THE DEPENDENCE OF FATIGUE CRACK PROPAGATION RATE AND CRACK PLANE
ON
CRYSTALLOGRAPHIC ORIENTATION IN Fe-3%Si SINGLE CRYSTALS

Y. Higo and S. Nunomura

Research Laboratory of Precision Machinery and Electronics
Tokyo Institute of Technology
4259 Nagatsuta, Midori-ku, Yokohama, 227 Japan

ABSTRACT

The effect of crystallographic orientation on the fatigue crack propagation rate, fatigue fracture surface morphology and threshold alternating stress intensity of long crack has been investigated in Fe-3%Si single crystals. The threshold stress intensity was found to vary widely, even for small changes in orientation. For stress intensities between the threshold and the Paris law region the fatigue crack growth rates had a strong orientation dependence and a crystalline fatigue fracture surface containing (100) and (110) facets. At higher stress intensities, in the Paris law region, all orientations were found to lie on the same Paris law growth rate line, and the fatigue fracture surfaces become smoother and non-crystallographic.

KEYWORDS

Fatigue crack propagation rate; threshold alternating stress intensity; crystallographic fatigue; Fe-3%Si; single crystal.

INTRODUCTION

A number of models have been proposed for the propagation of fatigue cracks in metals, based on the plastic deformation around the crack tip under cyclic loading. In these models the plastic deformation has usually been related to the crystallographic stress orientation and magnitude. The plastic deformation around a crack under cyclic loading is considered to be more complicated than under monotonic tensile loading. Despite this, the crystallographic deformation around the crack tip has an effect on the fatigue crack propagation rate and fracture morphology. It is therefor important to study the effects of crystallographic orientation on fatigue crack propagation, in order to understand what deformation occurs at the fatigue crack tip.
Neumann and others (1977) reported that fatigue cracks in Fe-3%Si single crystals propagated along (100) at low ΔK, where the fracture surface was cleavage-like. At higher ΔK, fatigue cracks propagated along (110), and fracture surface become ductile. In Cu-8%Al single crystals, fatigue cracks were found to propagate along (100) (Higo and Knott, 1980). These results support the idea that fatigue cracks occur due to cycle crystallographic plastic deformation at the crack tip.

In this paper, the relationship between crystallographic orientation, fatigue crack propagation rate, threshold cyclic stress intensity and fatigue crack morphology are investigated in Fe-3%Si single crystals.

EXPERIMENTAL PROCEDURE

The crystallographic orientations of large Fe-3%Si single crystals were determined by the X-ray Laue back-scattering technique, and CT specimens of approximately 25×25×5mm in size were carefuly cut from them using a wheel cutter. The damaged surface layer was then removed by chemical polishing and a notch was introduced with a spark cutter. The orientation of the loading direction, the notch plane and the initial fatigue crack propagation direction in each specimen are shown in Fig. 1-a,b,c.

