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In-situ crack propagation observation in fully lamellar Ti-49 % Al alloy①

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[Abstract] The fracture mechanism of lamellar Ti-49 % Al alloy was investigated through studying the interactions between crack and lamellae or grain boundary. The results indicated that the nucleation and propagation mechanisms of crack depends on not only the lamellar orientations within grain but also the types of grain boundaries. When the angle between tensile axis and lamellae is relatively large, the main crack parallel to the lamellae propagates by nucleation, growth and linkage with interfacial microcracks. When the tensile axis is nearly parallel to the lamellae, the main crack perpendicular to the lamellae propagates by nucleation, growth and linkage with two types of microcracks, e.g. translamellar microcrack and interface delamination. In addition, the interlock grain boundary nearly parallel to the tensile axis is benefit to fracture toughness, the grain boundary nearly perpendicular to the tensile axis is bad for the toughness.

[Key words] TiAl alloy; lamellae; crack; grain boundary; fracture mechanism
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1 INTRODUCTION

TiAl intermetallic compound has attracted a great deal of attention from the aerospace community for its low density, high elastic modulus and good oxidation resistance. In last decade the relationship between its mechanical behaviors and microstructures have been known more and more clearly[1,2]. Among four types of microstructures prepared by various thermomechanical processing, the fully lamellar (FL) structure has the highest fracture toughness and elevated temperature strength. The fracture behavior and toughening mechanism of FL structure had been investigated by many researchers[3~5]. The results indicated that the fracture mechanism of FL microstructures was characterized by multi steps fracture ahead of the crack tip, and microcrack nucleation and propagation along slip bands, accompanying with interface delamination, translamellar and intergranular fracture[2,4,5]. That is to say, these researchers focused on the relationships between microcrack nucleation and slip, the interaction between crack and lamellae or grain boundary was seldom referred to. So it is necessary to study the interaction between crack and lamellae or grain boundary in order to investigate fracture behavior and mode. In this article the in-situ SEM technique is used to investigate the nucleation and propagation path of crack in fully structure, the interaction between crack and lamellae or grain boundary is focused on.

2 EXPERIMENTAL

The alloy with a nominal composition of Ti-49 % Al (mole fraction) was prepared by arc melting technique. After aged at 1 400 ℃ for 30 min, in-situ tensile specimens having a gauge length of 5 mm and a transverse section of 2.5 mm × 0.8 mm were cut from the alloy, whose microstructures showed a fully lamellar structure. In-situ straining experiments were conducted in a JSM-5800 scanning electron microscope (SEM) equipped with a JEOL tensile stage, and the specimens were loaded manually. The crack path and microcrack nucleation were observed and recorded using secondary electron images.

3 RESULTS

3.1 Interaction between crack and lamellae within grain

Fig.1 shows the propagation process of the interfacial crack for case of the tensile axis lying at about 70° from the lamellae within grain. In this circumstance the main crack propagated along the lamellar interface, remaining at interface. An interfacial microcrack occurred at one side of the crack ahead of main crack (Fig.1(a)). Upon increasing stress, the same type of microcrack continued to nucleate. Thus, a fracture ligaments formed between microcracks or between main crack and microcrack (Fig.1(b)). The main crack propagated forward through linkage with

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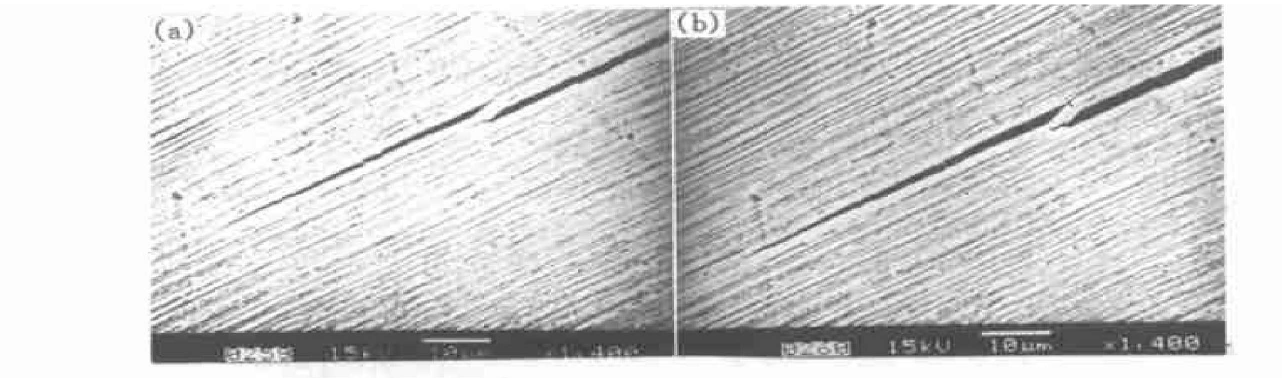

Fig.1 Propagation behavior of crack parallel to lamellae within grain for case of lamellae lying at 70° from tensile axis

(a) — Main crack and interfacial microcrack; (b) — New interfacial microcrack

microcracks by shearing or tearing ligament.

