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The effect of boron addition on brittle-to-ductile transition temperature and its strain rate sensitivity in gamma titanium aluminide

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Temperature dependence of tensile properties of Ti−47Al−2Mn−2Nb−0.8TiB_2 alloy was investigated and brittle-to-ductile transition temperature (T_{BD}) was evaluated accordingly within the strain rate range from 10^{-5} to 10^{-1} s^{-1}. T_{BD} and its strain rate sensitivity in Ti−47Al−2Mn−2Nb−0.8TiB_2 alloy were compared with those in Ti−47Al−2Mn−2Nb alloy. It is found that the minor addition of 1.0 at% boron reduces T_{BD} by more than 100 K and that T_{BD} in both alloys shows a positive sensitivity to the strain rate. But the B-doped alloy has a lower BDT activation energy (256 kJ/mol) than that of B-free alloy (324 kJ/mol). The effect of boron on T_{BD} and its strain rate sensitivity is attributed to the reduction in the grain size. © *2000 Kluwer Academic Publishers*

1. Introduction

Although gamma titanium aluminides, which are usually composed of a major phase of γ-TiAl and a minor phase of α_2-Ti_3Al, suffer from severe brittleness at low and intermediate temperatures, they tend to exhibit good ductility at temperatures high enough. TiAl alloys manifest brittle-to-ductile transition (BDT) around so called brittle-to-ductile transition temperature T_{BD}, which ranges from 600°C to 820°C, depending on chemical composition and microstructure [1–4]. Those alloys with duplex (DP) microstructure have lower T_{BD} than those with full lamellar (FL) or near lamellar (NL) microstructure [1, 2]. Moreover, T_{BD} was found qualitatively to increase with the strain rate in TiAl alloy with near gamma or DP microstructure by Lipsitts *et al.* [3] and Kumpfert *et al.* [4]. Wang *et al.* [5] have found that T_{BD} increase from 1023 to more than 1373 K when the strain rate increases from 10^{-5} to 10^{-1} s^{-1} for Ti−47at%Al−2at%Mn−2at%Nb (TiAlMnNb) alloy with NL microstructure.

Recently, a minor boron addition to TiAl alloy has been found to refine the grain and improve the strength effectively and improve on the brittleness to some extent [6–8]. Unfortunately, T_{BD} and its strain rate sensitivity has never been evaluated in B-doped TiAl alloy. Based on the previous investigation on T_{BD} and its strain rate sensitivity in TiAlMnNb alloy [5], Ti−47Al−2Mn−2Nb−0.8TiB_2 alloy was chosen in this paper to investigate the effect of boron addition on T_{BD} and its strain rate sensitivity.

2. Experimental

The investigated alloy, Ti−47at%Al−2at%Mn−2at%Nb−0.8vol%TiB_2 (TiAlMnNbB) alloy, was modified from the previously investigated TiAlMnNb alloy. Both alloys were produced by ingot metallurgy. Boron was added to TiAlMnNbB alloy in melting by XD technique. The casting ingots were thermally mechanically processed into about-6-mm-thick plates and heat treated to have NL microstructures at room temperature. Initial microstructures were etched and observed as was described previously [5].

Plate specimens with a gauge section of 15 × 3.5 × 1.8 mm were used. Their preparation has been accounted for previously [5]. Tensile tests were conducted on a Shimadzu AG-100kNA material testing machine [5]. The initial strain rate was chosen as 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2} and 10^{-1} s^{-1}, respectively. The testingtemperature was chosen as 285, 398, 523, 598, 673, 773, 873, 973, 1073, 1173, 1273 and 1373 K, respectively. The fracture morphology was analyzed by a S520-type scanning electron microscope (SEM), operating at an accelerating voltage of 20 kV.

3. Result

3.1. Initial microstructure

TiAlMnNbB alloy has initial NL microstructure shown in Fig. 1, where the initial NL microstructure of TiAlMnNb alloy [5] is juxtaposed for comparison. An addition of 1 at% boron effectively reduced the average

