FATIGUE CRACK INITIATION AND GROWTH IN ALPHA-IRON POLYCRYSTALS

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The surface relief development in stress and strain controlled cycling of polycrystalline alpha iron has been followed. These observations contribute to the understanding of the persistent slip band nucleation and primary crack initiation. Both intercrystalline and transcrystalline crack nuclei were observed. The crack growth rates of short cracks were above those of long cracks.

INTRODUCTION

The initiation and early growth of fatigue cracks represent an important period in the fatigue life of machine parts and structures subjected, in service, to varying loadings. In spite of numerous investigations in this area performed since the beginning of this century there is lack of the complete understanding of this problem and only limited information exists for a few engineering materials.

Considerable progress in this area has been achieved by applying high resolution scanning electron microscopy (SEM) in direct observation of the surface of single crystals (Mughrabi et al (1), Basinski and Basinski (2), Polák et al (3), and Hunsche and Neumann (4)), using the sectioning or the edge etching technique (Hunsche and Neumann (4) and Basinski and Basinski (5)) and the true replication technigue (5).

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These observations yield pieces of information leading to a new hypothesis of the surface relief formation and the crack initiation in single crystals (Polák (6)). Recent studies on crack initiation in polycrystalline materials (Anton and Fine (7), Cooper and Fine (8), Mughrabi (9)) suggest that in the early stages of crack initiation in polycrystals along PSB, similar processes take place as in the case of single crystals. The presence of grain boundaries in polycrystals, however, brings into consideration another important factor that proved to affect both the crack initiation and its growth.

As cracks initiate early in the fatigue life, considerable interest must be devoted to the growth of short fatigue cracks. A great number of experimental studies is devoted to this problem (for a recent review see Suresh and Ritchie (10) or for some results on low carbon steel see Klesnil et al (11)).

In this work, the crack initiation and the short crack growth have been studied in polycrystalline iron both in stress and strain controlled cycling. The crack nuclei in persistent slip bands were observed and crack growth rates were compared with those of long cracks.

EXPERIMENTAL PROCEDURE

The initiation and growth of fatigue cracks have been followed on specimens made of low carbon steel 12014 (0.02 %C). Cylindrical specimens with the diameter of 10 mm on the length of 15 mm have been adopted. For crack initiation and crack growth studies a shallow notch with the theoretical stress concentration factor 1.04 has been grinded in the central part of the specimen. The specimens were annealed for one hour at 700 °C in a vacuum furnace and furnace cooled down to room temperature. The resulting average grain size was 50 μm. The notch represents such a minor concentration so that the fatigue limit of a smooth and of a notched specimen do not differ appreciably.

The loading of specimens took place either in a resonance type Schenck testing machine or in a servohydraulic testing machine. The stress amplitude of the sinusoidal wave with a frequency of 50 Hz was controlled in the resonance machine. The cyclic stress-strain response was followed using a clip extensometer with 15 mm gauge length. The frequency response of this extensometer has been checked and a negligible phase lag between stress and strain was found at 50 Hz. The hysteresis loops were stored in the memory of a digital oscilloscope and recorded later using an X - Y recorder. The plastic strain amplitude ε_{ap} was obtained as a half of the width of the hysteresis loop at zero stress.

The testing in a servohydraulic testing machine proceeded with a control of the total strain using the clip extensometer along 14 mm gauge length. The triangular wave with a frequency corresponding to constant strain rate $\dot{\varepsilon} = 5 \times 10^{-3} s^{-1}$ was chosen. Both the stress amplitude and plastic strain amplitude could be measured during the test.

The small surface on the notched specimen was mechanically and chemically polished and a rectangular grid with a unit spacing of 0.5 mm was engraved on the central part of the notch. The grid did not exhibit any appreciable effect both on crack initiation and growth.

The observation of persistent slip bands and cracks on the marked area was performed using direct observation by light microscope or scanning electron microscope (Tesla BS 300 or Philips SEM 505) using secondary electrons at 25 kV. The development of the main crack has been followed using the plastic replica technique. The plastic replicas were taken at regular intervals during cyclic loading, metallized and observed in the scanning electron microscope.

EXPERIMENTAL RESULTS

The hardening-softening behaviour in a low amplitude region is characterized by softening (Polák et al. (12)). In strain cycling the softening is not appreciable but in stress cycling with constant stress amplitude σ_a, continuous growth of the plastic strain amplitude is apparent (Fig.1). For the smallest stress amplitudes, the plastic strain amplitude saturates. The specimens in which the plastic strain amplitude saturated did not fracture though all of them were subjected to more than 10^7 cycles. In a Wöhler curve a distinct limit is apparent.