Fig. 2 shows the propagation process of the translamellar crack for case of the tensile axis nearly parallel to the lamellae. In this condition, the nucleation mechanism of microcrack was relatively complex. As shown in Fig.2(a), several slip bands at the crack tip *A* and a lot of translamellar slips ahead of the crack tip occurred. Two types of microcracks nucleated ahead of the main crack tip. One was microcrack along lamellar interface (interface delamination), as indicating arrow in Fig.2(a). The other was translamellar microcrack, as labeled zones *B* and *C* in Fig.2(a). The magnified photographies of microcracks in zone *B* and *C* are shown in Fig.2(b) and (c) respectively. It can be seen from Fig.2(b) that the microcracks, e.g. *a*, *b*, *c*, *d* and *e*, formed along slip bands (slip planes). In fact, these microcracks formed by linkage with microcracks in nanometer level along slip planes. The microcrack *c* formed perpendicular to the lamellar interface, which might lay at $(0\bar{1}1)$, (001), etc, cleavage planes of γ phase or pyramidal plane of α_2 phase. These cleavage planes are perpendicular to the interface in lamellar structure of TiAl alloys. Unlike the microcracks in Fig.2(b), the translamellar microcracks in Fig.2(c) exhibited zigzag paths, obviously indicating they formed by linkage with small microcracks along different translamellar cleavage planes of γ phases. These microcracks nucleated not only at the lamellar interfaces, for example the microcracks *f* and *g*, but also within the lamellae, for example the microcracks *h* and *i*. The main crack propagated forward through linkage with these two types of microcracks.

3.2 Interaction between crack and grain boundary

Fig.3 and Fig.4 show the propagation processes of crack across the grain boundaries. When the main crack propagated nearly the longitudinal grain boundary (defined as the grain boundary nearly parallel to the tensile axis), as shown in Fig.3(a), it was hindered at the grain boundary, inducing microcrack nucleation in adjacent grain. Thus, a shear ligament formed at the grain boundary zone. Simultaneously, many microcracks nucleated within shear ligament

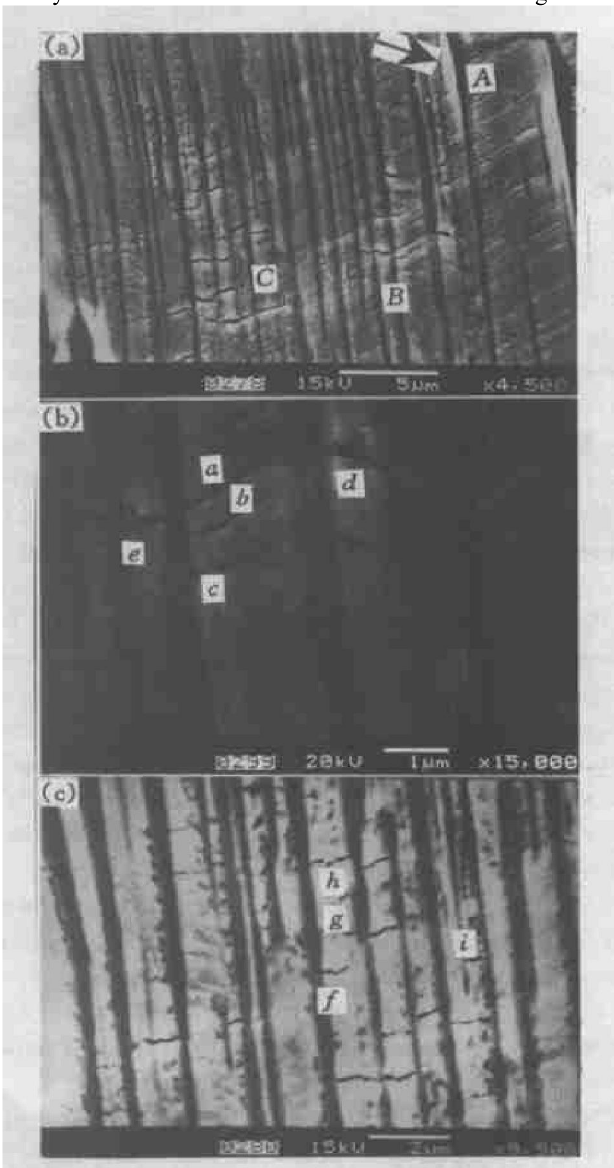

Fig.2 Propagation behavior of translamellar crack for case of tensile axis nearly parallel to lamellae

