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Influence of low cycle fatigue on deformation twins in commercial purity titanium

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Slip and twinning are the two main kinds of deformation modes in metallic materials. In general, slip is the dominant deformation mode and twinning deformation is seldom found in f.c.c. crystals. At low temperature or high strain rate, twinning frequently occurs in b.c.c. crystals. For h.c.p. crystals, slip and twinning are competitive and complementary deformation modes in a wide temperature range [1–3]. Thus, both the dislocation and twin substructures should be considered in h.c.p. crystals after plastic deformation. Sometimes, twinning deformation plays a more important role, such as in titanium, zinc and zirconium alloys [1–7]. It was recognized that twinning deformation in polycrystallines was associated with the strain value, strain rate, temperature and grain size [4–7]. However, few references were found on the influence of cyclic strain amplitudes and numbers of cycles on deformation twinning in fatigued metals. Based on the results of cyclic deformation twins in titanium and zirconium [8–11], the aim of the present paper is to quantitatively reveal the influence of cyclic deformation on twinning in commercial purity titanium for an adequate understanding of the fatigue mechanism of h.c.p. crystals.

Commercial purity titanium TA2 was machined to fatigue specimens, which were annealed at 750 °C for 2 h under 1.33×10^{-3} Pa in vaccum. A structure with 35 μm equiaxed α-Ti grains was obtained, and no annealing twins formed. Cyclic deformation was performed on a Schenck servo-hydraulic testing machine under constant total strain amplitude control at room temperature in air. A triangular wave with 4×10^{-3} s^{-1} strain rate was used. The selected strain amplitudes were 0.5, 0.75, 1.0, 1.5, 2.2 and 2.4%, respectively. At each strain amplitude, a group of specimens were stopped at certain cycles N_i, until fracture. After being cyclically deformed, these specimens were spark-cut from the gauge and polished. Deformation twins within the specimens were observed by optical microscopy and measured by an image scan analyser.

The results showed that the twin fraction (F_T) increased with increasing amplitude within fatigued fracture specimens, as shown in Fig. 1. It was found that the twin fraction (F_T) was very low at low strain amplitude ($\varepsilon_a \leqslant 1.0\%$). In Fig. 1b, the relation of twin fraction to number of cycles is shown. It is indicated that the twin fraction (F_T) has a linear relation with number of cycles at a strain amplitude of 1.5%. At a strain amplitude $\varepsilon_a = 2.4\%$, in the early stage of cyclic deformation, the same relation was true, however, the initiation rate dF_T/dN of twin fraction (F_T) decreased slowly in the later stage. When the specimens were deformed to different cycles at the same strain amplitude, the deformation twins do not change their size. Deformation twins with nearly the same size at a strain

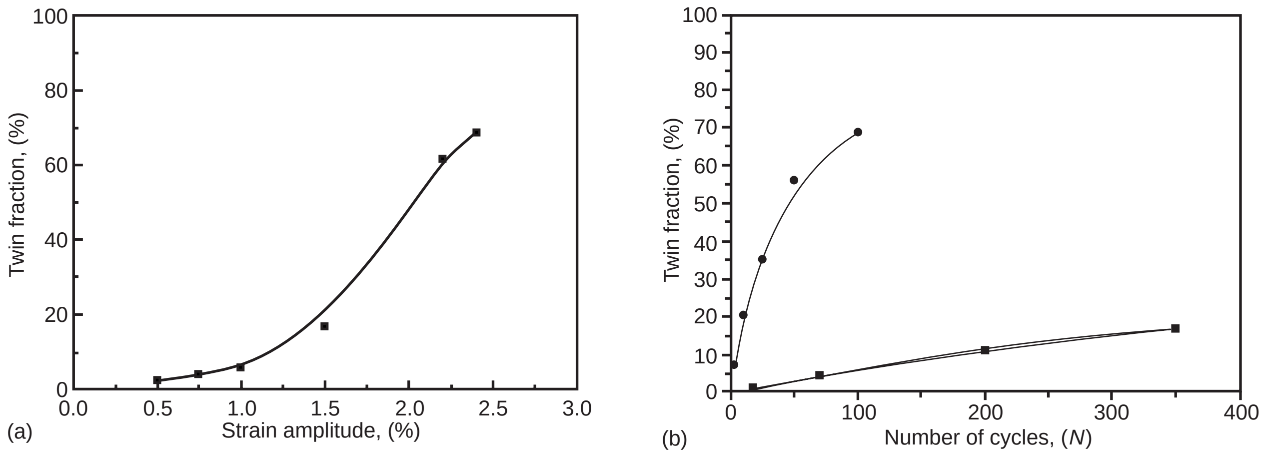

Figure 1 The influence of strain amplitude and number of cycles on deformation twinning in commercial purity titanium, (a) relation of twin fraction to cyclic strain amplitude, (b) relation of twin fraction to number of cycles, (●) 2.4%, (■) 1.5% strain.