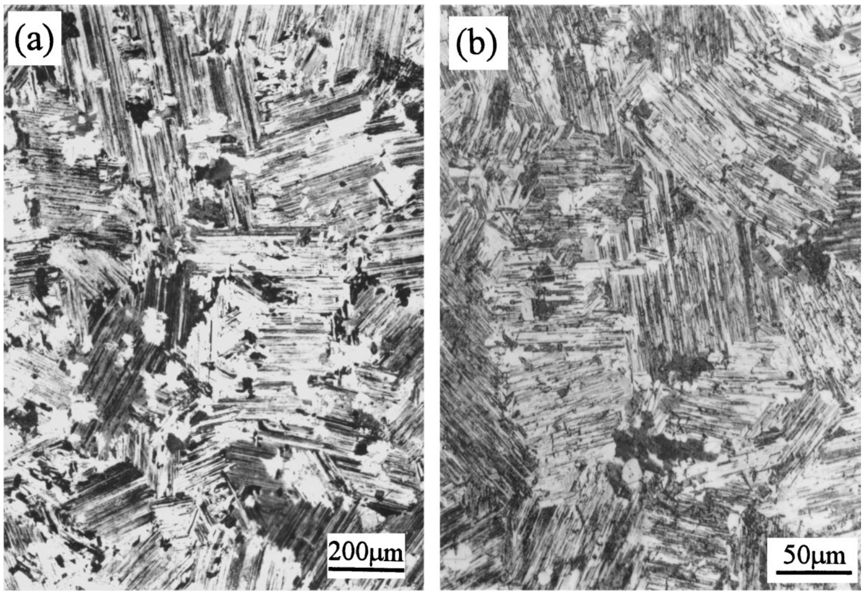

Figure 1 Initial microstructures of TiAlMnNb (a) and TiAlMnNbB (b) alloys.

grain size of about 500 μm in TiAlMnNb alloy to around 90 μm in TiAlMnNbB alloy.

3.2. T_{BD} values of the two alloys under different strain rates

Fig. 2 shows temperature dependence of 0.2% proof strength ($\sigma_{0.2}$) and elongation (δ) of TiAlMnNbB alloy under different strain rates. Given a level of the strain rate, with the increase of temperature, $\sigma_{0.2}$ falls off slowly while δ increases slightly until to a certain high temeprature. Above that temperature, $\sigma_{0.2}$ decreases severely while δ increases dramatiscally, exhibiting BDT. Such temperature dependence of tensile properties was also observed in TiAlMnNb alloy, as is shown Fig. 3 [5]. The values of T_{BD}, quantitatively defined in this and previous papers [5] as the temperature at which the elongation reaches 7.5% under different strain rates, are listed in Table I, where T_{BD} values of TiAlMnNb alloy are also listed for comparison.

Table I confirms that a minor B addition to TiAlMnNb alloy reduces its T_{BD} value by more than

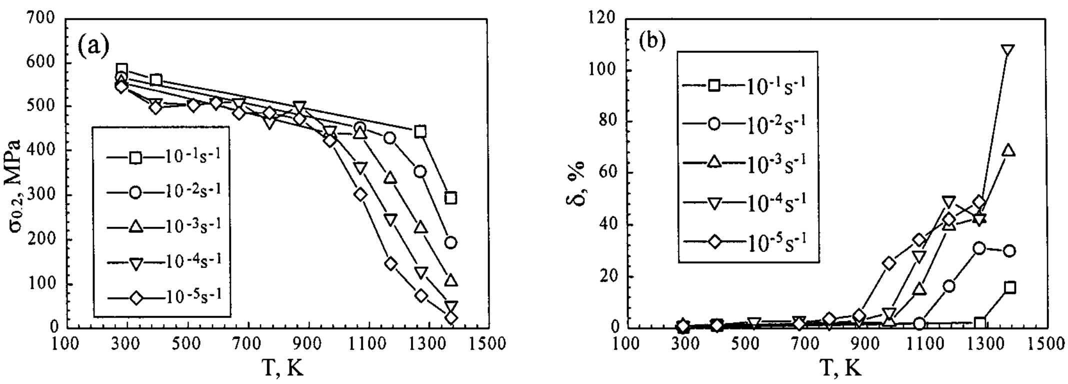

Figure 2 Temperature dependence of $\sigma_{0.2}$ (a) and elongation (b) in TiAlMnNbB alloy.