(a) — Microcracks ahead of main crack tip;
(b) — Magnified photography of zone *B*;
(c) — Magnified photography of zone *C*

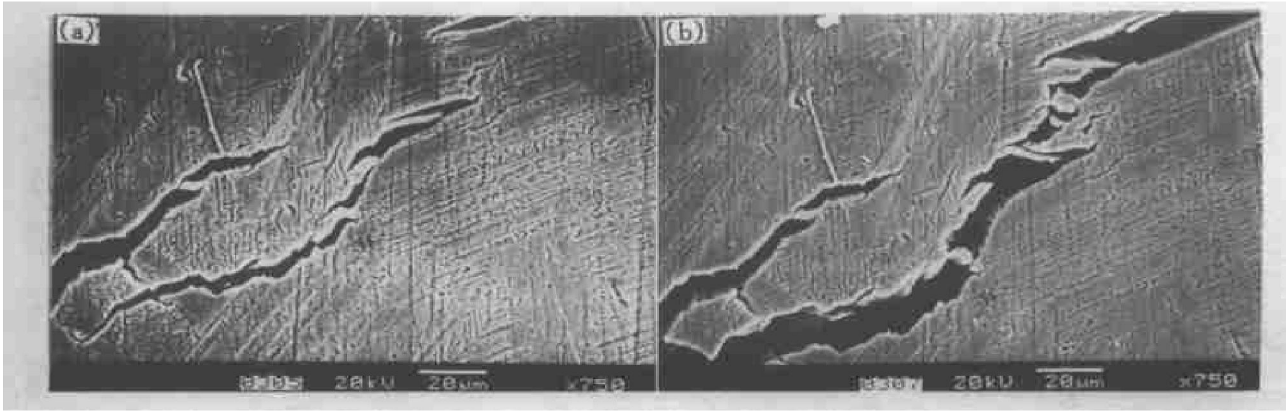

Fig.3 Propagation behavior of crack across longitudinal grain boundary
(a) —Microcracks along grain boundary induced by main crack ;(b) —Linkage of microcracks each other

Fig.4 Intergranular fracture induced by main crack tip

wake. Upon increasing stress, the microcracks expanded and propagated along grain boundary. In fact, the microcracks along grain boundary propagated by discontinuous nucleation and linkage each other because of interlock characterization of grain boundary in fully lamellar structure. Upon further increasing stress, the main crack propagated by linkage with microcracks through shear or tearing of ligament, as shown in Fig.3(b). The fractograph of adjacent grain boundary in this condition is shown in Fig.5. From Fig.5(a) we can see that the cleavage planes at both sides of grain boundary were lamellar interfaces which twisted a finite degree perpendicular to the grain boundary, the interfaces was teared and delaminated, which was accordant with the propagation process of crack across the grain boundary. When the main crack propagated near the transverse grain boundary (defined as grain boundary nearly perpendicular to the tensile axis), the crack tip may induce intergranular fracture along the transverse grain boundary, as shown in Fig.4. A typical fractograph is shown in Fig.6, from which we can see that the fracture behaviors of fully lamellar structure possessed complexity. Zone *A* represented the interfacial fracture facets, zone *B* was intergranular fractograph and zone *C* was translamellar fractograph.

4 DISCUSSION

It is well known that the lamellar structure is composed of a series of parallel γ and α_2 lamellae which possess general crystal orientation relationship $\{111\}_\gamma // (0001)_{\alpha_2}$, $\langle \bar{1}10\rangle_\gamma // \langle 11\bar{2}0\rangle_{\alpha_2}$, where the lamellar interface is assigned to be $(111)_\gamma$ plane[6]. When the γ phase rotates 60° respectively by [111] direction, six types of differently oriented order domains occur, they form three types of interfaces, e.g. true twin boundary, pseudo twin boundary and 120° type boundary. There exist 10 cleavage planes in γ phase, they include lamellar interface, translamellar slip planes and (011), (001) planes, etc, which have slight difference in cleavage energy. Several cleavage planes, for example $(0\bar{1}1)$, (001) planes, are perpendicular to the lamellar interfaces.

When the lamellae within the grain lay at relatively big angle from the tensile axis, in general the main crack nucleates and propagates along the lamellar interface under normal stress because of low cohesive strength at lamellar interface. Upon increasing external stress, the interfacial microcrack forms ahead of the crack tip under the combination effect of the normal stress coming from both crack tip and external load. Thus, the shearing ligaments form between the main crack and these microcracks or between these microcracks, which are beneficial to the fracture toughness.