amplitude of 2.4% ($N = 3$, 10, 50 and 100) are shown in Fig. 2. It is implied that the increase of twin fraction was associated with an increase in the number of twins, and not to the growth of the existed twins. Meanwhile, it was found that the individual twin size increased with increasing strain amplitudes, see Fig. 3, where the twins were formed at a strain amplitude of 1.5%.

Titanium, as one of the h.c.p. metal crystals, has complex slip and twinning systems. In general, the prismatic plane $\{1\,0\,\bar{1}\,0\}$, pyramidal plane $\{1\,0\,\bar{1}\,1\}$ and basal plane $(0\,0\,0\,1)$ are primary slip planes. Besides, the first-order pyramidal plane $\{1\,0\,\bar{1}\,1\}$ and the second-order pyramidal plane $\{1\,1\,\bar{2}\,2\}$ with $(c + a)$ Burgers vector are available for slip [2, 3]. The slip systems in titanium are shown in Table I.

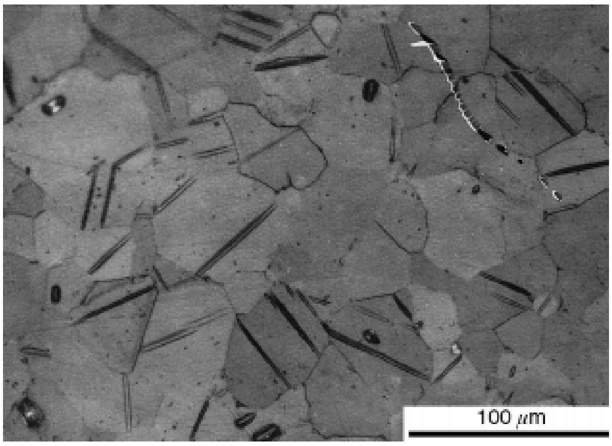

Figure 3 Deformation twins at $\varepsilon_a = 1.5\%$.

