Observation of Microfracture Process of TiAl-based Alloy

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Interaction of microfracture and lamellar microstructure has been studied using acoustic emission method and TEM observation. Ti-34Al-1Mn, -3Mn(wt%) alloy was prepared by arc-melting in Ar atmosphere. During the fracture toughness test microfracture behavior was monitored by acoustic emission method. Tests were stopped before the unstable fracture to facilitate a detailed study of the microfracture process. Then the specimens were sectioned at the plane in the thickness direction and examined using optical microscope. TEM foils were prepared by mechanical grinding to 0.1mm thickness, ultrasonic cutting, dimpling, and finally ion milling. Then the cracks formed in the foils were observed. AE behavior was found to vary with the orientation relationship between crack propagation and lamellar interfaces. Crack propagation behaviors parallel and across the lamellar interfaces were observed by TEM. A close-up view of the crack across the lamellar interfaces showed that the crack went approximately straight in the lamellae, but was deflected by lamellar interfaces. In the ligaments region remarkable plasticity was found.

Keywords: lamellar microstructure, fracture toughness, acoustic emission, microcrack, shear ligament, TEM observation, TiAl

I. Introduction

Intermetallic compounds based on titanium aluminide have great potential as materials for high temperature applications. However the alloy suffers from brittleness at ambient temperature. Room temperature ductility of two-phase titanium aluminides is superior than single phase TiAl, and has been improved by addition of Mn⁽¹⁾, Cr⁽²⁾ and V. The mechanical properties of the alloys significantly depend on the microstructure which can vary with heat treatment conditions. The lamellar microstructure which consists of α_2 and γ is superior than the duplex microstructure which consists of equiaxed γ and lamellar colonies in fracture toughness, high temperature strength and creep resistance.

Fracture process of two-phase titanium aluminides consists of lamellar microstructure has been investigated extensively in recent years. It has been considered that deformation twinning⁽³⁾, formation and fracture of shear ligament⁽⁴⁾⁽⁵⁾, formation of microcracks within a process

zone⁽²⁾ are the toughening mechanisms in the alloy. By transmission electron microscope observation of the crack in thin foils, it has been supposed that the lamellar interface causes crack deflection and the crack tip shielding contributes to crack growth resistance⁽⁶⁾. Investigation by transmission electron microscopy would be able to bring valuable information about microfracture mechanisms. In the present work interaction of cracks and the lamellar microstructure has been studied using acoustic emission method and transmission electron microscope.

II. Experimental

A two-phase gamma titanium aluminide alloys with compositions of Ti-34Al-1Mn(wt%) and Ti-34Al-3Mn were prepared by arc melting method. The alloys consist of lamellar colonies and a small amount of fine gamma grains along the colony boundaries. The lamellar colony size was 200-300 μ m. Specimens for three point bending fracture toughness test with dimensions of 5 $\times$ 10 $\times$ 40mm were cut by

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Figure 1. Cross section of specimens unloaded at $15 \text{ MPam}^{1/2}$ ((a),(c)), and $20 \text{ MPam}^{1/2}$ ((b), (d)).

spark erosion. The surfaces of the specimen were mechanically polished. Fatigue precrack has been conducted by compression-compression cyclic loading in $\Delta K=0.1$ and in 10Hz.

Fracture toughness tests were conducted under a cross head speed of 0.1mm/min, with a span of 30mm at room temperature. Simultaneously acoustic emission was detected to monitor microfracture process. AE signal is amplified with 54dB by preamplifier. Threshold value of this experiment is 0.128V and peak-to-peak value is 12.8V. The tests were stopped prior to specimen fracture for detailed study of microfracture process. Then the specimens were sectioned at the plane in the thickness direction, mechanically polished, chemically etched, and examined using optical microscope.

Slices for preparing transmission electron microscopy foils were cut from as-cast ingot. TEM foils were prepared by mechanical grinding to 0.1mm thickness with diamond slurry, ultrasonic cutting to 3mm-dia. disks, dimpling to 0.03mm thickness, and finally ion milling in condition of 4kV, 0.8mA. Cracks in TEM samples were introduced by a pin with sharp tip. TEM observations were carried out on a JOEL 2010 microscope using the operating voltage of 200kV.

III. Results and Discussion

1. Fracture process

Fracture toughness of both material is $23 \text{ MPam}^{1/2}$. Figure 1 shows optical microscope images of crack tip region in sectioned specimens which were unloaded at $K=15 \text{ MPam}^{1/2}$ (a), $20 \text{ MPam}^{1/2}$ (b) are shown. Main crack goes parallel to lamellae, and secondary crack has occurred parallel to main crack in Figure 1(a). A microcrack is observed in the neighboring lamellar colony. In Figure 1(b), the main crack goes perpendicular to lamellae, and microcracks occur parallel to lamellae in the neighboring colony ahead of crack tip. But microcracks crossing lamellar boundaries found in Figure 1(a) are not observed.

Accumulated AE events and AE amplitude versus stress intensity factor are shown in Figure 2. Figure 2 (a) and (c) correspond to the specimen unloaded at $K=15 \text{ MPam}^{1/2}$, and figure (b) and (d) correspond to the specimens unloaded at $K=20 \text{ MPam}^{1/2}$. There was a difference in each specimen of the same material.