When the lamellae are nearly parallel to the tensile axes, many slips occur ahead of the crack tip, in fact, in this circumstance, a lot of dislocations, including slips or twins, can emit from not only the crack tip but also the lamellar interface. Both twinning and slip deformation lead to strain localization on the translamellar {111} planes. Under the effect of the normal stress, the translamellar microcrack nucleates and propagates, in general they usually immobilize at the lamellar interface because of different orientation in adjacent lamellae. In the same γ lamellae, there exist 9 cleavage planes except for interface. The

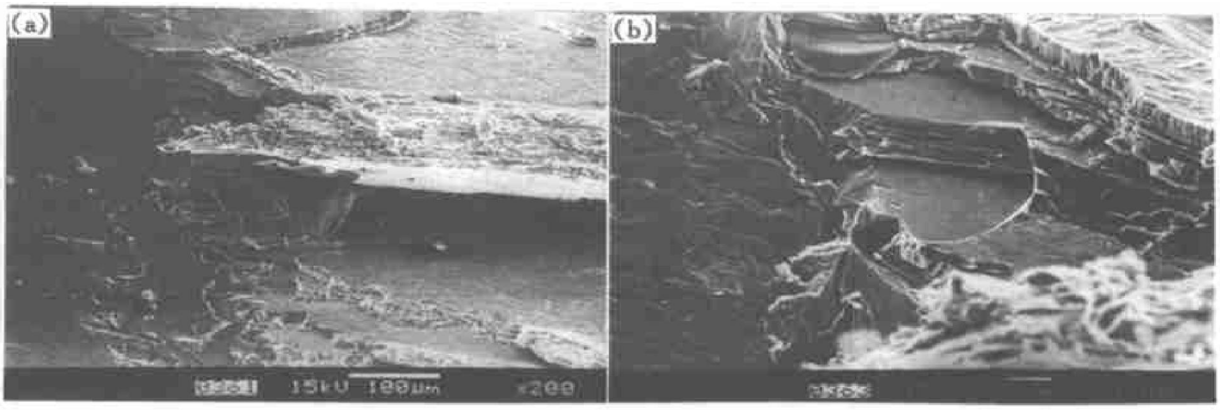

Fig.5 Fractograph of adjacent grain boundary corresponding with Fig.3
(a) —Overall photograph; (b) —Magnified photograph

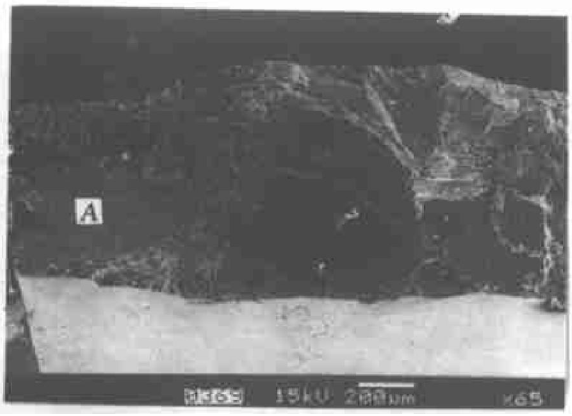

Fig.6 Fractograph of a typical sample

microcracks form along different cleavage planes, then link each other and become bigger microcrack. Thus, the translamellar crack usually exhibits zigzag path. At the main crack tip, the dislocations emitted from the crack tip pile up against the lamellar interface, inducing tensile stress against the lamellar interface. Under the combination effect of normal stresses from crack tip and dislocation pile-up the interface delamination occurs. Interface delamination can obviously reduce net stress intensively factor ahead of the crack tip, resulting in increase in fracture toughness[7]. The microcrack possesses twofold effects on the fracture. On one hand, microcrack may give path to the propagation of main crack, accelerating rupture of material; on the other hand, microcrack changes the distribution and level of stress ahead of the crack tip, making the maximum stress shift from the crack tip and decrease, which lift the fracture toughness[8].

In general, the grains at both sides of the grain boundary do not have a defined crystal orientation, so the crack can not propagate across the grain boundary directly. Thus the dislocations emitted from the crack tip may pile up against the grain boundary, inducing stress concentration at grain boundary. The concerted stress leads to nucleation of microcrack in the adjacent grain. The microcrack may lay along interface or translamellae, depending on the lamellar orientation of adjacent grain. When the main crack propagates across the longitudinal interlock grain boundary, many toughening mechanisms such as microcrack and shear ligament occur during the propagation of main crack, which is beneficial to the fracture toughness. When the main crack propagates near the transverse grain boundary, the stress field ahead of the crack tip first causes intergranular fracture of the transverse grain boundary, indicating the strength of grain boundary is lower than that of lamellar interface. Thus, the existence of transverse grain boundary is bad for the fracture toughness.

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