IN-SITU OBSERVATION OF CRACK PROPAGATION IN PST CRYSTALS OF Ti-49 %Al ALLOY①

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ABSTRACT The effects of loading axis to the lamellae on the fracture behavior of PST crystals have been investigated by SEM in-situ testing. The results show that the fracture behavior of PST crystals of γ-TiAl base alloys depend on not only the angles between cracks and lamellae, but also the angles of loading axis to the lamellae, and the cracks propagating along different paths show different toughening mechanisms, crack resistance, corresponding fracture behavior and fractography.

Key words PST crystal fracture behavior crack path toughness mechanism

1 INTRODUCTION

γ-TiAl base alloy has been of much interest as structural materials for elevated temperature aerospace applications because of its low density, good oxidation and burn resistance, and high temperature strength retention during the last decade[1,2]. Among the four types of microstructures formed by different thermomechanical processing, the fully lamellar(FL) structure has attracted more and more attention in the last several years because it not only has the highest fracture toughness, but also high anisotropy in mechanical properties[3,4]. The study of fracture and toughening mechanism of FL structure is always one of the focuses of studies of TiAl. Chan and Kim[5-7] and others[8] have done a lot of works in this respect. But these works are mostly focused on the relationships of lamellar structure, slip and fracture behavior and mechanism, the effect of the angle of loading axis to the lamellae on the fracture process has not been addressed. Moreover, these research works based on the polycrystalline γ-TiAl base alloy may be influenced by grain boundary and hydrostatic stresses because of deformation incompatibilities and lattice rotations between adjacent crystals and can not elucidate precisely the relationship between lamellae and fracture behavior. The polysynthetically twinned (PST) crystal composed of a series of parallel γ-TiAl and α_2-Ti_3Al plates eliminates the grain boundary so that the work conducted using PST crystals can reflect precisely the interaction between lamellae and crack. Therefore, the present work focuses on fracture behavior and mechanism of PST crystals of Ti-49 %Al alloy by in-situ tensile testing.

2 EXPERIMENTAL

The alloy was processed by the arc melting technique with a nominal composition of Ti-49 % Al(mole fraction). Rods with a size of 8 mm in diameter and 80 mm in length were cut from the ingot by spark machining, and then grew to PST crystals in an induction floating zone furnace at a growth rate of 5 mm/h under argon gas

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protection. In-situ tensile specimens were cut from the grown PST crystals with the tensile axis near parallel, perpendicular and at an intermediate angle to the lamellae. The specimens have a gauge length of 5 mm and a cross section of 2.5 mm × 0.8 mm. Fig.1 shows the optical and BSE images of the microstructure of the specimens.

In-situ straining experiment was conducted in a JSM-5800 scanning electron microscope (SEM) at room temperature. A JEOL tensile stage with a maximum load capacity of 1 960 N in the microscope chamber was used. The specimens were slowly step-loaded by manual method. During in-situ tensile test, the cracking paths were observed and recorded.

3 RESULTS

3.1 Tensile axis nearly perpendicular to lamellae($\phi = 70° \sim 90°$)

Fig.2(a) shows the near crack-tip fracture process when the tensile axis is nearly perpendicular to the lamellae. In this condition the fracture tip which was nearly controlled by K_I (K_I and K_{II} known as stress-intensity factors corresponding to the opening and sliding modes respectively[9]) kept sharpness and propagated facets surrounded by tearing or shear of ligaments(Fig.3(a)), and the facet is macroscopically flat and tearing or shear ligaments connecting the stepped facets are rather rough (Fig.3

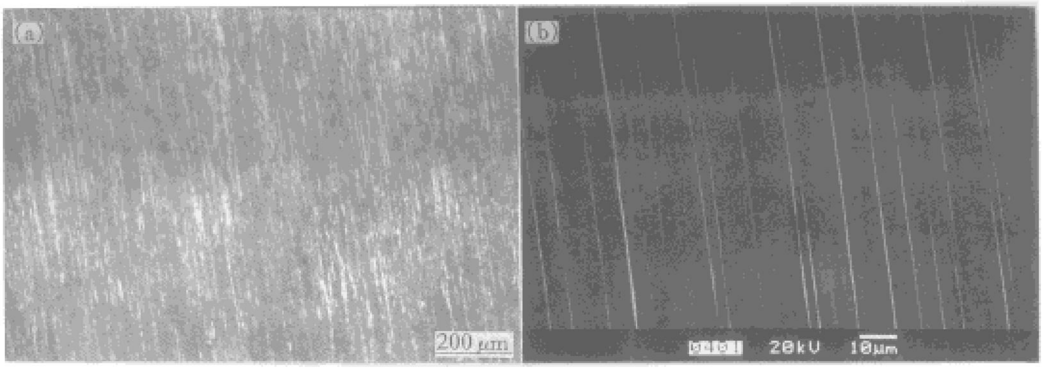

Fig.1 Microstructure of PST crystal of Ti-49%Al
(a) —Optical image; (b) —BSE image(the bright phase is α_2)

