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Fracture behavior of lamellar structure in Ti-48Al-2Mn-2Nb alloy produced by centrifugal spray deposition ①

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[Abstract] The effects of lamellar structure on deformation and fracture behavior in a Ti-48Al-2Mn-2Nb alloy produced by centrifugal spray deposition(CSD) were investigated. The deformation and fracture of samples after tensile and compressive tests were examined in a scanning electron microscope (SEM). The in situ tensile testing was further carried out in a SEM and the crack growth path of samples was observed. The result shows that there is a remarkable effect of lamellar structure of CSD TiAl alloy on its deformation and fracture process. Especially, the main crack extension is dependent on the lamellar direction relative to tensile loading axis. SEM observations indicate that there is a shielding toughening effect of lamellar structure on fracture in CSD samples, such as, crack deflection, crack path tortuousity, and crack branching, etc. Moreover, the crack growth path shows that the main crack grows tortuously and uncontinuously by ligaments bridging many microcracks in front of crack tip. The effect mechanism of microstructure on deformation and fracture process is discussed.

[Key words] Ti-48Al-2Mn-2Nb; centrifugal spray deposition(CSD); lamellar structure; deformation fracture
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1 INTRODUCTION

In recent years, a great deal of attention has been paid to gamma titanium aluminides because of their potentially attractive properties for high-temperature structural applications[1~3]. A lot of fundamental studies on gamma titanium aluminides have been made worldwide to further understand the relationship between their microstructure and mechanical properties[2~6]. However, because the ordered crystal structure of TiAl retards dislocation motions and offers only a limited number of independent slip systems, it shows poor ductility and low fracture toughness at ambient temperature. It is well recognized recently that the new forming processes, such as powder metallurgy and spray forming, can provide TiAl intermetallics with homogeneous and fine microstructure so that they could be beneficial to the ductility at room temperature. It should be noted that the spray forming process has been developed, and especially, a processing technique —so called "centrifugal spray deposition (CSD" has been successfully used to produce the preform of titanium aluminides in the University of Birmingham[7,8]. The advantages of CSD over more traditional metal forming processes include better chemical homogeneity and more refined microstructure than that by ingot metallurgy, lower interstitial contamination and higher density than that by powder metallurgy, and the production of preform shapes without the need for difficult thermo-mechanical working. Spray forming is a single stage process with forming and consolidating the powders within the same chamber, and especially, CSD is atomized under the atmosphere of argon or vacuum without the aid of gas jet so that no reaction of oxidation should occur. However, few studies about the microstructure and mechanical properties of the processed alloys have been reported so far. Moreover, the research results of the authors proved that the plasticity of Ti-48Al-2Mn-2Nb alloy could be improved by centrifugal spray deposition (CSD)[9,10]. In this study, the deformation and fracture behavior of Ti-48Al-2Mn-2Nb alloy produced by CSD are investigated, and especially, the effects of lamellar microstructure on the fracture behavior during plastic deformation are discussed in detail.

2 EXPERIMENTAL PROCEDURE

2.1 Material preparation

The material used in this study was from the spray forming preform of TiAl-based intermetallics with a nominal composition of Ti-48Al-2Mn-2Nb (mole fraction, %), which was produced by CSD under a low vacuum pressure condition, at IRC in Materials for High Performance Applications, the University of Birmingham, UK. A TiAl ingot was first cast from elemental stock in the plasma-melting fur-

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nace. The spray forming chamber was bolted underneath the melting chamber. The melting and spray forming operations were monitored by a series of sensors linked to a data acquisition system. The bottom poured molten stream from the remelting crucible fell freely on to a water-cooled copper disc that rotated at about 3 000 r/ min, which was 250 mm below the nozzle. Thus centrifugal forces broke up the stream into droplets, which were sprayed approximately horizontally onto the inside surface of a preset steel substrate to produce a ring preform of 400 mm in diameter, 150 mm in height and 10 mm in thickness[7,8].

2.2 Microstructure and deformation observation

The section of CSD TiAl ring preform was center-cut into some samples for microstructure and properties studies. Some samples were well polished and then etched using a Kroll's II etching reagent for OM and SEM observations. A check of chemical homogeneity of samples was also carried out by chemical analysis and on a SEM using EDX system, respectively.

Tensile, compressive and fracture toughness tests were conducted in air at room temperature using an INSTRON 1185 machine. Especially, the interrupted compressive tests at various strain levels were adopted to examine the deformation, initiation and growth of microcracks, and fracture behavior of TiAl intermetallics. The interrupted compressive tests were performed at an ambient temperature with the pre-strains of 1 %, 3 %, 5 %, 10 % and 20 % respectively at a strain rate of 1×10^{-4} s^{-1}. The specimens were machined into 4 mm × 4 mm × 8 mm. Each side of the surfaces was well mechanically polished and one side was etched for surface appearance observation. To avoid the end effects, the upper and lower contact surfaces of the specimens were lubricated before loading. The surface appearance of deformation and fracture behavior of samples, which experienced different strains, were observed in a JSM-35CF scanning electron microscope.