Fatigue tests were performed under tension-tension loading on a servohydraulic

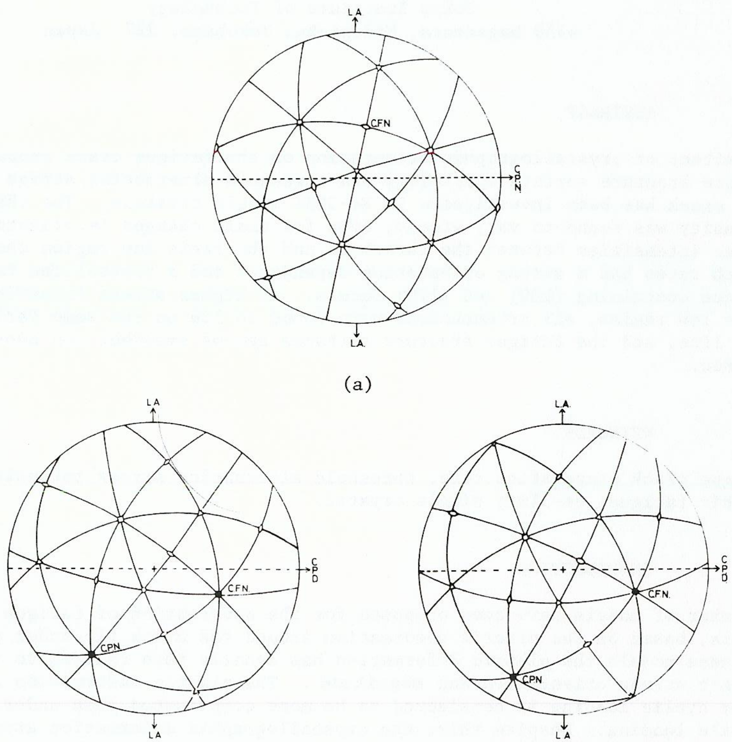


Fig. 1. Stereographic projections showing the loading direction (LA), the initial crack propagation direction (CPD), the crystallographic fatigue facet normal (CFN), and the final cleavage fracture plane normal (CPN) for single crystal fatigue specimens.

a) Specimen A, b) Specimen B, c) Specimen C

fatigue testing machine under load control, with on R-ratio of 0.1. Fatigue crack lengths were measured by the potential drop method, and the measured crack lengths used to control the applied loads so as to keep ΔK constant. The fatigue crack was initiated at a higher ΔK, after which ΔK was slowly reduced until a threshold value was obtained. It was then increased again and the crack growth rate measured. Finally, the control made was changed from constant-ΔK to constant cyclic load, and the fatigue crack grown until cleavage fracture occurred. After testing, the fatigue fracture surfaces were analysed using both the scanning electron microscope and optical goniometer.

RESULTS AND DISCUSSION

Figure 2 shows the fatigue crack growth rate as a function of applied alternating stress intensity (ΔK) for each of the three crystal orientations shown in Fig.1.

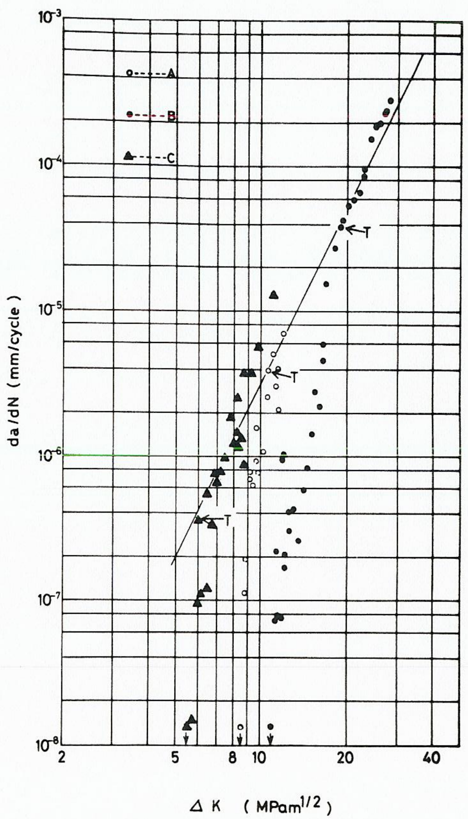
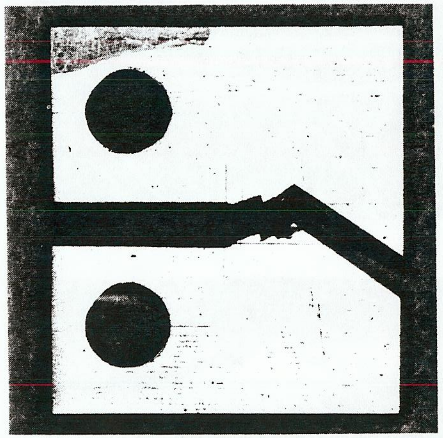


Fig. 2. Fatigue crack growth per cycle versus ΔK curves for specimens A,B and C. Arrows indicate the threshold ΔK, ΔK_{th}. Points T indicate the transition from crystallographic fatigue to the Paris law region.