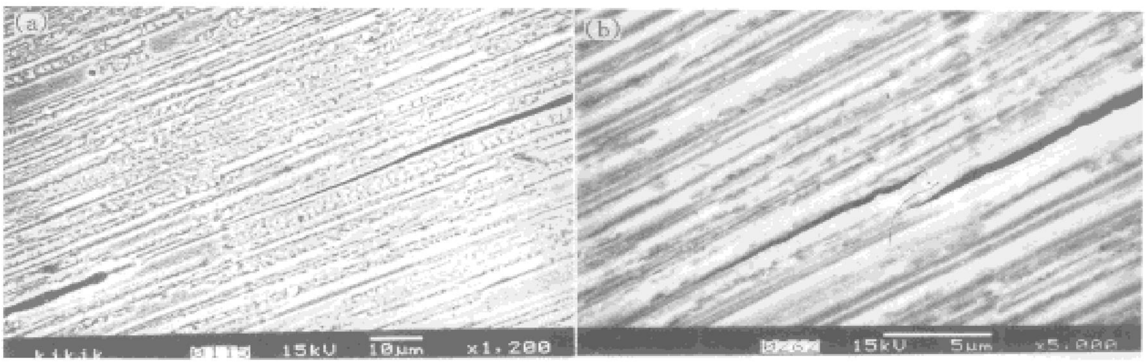

Fig.2 Crack propagation along interlamellar interfaces with tensile axis nearly perpendicular to lamellae
(a) — Main crack along interface; (b) — Microcracks parallel to interfaces

Fig.3 Fractographic facets after specimen fractured under tensile loading with axis nearly perpendicular to lamellae
(a) —Low magnification of fracture surface corresponding to Fig.2(b);
(b) —Tearing and shear of ligaments connecting facets

(b)).

It could often be seen that a few microcracks nucleated and propagated on parallel interfaces(Fig.2(b)) at one side of the main crack, forming shear ligaments. Fig.3(a) shows the fracture surfaces corresponding to Fig.2(b). The main feature is that the large stepwise fracture enhances the fracture toughness effectively in this orientation.

3.2 Tensile axis nearly parallel to lamellae ($\phi = 0° \sim 20°$)

Fig.4 shows the near-tip fracture process when the tensile loading axis is nearly parallel to the lamellae. In this condition the crack tip was also controlled by K_{I} and, with the crack propagating, the main crack-tip quickly blunted and stopped propagating presumably because of interface sliding. Abundant microcracks nearly perpendicular to the $\gamma/\alpha_2/\gamma$ lamellae nucleated in the area both ahead of and besides the main crack, forming a diffuse microcrack zone(Fig.4(a)) which further blunted the main crack tip. With further propagation of the crack, the existing microcracks opened to a different extent and linked each other by delamination of interface or tearing, and then new microcracks might nucleate ahead of existing microcracks and grew continuously(Fig.4(b)), eventually some linked microcracks propagated and linked to the main crack (Fig.4(c)). Obviously in this case, many toughening mechanisms such as crack-tip blunt, redistribution of stress, plane stress and microcrack may affect propagation of the crack. Fig.4(d) is the typical fractography of the samples loaded parallel to lamellae, which clearly shows translamellar facets with secondary crack along the lamellar interfaces. The lamellar splitting or secondary cracks caused by the crack-tip stress could relax the lamellar constraint which was beneficial to fracture toughness.

3.3 Tensile axis inclined at an intermediate angle to lamellae($\phi = 30° \sim 60°$)

Fig.5 and Fig.6 reveal the fracture process when the loading axis is inclined at about 30° ~ 60° to the lamellae. In this condition the crack-tip was controlled by combination effect of mode I and mode II (if the two orientations described above are defined as mode I and mode II) and, as a result, the main crack propagated in an alternate mode between the delamination and translamellae. When ϕ was relatively large (e.g. 50° ~ 60° in Fig.5), the interface delamination was dominant in the process since a few microcracks parallel to the interfaces were always found to form first around the head of the main crack tip(Fig.5(a)), forming a few shear ligaments. With further propagation of the crack, the main crack and microcracks opened and grew