A systematic investigation of the surface relief formation during fatigue life has been performed by interrupting the test and subjecting the specimen to SEM observations for different numbers of cycles. Numerous data on the PSB distribution, its development during fatigue life and crack initiation and growth were obtained. Only a few of them can be documented here.

Most surface observations were done in strain cycling experiments with constant total strain amplitude $\varepsilon_a = 9.5 \times 10^{-4}$ resulting in the fatigue life of 2.8×10^5 cycles.

Early in the fatigue life (2×10^3 cycles, i.e. less than 1% N_f) the PSBs, characterized by extrusions and intrusions in some grains were identified. With continued cycling the existing PSBs intensify and new ones appear within a grain or in neighbouring grains. In Fig.2, a single grain containing PSBs inside the grain is shown. PSBs within the grain are characterized by alternating irregular extrusions and intrusions along the PSB line. The grain boundary can become persistent too, i.e. it contains extrusions and intrusions. In this case, the grain boundary is cracked as seen in detail in Fig.2b. To reveal the crack in the grain boundary, the specimen has been tilted so that the grain boundary plane became approximately parallel to the primary beam in the SEM as shown in Fig.2b. Another important detail is shown at a higher magnification in Fig. 2c. The embryonic stage of a short PSB having the length of approximately 3 µm is apparent. It is characterited by alternating extrusions and intrusions along the PSB in a similar way as observed recently on copper single crystals (3).

The most dangerous cracks from which macroscopic cracks develop originate in the majority of cases along the grain boundaries. Fig.3 illustrates the grain boundary crack in a region where considerable surface strain was present. Cracked PSBs contribute significantly to its growth.

Two stages of the grain boundary crack are shown in Fig.4. Early in the fatigue life at 5 kc (Fig.4a), a short microcrack along the PSB close to the grain boundary is initiated. In continued cycling the grain boundary crack is developed from this crack nucleous. This crack is capable of further growth and its surface length achieves 0.3 mm at the fracture caused by propagation of the main crack.

The growth of fatigue cracks has been followed in stress cycling at amplitudes slightly above the fatigue limit using plastic replica techniques. Fig.5 shows two typical dependences of the crack growth rate vs. the crack length in cycling with σ_a = 140 MPa resulting in the main crack. Two types of the crack growth have been identified. The full points denote a crack initiated inside the grain that decelerated when approaching the grain boundary. The open points characterize a crack initiated across the two grains along PSB or along the grain boundary whose growth rate monotonically increased. The full line to the left corresponds to the crack growth rate of a hypothetical surface crack derived from the plot of the crack growth rate vs. stress intensity factor amplitude found for long cracks.

DISCUSSION

A systematic observation of the surface of polycrystalline α-iron during the fatigue life revealed several basic stages of the fatigue damage resulting in fatigue fracture.

Early in the fatigue life the plastic strain amplitude is distributed inhomogeneously and PSB's in individual grains arise. The PSB nucleation within an individual grain and the surface relief formation is very similar to that in a single crystal. PSB nuclei in the surface grains give rise to alternating extrusions and intrusions along the PSB in a similar way as in a copper single crystal (3). Relatively early in the fatigue life ($N < N_f/20$), a considerable part of PSB's contain surface cracks. Surface cracks arise also along suitably oriented grain boundaries that become "persistent", too, i.e., the surface relief simultaneously with their cracking develops. In some cases the cracking close to grain boundaries starts without any expressive surface relief formation.

The formation of the macroscopic crack proceeds by the growth of short cracks. A considerable number of cracks is able to grow simultaneously and joining of individual surface cracks is an important mechanism contributing to the crack advance. The grain boundaries represent hard obstacles to the growth of short cracks and some cracks are decelerated or even stopped there.

The comparison of crack growth rates of short cracks with those of long cracks derived from fracture mechanics parameters assuming a semi-circular shape of the surface crack shows higher crack growth rates of short cracks. The inhomogeneous distribution of cyclic plastic strain and its concentration into PSB's is most probably the reason for higher crack growth rates. The growth of surface cracks in the early stage proceeds by an unslipping mechanism (modes II and III along the crack front) in which the environment plays an important role (9). The kinetics of short crack growth is similar to that in low carbon steel (12), (13).

CONCLUSIONS

The most important findings derived from a study of the initiation and the growth of short cracks in polycrystalline iron can be summarized as follows:

(i) Inhomogeneous distribution of the plastic strain results in an early PSB formation. The initial surface relief of a PSB consists of the alternating extrusions and intrusions as in the case of single crystals.

