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**Materials**

# Effect of Lamellar Orientation on Crack Paths in PST Crystals of γ-TiAl Based Alloys

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**Abstract:** The effect of lamellar orientation on crack paths in PST crystals of γ-TiAl based alloys was investigated by *in-situ* SEM technique. The results indicate that the crack paths in PST crystals of γ-TiAl based alloys are strongly dependent on lamellar orientation of PST crystals, and the differently oriented PST crystals show different nucleation and propagation mechanisms of crack, resulting in different levels of fracture toughness.

**Key words:** γ-TiAl based alloy; PST crystal; lamellar orientation; crack path

There has been great progress in understanding the relationship between microstructure and mechanical properties of γ-TiAl based alloys. It has been recognized that the mechanical behavior of γ-TiAl based alloys is strongly dependent on its microstructure [1,2]. Among the four types of microstructures formed by different hot-works and heat treatments, the lamellar structure consisting of γ-TiAl and $\alpha_2$-$Ti_3Al$ plates possesses higher fracture toughness, high-temperature strength and creep behavior, but lower ductility than others. Such inverse relation between toughness and ductility occurring in lamellar structures and causing unbalanced mechanical properties is one of the key deficiencies of current properties of FL microstructure and restrict in application for high temperature structures [3]. The experimental results of polysynthetically twinned (PST) crystals have shown that the mechanical properties of lamellar structure, including strength, ductility [4] and fracture toughness [5], are highly anisotropic, depending on the angle of loading axis to the lamellae.

Many researchers have studied the fracture behavior of the lamellar structure. Yokoshima and Yamaguchi first proved the high anisotropy behavior of fracture of PST crystals depending on the notch orientation with respect to the lamellar boundaries and crystal orientation of the lamellae by using three-point bending tests of specimens which are notched, fatigue-precracked and side-grooved [5]. Chan and Kim investigated the relationships of slip morphology, microcracking and fracture resistance in TiAl alloys with fully lamellar structure by J testing [6,7]. These studies focused on the relationship between lamellar structure, slip and fracture behavior and mechanism, but the effect of lamellar orientation of PST crystals on the fracture process is seldom referred to. This present work is focusing on fracture behavior and mechanism of PST crystals of Ti-49%Al alloy (in atomic fraction) by in-situ tension testing.

## 1 Experimental

PST crystal of Ti-49%Al (in atomic fraction) was grown at a speed of 5 mm/h in an induction floating zone furnace under argon protection. In-situ tensile specimens were cut from the PST crystals with the tensile axis near parallel, perpendicular and at an intermediate angle to the lamellae and then mechanically and electrically polished. The specimen has a gauge length of 5 mm and a cross section of 2.5 mm×0.8 mm. **Figure 1** shows the optical and BSE morphology of PST crystal respectively. In-situ straining experiment was conducted in a JSM-5800 scanning electron microscope (SEM) equipped with a JEOL tensile stage, and the crack path and microcrack nucleation were observed and recorded during the in-situ tests.

## 2 Results

(1)Tensile axis nearly perpendicular to lamellae ($\phi$ = 70°–90°).

**Figure 2** (a) shows the near crack-tip fracture process when the tensile axis was nearly perpendicular to the lamellae. In this condition the fracture tip propagated along the interface, keeping sharpness. It could usually be seen that a few micro-cracks nucleated and propagated along parallel interfaces (figure 2(b)) at one side of the main crack, forming shear ligament. **Figure**

3(a) shows the fracture surfaces corresponding to figure 2(b). The main feature is the large stepwise fracture facet surrounded by tearing or shear of ligaments (figure 3(a)), and the facet is macroscopically flat and tearing or shear ligaments connecting the stepped facets are rather rough (figure 3 (b)). Obviously in this circumstance, only the tearing or shear of ligaments could enhance the fracture toughness effectively in this orientation.