In the specimen (a) with the composition of Ti-34Al-1Mn the number of AE event was about 30 until stress intensity factor reaches $15 \text{ MPam}^{1/2}$. But in another specimen accumulated AE event number was 2 while stress intensity factor was under $15 \text{ MPam}^{1/2}$, then it increased to 60 until unloaded at $20 \text{ MPam}^{1/2}$. The stress intensity factor value at which AE event rapidly increased (K_{AE}) was also different.

Figure 2. Accumulated AE events number and AE amplitude versus stress intensity factor in specimens unloaded at 15 ((a),(c)) and 20 $\text{MPam}^{1/2}$ ((b),(d)).

K_{AE} is $13\text{MPam}^{1/2}$ in specimen (a) and $16\text{MPam}^{1/2}$ in specimen (b). Amplitude of most AE was lower than 0.5V in both specimen.

In the specimen (c) with composition of Ti-34Al-3Mn about 70 AE events were detected. In the specimen (d) about 180 events were detected, and 40 events occurred while stress intensity factor was under $15\text{MPam}^{1/2}$. Only in this specimen AE events over 6.4V in amplitude were detected. AE event number of 3Mn materials is higher than 1Mn.

Acoustic emission is considered to originate from twin, microcrack, and stable crack growth. Therefore the differences of AE behavior would be caused by the microstructure shown in figure 1. Therefore, when the crack tip direction is perpendicular to lamellae a crack starts to propagate at relatively high K value, and then K_{AE} value becomes higher.

2. TEM Observation

In this observation it is not clear that what kind of stress has caused the crack generation and propagation. And fracture process is different between plane strain and plane stress condition. So the deformation structure around cracks could not be compared directly with fracture and deformation structure occurred in bulk materials. However crack morphology observed in thin foils must bring valuable

information about microfracture processes. Therefore the following photographs are important.

Two types of cracks were typically observed.

Figure 3 shows decohesion of lamellar boundaries. Dislocations are emitted from lamellar boundaries. But the density of dislocations is small. The orientation relationship between γ phase and α_2 phase is well documented to be $(111)\gamma// (0001)\alpha_2$ and $\langle 110\rangle\gamma//\langle 1120\rangle\alpha_2$. The interface planes are $(0001)\alpha_2$ and $\{111\}\gamma$. Since the $\langle 110\rangle$ and $\langle 101\rangle$ directions in the $L1_0$ structure are not equivalent, there are six differently γ variants in the lamellar structure. In addition to the α_2/γ interfaces, therefore, different types of γ/γ interfaces occur. These interfaces also contain misfit dislocations.

Wunderlich et al.⁽²⁾ remarked that interface dislocations move into the surrounding matrix either by planar or by cross slip, if they are not needed for misfit accommodation or a certain internal stress originates by external forces from neighboring grains, e.g. bending of lamellar. Cross slip on $\{111\}$ planes other than the interfaces plane is another possible dislocation source. For these movement, a certain shear stress in the cross slip plane is required.

Decoherence of lamellar boundaries does not lead to remarkable deformation. Then it is considered that the fracture resistance is relatively low.

Figure 3. Decohesion of lamellar boundaries.

Figure 4. Crack propagation across lamellar boundaries.

Figure 4 shows a crack propagation across lamellar boundaries. From the crack tip dislocations occurred straight in the same direction of crack propagation, then turned different direction in forward lamellae. In the neighboring lamellae, dislocations occurred in relatively large area. And then in the next lamellae, a few dislocations were observed. Thus a crack crossing boundaries leads remarkable deformation, and it shows that the fracture resistance is relatively high.

Appel et al have also studied a crack generated in the thin foil. They mentioned that cracks follow $\{111\}$ planes

indicating cleavage like fracture and are deflected by lamellar interfaces. And crack deflection at lamellar boundaries and crack tip shielding stabilize crack propagation across the lamellae⁽⁶⁾. In this study, it is also found that a delamination perpendicular to crack propagation effects the crack propagation and fracture toughness of these materials.

Thus plastic deformation in lamellar microstructure shows different morphology in each lamellae even if they are neighboring. It is considered that have weak bonding of lamellar boundaries brings relatively high fracture toughness of lamellar TiAl. Therefore smaller lamellar spacing would be effective to toughen TiAl-based alloys. It is necessary to examine the respective role of γ and α_2 phase and the crystallographic morphology in microfracture process. It is still remained to be resolved that the role of mechanical twinning in the initiation of cracks.

IV. Conclusions

Interactions of lamellar microstructure and crack morphology have been studied by optical and transmission electron microscopes and acoustic emission method. The following conclusions could be drawn.

- (1) Microstructure of lamellar of this alloy has great influence on the microfracture process and affects on the fracture toughness. The increase of AE activity due to microcracks related to the increase of toughness.
- (2) The increase of dislocation density and the delamination at lamellar interface were found by TEM observation when a crack propagates across lamellar boundaries. These boundaries are more effective to enhance the fracture toughness of this alloy.

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