(ii) With continued cycling, the majority of PSB's becomes cracked. In addition to that some PSB's close to the suitably oriented grain boundaries give rise to grain boundary cracks.

(iii) Both grain boundary cracks and true transcrystalline PSB cracks contribute to the macroscopic crack initiation. The initiated cracks grow with a considerable contribution of crack joining. In most cases the grain boundaries represent an obstacle to microcrack growth.

(iv) The crack growth rates of short cracks are considerably above those of long cracks if fracture mechanics criteria are used for comparison.

SYMBOLS USED

σ_a = stress amplitude (MPa)

ε_a = strain amplitude

ε_{ap} = plastic strain amplitude

$\dot{\varepsilon}$ = strain rate (s^{-1})

a = half length of the surface crack (m)

N = number of cycles

$\frac{da}{dN}$ = crack growth rate (m/cyclus)

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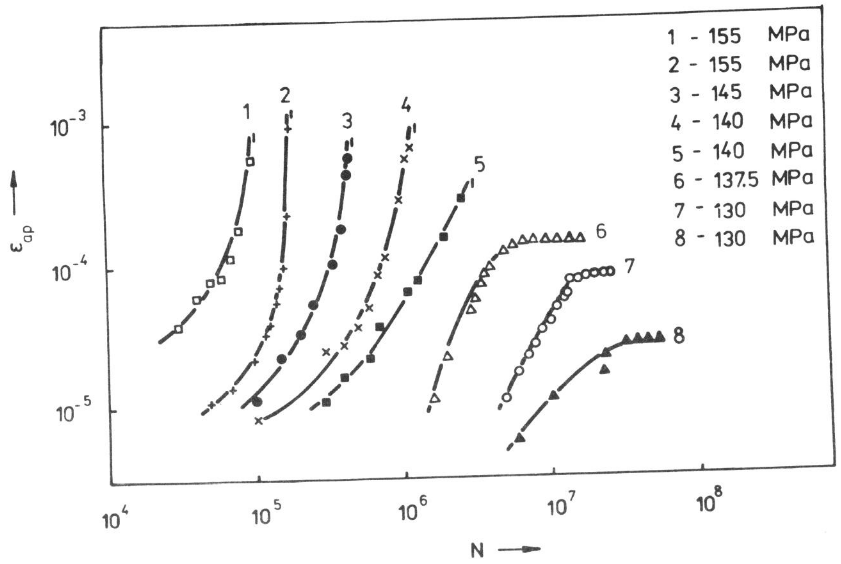

