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Crystallographic study of fatigue crack growth in Fe–Si alloy single crystals

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ABSTRACT

Crystallographic fatigue crack growth has been studied using iron–silicon single crystals having a notch plane of (1 1 0) or (1 1 2). In crystals containing a notch direction within an angle of ∼35° to [0 0 1] on a notch plane of (1 1 0), a crack grows by the separation of slip planes on the basis of evenly operated alternating shear on the intersecting slip systems at the crack tip. These crystals exhibit considerably high resistances to fatigue crack growth. In a crystal with a notch direction rotated at an angle of ∼55° to [0 0 1] on (1 1 0), two competing mechanisms, i.e. cleavage-like cracking related to the generation of sessile dislocations and saw-toothed feature formation due to the activation of multiple slip systems, appeared instead of an alternating shear mechanism. When alternating shear occurs unevenly on asymmetrically arranged slip planes, the fatigue crack growth resistance is low as compared to that in the case in which it occurs evenly.

1. Introduction

It is well established [1,2] that the fatigue process of metals consists of the cumulative damage resulting from the irreversible motion of dislocations, crack initiation via the development of persistent slip bands, and crack propagation based on cyclic plasticity at the crack tip; fatigue eventually leads to catastrophic failure. Hence, a significant amount of effort has been devoted to the prevention or homogenization of plastic deformation by metallurgical and mechanical techniques in order to modify fatigue characteristics. The possible fatigue-strengthening approaches are the improvement of yield strength, removal of stress concentration, compressive residual stresses, etc. Recently, layered steels with excellent crack arrestability against brittle fracture have been developed [3–5]. It is particularly important to understand the intrinsic resistance of materials to crack growth by texture strengthening.

Since the crystallographic orientation at the fatigue crack tip dominates the fatigue crack growth behaviour in crystalline metals and alloys, an inspection of the underlying crack growth mechanisms of single crystals provides essential information for understanding the intrinsic fatigue crack growth resistance of materials. Generally accepted models [6,7] elucidate the crystallographic fatigue crack growth process on the basis of the separation of slip planes by alternating shear on two intersecting planes at the crack tip, i.e. a slip-off process. Such elucidation is supported by many experimental results addressing the dependence of fatigue crack growth on the crystallographic orientation in face-centred cubic (fcc) metals and alloys [8–11]. On the other hand, in the case of body-centred cubic (bcc) materials, the crystallographic orientation dependence of fatigue crack growth has not been investigated systematically [12–16], while several fracture features other than striations appear on the fatigue surfaces of α-ferrite iron [17]. This may be partly due to the fact that the activity of slip systems in bcc metals is more complicated than that in fcc metals. Among bcc metals, an α-ferrite iron phase is one of the main constituents of steels. It is extremely important to elucidate the dependence of its crystallographic fatigue cracking processes on the mobility of dislocations in order to develop advanced steels with a high resistance to fatigue crack growth. This study examines the dynamic that controls crystallographic fatigue crack growth in Fe–3 mass% Si alloy single crystals from the crystallographic perspective.

2. Materials and experimental methods

The material used in this study was an iron–silicon alloy. This alloy contained 0.0010 C, 3.00 Si, 0.003 Mn, 0.0011 P, 0.001 S, 0.0013 O, and 0.001 Al (in mass%), and the remainder was Fe. Coarse grains having a size of a few tens of millimetres were obtained by using a strain-annealing technique. Their crystallographic orientations were determined using a back-reflection X-ray Laue method. Single-edge-notched (SEN) three-point bending specimens having nominal sizes of 5 mm × 5 mm × 23 mm (with a bending span of 18 mm) were cut from the coarse-grained bars. A

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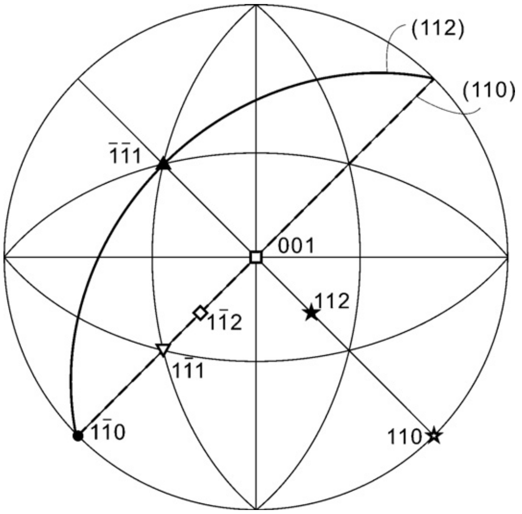

Fig. 1. Pole figure representing notch planes and directions of $(1\,1\,0)$ $[0\,0\,1]$, $(1\,1\,0)$ $[1\,\bar{1}\,2]$, $(1\,1\,0)$ $[1\,\bar{1}\,1]$, $(1\,1\,2)$ $[1\,1\,\bar{1}]$, and $(1\,1\,2)$ $[1\,\bar{1}\,0]$.

Table 1
Relative shear stress $\tau' = \tau\sqrt{2\pi r}/K_{\rm I}$ imposed on predicted slip systems in crystals with $(1\,1\,0)$ notch plane.