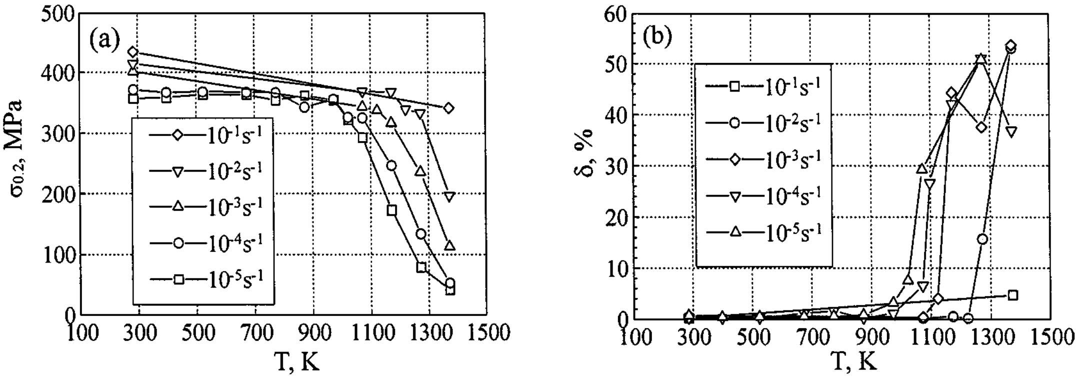

Figure 3 Temperature dependence of $\sigma_{0.2}$ (a) and elongation (b) in TiAlMnNb alloy [5].

TABLE I T_{BD} of TiAlMnNb and TiAlMnNbB TiAlMnNbB alloys at different strain rates

Strain rate (s^{-1}):		10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}
T_{BD}, K	TiAlMnNb [5]	1023	1098	1173	1273	>1373
	TiAlMnNbB	885	980	1015	1110	1310

100 K. T_{BD} in TiAlMnNbB alloy, just as that in TiAlMnNb alloy [5], shows a positive strain rate sensitivity. Its value rises from 1023 K to more than 1373 K for TiAlMnNb alloy and from 885 K to 1310 K for TiAlMnNbB alloy when the strain rate is lifted from 10^{-5} s^{-1} to 10^{-1} s^{-1}.

3.3. The effect of strain rate on tensile properties

Fig. 4 exhibits the variation of tensile properties of TiAlMnNbB alloy with the strain rate at a typical temperature of 1073 K. With the increase of the strain rate, $\sigma_{0.2}$ increases monotonically while δ decreases steadily down to a brittle level (<7.5%). Similar variation trend was observed in TiAlMnNb alloy [5]. It can be drawn from Figs 3 and 4 that, just as in TiAlMnNb alloy, raising the strain rate and lowering the temperature produced equivalent effects on tensile properties in TiAlMnNbB alloy, and, that not only the variation in temperature, but also the variation in the strain rate can bring about BDT. This indicates that BDT in the B-doped alloy, just as that in the B-free alloy [5], is a thermally activated process.

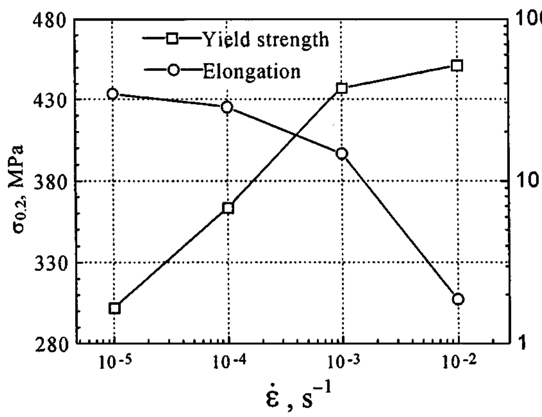

Figure 4 Variation of $\sigma_{0.2}$ and δ with the strain rate $\dot{\varepsilon}$ at 1073 K in TiAlMnNbB alloy.

3.4. Fractography

Figs 5 are SEM fractographs from TiAlMnNbB alloy samples fractured at the strain rate of 10^{-4} s^{-1}. Transgranular cleavage and inter-granular separation appear to be the predominant modes of failure below T_{BD} (Fig. 5a). Dimples start to burst out around T_{BD} (Fig. 5b), above which the entire fracture surface is full of dimples (Fig. 5c).

Fig. 6 demonstrates SEM fractographs at 1073 K. Under the strain rate of 10^{-5} s^{-1}, with the corresponding T_{BD} (885 K) lower than the testing temperature, the fracture mode is dimple failure (Fig. 6a) while under the strain rate of 10^{-2} s^{-1}, with the corresponding T_{BD} higher than the testing temperature, the fracture mode is mainly transgranular cleavage (Fig. 6b).

4. Discussion

A careful comparison between tensile properties of TiAlMnNb and TiAlMnNbB alloys (Figs 2 and 3) reveals that the minor B addition raises the strength substantially and raises the ductility considerably at low and intermediate temperatures. Meanwhile, the addition does not impair the strength or ductility at high temperatures. As a result, T_{BD} decreases.

