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Deformation and damage behavior of colonies in a small-sized α/β Ti alloy

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The mechanical behavior of small-sized Ti alloy containing only a few colonies is expected to be different from that of its bulk counterpart. Here, we found that depending on the relation between the geometrical and colony scales of the small-sized Ti alloy, fracture did not always occur preferentially in the colony with the maximum Schmid factor. The proposed model suggests that the local strain level in the colony is a dominant factor.

Keywords: Titanium alloy; Scale; Slip; Strain; Schmid factor

Many engineering materials consist of two/multiple phases, typically with a lamellar structure, such as pearlitic steel, TiAl alloys, fully lamellar α/β Ti alloys and eutectic alloys, etc. Extensive investigations have shown that such a lamellar structure plays a key role in mechanical properties of the materials [1–5]. The α/β Ti alloy with typical Widmannstätten colonies consisting of α/β lamellae can exhibit good fracture toughness and high resistance to fatigue crack propagation [4–8]. In particular, Ti alloys have also recently been used as microcomponents in microelectromechanical systems (MEMS) devices, e.g. bioMEMS [9], and in biomaterials (dental and medical implant materials), e.g. porous Ti and Ti alloy foams [10–12]. Since the Widmannstätten colony containing a bundle of α/β laths is usually of dimensions ranging from several tens to hundreds of micrometers, which is comparable to the scale of the small-sized Ti alloy components and columns in porous Ti alloy foams, the question arises as to how deformation and damage develops in small-sized α/β Ti alloy, which contains only a few colonies. Obviously, an understanding of the mechanical behavior and basic mechanisms of Widmanstätten colonies would be important for both bulk and microscale Ti alloys, and may also be beneficial to other engineering materials with lamellar structures.

A few studies on the mechanical properties of individual colonies in α/β Ti alloys have been conducted [3,13–18] in recent years. Chan found that Schmid's law was not obeyed except for prismatic slip parallel to the β lamellae in Widmannstätten colonies of Ti–8Al–1Mo–1V alloy [3]. The yield stress and the strain-hardening rate both increased with decreasing values of the angle between the slip direction and the normal to the β platelets [13]. A more pronounced anisotropy was observed in the critical resolved shear stress for the three basal slip systems at room temperature [14,15]. Nonetheless, these investigations of mechanical behavior of the individual colonies in α/β Ti alloys have not yet been correlated with both the geometrical and microstructural scales of the material, which may be associated with the coordinated deformation capacity among different colonies.

In this paper, we investigate the damage behavior of a small-sized, single-colony-thick α/β Ti alloy, whose gauge dimensions are comparable to the scale of one or several α/β colonies using in situ scanning electron microscopy (SEM) tensile tests. From microscopic characterizations of the damage behavior of the colonies, a model has been proposed to elucidate the relation between the crystallographic anisotropy of the α/β lamellae in the colonies and the scales of the colonies relative to the material dimensions.

A Ti–6.5Al–3.5Mo–1.5Zr–0.3Si alloy, namely TC11, was selected here not only because it is used in turbine compressor disks and other aerospace components but also because it is simple to obtain relatively large colonies with typical α laths through heat treatment. The alloy was first annealed at 1040 °C for 30 min and then cooled in vacuum. The alloy contained Widmannstätten colonies with a

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typical α/β lamellar microstructure. Characterization of the microstructure of the alloy by SEM (LEO Supra 35) and transmission electron microscopy (JEOL FX2000II) shows that the average size of prior β grains is 715 μm, and each grain contains three or more α/β colonies with different lamellar orientations (see Fig. 1a). A colony with an average size of 171.06 μm consists of α and β laths with average widths of 1.71 and 0.22 μm, respectively. To prepare small-sized, single-colony-thick samples for in situ tensile testing, a thin sheet ~600 μm thick was cut from the as-received material using an electrical spark-cutting machine, then mechanically polished into a thin foil ~200 μm thick. Dog-bone-shaped tensile samples with gauge dimensions of 600 × 800 μm^2 (see Fig. 1a) were machined from the thin foil. Such a small deformation region may only contain ~3–4 colonies in the foil plane (see Fig. 1b). To ensure that there was only a single colony in the through-thickness direction (TTD) of the sample, in situ tensile samples were carefully mechanically polished to a thickness of ~100 μm, and then electropolished in a solution of 59.4% methyl alcohol, 34.6% butyl alcohol and 6% perchloric acid at 20 V/253 K.

In situ tensile experiments were conducted in the scanning electron microscope equipped with a Gatan MTEST2000ES tensile tester at tensile strain rate of $9 \times 10^{-4}\ s^{-1}$. A specific colony was chosen and examined by electron backscatter diffraction (EBSD) before testing, at strain ε = 1%, and after fracture. In addition, EBSD was also used to identify the crystallographic orientations of all the α laths in different colonies in the gauge section after the in situ tensile tests.

