THE EFFECTS OF LOCALISED STRESS FIELD NEAR THE CRACK TIP ON FATIGUE STRIATION ALIGNMENT IN Fe-3%Si SINGLE CRYSTALS

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ABSTRACT

The effects of crystal orientation and localised stress field at the crack tip on striation alignment have been investigated in Fe-3%Si single crystals. The alignment of striations was approximately perpendicular to the notch direction (ND) at any crystal orientations tested, but did not lie in a crystallographic direction based on crystallographic alternative shear mechanisms. However, striations were curved around a pore. It is suggested that the change in striation alignment is caused by the difference in crack extension per cycle due to the change in localised stress field along the crack front.

KEYWORDS

Stress field, pore, single crystal, iron-silicone alloy, crack growth, striation.

INTRODUCTION

Fatigue crack growth behaviour and striation formation mechanisms in single crystals have been studied by some researchers (Pelloux, 1969; Stubbington, 1963; Bowles and Broek, 1972; Neumann, 1974). Alternative shear mechanisms have been proposed for the crack growth in single crystals (Pelloux, 1969; Stubbington, 1963; Bowles and Broek, 1972; Neumann, 1974), in which two intersecting conjugate slip planes activate alternatively at the crack tip. In single crystals with particular orientations which are preferential for the occurrence of an alternative shear mechanism, crack growth behaviour has been studied systematically. It has been found that in such a crystal the fatigue crack grows almost perpendicular to the loading direction and the striations lie perpendicular to the notch direction which is a particular crystallographic direction such as <111>, <110>. It is generally accepted that striation spacing corresponds to the crack extension per cycle in single crystals as well as polycrystals.

In polycrystals, striation alignment is normally perpendicular to the macroscopic fatigue crack growth direction, however, the striation alignment changes microscopically due to the existence of grain boundaries and differences in grain orientations (Forsyth, 1963; Hoeppner, 1967).

However, a small number of studies have been carried out on fatigue crack growth behaviour in single crystals whose orientations are not ideal for the occurrence of an alternative shear mechanism. Especially, the effect of localised stress field on striation alignment has not been studied in single crystals.

In this study, fatigue crack growth tests are performed on Fe-3%Si single crystals and the effects of grain orientation and localised stress field on fatigue striation alignments are investigated.

EXPERIMENTAL PROCEDURE

Material and fatigue testing

The material used in this study is an Fe-3%Si alloy. A strain-anneal method was used to obtain large grains. The grain size obtained was approximately 30~50 mm in diameter. Some plates of 200x30x5 mm^3 were cut from the material. Then, the work hardened surface layers which might have been introduced by the machining were removed by chemical etching, and the plates were annealed again to remove any residual stresses. The crystallographic orientations of crystals in the plates were determined using an X-ray Laue back-scattering technique. Single crystal CT specimens of approximately 25x25x5 mm^3 in size were carefully fabricated from the plates using a wheel cutter. A notch was introduced on each specimen by electro-discharge machining. The crystal orientations of the specimens with regard to the loading direction (L.D) and the notch direction (ND) are shown in Fig. 1.

Fatigue crack growth tests were performed at a cyclic frequency of 10 Hz using a closed-loop servo hydraulic fatigue machine under constant load range conditions at a stress ratio of 0.1. The tests were performed at room temperature in air. The crack length was monitored using a direct-current potential drop technique. After the cyclic tests, the striations on fracture surfaces were observed using a scanning electron microscope (SEM).

In a specimen which has the same orientation as specimen No. 1, the crack grew fortuitously through a pore of 300 μm in diameter, which may have been generated during solidification, as schematically shown in Fig. 2. The striation alignment and spacing were intensively analysed around the pore. Note that no pore was found in any other specimen.

Finite element analysis

Finite element calculations were performed using general purpose finite element software (NASTRAN) on a super-computer (ETA10). A finite element model in which the crack front is situated at 35 mm ahead of the leading edge of the pore is shown in Fig. 3(a). A three-dimensional finite element mesh consisting of 1740 isoparametric brick elements and 2346 nodal points was used to represent a quarter of the CT specimen with a pore. A cylindrical hole of 300μm diameter was used to simulate the pore as shown in Fig. 3(b) in order to simplify the calculations though the pore might

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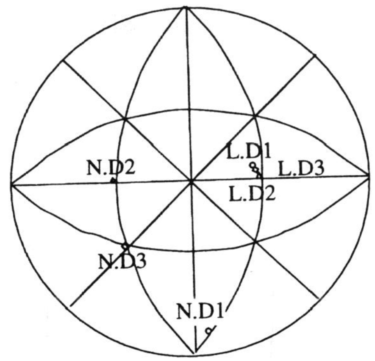


Fig. 1 The crystal orientations of single crystal specimens employed, with respect to loading direction (LD) and notch direction (ND), plotted in a (001) standard stereographic projection.