There are three ways for B atoms to distribute in wrought TiAl alloy: to be present as solid-solution in the matrix phase of γ-TiAl, to precipitate as dispersed TiB_2 particles and to segregate along grain boundaries [9]. The finer microstructure of TiAlMnNbB 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 out by Larsen [6] and Pu [9]. Accordingly, B addition is expected to influence mechanical properties of TiAl alloy through the following three mechanisms: solid-solution strengthening, dispersion strengthening and microstructure-refining strengthening. As the solubility of B in Ti−48Al−2Mn−2Nb,

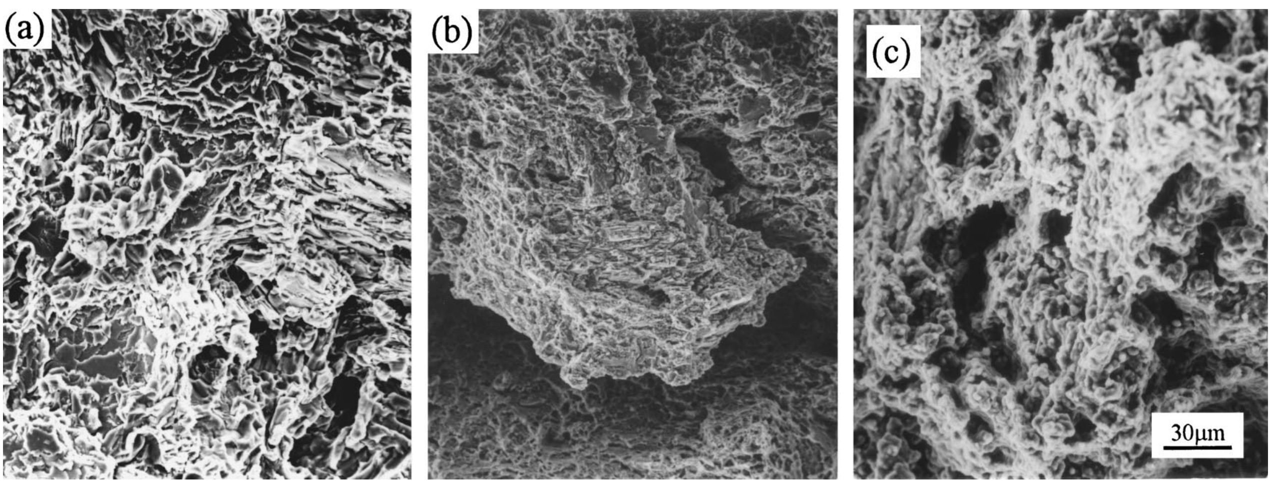

Figure 5 Fractographs of TiAlMnNbB alloy at 973 K (a) 1073 K (b) and 1173 K (c), $\dot{\varepsilon} = 10^{-4}$ s^{-1}.

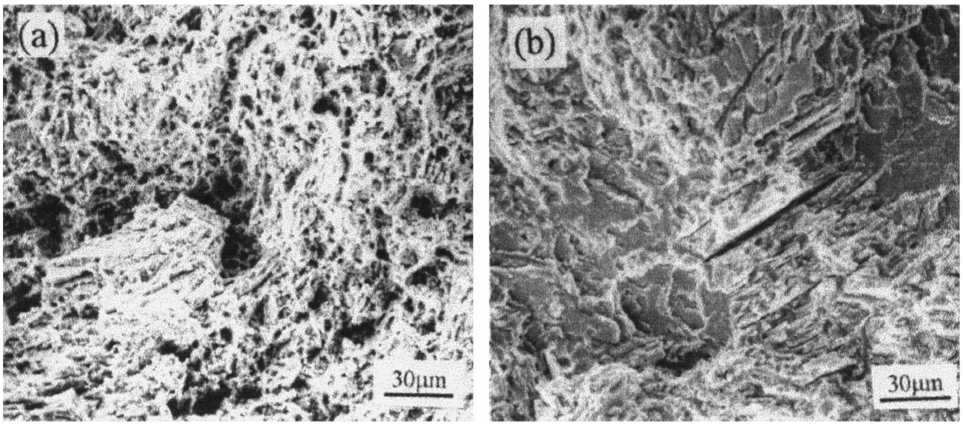

Figure 6 Fractographs of TiAlMnNbB alloy at 1073 K, $\dot{\varepsilon} = 10^{-5}$ s^{-1} (a), 10^{-2} s^{-1} (b).