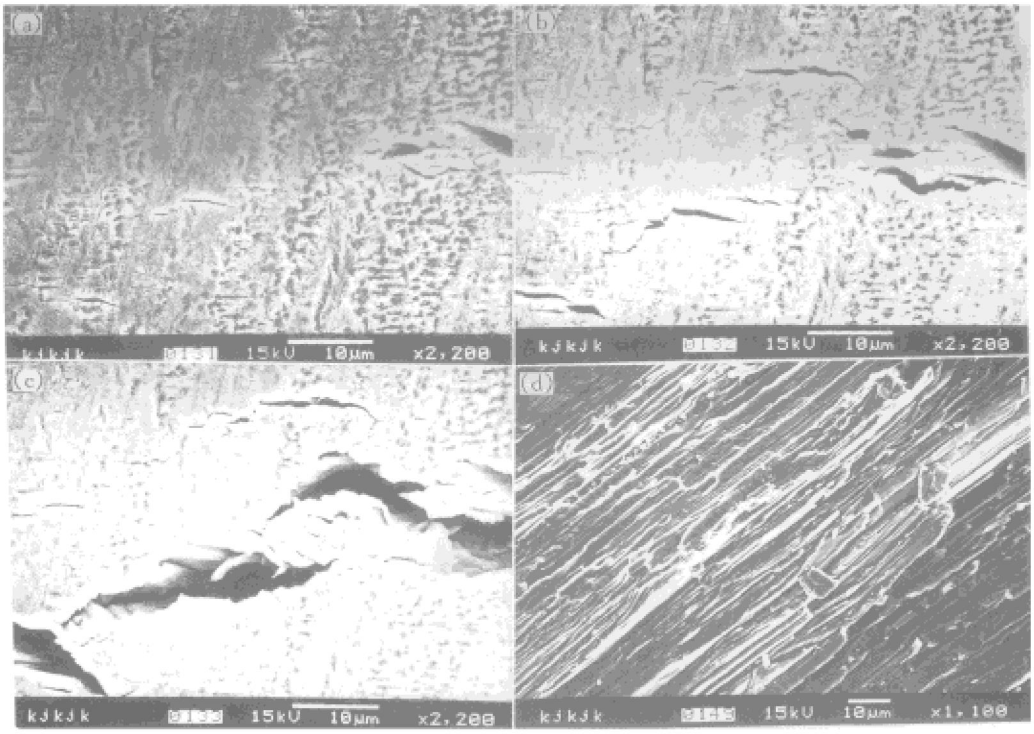

Fig.4 Crack propagation process and corresponding fractography of specimen loaded with axis nearly parallel to lamellae

(a) —Microcracks at ahead of main crack; (b) —Growth of microcracks; (c) —Linkage between main crack and microcracks; (d) —Corresponding fractography

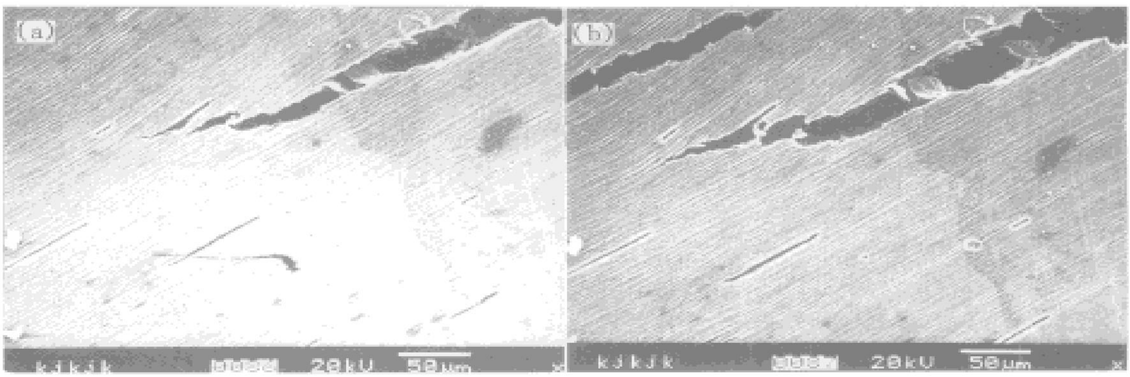

Fig.5 Crack propagation process in samples with tensile axis inclined at 50° ~ 60° to lamellae

(a) —Microcracks along interfaces ahead of main crack;

(b) —Linkage between main crack and microcracks

simultaneously, and the shear ligament fractured by tearing or shearing across the lamellae led to linkage of main crack and the microcracks (Fig.5 (b)), and thus the main crack propagated forward.