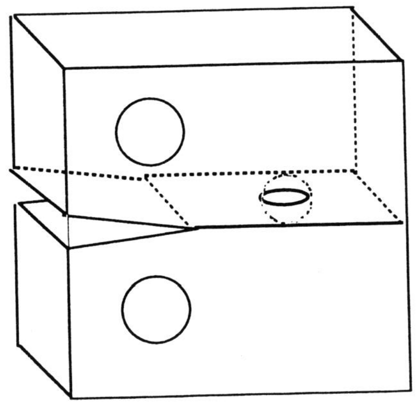
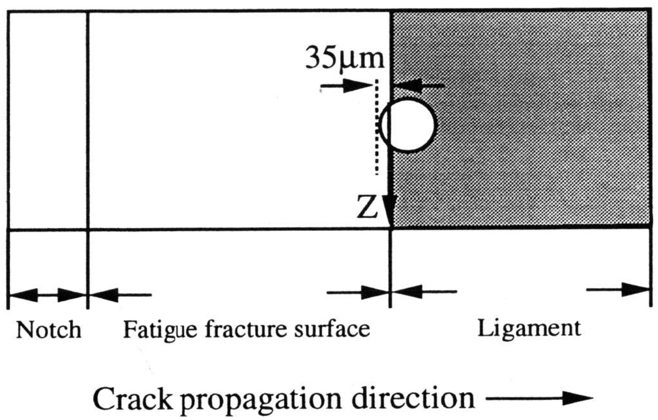


Fig. 2 A schematic drawing of a CT specimen with a pore

(a)



(b)

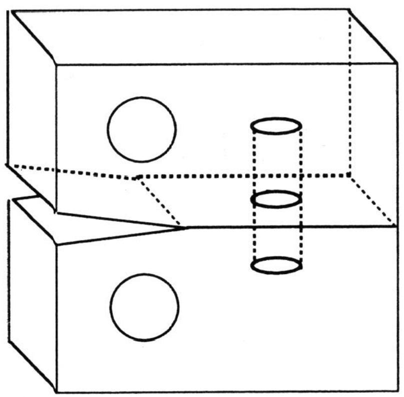


Fig. 3 Crack situation with respect to the porosity employed in the calculations (
finite element analysis (a) and an assumed CT specimen with a cylindric
hole used in the finite element analysis simulating a porosity.

be shaped as shown in Fig. 2(a). The material was assumed to be isotropic with a Young's modulus of E = 140 GPa and a Poisson's ratio of g = 0.33. Stress intensity factors (K) along the crack front were calculated using an extrapolation method.

RESULTS AND DISCUSSION

Figure 4 shows the effect of crystal orientation on striation alignment of the Fe–3%Si alloy. The striation spacing of each orientation is comparable to the crack propagation rate which is $2\text{x}10^{-7}$ m/cycle at the position of this figure. This crack growth rate is associated with the Paris regime in the crack growth rate (da/dN) vs. stress intensity factor range (ΔK) curve of this material. (Crack growth rate is independent of crystal orientation in this material in the Paris regime. (Uchida, 1993)) Striations are observed throughout the Paris regime. The striation alignment in specimen No. 1 is almost perpendicular to the notch direction. However, in the other specimens, the alignment of striations is neither perpendicular to the notch direction nor in a particular crystallographic direction such as <111>, <110>, <012> or <113>.

It has been reported that the main slip planes of b.c.c. crystals are {110}, {112} and {113} and that the slip direction is <111>. According to crystallographic crack growth models such as the alternative shear mechanisms in which slips occurs on {110}<111> systems, the alignment of striations would be parallel to a <111> direction. Carlson, et al (Carlson and Koss, 1978) reported that striations lay parallel to either <110>, <012> or <113> direction in Ti-40%V alloy single crystals (b.c.c.), occurring by a crystallographic crack growth mechanism in which {112}<111> slip systems were activated.

However, striation alignment is not always crystallographic in the present study. This is probably because the specimen orientations are not ideal orientations for the occurrence of a crystallographic crack growth mechanism. This means that stress directions are more dominant for striation formation in this material than crystal orientations (provided that no cleavage fracture occurs).