which is almost identical to TiAlMnNb alloy in chemical composition, is no more than trace level of 0.01 wt% (~0.035 at%) [10], less than the concentration of impure oxygen in conventional TiAl alloys (~0.2 at%) [8, 9], and because TiB_2 particles take up only 0.8% volume of TiAlMnNbB alloy, the solid-solution strengthening and dispersion strengthening produced by the B addition should be excluded from the main mechanism for the improvement on mechanical properties and the microstructures-refining has to be attributed the improvement to. An evidence is the concurrent improvement on strength and ductility, which can not be realized by the two excluded mechanisms.

As can be seen from Figs 4 and 5, just as in TiAlMnNb alloy, BDT in TiAlMnNbB alloy, either caused by variation in the temperature or in the strain rate, concurs with the burst of dimples on the fracture surface. The concurrence justifies the definition of T_{BD} as the temperature corresponding to 7.5% elongation. Furthermore, from the similarity between Figs 5a and 6b, Figs 5c and 6a, increasing strain rate and lowering temperature are found to make equivalent effects on the fracture mode, just as on tensile properties.

The strain rate dependence of T_{BD} values for the two alloys, listed in Table I, shows the existence of linear relationship between the natural logarithm value of the strain rate (ln $\dot{\varepsilon}$) and $1/T_{BD}$ (Fig. 7), which appears to fit Arrhenius equation and yields activation energies of 324 and 256 kJ/mol for TiAlMnNb and TiAlMnNbB alloys, respectively. The two activation energies approximate to 291 kJ/mol [11], the self-diffusion activation energy of Ti atoms in TiAl phase, and 295 kJ/mol [12], the inter-diffusion activation energy of Ti and Al atoms in TiAl phase. The approximation leads to the speculation that BDT in the two TiAl alloys is controlled by an atomic diffusion process. Such an atomic diffusion process, in the view point of dislocation motion, has been found to be dislocation climbing by TEM [13].

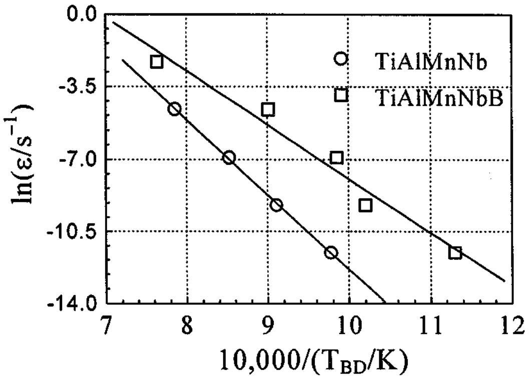

Figure 7 Linear relationship between ln $\dot{\varepsilon}$ and $1/T_{BD}$.

When dislocation climbing is considered to be responsible for the BDT in TiAlMnNb and TiAlMnNbB alloys, the reduction in activation energy with the addition of boron can be explained. Dislocation climbs not only inside grains, which are actually lamellar colonies in the case of NL microstructure, but also along grain boundaries. It is well known that the activation energy of atomic diffusion along grain boundaries is lower than that in bulk. The finer the grains, the higher the volume fraction of grain boundaries, and the lower comprehensive activation energy of dislocation climbing, atomic diffusion in nature, for the entire alloy. In short, the reduction in apparent activation energy of BDT in wrought B-doped TiAl alloy also results from microstructure refinement produced by boron addition.

5. Conclusion

(1) Variation either in temperature or in the strain rate may cause brittle-to-ductile transition in wrought B-doped TiAl alloy. Transgranular cleavage and intergranular separation are the predominant fracture mode below T_{BD} while dimple failure is the main fracture mode above T_{BD}.

(2) An addition of 1 at% boron to wrought TiAlMnNb alloy reduces its T_{BD} value by more than 100 K within the strain rate range from 10^{-5} to 10^{-1} s^{-1}.

(3) T_{BD} also manifests positive sensitivity to the strain rate in B-doped TiAlMnNbB alloy: when the strain rate increases from 10^{-5} s^{-1} to 10^{-1} s^{-1}, its value rises from 885 K to 1310 K. But the corresponding activation energy (256 kJ/mol) in the B-doped alloy is lower than in the B-free alloy (324 kJ/mol).

(4) The effect of boron addition on T_{BD} and its strain rate sensitivity is regarded to be realized mainly by microstructure refinement.

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