(2) Tensile axis nearly parallel to lamellae ($\phi$ = 0–20°).

**Figure 4** shows the near-tip fracture process when the tensile loading axis was nearly parallel to the lamellae. In this condition the main crack-tip fast blunted and stopped propagating presumably because of interface sliding, and abundant microcracks nearly perpendicular to the $\gamma/\alpha_2/\gamma$ lamellae were nucleated in the area both ahead of and besides the main crack, forming a diffuse microcrack zone (figure 4(a)), the existence of diffuse microcrack zone further blunted the main crack tip. With the crack further propagating, the existing microcracks opened to a different extent and linked

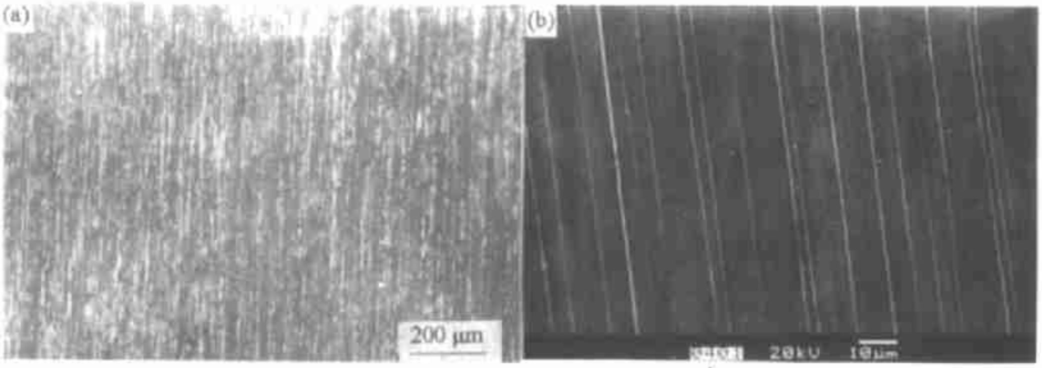


**Figure 1 Morphology of PST crystal. (a) Optical photography, (b) BSE photography.**

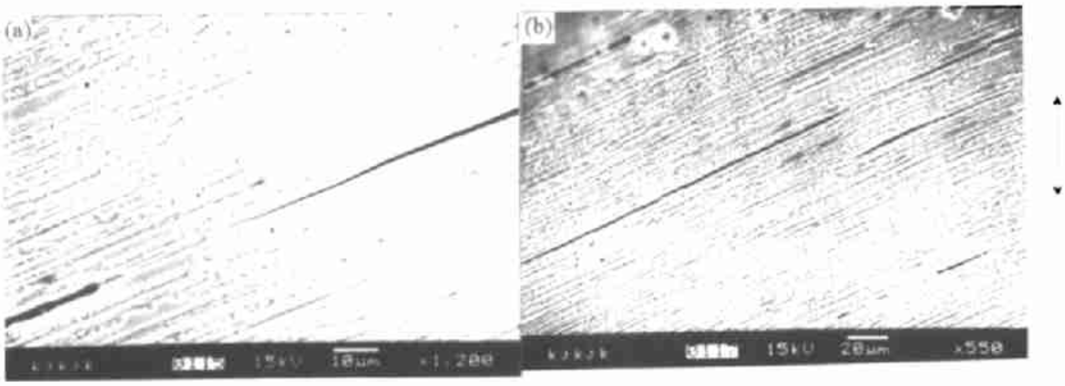


**Figure 2 Cracks propagated along the interlamellar interface for the case of the tensile axis nearly perpendicular to the lamellae. (a) Main crack along interface, (b) microcracks parallel interfaces, and double arrows mark represents the loading axis.**