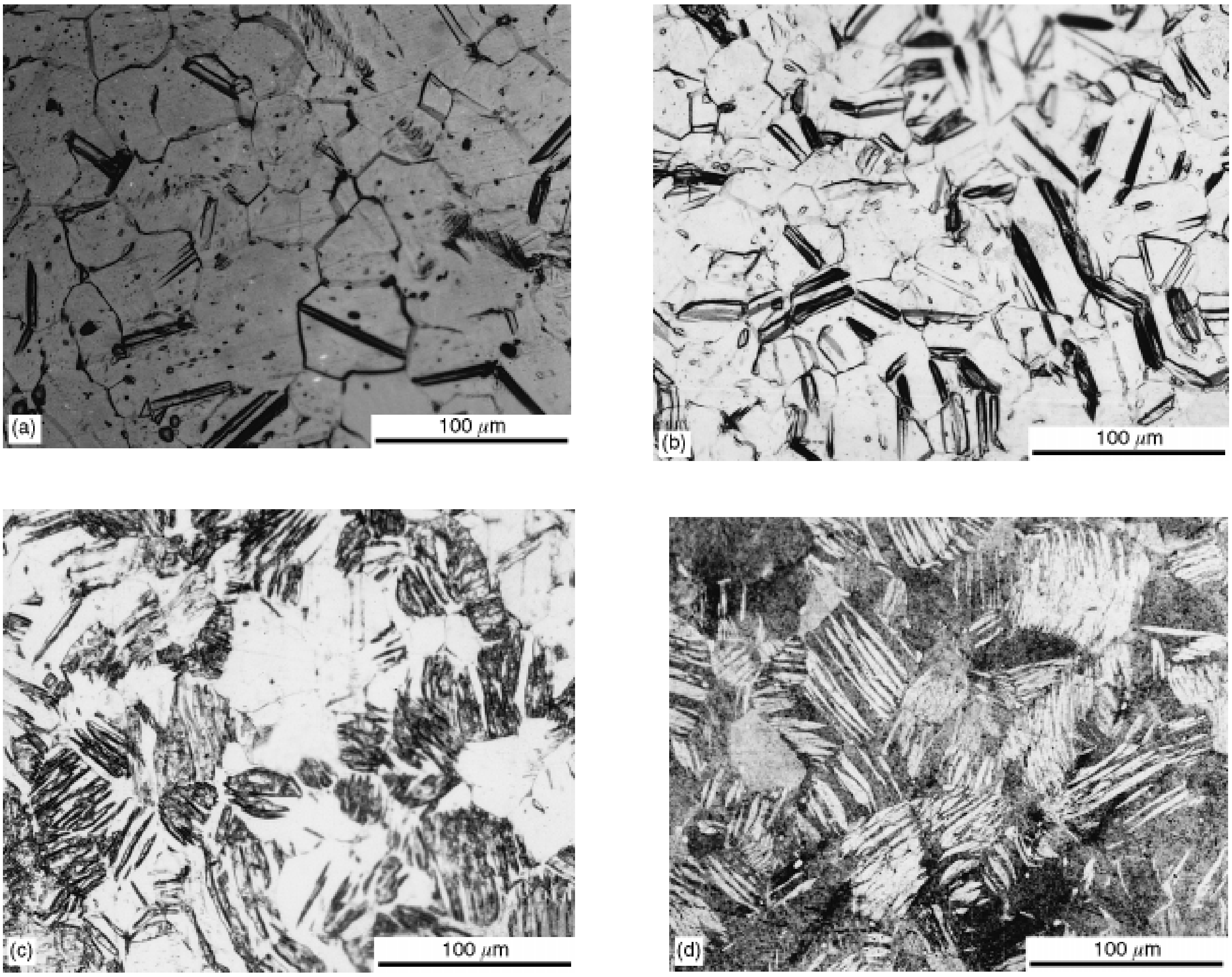

Figure 2 Deformation twins at $\varepsilon_a = 2.4\%$, (a) $N = 3$ cycles, (b) $N = 10$ cycles, (c) $N = 50$ cycles, (d) $N = 100$ cycles.

TABLE I Modes of slip in α-Ti

Direction	Plane	Crystallographic elements	Number of independent slip systems
	Basal slip	$(0\,0\,0\,1)\langle 1\,1\,\bar{2}\,0\rangle$	2
a	Prismatic slip	$\{1\,1\,0\,0\}\langle 1\,1\,\bar{2}\,0\rangle$	2
	Pyramidal slip	$\{1\,1\,0\,1\}\langle 1\,1\,\bar{2}\,0\rangle$	4
$c + a$	Pyramidal slip	$\{h\,k\,i\,l\}\langle 1\,1\,\bar{2}\,3\rangle$	5

On the other hand, it was also believed that twinning deformation in titanium played a more important role than that in cubic metals. In Table II, six twinning systems are listed, and of these twinning systems, three ($\{11\bar{2}4\}$, $\{11\bar{2}2\}$ and $\{10\bar{1}1\}$) are activated by compressive stress along the c-axis, while the other three systems ($\{10\bar{1}2\}$, $\{11\bar{2}3\}$ and $\{11\bar{2}1\}$) are activated by c-axis tension [7, 8]. Acording to the Von Mises criterion, five independent slip systems are necessary for metal crystals to provide homogeneous plastic deformation without cracking. From Table II, it is known that the four slip systems of basal and prismatic planes are correlated with the pyramidal planes. An additional deformation mode must be required to satisfy the Von Mises criterion besides the four independent slip systems. In practice, it was provided by twinning or second-pyramidal slip, especially, twinning deformation played a more important role below 300 °C.

In general, it was reported that the nucleation of twinning required a critical strain which decreased with increasing grain size [5]. Similarly, a critical stress to activate the deformation twins was found in some materials [13]. Thus, this might be why few twins were observed when the strain amplitude was below 1.0%. When the strain amplitude was higher than 1.5%, cyclic stress and strain amplitudes would be over the critical value of stress and strain required to nucleate twinning, the number of cycles would have a relatively important effect on the nucleation of deformation twins (see Fig. 1b).

Here, we may consider cyclic deformation as a multi-tension and compression process. When the stress and strain amplitudes were higher than the critical stress and strain of nucleating twins, deformation twins would be produced, in every cycle, with the same size. The higher the strain amplitude, the more and larger twins were produced in each cycle, see Fig. 1b and Fig. 2. At a strain amplitude of 1.5%, few twins with small size were observed (see Fig. 3). The initiated twins would have little effect on the formation of new deformation twins. This would result in the twin fraction F_T increasing nearly linearly with the number of cycles N (see curve 1 in Fig. 2). When the strain amplitude was increased to 2.4%, more and larger twins were observed in each cycle. With further cyclic deformation, twinning occurred within most grains, thus the nucleation of new deformation twins would become so difficult that the initiation rate F_T decreased slowly in the later stage. From Fig. 1b, the initiation rates of twin fraction at different strain amplitudes were calculated as follows

