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Crystallographic orientation dependent crack nucleation during the compression of a widmannstätten-structure α/β titanium alloy

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ABSTRACT

Based on the observation on slip trace and crystallographic orientation, the corresponding slip system, Schmid factor (SF) and geometric compatibility parameter (m') around the crack were calculated during compression of a widmannstätten-structure α/β titanium alloy. The difficult slip transfer, mainly occurring at a low m', induces a stress concentration on the grain boundary α (α_{GB}) and at the junction of several α colonies in the β grain, and then arouses a corresponding crack nucleation. The α_{GB}-α colony boundary, α-β interface, colony-colony boundary and slip plane could act as the crack propagation ways according to the different crack nucleation site.

α/β Titanium alloys are widely used as the airplane structural parts due to their attractive combinations of strength, toughness and fatigue resistance [1]. The fracture acts as a nonnegligible failure mode during the fabrication and service of the structural titanium alloys. Therefore, the investigation on the relationship between microstructure and fracture behavior is significant to optimize the processing parameters, as well as arouse a new idea on microstructure design of titanium alloys.

Generally, the secondary α phase (α_s) precipitates in α/β titanium alloys with a lamellar or acicular morphology [2], and their precipitation sites and morphologies have the specific effect on fracture behavior [2–7]. During plastic deformation, as the fine acicular α_s precipitated in the β matrix, the strain in β phase would be higher than that in the α_s. This inhomogeneous strain caused the formation of microvoids at the α/β interface, which could merge to be a crack [3, 4]. The α_s, precipitating on grain boundary (α_{GB}), was softer than the β matrix which contained many fine α_s. Thus, the α_{GB} experienced a preferential deformation and aroused a crack nucleation along the α_{GB} [5, 6]. For the widmannstätten-structure titanium alloy, cracks were primarily initiated on the α-β interface along α lamellae in the α colony [7]. During fatigue loading, the fatigue crack depended on the crystallographic orientation. The α grains favoring fatigue crack initiation were primarily those with a moderately high Schmid factor (SF) for basal slip [8]. However, a limited investigation focuses on the relationship between crystallographic orientation and crack nucleation site selection during the plastic deformation, which hinders the precise prediction of the preferential crack nucleation site.

A quasi in-situ experiment was used to trace the crack nucleation process during the compression of a Widmannstätten-structure TA19 titanium alloy. Based on scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) observations, this work not only determines the crack nucleation site according to the geometric morphology, but also reveal the relationship between the crack nucleation and crystallographic orientation by analyzing the slip transfer behavior and stress concentration around the crack.

The as-received TA19 titanium alloy consists of a Widmannstätten structure in which the volume fractions of lamellar α and interlayer β phase are 94.4% and 5.6%, respectively. Its β transus temperature is approximately 1000 °C. The chemical composition (wt%) of the alloy is of 5.80 Al, 1.88 Sn, 1.91 Mo, 3.78 Zr, 0.08Si, 0.02 Fe, 0.01C, 0.11 O, and balance Ti.

A cuboid specimen with dimensions of 6 mm (transverse direction, TD) × 8 mm (normal direction, ND) × 10 mm (compressing direction, CD) is machined for the compression. For the quasi in-situ observation on crack nucleation behavior, before the compression, one of CD-ND planes is treated by mechanical grinding and electrochemical polishing for the SEM and EBSD observations.

Compression experiment is performed at room temperature on a testing machine (SHIMADZU AG-× 10 KN) with a constant displacement rate of 0.6 mm/min. The cuboid specimen is compressed along the CD with a reduction of 7.96%. After the compression, a field-emission SEM (Tescan MIRA3) equipped with an EBSD analysis system (Channel 5, HKL Technology-Oxford Instruments) is employed to

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characterize the slip trace and crystallographic orientation on the pretreated CD-ND plane of the compressing specimen.

After compression, this work catches four typical crack nucleation sites, which are located around the α_{GB} (Figs. 1 and 2), and at the junction among several colonies inside the β grain (Figs. 3 and 4), respectively.

Fig. 1a shows that two α colonies distribute on the two sides of the α_{GB1}, and the two α colonies are named as G1 and G2 for simplifying the description. The Euler map (Fig. 1c) shows that the G1 colony has a same crystallographic orientation with $\alpha_{GB1,}$ but G2 colony does not. As referred in previous works [9–11], on the β GB, at least one of the two adjacent β grains was selected to be the nucleated site of α_{GB}, and the α_{GB} and selected β grain maintained the Burgers OR, i.e. $\{0001\}_{\alpha}//\{110\}_{\beta}$ and $\langle 11\bar{2}0\rangle_{\alpha}//\langle 111\rangle_{\beta}$. Subsequently, the α colony could nucleate on the α_{GB} with a same crystallographic orientation and grow into the selected β grain. Therefore, the same crystallographic orientation between G1 colony and α_{GB1} can be attributed to the nucleation of G1 colony on the α_{GB1}.