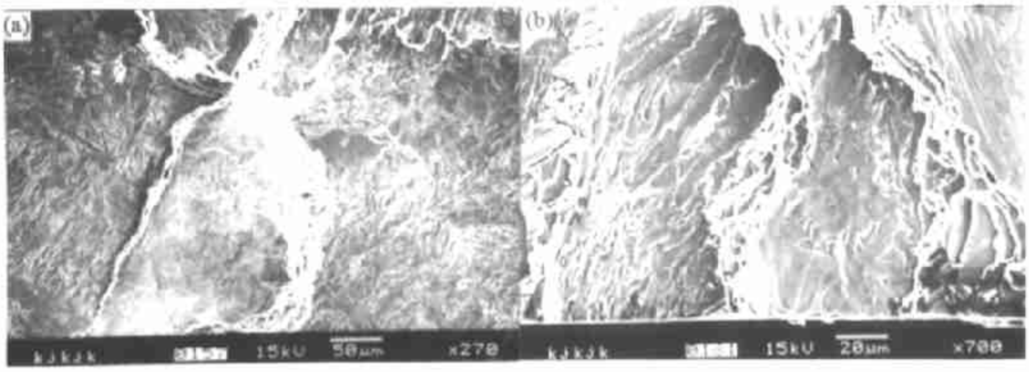


**Figure 3 Fractographic facets of the fractured specimen for the case of the tensile loading with the axis nearly perpendicular to the lamellae. (a) Low magnification of fracture surface corresponding to figure 1 (b), (b) tearing and shear of the ligaments connecting the facets.**

each other by delamination of interface or tearing, and then new microcracks might nucleate ahead of existing microcracks and grew continuously (figure 4(b)), thus, eventually some linked microcracks propagated and linked to the main crack (figure 4(c)). Obviously in this case, that many toughness mechanisms such as crack-tip blunt, redistribution of stress, plane stress, micro-crack may affect propagation of the crack. Figure 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 is beneficial for the fracture toughness.

(3) Tensile axis inclined at an intermediate angle to lamellae ($\phi = 30°–60°$).

**Figure 5** reveals the fracture process when the loading axis was inclined at about 50°–60° to the lamellae. The main crack propagated in an alternate mode between the delamination and translamellae. 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). But it appears that the delamination was dominant in the process since a few microcracks parallel to the interfaces was always found to form first around the ahead of the main crack tip marked by arrow in figure 5(a). With the increase of stress value, the main crack and microcracks opened and grew simultaneously, and the shear ligament fractured by tearing or shearing across the