2.3 SEM in situ tensile tests

The specimens for in situ tensile tests were prepared using EDM from CSD TiAl blanks. They were mechanically ground, well polished and etched to thin slices with gauge dimensions of 0.1 mm × 3 mm × 38 mm with a single-edge notch length of 0.5 mm. An in situ tensile test was carried out within the chamber of a JSM-35CF scanning electron microscope equipped with a loading stage to investigate the deformation, the crack growth path and the fracture procedure of samples.

3 RESULTS AND DISCUSSION

3.1 Microstructure of CSD Ti-48Al-2Mn-2Nb

The optical micrographs of the CSD samples of Ti-48Al-2Mn-2Nb alloy show a typical lamellar microstructure in Fig.1. It consists of fine and random arrangements of lamellar colonies with some small pores, which are much finer than that of ingot metallurgy and much higher dense than that of powder metallurgy. The average size of lamellar colonies is found to be about 50 ~ 200 μm in diameter. Within a lamellar colony, the laths of lamellar align themselves in nearly the same orientation in which the plates are parallel. But, they are random arrangements from one lamellar colony to another which intersect each other serrated-like among the colonies and no obvious normal grain boundaries are formed. No abnormal lamellar characterization is found in OM observation. The lamellar structure of the CSD samples, in which the spacing of laths varies from 1 μm to 2 μm, was also observed using TEM and analyzed by diffraction patterns using selected area electron diffraction (SAED)[10]. The 2 % porosity level of the samples was quantitatively measured using a Quantimet Image Analyze System. The interstitial pick up shows that there exist (300 ~ 750) $\times 10^{-6}$ of oxygen and (100 ~ 200) $\times 10^{-6}$ carbon (mass fraction).

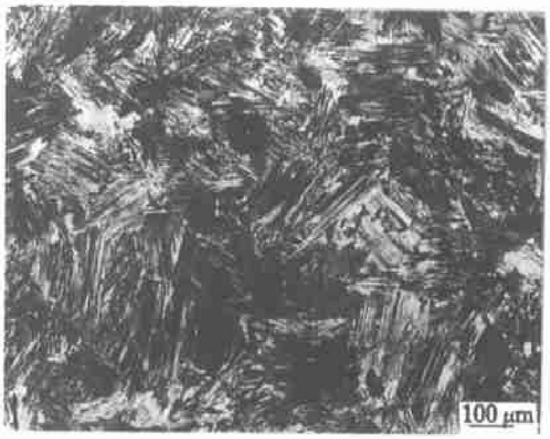

Fig.1 OM micrograph of CSD Ti-48Al-2Mn-2Nb samples

3.2 Deformation and fracture process of lamellar structure

The mechanical properties of the CSD samples have been investigated. The tensile, compressive and bending tests were carried out at ambient temperature. The results show that the elongation for the CSD samples is 2.8 %, while the maximum compressive ratio is 37.8 % that has excellent compressive properties with a higher compressive strength 2 210 MPa. An outstanding advantage of the CSD materials is the quite high plasticity obtained in compression conditions. The deformation and fracture mechanisms were well characterized by means of a series of compressive strain tests. Fig. 2 shows the crack initiation and growth of CSD TiAl samples under compression condition. Fig.2(a) shows that the

Fig.2 SEM micrographs showing crack initiation and propagation under compression condition
(a) —1 % strain; (b) —5 % strain; (c) —10 % strain

initiation of microcracks is mainly concentrated on some lamellar; Fig.2(b) indicates the direction of crack extension; and it is obvious from Fig.2(c) that the cracks can initiate and extend in many places not just along a single way, and one can also find out the phenomenon of "lamellar extrusion" on the surface of samples[9]. In fact, the CSD specimens can be deformed severely up to more than 30 % strain although some microcracks have reached to about 10, 100 and 200 μm at strain levels 1 %, 5 % and 10 % respectively, and the crack density also increases with increasing strain levels. It should be also noted that the slip bands or lines, which occurred under the compressive stress, are well related to the lamellar structure. The result shows that there is a remarkable effect of lamellar structure on the deformation and fracture process. The main crack extension depends on the lamellar direction relative to the tensile loading axis. The observation of plastic deformation of samples shows the uneven deformation in lamellar structure. Under the loading, the process of deformation of lamellar structure is related to the orientation with the stress. Especially, there are some lamellar domains that are easy to deform and produce microcracks first. An interesting result is believed that slip runs along the interfaces between the lamellae under the compressive stress, but cracks open nearly perpendicular to the lamellae nor along the interfaces between the lamellae[9], as shown in Fig.2.

