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High strain rate tensile properties of a TiAl alloy in duplex and fully lamellar microsturctural forms①

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Abstract: A self-designed Split-Hopkinson tensile bar setup with a rotating disk was used to investigate room-temperature tensile properties of a γ-TiAl alloy in duplex (DP) and fully lamellar (FL) microstructural forms under the dynamic strain rates between 70 and 800 s^{-1}. It was found that for both forms the alloy is brittle at these strain rates, exhibiting near-zero ductility. The σ_b at dynamic strain rate is greater than that at the static strain rate of $5\times10^{-1}\ s^{-1}$, and the σ_b of the DP material is higher than that of the FL material. Fractography analysis indicated that both materials at dynamic strain rates fracture in a mixed mode of predominant transgranular cleavage and minor intergranular cracking, which is similar to that at the static strain rate. The room-temperature brittleness of the alloy is not environmentally related.

Key words: titanium aluminide; tensile property; high strain rate **Document code: A**

1 INTRODUCTION

Two-phase γ titanium aluminides, composed of a major phase of γ-TiAl and a minor phase of α_2-Ti_3Al, have received significant attention because of their high specific strength and stiffness, excellent oxidation resistance, and low density[1]. As the alloys are expected to be used as structural materials, their mechanical properties have been evaluated extensively. However, the investigation is far from being complete. Almost all of the investigations on the mechanical properties of TiAl alloys have been limited to static or quasi-static loading, at strain rates lower than 10 s^{-1}. In the process of machining and utilization, however, parts made of TiAl alloys may be subjected to dynamic and/or shock loading, which necessitates the understanding of mechanical behaviors under high, or dynamic strain rates. Although there are several reports dealing with mechanical responses to high-rate loading using Split-Hopkinson pressure bar technique for TiAl alloys, the deformation modes have been limited to compression[2~5]. Two exceptions were the recent investigations on dynamic tensile properties of polysynthetically twinned TiAl crystal and Ti-45Al-1.6Mn with duplex microstructure made by Chen *et al*[6] and Sun *et al*[7], respectively. In this experiment, a self-designed Split-Hopkinson Tensile Bar (SHTB) setup was used to study tensile behaviors of Ti-47%Al-1.5%Cr-0.5%Mn-2.8%Nb in both duplex and fully lamellar microstructural forms under the strain rates between $5\times10^{-4}\ s^{-1}$ and 800 s^{-1}.

2 EXPERIMENTAL

The starting material was a forged plate of alloy Ti-47%Al-1.5%Cr-0.5%Mn-2.8%Nb (mole fraction). Two sample pieces from the plate were heat-treated at 1 290 ℃ for 3 h and at 1 385 ℃ for 20 min, respectively, and furnace cooled to 900 ℃, followed by air cooling to room temperature. These resulted in duplex (DP) and fully lamellar (FL) microstructures, respective-

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ly. The samples were then aged at 900 ℃ for 6 h and air cooled to room temperature. The specimens were etched with a solution of 2.5 % HF + 2.5 % HNO_3 + 95 % H_2O (volume fraction), and were observed under the optical microscope.

Flat tensile specimens, with gauge size of 18.0 mm × 3.2 mm × 2.0 and 8.0 mm × 4.0 mm × 1.3 mm for static and dynamic testing, respectively, were cut from the heat-treated samples by EDM (electro-discharging machining). Their surfaces were carefully ground using emery paper and then mechanically polished using W1 diamond paste. Static tensile tests were conducted on a Shimadzu AG-100kNA testing machine at room temperature under the strain rate of $5 \times 10^{-4} s^{-1}$. Dynamic tensile tests were carried out on a self-designed SHTB apparatus whose setup is shown in Fig. 1. Its measuring principle will be described in details elsewhere[8]. Fracture surfaces of the specimens tested at static and dynamic strain rates were studied under S520 scanning electron microscope (SEM).

3 RESULTS

Both DP and FL microstructures are shown in Fig. 2. DP material consisted of mainly equiaxed gamma grains (grain size GS is 25 μm) with fine (not resolved in Fig. 2(a)) α_2 particles, while FL material consisted of lamellar colonies averaged to be about 1 600 μm (Fig. 2 (b)).

