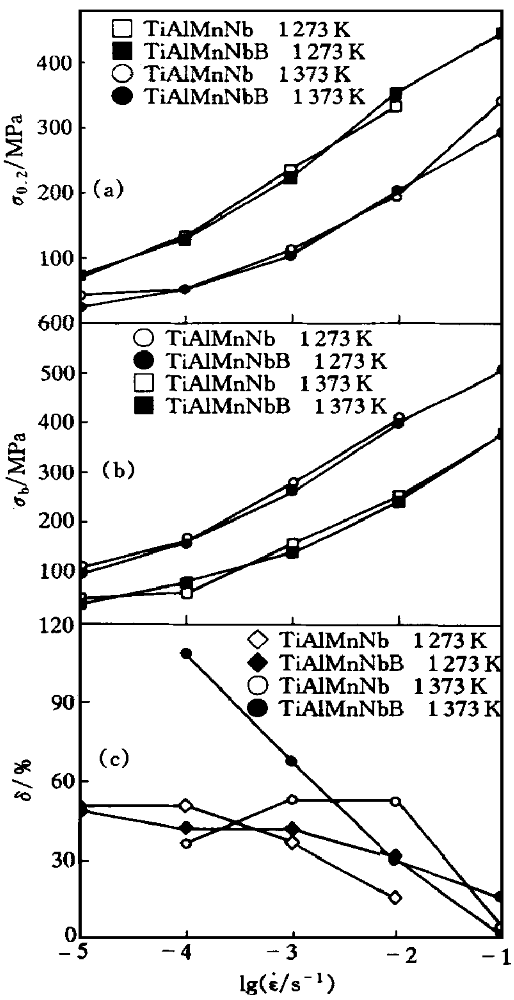

Fig.4 Difference in $\sigma_{0.2}$(a), σ_b(b) and δ(c) between two alloys at 1 273 K(1 373 K) and different strain rates

microstructure refinement. Another evidence for microstructure refinement comes from an estimation using the value of Hall-Petch coefficient $k_y = 4 \sim 5$ MPa·$m^{-1/2}$ estimated by Kim[11] for TiAl alloys with FL or NL microstructure, and the average grain sizes of the two alloys investigated (500 μm vs 90 μm). According to the well known Hall-Petch equation, a difference of about 240 MPa in the strength was expected between the two alloy. The estimated difference agrees well with the actual difference obtained in this paper, 200 ~ 250 MPa (Fig.2 and Fig.3), justifying that grain size reduction is enough to account for the strength improvement below T_{BD}. But at high temperature, as B solubility in γ and α_2 phases increases substantially[6], strengthening of solid-solute boron may contribute to the strength of TiAlMnNbB alloy.

An addition of 0.1 % B to polycrystalline Ni_3Al alloy was found to suppress intergranular failure tendency of the alloy, convert its fracture mode from intergranular failure to transgranular failure, and improve its ductility substantially at room tempera-