Fig.3 shows the fractographs of samples by tensile and compressive tests. The fractograph of tensile sample (Fig.3(a)) shows the feature of brittle fracture mode which characterised as mainly transgranular cleavage fracture, and with some inter-lamellar and trans-lamellar fracture. The fractograph of compression sample (Fig.3(b)), however, shows that the fracture is mainly trans-lamellar with the direction perpendicular to the lamellar interfaces. More attention should be paid to some curved or bend traces of lamellar in the compression fractograph. The specimens for compression show some ductile appearances (actually the local gamma lamellar colonies are apparently deformed), while the specimens for tensile test display mainly inter-lamellar or trans-lamellar fracture. Usually, the fracture surface appears rougher with more inter-lamellar fracture or a mix of inter and trans-lamellar, in predominantly trans-lamellar fracture with occasional inter and intra-lamellar facets. Fracture surface mode was transgranular cleavage or microcleavage which was less sensitive to the colony orientation dominant but to the direction with the tensile loading axis. Our previous work[9] also showed that the slip bands on the surfaces of CSD specimens after compression is strongly related to the lamellar structure of TiAl.

3.3 Crack growth in SEM in situ tensile tests

The initiation and growth processes of microcracks in near crack tip regions were investigated by in situ tensile tests using SEM. The typical observations of crack growth paths are shown in Fig.4.

The crack growth path of CSD TiAl sample shows the main crack grows tortuously and uncontinuously by ligaments bridging many microcracks in front of crack tip under the tensile loading. It should be noted that the crack growth does not grow preferentially along lamellar lath interfaces or develop along the lamellar colony boundaries. If the lamellar direction is perpendicular to the tensile loading axis, the main crack extension occurs fairly easily, whereas the lamellar direction is unfavorable, so that there will be

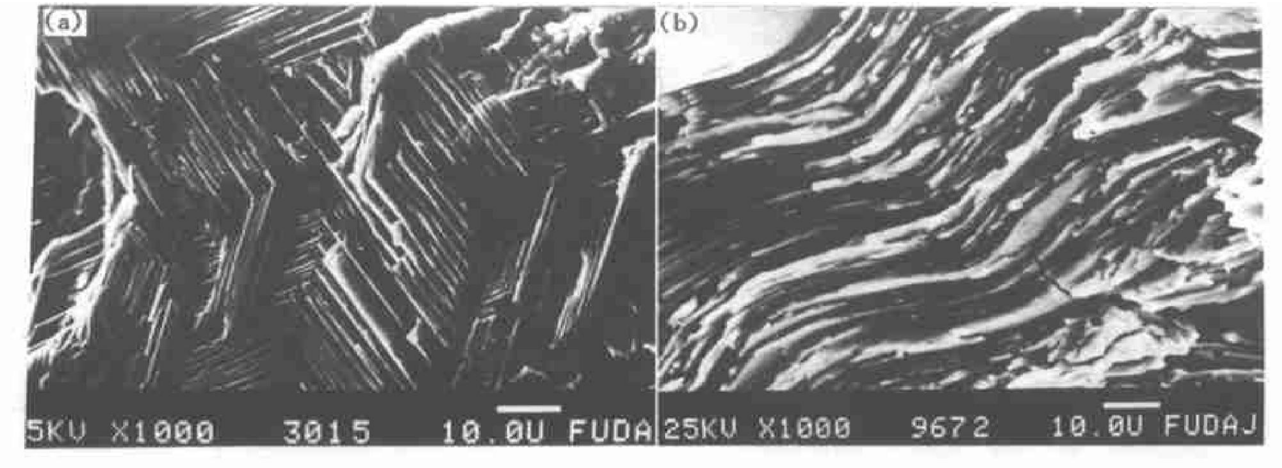

Fig.3 SEM fractographs of CSD Ti-48Al-2Mn-2Nb samples after tension (a) and compression (b)