Figure 1 Cyclic hardening/softening curves in stress cycling

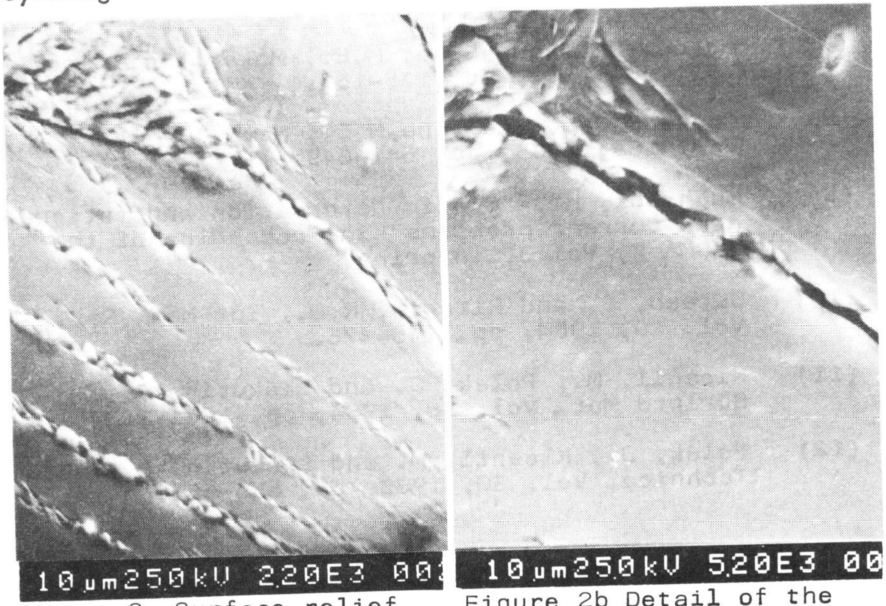

Figure 2a Surface relief of a single grain

Figure 2b Detail of the crack along grain boundary

Figure 2c Embryonic stage of the PSB

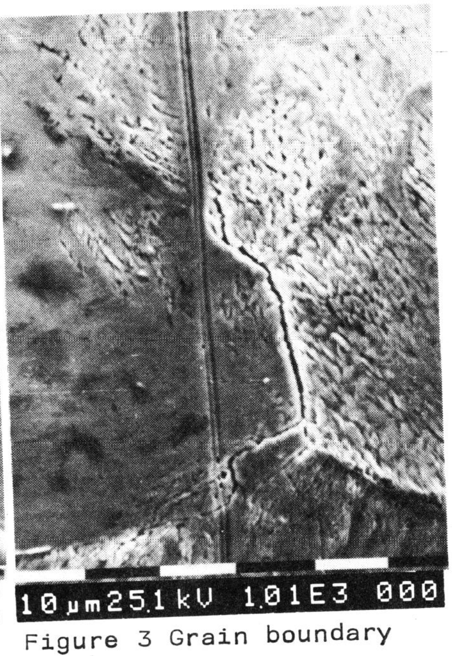

Figure 3 Grain boundary crack

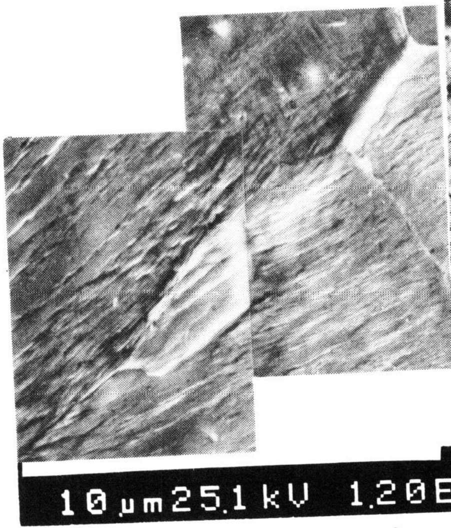

Figure 4a Surface relief at 5 kc

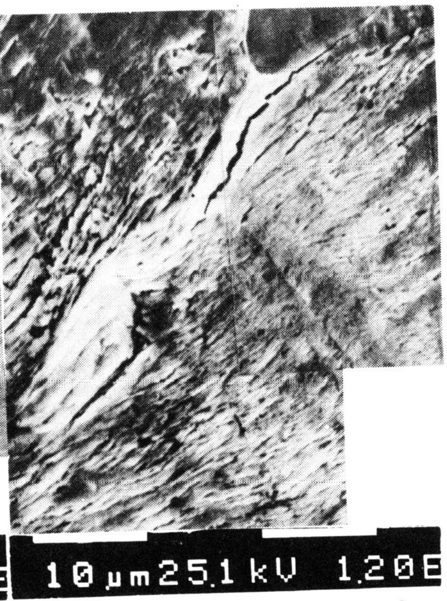

Figure 4b Surface relief at 125 kc

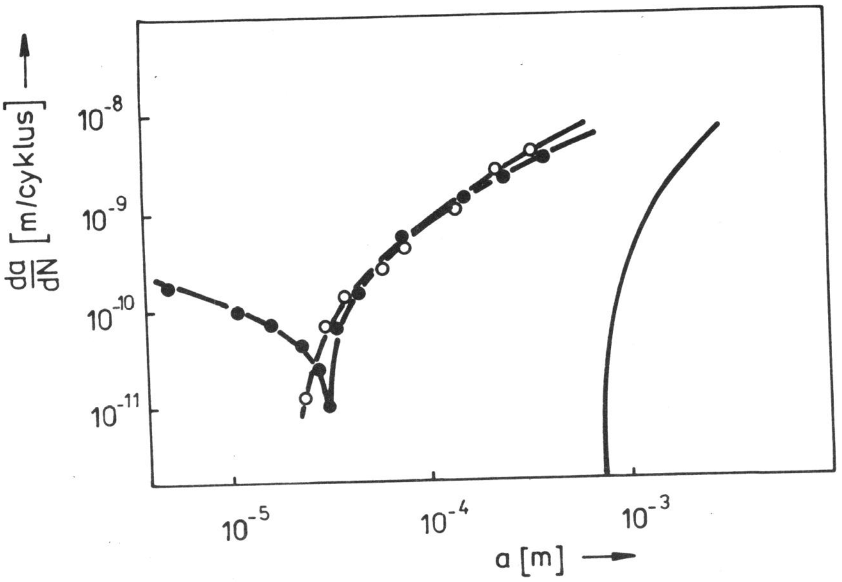

Figure 5 Crack growth rate vs. crack length in cycling with σ_a = 140 MPa