TABLE II Six twinning systems in α-Ti

K1	K2	$\eta 1$	$\eta 2$	S
$\{10\bar{1}1\}$	$\{10\bar{1}3\}$	$\langle 10\bar{1}2\rangle$	$\langle 30\bar{3}2\rangle$	0.105
$\{10\bar{1}2\}$	$\{10\bar{1}2\}$	$\langle 10\bar{1}1\rangle$	$\langle 10\bar{1}1\rangle$	0.167
$\{11\bar{2}2\}$	$\{11\bar{2}4\}$	$\langle 11\bar{2}3\rangle$	$\langle 22\bar{4}3\rangle$	0.225
$\{11\bar{2}4\}$	$\{11\bar{2}2\}$	$\langle 11\bar{2}1\rangle$	$\langle 11\bar{2}3\rangle$	0.254
$\{11\bar{2}3\}$	$\{11\bar{2}5\}$	$\langle 33\bar{6}2\rangle$	$\langle 55\overline{10}2\rangle$	0.533
$\{11\bar{2}1\}$	$\{0001\}$	$\langle 11\bar{2}6\rangle$	$\langle 11\bar{2}0\rangle$	0.638

$$\frac{dF_T}{dN} = 0.05\% \qquad (\varepsilon_a = 1.5\%)$$

$$\frac{dF_T}{dN} = \frac{(1 - F_T)^2}{40} \qquad (\varepsilon_a = 2.4\%)$$

Twinning deformation in materials may reduce the internal stress concentration and make further deformation easy, however, materials containing deformation twins might initiate fatigue micocracks near the twins. In Fig. 4a, microcracks forming along the twin boundary are shown. There was another kind of microcrack, which was produced by two twins from different directions impinging, as indicated in Fig. 4b. In general, it was recognized that twinning would produce shape changes in its own right and could also permit dislocations to glide by re-orientating regions of metals, meanwhile, twinning could also introduce barriers to dislocation movement [2]. It is necessary to investigate the interactions of twin-twin and twin-dislocation, which might reveal the mechanism of fatigue damage in metals.

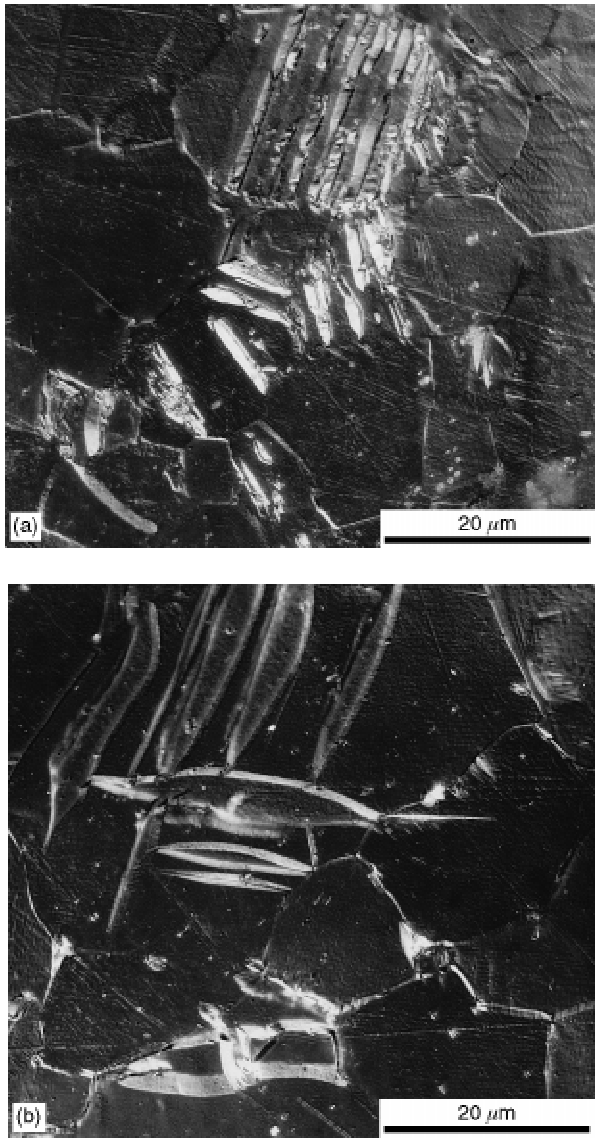

Figure 4 Fatigue microcracks near twins, (a) fatigue crack along twin boundary, (b) fatigue crack by interaction of twins.

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