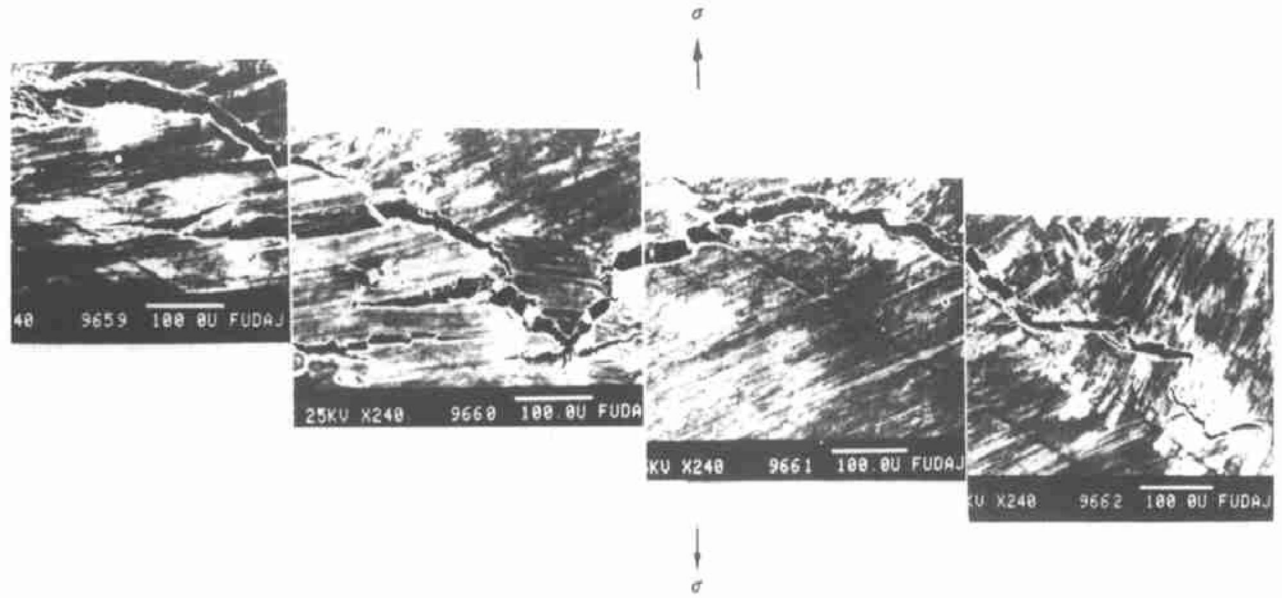

Fig.4 SEM in situ observation of crack growth path of CSD TiAl samples

numerous microcracks ahead of the main crack. There is a considerable amount of evidence from SEM observations indicating shielding toughening of lamellar in CSD samples, such as, crack deflection, crack path tortuosity, and crack branching, etc. It indicates that the lamellar structure could undertake large strains in crack tip, which could relax the stress contraction. There is a large crack growth resistance when the crack crosses different lamellar domains with random orientations and connects the microcracks. It is clear that the lamellar structure appears its excellent deformation ability of resisting the crack growth under tensile loading and makes a contribution to improve the crack growth resistance. The crack advances then strongly depends on the underlying microstructure and tends to produce a tortuous crack path.

Moreover, different crack growth models were found by SEM observations. As mentioned above, there are shielding toughening (crack deflection, crack path tortuosity, crack branching, etc), ligament toughening and microcrack toughening in the crack growth process as CSD lamellar domains are finer and random orientations. Here ligament toughening should be stressed, which is one of the most important toughening models in TiAl alloys, as shown in Fig.5. This is considered to be a consequence of shielding effects from crack deflection and branching, and most importantly, from bridging by shear ligaments, in fact, lath colonies is the crack wake. Previous studies on fatigue[11~13] have also suggested the superior fracture resistance of lamellar structure. The details of this phenomenon are under investigation.

4 CONCLUSIONS

1) CSD Ti-48Al-2Mn-2Nb alloy shows a fine

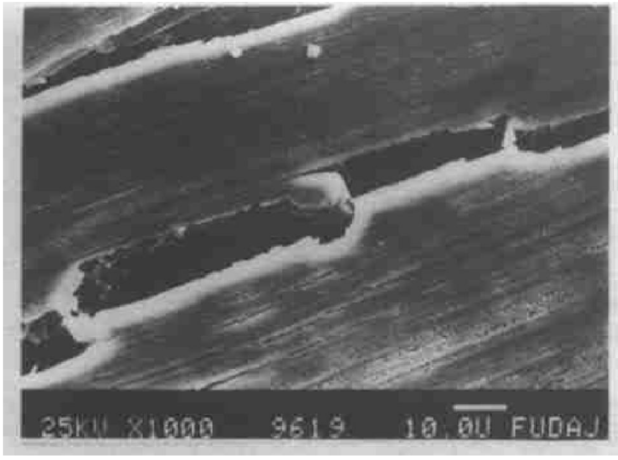

Fig.5 Ligament toughening in lamellar structure of CSD samples

and random arrangement of fully lamellar structure about 50 ~ 200 μm in diameter. There is a remarkable effect of the lamellar structure on resisting deformation and fracture process. The main crack extension is dependent on the direction of lamellar relative to loading axis.

2) SEM in situ tensile observation found that the main crack path of CSD samples grows tortuously and discontinuously by ligaments bridging many microcracks in front of crack tip.

3) The lamellar structure of CSD TiAl shows shielding toughening, ligament toughening and microcrack toughening during fracture.

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