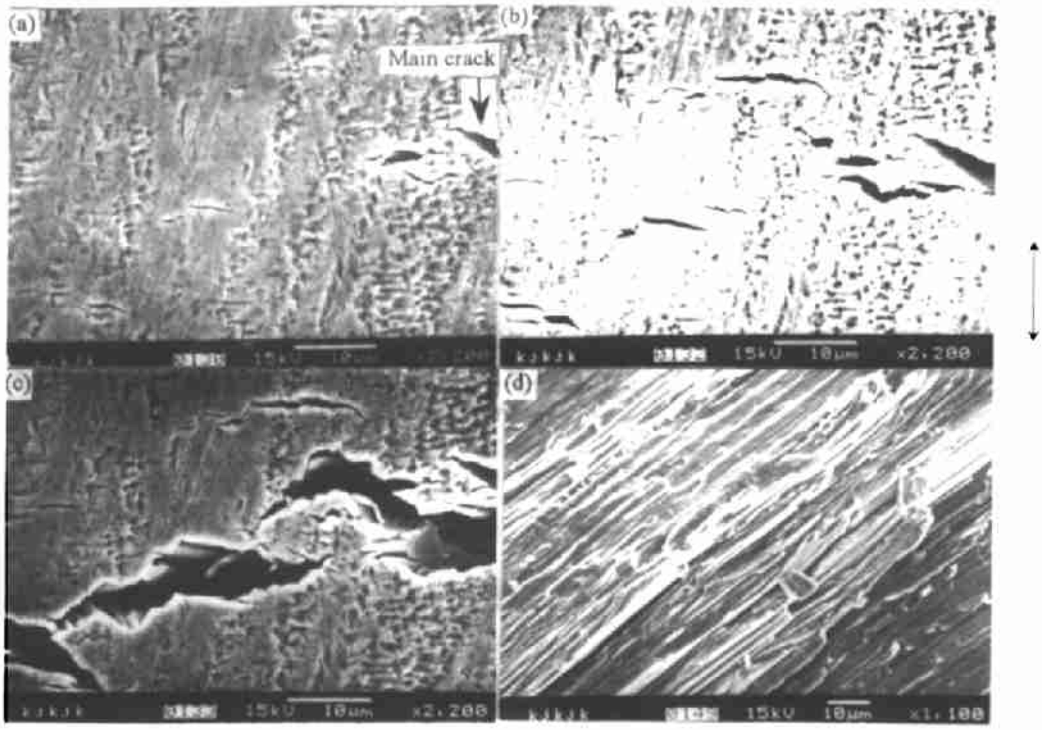


**Figure 4 Crack propagation process and corresponding fractography of the specimen loaded for the case of the axis nearly parallel to lamellae. (a) Microcracks at ahead of the main crack, (b) growth of the microcracks, (c) linkage between main crack and microcrack, and (d) corresponding fractography.**

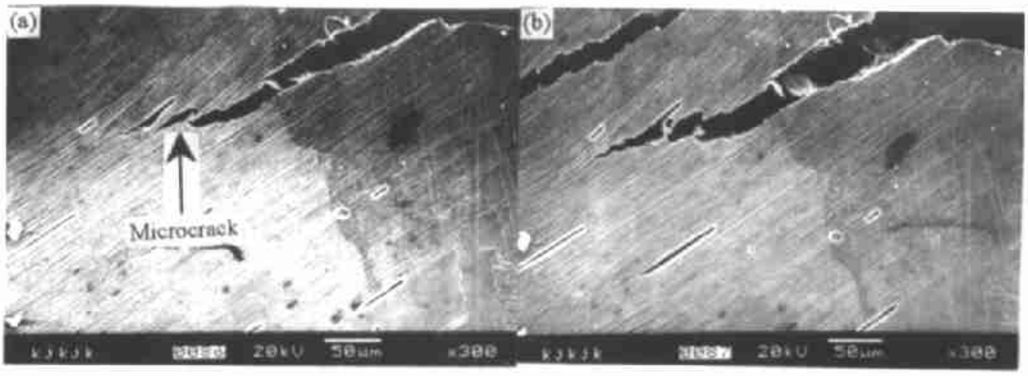


**Figure 5 Crack propagation process in the sample for the case of tensile axis inclined at 50°–60° to the lamellae. (a) Microcracks along interfaces ahead of main crack, and (b) linkage between the main crack and microcracks.**

lamellae led to linkage of main crack and the microcracks (figure 5(b)), and thus the main crack propagated forward.

When $\phi$ was relatively small (*e.g.*, 30°–40° in **figure 6**), the translamellae dominated the fracture process of near-crack tip (figure 6 (a)). The zone of the main crack-tip was enlarged in figure 6(b), from which it could be seen the crack tip was nearly normal to the lamellae and a few microcracks perpendicular to the lamellae nucleated in the diffuse microcrack zone. With the crack further propagating, more microcracks perpendicular to lamellae formed and grew in the diffuse zone (figure 6 (b)), some of which linked each other or linked with the main crack through the delamination of the lamellae (figure 6(c)). In this way, the main crack propagated forward by zigzag path through nucleation of microcrack perpendicular to the lamellae and interface delamination. Figure 6(d) shows that the typical fracture surface corresponding to above fracture process is very rough mixed with delamination facets and cleavage translamellar facets.