Figure 2a presents a low-magnification SEM image of the tensile sample after fracture, showing the fracture path and the distribution of the colonies in the gauge section. The crystallographic orientations of these colonies were extracted from the EBSD data. Based on SEM observation and EBSD characterization, the locations of the colonies in the gauge section and corresponding α unit cells for each bundle of α laths in the colonies can be determined as shown in Figure 2b, where these colonies are named colony A, colony B, etc. Comparing the fracture path in Figure 2a

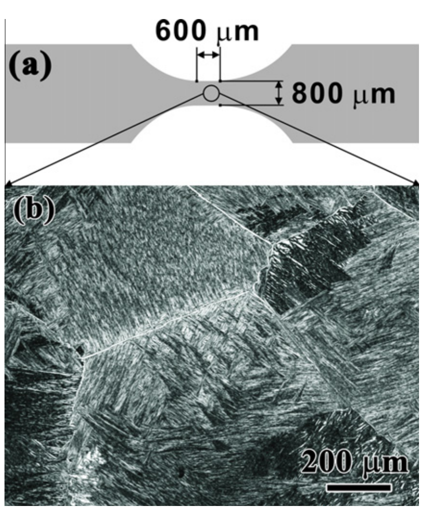

Figure 1. (a) Schematic of tensile sample for in situ testing, showing the sample has a small gauge region containing only several α/β colonies of Ti–6.5Al–3.5Mo–1.5Zr–0.3Si alloy; (b) SEM observation of the α/β lamellar microstructure in the alloy.

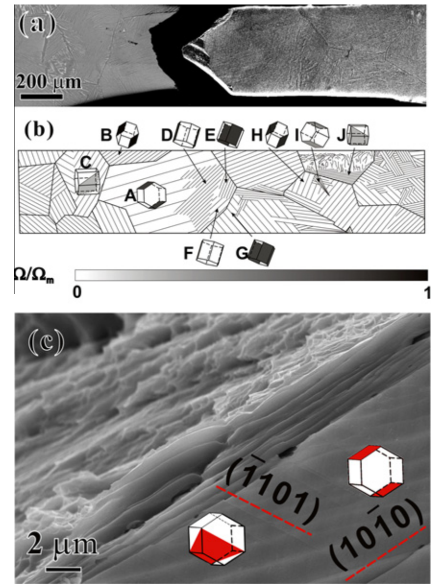

Figure 2. (a) SEM image of the tensile sample after fracture. (b) Schematic illustration of crystallographic orientations of colonies in the gauge section of the small-size tensile sample. Activated slip planes were also present in the α unit cells as indicated by the relative gray level based on the magnitude of the Schmid factor (Ω) normalized by the maximum Schmid factor (Ω_m). (c) SEM micrograph of slip lines appearing in colony A.

with the locations of the colonies in Figure 2b, it is clear that fracture predominantly occurred in colony A.

Furthermore, the Schmid factors (Ω) of all slip systems in the different colonies were calculated based on the EBSD data. Since there are three kinds of slip along prismatic, basal and pyramidal planes in the hexagonal α crystal, which have different critical resolved shear stresses (τ_{CRSS}), the normalized Schmid factor $\bar{\Omega}$ defined by the Ω/τ_{CRSS} ratio was estimated. It is worth noting that the CRSS ratio of a Ti alloy may vary with composition and testing conditions; it is normally 1:1 ~ 6:3 ~ 15 [15,19–26], and in particular no CRSS has yet been measured directly in TC11. Thus, here we selected the CRSS ratio of prismatic:basal:pyramidal slip as 1:2:3, not only because this has been obtained experimentally in α-Ti [19] but also for ease of the present calculation. Table 1 lists all slip systems with the largest $\bar{\Omega}$ in each colony. From Table 1, we can find that among the three kinds of slip, the prismatic slip in almost all the colonies has the highest $\bar{\Omega}$, implying that the prismatic slip would be activated preferentially. In particular, most of the colonies (A, B, D–F and H) in the gauge section have high $\bar{\Omega}$ for prismatic slip. Colony B has the highest $\bar{\Omega}$ for prismatic slip, while the $\bar{\Omega}$ of colonies D and H is quite close and slightly smaller than that of colony B. The $\bar{\Omega}$ of colonies A, E and F are similar but smaller than those of colonies D and H.

In order to visualize these slip systems with high $\bar{\Omega}$ in the colonies of the fractured sample, the slip planes that may be activated in the α unit cells are illustrated schematically by gray planes with different gray levels based on $\bar{\Omega}$ normalized by Ω_m (the maximum $\bar{\Omega}$ of colony B in Table 1). Correlating the visualized slip planes in the α unit cells with the positions of the colonies, it can be seen that fracture failure of the sample did not occur in colonies B, D and H with higher $\bar{\Omega}$, but in colony A with moderate $\bar{\Omega}$ (Fig. 2b). This