It can be seen that the threshold alternating stress intensity (ΔK_{th}) varies widely for the three orientations, from 5.5 to 11 $MPam^{\frac{1}{2}}$. In particular, the angle between B and C was only 10°, but ΔK_{th} varied by a factor 2. This is much greater than the changes in ΔK_{th} in fcc Cu-8%Al alloy for similar orientation changes (Higo and Knott, 1980). The large change in ΔK_{th} between B and C is attributed to a change in the slip system, which in bcc metals is determined by both the applied stress direction and sign (Stein and others, 1973), and indicates the crystallographic nature of the plastic deformation during fatigue crack growth.

The region from the threshold until the transition to the Paris law region, point T, also shows a great dependence on crystallographic orientation, with orientations B and C showing the greatest difference. However, after the transition point T, in the Paris law region, all three orientations appear to lie on the same straight line, Fig.2. The slight deviations with increasing ΔK, in the range 8 - 11 $MPam^{\frac{1}{2}}$ for specimen C, and 25 - 28 $MPam^{\frac{1}{2}}$ for specimen B, are due to the changeover of the load control mode from constant ΔK to constant cyclic load.

Figure 3 shows specimen B after fracture. The dark region in one corner is a second grain, all the rest of the specimen is a single crystal. The final failure was by cleavage, which occurred during the fatigue. The fatigue crack surface has a macroscopically zig-zag appearance, which is associated with crystallographic fatigue.



1 cm

Fig. 3. Photograph of specimen B, showing the stepped crystallographic fatigue crack region and the final cleavage failure.

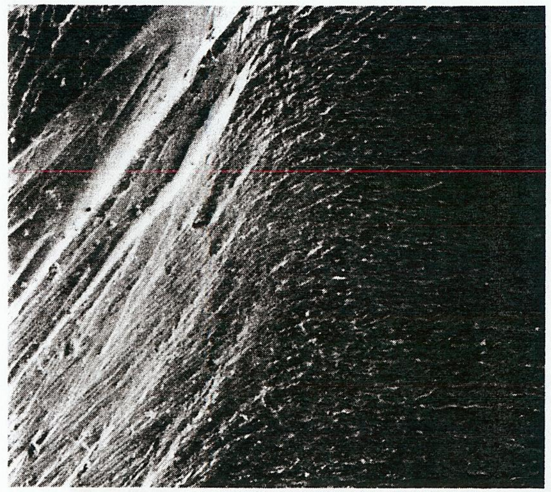
The fatigue fracture surfaces of all specimens consisted of two regions, a comparatively rough faceted region from ΔK_{th} to the transition to the Paris law region,T, and a smoother non-faceted region from T up to the final cleavage failure. This is shown for specimen B in Fig. 4(a). Higher magnification SEM micrographs of the low ΔK crystallographic region, region b in Fig. 4(a), and the Paris law region, region c in Fig. 4(a), are shown in Fig. 4(b) and 4(c) respectively. The striation-like pattern visible in Fig. 4(c) is in fact due to micro-cracks, not striations, and the surface shows no crystallographic features.

The crystallographic nature of the fatigue surface in the ΔK_{th} to point T region is shown for specimen C in Fig. 5. Here the specimen was tilted about 35° in the SEM to show the step-like nature of the fracture surface, which consists of planar

steps separated by rougher regions. The crack propagated diagonally from the left bottom to the right top corner, and points 'X' are the same in both Fig. 5(a) and Fig. 5(b). The orientation of the planar steps was measured with an optical goniometer, and was found to be(100). Analysis of the planar steps on specimen B low ΔK fracture surface gave the same result. These orientations are marked in Fig. 1(b) and 1(c). The orientations of the final cleavage fracture planes, which are different (100), also marked in Fig. 1(b) and 1(c).