In polycrystals, it has been observed that striation alignment changes when the crack front is passing by precipitations or inclusions (Hornbogen and Karl-Heinz, 1976). However, to the authors' knowledge, no studies have been performed in the effect of localised stress field of microscopic striation alignment in single crystals.

In a specimen which has the same crystal orientation as specimen No. 1 in Fig. 1, the crack grew fortuitously through a pore which may have been generated in the solidification process. Figure 5(a) shows a part of the fracture surface near the pore. The upper left corner of the photograph is the pore. The alignment of striations which are situated far from the pore (the lower side of the photograph) is almost perpendicular to the notch direction. In an area close to the pore, however, the alignment gradually changes. Adjacent to an edge of the pore (for example, indicated as 'B' in the Fig. 5(a)), the striation spacing is remarkably wide compared with that far from the pore. The striation spacing gradually decreases with an increase in distance from the pore. The striation spacing at the position 'A' which is 50µm away from the pore is ≈0.67µm and is approximately 1.2 times wider than that measured at 700µm away from the pore.

Figure 6 shows the distribution of stress intensity factor (K) along the crack front calculated using the finite element model shown in Fig. 3. *Z* indicates the distance

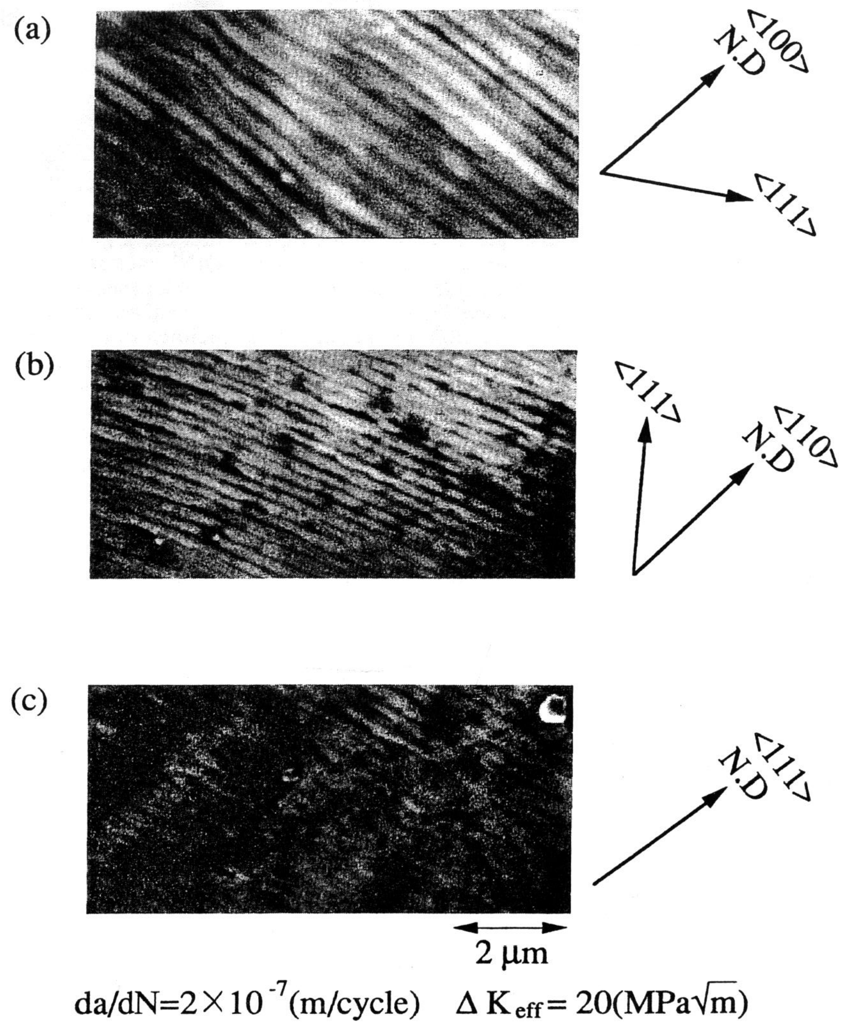


Fig. 4 SEM photographs showing the fatigue fracture surfaces of specimens No. 1 (a), No. 2 (b) and No. 3 (c).