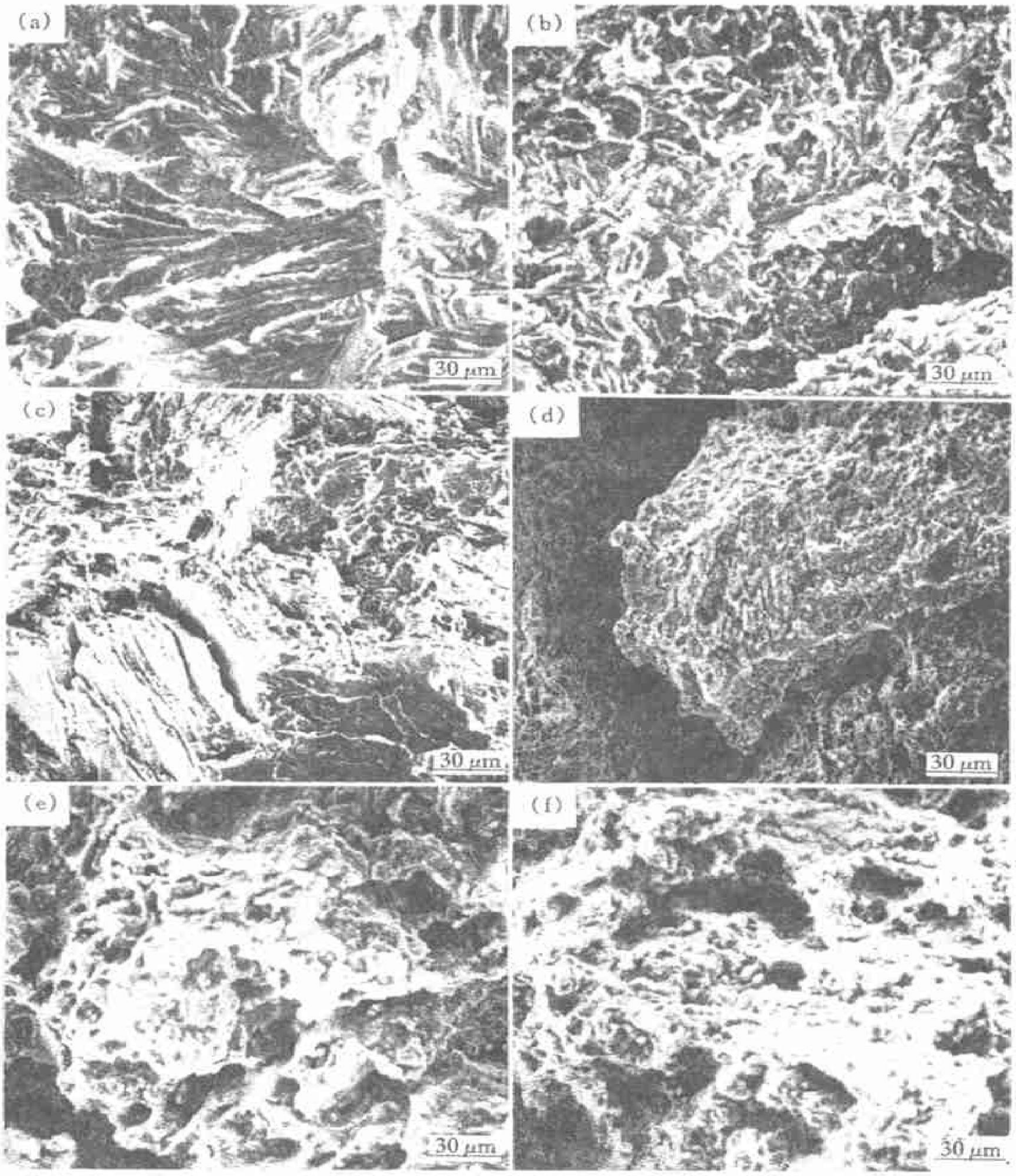

Fig.5 Fractographs of TiAlMnNb ((a),(b),(c)) and TiAlMnNbB ((d),(e),(f)) at 285 K ((a),(b)), 1 073 K ((c),(d)) and 1 273 K ((e),(f)) under strain rate of 10^{-4} s^{-1}

ture[9]. Unfortunately, the similar effect was not reproduced in the investigated TiAl alloy. The brittleness in polycrystalline Ni_3Al alloy is attributed to its weak grain boundary cohesion. The added B, although minor, strongly segregates along grain boundaries, enhances grain boundary cohesion, and suppresses environmental embrittlement through retarding the diffusion of hydrogen atoms along grain boundaries, thereby not only improving its room temperature ductility but also changing its fracture mode. However, the room temperature brittleness in TiAl alloy neither arises mainly from environmental effect, nor from low grain boundary cohesion[5], which was reflected by the minor intergranular failure in the two alloys in this paper (Fig.5(a), (b)). Rather, it is probably caused by the low mobility of its dislocations[1]. Consequently, no matter whether the added B atoms segregate along grain boundaries, so as to enhance grain cohesion and suppresses hydrogen diffusion along grain boundaries, it neither substantially improves the room temperature brittleness in TiAl alloy (Fig.2(b), Fig.3(b)) nor changes the fracture mode (Fig.5(a), (b)). Its limited effect on ductility is realized through microstructure refinement.

At high temperatures, as strength is usually lower along grain boundaries than the inner of grains, fine microstructure tends to have lower strength than coarse microstructure does. But such is not the case in this paper. Fine-microstructured TiAlMnNbB alloy has tensile strength comparable to that of coarse-microstructured TiAlMnNb alloy (Fig.4(a), (b)). Such apparent anomaly is attributed to the above-discussed strengthening from solid-solute boron, to the interlocking of LCs in TiAlMnNbB alloy (Fig.1 (b)), which not only enhances LC cohesion, but also impedes sliding along LC boundaries at high temperatures.

5 CONCLUSIONS

1) An addition of 1.0% (mole fraction) boron effectively refines the nearly lamellar microstructure of the TiAlMnNb alloy, significantly increases its strength and, although to a less degree, improves its ductility below T_{BD}, does not impair its strength above T_{BD}, and is therefore proved to be a potentially effective way to improve comprehensive properties of wrought TiAl alloys.

2) The boron addition does not obviously change the fracture mode except for at temperatures around T_{BD}.

3) The effect of B addition on mechanical properties may be realized mainly through microstructure refinement.

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