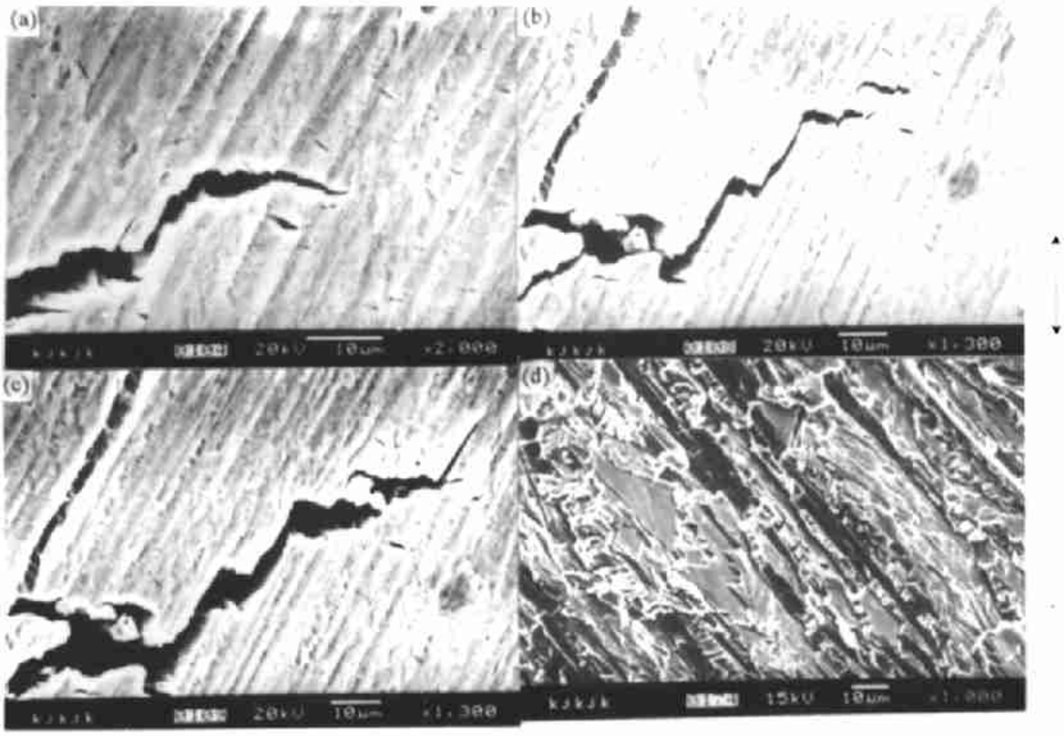


**Figure 6 Crack propagation process and fractography of the samples for the case the tensile axis inclined at about 40° to the lamellae. (a) Microcracks perpendicular to lamellae, (b) growth and linkage of microcracks, (c) the crack-tip deflected into interface, and (d) corresponding fractographic facets.**

## 3 Discussion

The in-situ straining experiment clearly shows that the microcrack nucleation and crack path of PST crystals are strongly dependent on lamellar orientation of PST crystals.

When the tensile axis is nearly perpendicular to the lamellae, crack-tip parallel to the lamellae is only controlled by uniaxial tensile perpendicular to the crack plane, and the crack propagates through interface delamination controlled by the normal stress ahead of the crack tip. In this condition, in general, the crack-tip keeps sharpness according to the observation. Thus the main crack propagates forward along the interface boundary and no extrinsic toughness mechanism except shear ligament has an effect on the crack tip, which leads to lower fracture toughness.