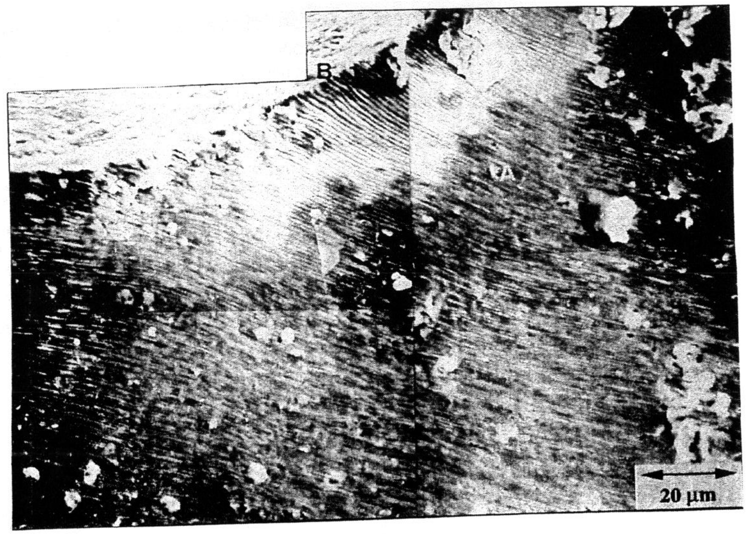


Fig. 5 An SEM photograph of fracture surface near the pore.

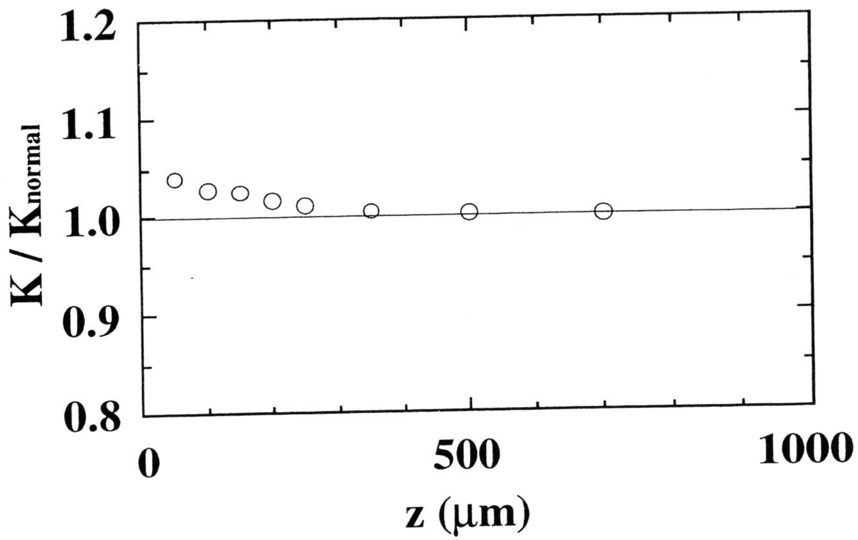


Fig. 6 Normalized stress intensity factor (K / K_{normal}) vs. distance from the pore (Z).

from the pore in the specimen thickness direction (along the crack front) and K_{normal} indicates the stress intensity factor for a plain specimen (without any pore). The effect of the pore on the increase in stress intensity factor decreases gradually as the distance increases, and is negligible at $Z > 500\mu m$.

At a distance of 50µm from the pore,

$$K / K_{normal} = 1.04 \quad (1)$$

Assuming that the local crack closure level does not change if there is a pore, the effective ΔK must increase by 4% compared with a plain specimen, that is:

$$\Delta K / \Delta K_{normal} = 1.04 \quad (2)$$

In general, crack propagation rate is a function of ΔK and can be described in Paris regimes as (Paris and Erdogan, 1963):

$$da/dN = C(\Delta K)^m \quad (3)$$

where C and m are constants. The exponent, m, of this material is 4.1 (Uchida, 1993). A substitution of the equation (3) with (2), then, gives:

$$(da/dN)_{50\mu m} = 1.17\ (da/dN)_{normal} \quad (4)$$

where $(da/dN)_{50\mu m}$ indicates the crack propagation rate at a distance of Z = 50 µm, and $(da/dN)_{normal}$ indicates the crack propagation rate without any pore under the same loading condition. This is in good agreement with the result that the striation spacing at the position 'A' in the Fig. 5(a) is approximately 1.2 times wider than that at far from the pore.

It is, therefore, concluded that the change in striation alignment is caused by the difference in crack extension per cycle due to the localised stress field along the crack front produced by the pore. This suggests that stress field is a more dominant factor for striation alignment than crystal orientation in single crystals.

CONCLUSION

The effects of crystal orientation and localised stress field at the crack tip on striation alignment have been investigated. Striations are not aligned along a crystallographic direction based on a alternative shear decohesion mechanism, but are curved due to a localised stress field at the crack tip. It is suggested that stress field is a more dominant factor for striation alignment than crystal orientation in single crystals.

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