When ϕ was relatively small (e.g. 30° ~ 40°

in Fig .6) , the translamellae dominated the fracture process of near-crack tip(Fig .6(a)) . The zone of the main crack-tip was enlarged in Fig .6 (b) , from which we could see that the crack tip was nearly normal to the lamellae and a few microcracks perpendicular to the lamellae nucleated in the diffuse microcrack zone . With further propagation of the crack , more microcracks perpendicular to lamellae formed and grew in the diffuse zone(Fig .6(c)) , some of which linked each other or linked with the main crack through the delamination of the lamellae(Fig .6(d)) . In

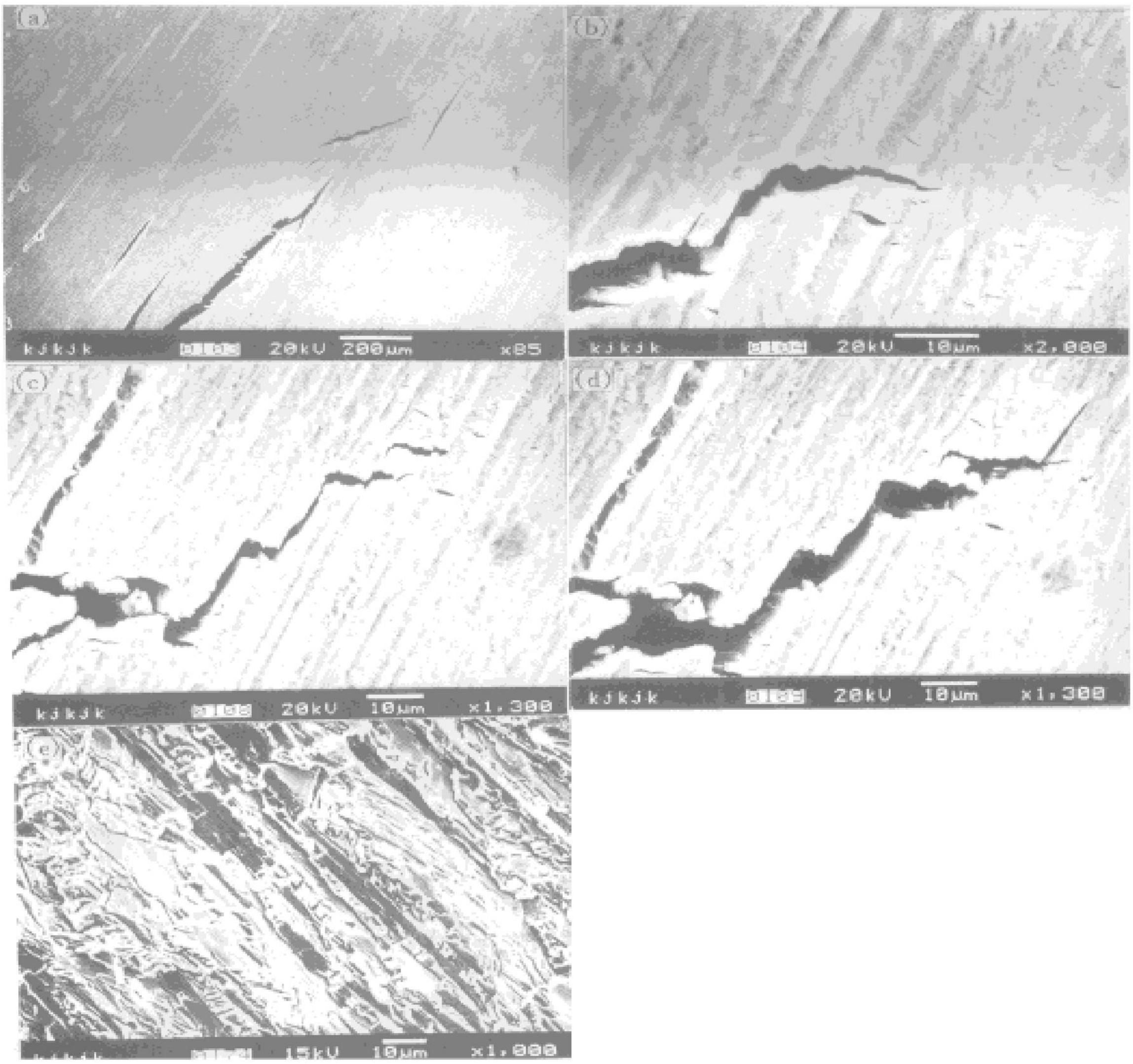

Fig .6 Crack propagation process and fractography of samples with tensile axis inclined at about 40° to lamellae

(a) —Near-tip fracture process ; (b) —Microcracks perpendicular to lamellae ; (c) —Growth and linkage of microcracks ; (d) —Crack-tip deflected into interface ; (e) —Corresponding fractography this way, the main crack propagated forward by tortuous path through nucleation of microcracks perpendicular to the lamellae and interface delamination. As shown in Fig.6(e), we can see that the typical fracture surface in this way is very rough mixed with delamination facets and cleavage translamellar facets.