Fig. 3 shows the tensile stress-strain curves of DP and FL specimens at the strain rates between $5 \times 10^{-4} s^{-1}$ and $800 s^{-1}$. The deformation was mainly in the elastic stage, with short plastic flow. The ultimate tensile strengths (σ_b) were determined and were plotted against strain rate in Fig. 4(a). For both microstructures, the σ_b at dynamic strain rates ($\geqslant 70 s^{-1}$) is higher than that at the static strain rate of $5 \times 10^{-4} s^{-1}$. DP material exhibits higher σ_b than FL material at both dynamic and static strain rates. As strain rate increases, σ_b increases gradually for FL material while, for DP material, it increases to a plateau value at strain rate of $70 s^{-1}$ and then decreases to lower values which, however, are still higher than that at $5 \times 10^{-4} s^{-1}$. For all conditions, the plastic strain was measured to be less than 0.2 %, as shown in Fig. 4(b).

Fig. 5 shows fractographs of DP and FL materials failed at the strain rate of $800 s^{-1}$. Similar fracture surfaces were observed on the specimens failed at other dynamic strain rates. Both materials showed predominantly transgranular cleavage-like failure, which was manifested by fully developed "river" patterns on the fracture surfaces for DP specimens, and both translamellar and interlamellar fracture for FL specimens. Moreover, no apparent differences in fracture mode were observed between dynamic and static strain rates for both materials.

4 DISCUSSION

Further experimental investigation is needed

Fig. 1 Sketch of tensile impact setup
1 —Hammer; 2 —Block; 3 —Short metal bar; 4 —Input bar;
5 —Specimen; 6 —Output bar; 7 —Strain gauges