The magnifying image (Fig. 1b) shows that the crack around the α_{GB1} actually nucleates at the junction between the G2 colony and α_{GB1}. Generally, crack nucleation is caused by the stress concentration, which is largely related to the slip transfer behavior during deformation. A difficult slip transfer would arouse a dislocation pilling and stress concentration on the boundary [12]. In this work, SEM observation clearly catches the morphologies of slip traces. As seen from Fig. 1b, around the crack, there are two geometric directions of slip traces in the G1 colony and one direction in G2 colony, which indicates two types of slip system exist in G1 colony and one type in G2 colony. Based on the crystallographic orientation and slip trace direction, the corresponding slip systems and SF can be classified [13–15], as marked in the Fig. 1b. It is notable that the slip trace is continuous between lamellar α and interlayer β phase in one α colony, as seen from Fig. 1a. Due to the Burgers OR, the slip plane and direction of basal slip ($(0001)[11\bar{2}0]$) and prismatic slip ($(10\bar{1}0)[1\bar{2}10]$) in α phase are perfectly compatible with the slip systems of $(110)[1\bar{1}1]$ and $(112)[\bar{1}11]$ in β phase. Thus, the slip in α phase can easily transfer into the β phase and arouse a continuous slip trance [13].

The unimpeded slip transfer between lamellar α and interlayer β phase makes one α colony act as one integrated grain [16, 17]. Meanwhile, due to the same crystallographic orientation between α_{GB1} and G1 colony, the slip trace is continuous between G1 colony and α_{GB1}, indicating an unimpeded slip transfer behavior. However, the slip traces in both α_{GB1} and G2 colony end at the α_{GB1}-G2 colony boundary, rather than transfer into each other, indicating a difficult slip transfer between them.

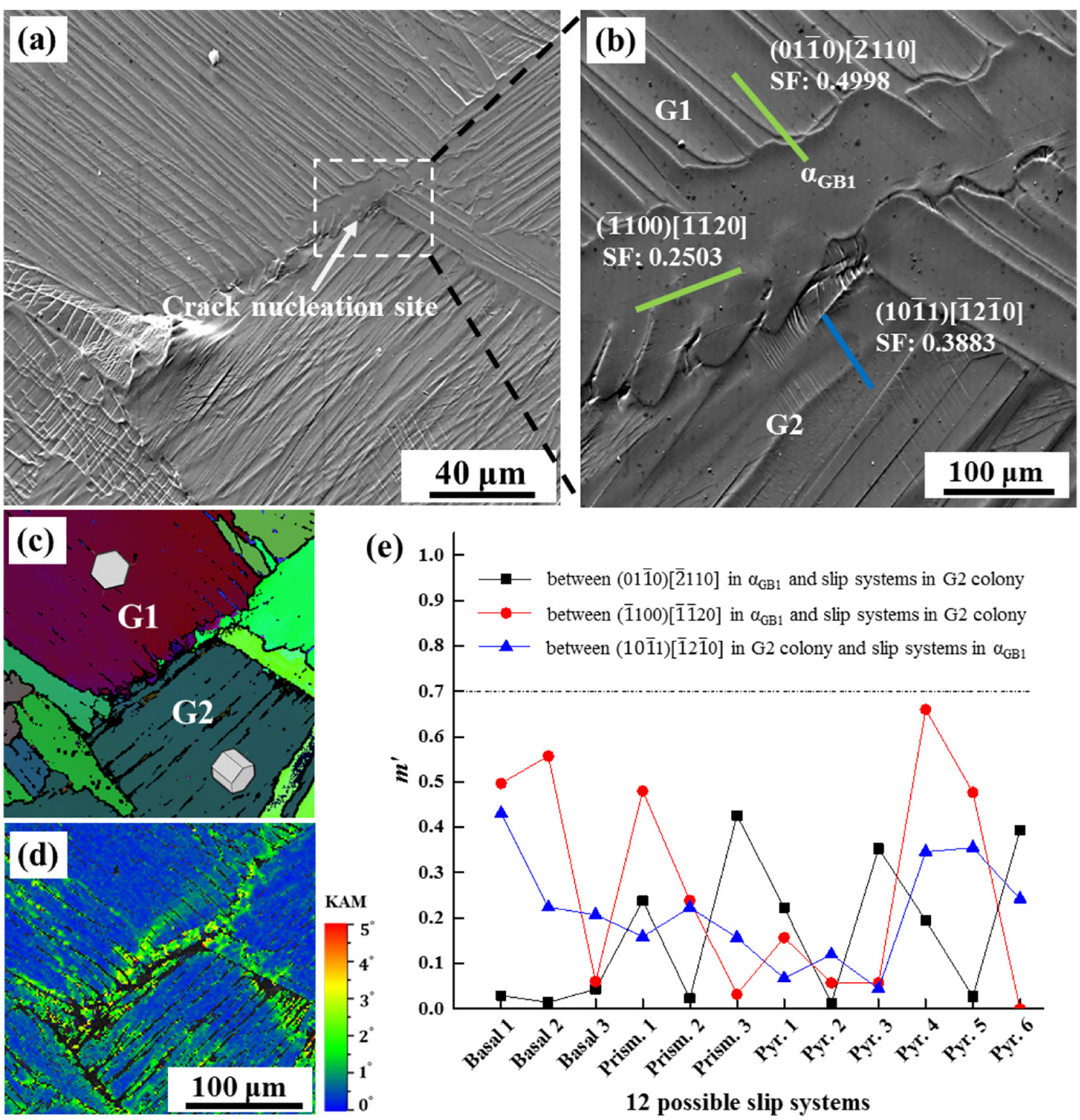

Fig. 1. Crack nucleates at the junction between α_{GB} and α colony: (a) SEM image, (b) Local magnifying image of (a), (c) Euler map, (d) KAM map, (e) *m'* distribution map.