4 DISCUSSION

It may be summarized from above experimental facts that fracture behavior of the PST crystals is strongly dependent on the angle of loading axis to the lamellae. When the sample is in 90° orientation, the fracture process is characterized by nucleation and propagation of crack along lamellar interface, and only the ligament toughening has an effect on the crack tip. When the tensile axis is parallel to the lamellae, the fracture process is closely related with nucleation, growth and linkage of the translamellar microcrack, and a lot of toughening mechanisms have effects on the crack tip, leading to high fracture toughness. When the tensile axis lies an intermediate angle from the lamellae, the crack propagates by alternate modes described above. When the axis changes from parallel to perpendicular to the lamellae, the microcrack ahead of crack tip nucleates from along the interfaces to perpendicular to the lamellae accordingly, which indicates that the normal stress plays a dominant effect in nucleation of microcrack.

When the tensile axis is perpendicular to the lamellae, $K_{\rm II} = 0$ and $\varphi(\approx K_{\rm II}/K_{\rm I}) = 0$ for crack propagation, and there is no shear stress τ_{xy} component on the interfaces according to the calculation of mode Ⅰ crack-tip stress of $(111)[1\bar{1}0]$ crack which may represent a crack along lamellar interface perpendicular to the load axis by Yoo *et al*[10]. The maximum normal stress located at the crack tip induces the interface delamination to occur. Only a ligament mechanism has an effect on the crack tip, leading to low fracture resistance[4]. When the tensile axis is parallel to the lamellae, normal stress σ_x, σ_y and shear stress τ_{xy} are not zero as calculated by Yoo *et al*[10] for mode Ⅰ $(11\bar{2})[1\bar{1}0]$ crack which may represent a translamellar crack perpendicular to lamellar interfaces. According to the Stroh's theory, τ_{xy} may activate dislocations along the slip planes across the interface, leading to dislocation pile-up at the interface. As a result, shear stress due to dislocation pile-up cause the interface to slide, leading to the crack-tip being blunted, and the normal stress due to the pile-up may induce microcracks nearly perpendicular to the interface, forming diffuse microcrack zone which may blunt the crack-tip further. σ_x and σ_{xy} also induce the interfacial delamination which absorbs the energy during the crack propagation, thus the fracture toughness is enhanced. Various toughening mechanisms such as crack-tip blunting, microcracking, crack deflection and shear ligament may all have effects upon the crack-tip, leading to high resistance of crack propagation. When the tensile axis is inclined at about 30° ~ 60° from the loading axis, $K_{\rm II} \neq 0$, there is a certain shear stress τ_{xy} parallel to the interfaces, and $\varphi \neq 0$, the shear stress may cause the interface sliding, resulting in crack-tip blunting. When $\varphi < \varphi_{\max}$ ($\varphi_{\max}$ is a critical value), the crack-tip normal stress may first cause the interface delamination ahead of crack-tip; when $\varphi \geq \varphi_{\max}$, the shear stress ahead of crack-tip first nucleates the microcrack nearly perpendicular to the lamellae. The crack-tip may deflect back and forth between the interface delamination and translamellae. In this circumstance, deflection of main crack, formation of a diffuse zone of microcracks and bridging ligament would be expected, leading to a rough fracture surface and a high resistance of crack propagation.

5 CONCLUSIONS

(1) The fracture behavior of PST crystals of γ-TiAl base alloy depend on not only the orientation of PST crystals but also the angles between cracks and lamellae. The cracks possessing different paths have different toughening mechanisms, crack resistance and corresponding fracture behavior and fractographic facets.

(2) When the tensile axis is nearly perpendicular to the lamellae, the crack parallel to the lamellae propagates along the lamellar interface,

and only a few microcracks parallel to the lamellae nucleate ahead of the crack tip.

(3) When the tensile axis is parallel to the lamellae, the crack perpendicular to the lamellae propagates by nucleation, growth and linkage of translamellar micro-cracks. A diffuse microcrack zone exists ahead of the crack tip.

(4) When the tensile axis lies at an intermediate angle from the lamellae, both K_{I} and K_{II} have effects on the crack propagation, and the crack propagates by deflecting back and forth between the interface and translamellae. A diffuse microcrack zone also exists ahead of the crack tip.

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