Materials Science and Engineering A 528 (2011) 7570–7578

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Crystallographic fatigue crack growth in titanium single crystals

Yoji Mine[a,*], Shinji Ando[b], Kazuki Takashima[b]

[a] Department of Mechanical Engineering, Kyushu University, Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan
[b] Department of Materials Science and Engineering, Kumamoto University, Kurokami, Kumamoto 860-8555, Japan

ARTICLE INFO

Article history:
Received 7 April 2011
Received in revised form 20 May 2011
Accepted 26 June 2011
Available online 2 July 2011

Keywords:
Mechanical characterization
Titanium alloys
Dislocation
Fatigue
Orientation relationships
Twinning

ABSTRACT

The crystallographic dependence of fatigue crack growth in titanium single crystals is characterized by striation formation, herringbone-pattern formation and twin-related basal plane separation. In crystals that are oriented favourably to prismatic slip, i.e. soft-oriented crystals, the crack grows parallel to a prismatic plane while forming striations. The crack is thought to extend by alternating shear on two intersecting planes composed of prismatic and pyramidal slip systems at the crack tip. When the crack grows along a direction within ~40° of [0 0 0 1], herringbone patterns are formed by complementary operation of two sets of pyramidal slip systems containing the $\langle c+a\rangle$ slip directions. In crystals oriented unfavourably to the glide, i.e. hard-oriented crystals, the activation of $\{0 1 \bar{1} 2\}$ micro-twins participates in the crack growth parallel to the basal plane. The resistance to fatigue crack growth is higher in the hard-oriented crystals than in the soft-oriented crystals.

1. Introduction

The aim of this study is to elucidate a possible mechanism for crack growth in α-titanium with a hexagonal close-packed (hcp) structure under cyclic loading. Fatigue crack growth in crystalline metals and alloys is fundamentally based on cyclic plastic deformation processes at the crack tip [1]. The crack growth increment for each load cycle, da/dN, in such materials is often in the range of 10^{-9}–10^{-6} m. This crack extension is usually much smaller than the grain size of metallic materials except for ultrafine-grained and nanocrystalline materials. Hence, the inspection of the underlying crack growth mechanisms that occur in single crystals provides essential information for understanding the intrinsic fatigue crack growth resistance of materials. There have been several investigations into the fatigue crack growth mechanisms for face-centred cubic (fcc) and body-centred cubic (bcc) crystals. For fcc crystals, Neumann [2,3] and Pelloux [4] proposed fatigue crack growth models based on the separation of slip planes by alternating shear on two intersecting planes at the crack tip, e.g. (1 1 1) and $(1 1 \bar{1})$ if the crack growth direction is $[\bar{1} \bar{1} 0]$. This model agrees well with experimental results [2–6], which showed the formation of striations along the intersection of the two activated slip planes on fracture surfaces. Similar crack growth models based on the alternating shear of two slip planes have also been presented for bcc [7–10] and hcp crystals [11–13]. However, various fracture features other than striations are prevalent on the fatigue surfaces of hcp crystals [11–15]. This may be partly due to the fact that the deformation process in hcp crystals is highly dependent on their crystallographic orientation [16,17]; therefore the crack growth mechanism is complicated to understand. A prismatic or basal slip system is preferentially activated by loading along the ⟨a⟩-axis of the hcp crystal (soft-oriented crystal) because of its lowest critical resolved shear stress (CRSS). In contrast, in crystals oriented unfavourably to the prismatic and basal slips (hard-oriented crystals), mechanical twinning as well as pyramidal slipping may occur causing deformation along the *c*-axis.

Among hcp crystals, α-titanium and its alloys have been applied in aerospace structures and engine components because of their excellent specific strength and corrosion resistance. Therefore, it is important to address the fundamental behaviours of such materials. In the current study, the fatigue crack growth mechanisms in α-titanium single crystals was examined from the crystallographic perspective.

2. Material and experimental methods

The material used in this study was a 22 mm thick plate of commercially pure titanium (JIS-Grade 1) containing Ti with 0.055 mass% Fe, 0.085 mass% O and 0.0054 mass% N. The grain was coarsened by annealing as follows. Bar samples with dimensions of 17 mm × 75 mm × 6 mm were cut from the plate and encapsulated in silica tubes under a vacuum pressure of 3×10^{-3} Pa to

* Corresponding author. Tel.: +81 92 802 3286; fax: +81 92 802 3065.
E-mail address: mine@mech.kyushu-u.ac.jp (Y. Mine).