When the tensile axis is nearly parallel to the lamellae, crack-tip perpendicular to the lamellae is controlled by uniaxial tension perpendicular to the crack plane. In this circumstance, the main crack propagates by nucleation, coalescence and linkage of the microcracks perpendicular to the lamellae. Normal stresses $\sigma_x$, $\sigma_z$ and shear stress $\tau_{xz}$ have been calculated by Yoo, *et al.* using the anisotropic elastic solutions for an orthotropic symmetry case [8] or by Lu using finite element method based on micromechanical model [9]. $\tau_{xz}$ may cause dislocation along the slip planes across the interface to active, leading to dislocation at the interface. According to Stroh theory [10], the microcrack nucleation may be induced by dislocation pileup in $\gamma$ lamellae, and the microcrack nucleation plane should lie at about 70.5° from the slip plane. If it is assumed that <110> direction of the $\gamma$ plates are perpendicular to loading axis, the slip planes across the interface lying at an angle of 70° to the interface may exist. When the dislocation pileup on these slip planes occurs under the shear stress ahead of the crack-tip, a normal stress due to the dislocation pileup may be built up and has a maximum value in the direction nearly parallel to the lamellae, and shear stress parallel to the interface of dislocation pileup was slack because of interface sliding, as illustrated in **figure 7**. Therefore, under effect of the normal stress par-

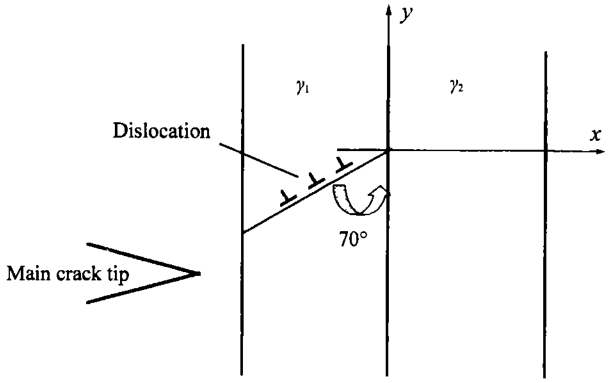


**Figure 7 A schematic of crack propagation for the case of the tensile axis parallel to the lamellae.**

allel to the lamellae, the cleavage might occur in the adjacent lamella first on the planes perpendicular to the lamellae such as (100), (001) and (110), not on the slip planes such as (111) plane because of small difference in cleavage energy between (100), (001), (110) and slip plane (111) [8]. The experimental fact shows that the microcrack nucleation planes nearly perpendicular to lamellae may be explained on the basis of the assumption. When the crack tip is blunted at the interfaces, the site of the maximum shear stress ahead of crack-tip shifts from the blunted crack-tip and the diffuse zone of the microcracks shifts from the crack tip simultaneously. Thus, the fracture resistance is increased considerably. During this procedure various toughness mechanisms such as crack-tip blunting, microcracking, crack deflection and shear ligament have strong effect on propagation of the crack-tip, leading to high resistance of crack propagation.

When the tensile axis is inclined at an intermediate angle from the lamellae, the main crack propagates in the alternate mode between interface delamination and translamellar crack. When the angle is relatively large, the normal stress ahead of crack-tip is dominant and causes the interface delamination first in the interfaces because of stress asymmetry, which forms the shear ligament, the main crack propagates by tearing and shearing the ligament, leading to a little high fracture toughness. When the angle is relatively small, the shear stress would be dominant and first causes the microcrack nucleation normal to the lamellae in the microcrack diffuse zone, and the crack-tip might deflect back and forth between interface delamination and translamellae. During this procedure deflection of the main crack, formation of a diffuse zone of microcracks and bridge ligament would be expected, leading to a rough fracture surface and a high resistance of crack propagation.

## 4 Conclusions

The crack paths in PST crystals of $\gamma$-TiAl based alloys are strongly dependent on the lamellar orientation of PST crystals, the differently oriented PST crystals show different nucleation and propagation mechanisms of crack related to different level of fracture toughness.

(1) When the tensile axis is nearly perpendicular to the lamellae, the crack parallel to the lamellae propagates along the lamellar interface, only a few microcracks parallel to the lamellae nucleate ahead of the crack tip.

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

(3) When the tensile axis lies at intermediate angle from the lamellae, $K_{\rm I}$ and $K_{\rm II}$ both have effects upon 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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