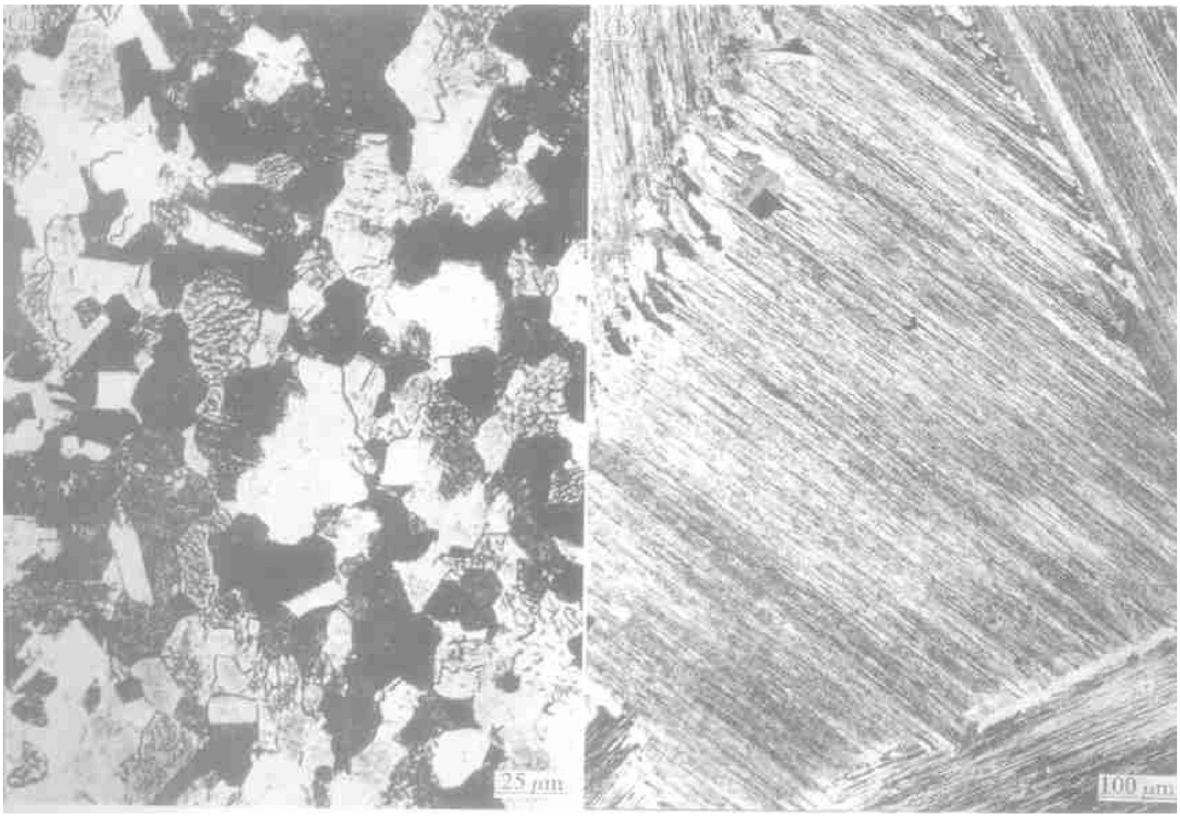

Fig.2 Initial microstructures
(a) —DP; (b) —FL

Fig.3 Tensile curves of TiAl alloy with DP (a) and FL (b) microstructures at different strain rates

to interpret why the dynamic σ_b of the DP mate- rial levels off and even decreases slightly with the

Fig.4 Strain rate dependence of σ_b(a) and elongation (b) for TiAl alloy with DP and FL microstructures

strain rate while that of FL material increases gradually. If the error range is taken into account, the data shown in Fig.4(a) may actually indicate that after an initial rapid increase, the dynamic σ_b of DP materials is insensitive to the strain rate, which was also reported in Ref.7.

Several explanations have been made for the causes of room-temperature brittleness of γ-TiAl alloy under static strain rates. These include low mobility of dislocations[9], directional bonds of Ti—Ti and Ti—Al[10], or low cohesive strength along γ/γ and γ/α_2 interface[11]. These explanations also seem true at dynamic strain rate. One possible macroscopic evidence is that similar fracture modes were observed under dynamic and static strain rates. Sun *et al*[7] also pointed out that dislocation motion becomes sufficiently difficult in Ti-45Al-1.6Mn alloy at high strain rates.

A question arises whether environmental embrittlement plays an important role in the embrittleness of the alloy. If the environmental effect plays a main role, the ductility is expected to rise as the strain rate is raised from static to dynamic levels. As the investigated alloy has elongation less than 0.2%, its plastic deformation under a strain rate higher than $10\ s^{-1}$ was completed within 2×10^{-4} s. In such a short time, it is hardly imaginable for atomic hydrogen to generate through surface chemical reaction[12] and to diffuse to the tip of cracks to embrittle the alloy. The fact that neither DP nor FL material exhibited higher dynamic ductility than static ductility (Fig.4(b)) rules out the possibility of environmental embrittlement as the main cause of room-temperature brittleness of the alloy.

It is noteworthy that the alloy partly fractures intergranularly (DP material) and along interlamellar boundaries (FL material). Since almost no plasticity was observed under the dynamic loading conditions, the deformation incompatibility may explain these boundary fractures occurring even at the elastic deformation stage. This implies that the cohesive strengths of some boundaries are lower than the cleavage strength of the materials at room temperature. It is speculated that there exist some elements enhancing boundary cohesion and that their additions may help to increase the ductility.

5 CONCLUSIONS

(1) Ti-47%Al-1.5%Cr-0.5%Mn-2.8%Nb(mole fraction), in both duplex (GS is 25 μm) and fully lamellar (GS is about 1600 μm) microstructural forms, exhibits brittle fracture at room temperature under strain rates of $5\times10^{-4}\ s^{-1}$ and $70\sim800\ s^{-1}$, with almost no ductility.

(2) For both forms, σ_b increases when the strain rate increases from static to dynamic levels, with σ_b of DP material being consistently higher.

(3) At all strain-rates, both materials fracture predominantly by transgranular cleavage, with occasional boundary failure.

(4) Environmental embrittlement does not play a main role in the room-temperature brittleness of the TiAl alloy.