0921-5093/$ – see front matter
doi:10.1016/j.msea.2011.06.079

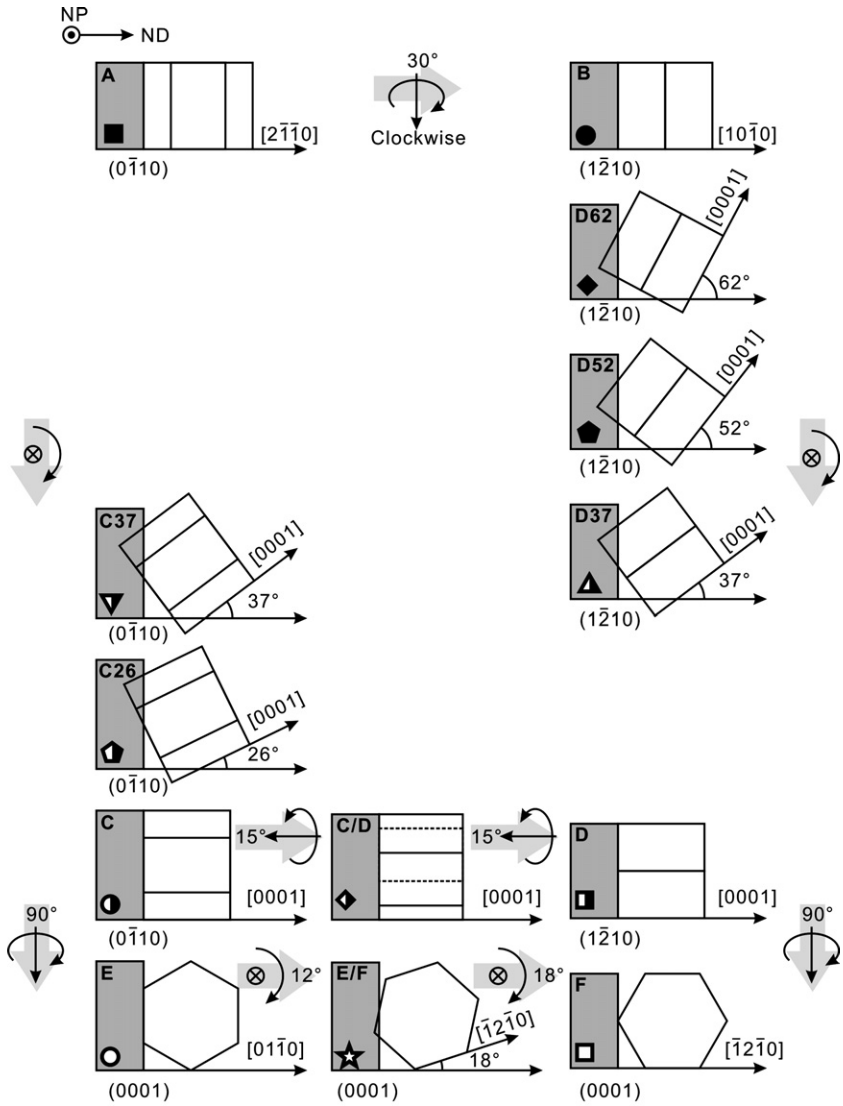

Fig. 1. Schematic illustration of the crystallographic orientations of the notch plane and direction.

prevent severe oxidation during the heat treatments. The samples were heated to a temperature of 1473 K within the β phase region at a heating rate of 0.1 K s^{-1} and held at this temperature for 10.8 ks. Subsequently, the samples were furnace-cooled to a temperature of 1123 K within the α phase region and just below the β transus (1155 K) and held for 86.4 ks followed by furnace cooling to room temperature. These heat treatments provided coarse grains with a size of approximately 15 mm throughout the bar. Their crystallographic orientations were determined using a back-reflection X-ray Laue method. Compact-tension (CT) specimens with a width of 9 mm and a thickness of 1.5 mm were cut from the coarse-grained bars. A 0.3 mm through-thickness notch was introduced mechanically with a diamond saw to obtain an a_0/W ratio of 0.25, where a_0 is the initial notch length and W the width of the CT specimen. Single-crystalline specimens with the six representative orientations and their intermediates were obtained, as illustrated in Fig. 1, representing the crystallographic orientations of the notch plane and direction. The specimens with notch planes and directions of $(0\bar{1}10)[2\bar{1}\bar{1}0]$, $(1\bar{2}10)[10\bar{1}0]$, $(0\bar{1}10)[0001]$, $(1\bar{2}10)$ $[0001]$, (0001) $[01\bar{1}0]$, and (0001) $[1\bar{2}10]$ were designated as the A-, B-, C-, D-, E-, and F-specimens, respectively. Table 1 shows the deformation mode favoured for each crystal.

Table 1
Primary deformation modes for A-, B-, C-, D-, E-, and F-specimens.

	A	B	C	D	E	F
Loading direction	$[0\bar{1}10]$	$[1\bar{2}10]$	$[0\bar{1}10]$	$[1\bar{2}10]$	$[0001]$	$[0001]$
Notch direction	$[2\bar{1}\bar{1}0]$	$[10\bar{1}0]$	$[0001]$	$[0001]$	$[01\bar{1}0]$	$[\bar{1}2\bar{1}0]$
Primary deformation mode	Prismatic slip	Prismatic slip	Prismatic slip	Prismatic slip	$\{01\bar{1}2\}$ twin	$\{01\bar{1}2\}$ twin