	$(1\,1\,\bar{2})$	$(\bar{1}\,2\,\bar{1})$	$(0\,1\,\bar{1})$	$(\bar{1}\,1\,0)$
$(1\,1\,0)$ $[0\,0\,1]$ crystal	0.363	0.181	0.314	0
$(1\,1\,0)$ $[1\,\bar{1}\,2]$ crystal	0.319	0.301	0.354	0.179
$(1\,1\,0)$ $[1\,\bar{1}\,1]$ crystal	0.269	0.327	0.334	0.247
$(1\,1\,0)$ $[1\,\bar{1}\,0]$ crystal	0.207	0.291	0.244	0.289

Table 2
Relative shear stress $\tau' = \tau\sqrt{2\pi r}/K_{\rm I}$ imposed on predicted slip systems in $(1\,1\,2)$ $[1\,1\,\bar{1}]$ crystal.

$(1\,1\,2)$ $[1\,1\,\bar{1}]$ crystal	Slip plane		
Slip direction $[1\,1\,1]$	$(\bar{1}\,\bar{1}\,2)$ 0.385	$(\bar{1}\,0\,1)$ 0.333	$(\bar{2}\,1\,1)$ 0.193
Slip direction $[1\,1\,\bar{1}]$	$(\bar{1}\,\bar{1}\,0)$ 0.209	$(\bar{2}\,\bar{1}\,\bar{1})$ 0.205	$(\bar{1}\,\bar{2}\,1)$ 0.184

through-thickness notch was introduced mechanically using a diamond saw (thickness: 0.3 mm) so that the ratio a_0/W was 0.25, where a_0 is the initial notch length and W is the width of the SEN specimen. Single-crystalline specimens with five different orientations were obtained, as illustrated in Fig. 1, representing the crystallographic orientations of the notch plane and the notch direction. In the crystals having notch planes and directions of $(1\,1\,0)$ $[0\,0\,1]$, $(1\,1\,0)$ $[1\,\bar{1}\,2]$, and $(1\,1\,0)$ $[1\,\bar{1}\,1]$, possible slip systems were symmetrically situated with respect to the notch plane, whereas the $(1\,1\,2)$ $[1\,1\,\bar{1}]$ and $(1\,1\,2)$ $[1\,\bar{1}\,0]$ crystals were asymmetrically oriented. Although the crystallographic crack growth in single crystals often results in mixed-mode cracking, we discuss the case when the crack grows on the first principal stress plane. Tables 1–3 list the relative shear stresses, $\tau' = \tau\sqrt{2\pi r}/K_{\rm I}$, on predicted slip planes, assuming an elastic isotropic medium with a

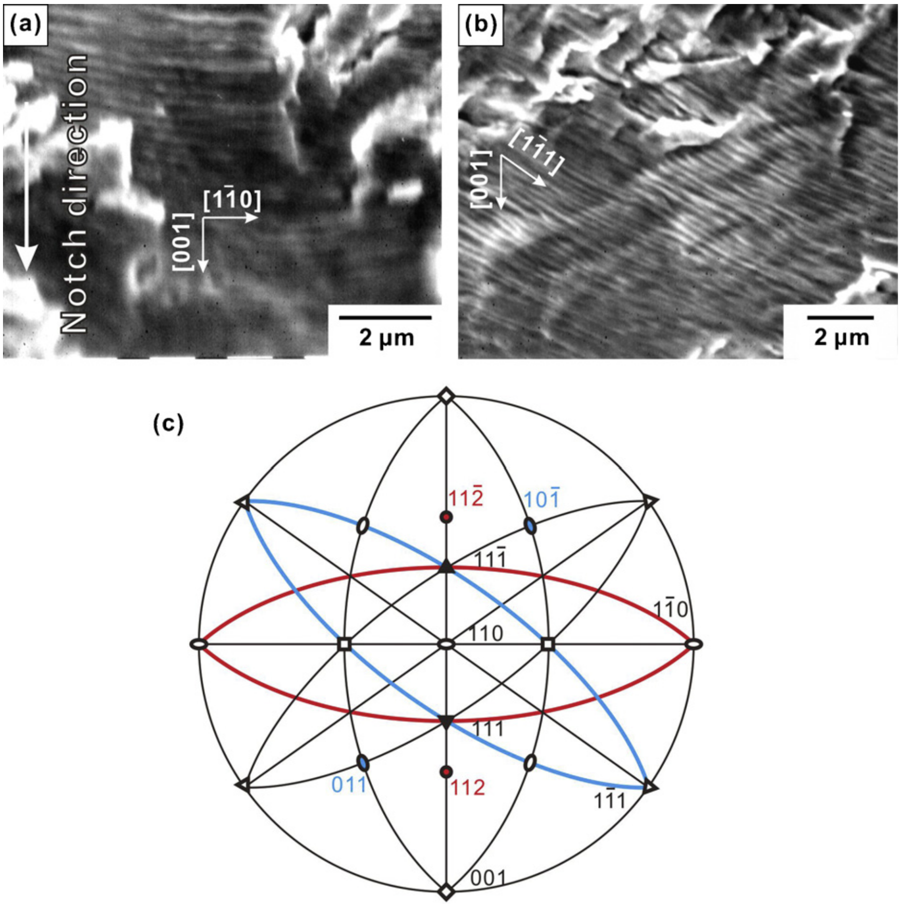

Fig. 2. (a and b) Striations on fatigue surface of $(1\,1\,0)$ $[0\,0\,1]$ crystal and (c) pole figure representing their crystallographic orientation relationships with possible slip systems projected on $(1\,1\,0)$ crack plane.