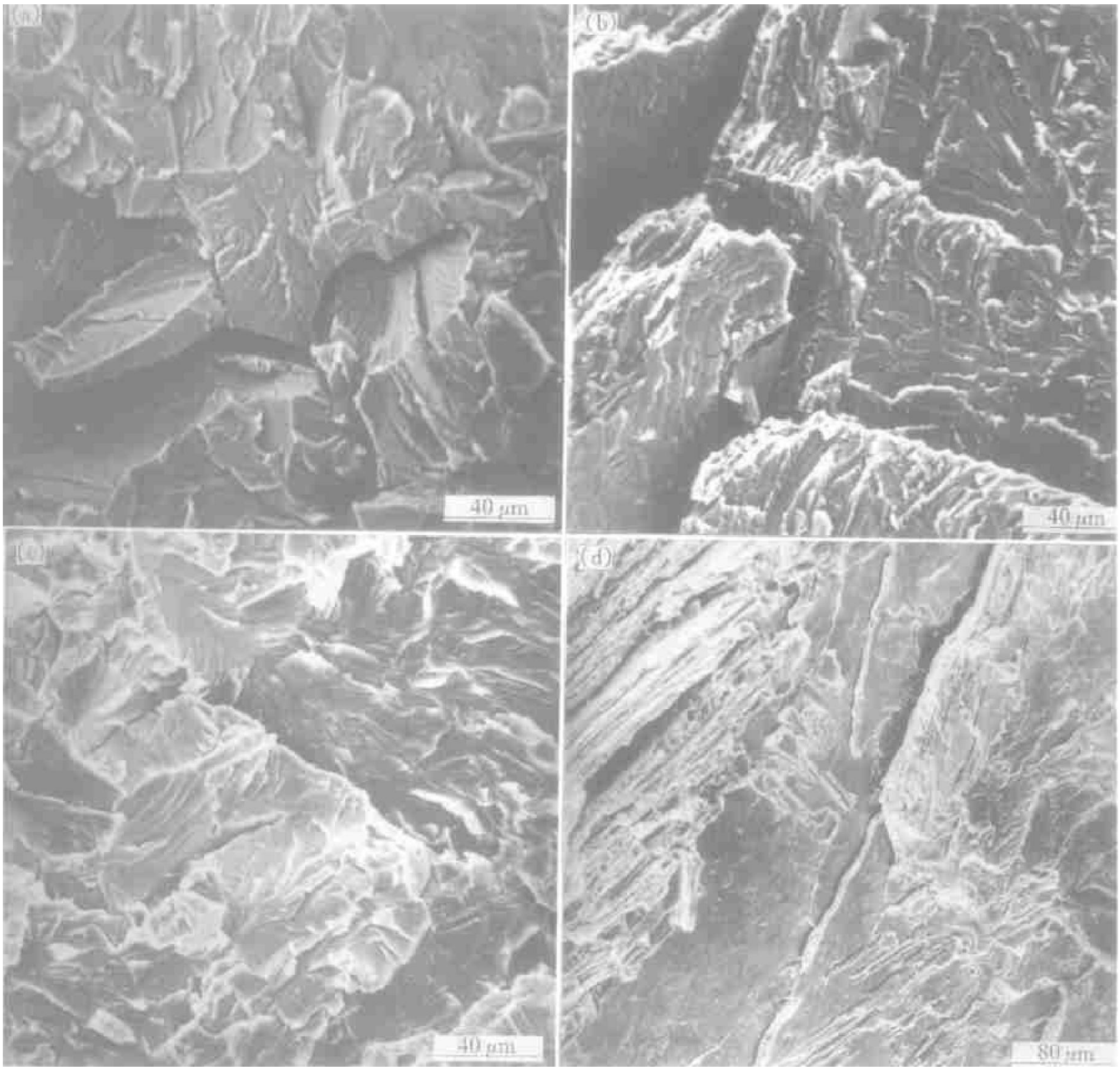

Fig.5 SEM fractographs of DP (a,c) and FL (b,d) specimens fractured under dynamics (a,b) and static (c,d) strain rates

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