Specimen A gave a rather different result, in that although the low ΔK region up to near point T gave a crystallographic fracture surface, the steps on it were smaller and more confused, and hence difficult to analyse. However, those to point T, larger facets were visible, and were found to be (110). Neumann and others(1977) also found that in Fe-3%Si, fatigue cracks followed (110) at higher ΔK and (100) at low ΔK, although the values of ΔK and the crack growth rate were not given. In the present work, a similar result was obtained, except that the low ΔK (100) region occurred from the threshold to just before point T, and the higher ΔK (110) region occurred from there until point T. After point T, in the Paris law region, no crystallographic dependence was found, in strong contrast to the region from initiation to point T. A possible explanation of this is that in the low ΔK region, fatigue crack propagation is controlled by crystallographic slip, while in the higher ΔK Paris low region it is controlled by the dislocation cell structure, as in the fatigue of polycrystals. The crystallographic fatigue plane actually observed depends on both the crystal orientation and the applied stress level.

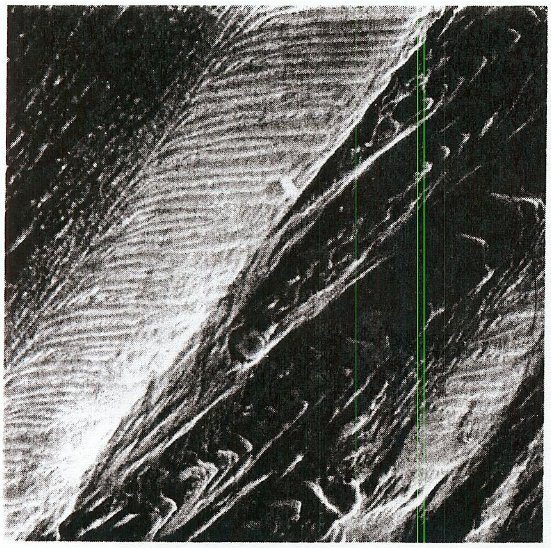
In specimen B and C, the same (100) law ΔK crystalline fatigue surface orientation was observed, although the crack propagation rates were very different. This suggests that the propagation rate was controlled by the ease of slip, and hence the slip system operative at the crack tip, but that the actual fatigue facets produced were less dependent on the slip system. This may also explain why, although both fatigue surface facets and final cleavage planes are of the same type,



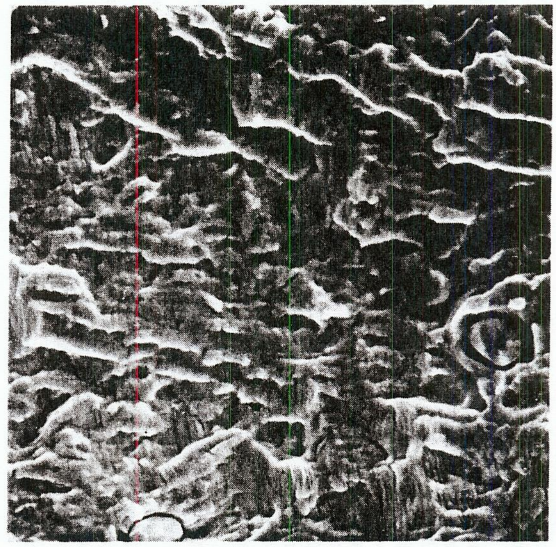
↑
T

350μ CPD ➔

Fig. 4. a)



(b)



(c)

Fig. 4. SEM micrograph showing the transition at point T from a rough faceted to a smoother non-crystallographic fatigue fracture surface.
Crack propagation direction (CPD) and the direction of increasing ΔK is from left to right.
a) Transition point T.
b) Magnified view of region b in (a)
c) Magnified view of region c in (a)

(a)

(b)

Fig. 5. SEM micrographs showing the faceted crystallographic low ΔK fatigue surfaces. Crack propagation (CPD) is diagonally from bottom left to top right.
a) Specimen C.
b) Same area as (a), but tilted 35° in SEM.
Facet 'X' is the same in both micrographs.

they are different, the former being (100) and the latter (001). Future observation of the fatigue crack tip region dislocation structure may settle this question.

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