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Life prediction by ferrite–pearlite microstructural simulation of short fatigue cracks at high temperature

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ABSTRACT

This paper dealt with fatigue behavior simulation based on ferrite–pearlite microstructure modeled by correctional Voronoi-polygons. The model took grain size, grain orientation and the percentage of pearlite and ferrite into consideration. The basal energy was proposed to represent the inherent energy for slip-band and grain boundary to cracking. The driving force for crack initiation and propagation caused by load condition was considered as the energy increment of slip-band and grain boundary. The fatigue behavior including crack initiation, propagation, coalescence and interference were simulated based on Monte Carlo method. The simulation results show a satisfying agreement with the experimental ones.

1. Introduction

With the development of technology, decreasing few long cracks appear in the materials and engineering structures, whereas fatigue short cracks are mostly observed [1]. Short fatigue crack behavior, differing from long crack's, is significantly influenced by material microstructures such as grain size, grain orientation, gain boundary distribution, material composition and local anisotropy [2–5]. Researches indicate that the major cause of short fatigue crack initiation is the dislocation accumulation in grain interior slip bands [6]. Different grain orientations form different types of cracks. If grain orientation tends to vertical to the specimen surface, it appears vacancy dipoles or extrusions, eventually it grows into transcrystalline crack on the slip band. If grain orientation parallels to the specimen surface, it is prone to producing dislocation accumulation near the grain boundary. The adjacent boundary stress concentration leads to the formation of intercrystalline cracks [7]. High temperature helps the grain boundaries slip, the slip results in the local diffusion and holes aggregation, which accelerate the formation of intercrystalline cracks [8–10]. For the low carbon steel, the three zones are all crack nucleation zones: ferrite and pearlite grain boundary, the large angle grain boundary between the adjacent ferrites and the persistent slip bands (PSBs) in ferrite grain boundaries [11].

The life prediction methods under fatigue loading have been thoroughly studied during the past years [12–15]. Some conventional life prediction models such as Linear cumulative damage rule, Frequency-modified rule, Strain range partitioning method, Strain energy partitioning method have been proposed to describe the cracking behavior [16]. Hoshide et al. [17–22] simulated the fatigue behavior of the slip-band crack in various material microstructure modeled by Voronoi-polygons under room temperature. Hünecke et al. [23] and Brückner-Foit and Huang [24] predicted the fatigue life based on this slip-band crack initiation model. However, the crack initiation and propagation mechanism of low carbon steel under high temperature is not only along the slip bands but also along the grain boundary. In this paper, a ferrite–pearlite microstructure based on correctional Voronoi-polygons is used to simulate short fatigue crack behavior in low carbon structure steel. The model took grain size, grain orientation and the percentage of pearlite and ferrite into account. The basal energy was proposed to represent the inherent microstructure's energy to cracking. The crack initiation and propagation were simulated based on incremental energy method. The crack coalescence and interference were happened in the specified zone by the definite criterion. The number of cycles of failure life was numerically calculated and compared to experimental data.

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2. Experiments

2.1. Material and specimens

The experimental material is low carbon structure steel treated with annealing. The chemical composition is 0.20% C, 0.51% Mn, 0.23% Si, 0.024% P and 0.011% S in weight percentage. The mechanical properties of material at room temperature (20 °C) and high temperature (500 °C) are shown in Table 1. The experimental specimens shown in Fig. 1 are cylindrical bars with annular notches for being closer to the realistic complex stress state. The notches were processed with turning and polishing, corroded in nitric acid alcohol solution of 4% volume percentage, and then observed under metallographic microscope.

2.2. Testing techniques and optical observation

Continuous strain-controlled push–pull cyclic loading was applied using MTS Landmark 100KN closed-loop hydraulic servo testing system with a strain ratio of $R = -1$. The nominal strain amplitudes were controlled at 0.20%, 0.24%, 0.28% and 0.32% using a high temperature axial extensometer with the gauge length of 25 mm. Test temperature was controlled at 500 °C by the MTS-635 high-temperature furnace. The loading waveform was symmetrical triangular wave. The experiment would be interrupted if it reached the pre-set number and the tiny area at the middle surface of the specimens would be observed and recorded by metallographic microscope (CMM-33E) and CCD-camera (JVC TKC921EC), after that the experiment continued until the next pre-set number of cycles accomplished. The area at the middle notch-root surface for optical observation was a tiny area similar to a point, which was infinitely close to plane at micro level. Therefore, it was easy to observe under metallographic microscope.

2.3. Experimental observation results

A brief experimental results was mentioned in paper [25]. The microstructure of experimental material shown in Fig. 2 consists of about 80% ferrite (gray) and 20% pearlite (black). The average grain diameter is about 15.9–18.9 μm. Fatigue experiment observation found that the short fatigue crack initiates along the ferrite internal persistent slip band (PSB) as well as grain boundary (GB) as shown in Fig. 3. In Fig. 3, grain A, B, C are three adjacent ferrite grains. The GB between grain A and C (in red circle) grows into transcrystalline crack. The PSB in grain B (in blue box) becomes intercrystalline crack. The short fatigue crack in grain D (in yellow circle) shown in Fig. 4 initiates one grain's length when the life time reaches 1000 cycles. It grows 50 μm when the life time reaches 4000 cycles. Until 9000 cycles it becomes deeper and thicker rather than longer. It is a common phenomenon in experimental observation. The short fatigue crack's behavior is effected by the microstructure during the crack propagation. Grain or phase boundaries acted as micro-structural barriers to short crack propagation. Crack coalescence is found frequently at the middle and later period of fatigue life as shown in Fig. 5 and the coalesced cracks (in pink box) form the "dominant" crack eventually. Experimental observation also found that the short cracks near the "dominant" crack grow slowly or even stop growing. Crack interference also plays an important role during the crack behavior.

Table 1
Mechanical properties of low carbon structural steel.

Name of parameter	Units	Room temperature	High temperature
Temperature	(°C)	20	500
Yield strength	(MPa)	335.5	316.1
Tensile strength	(MPa)	471.98	412.37
Elongation	(%)	32	45
Elastic Modulus	(MPa)	2.28×10^5	2.05×10^5
Poisson's ratio		0.303	0.301
Fracture energy density	(kJ/m^2)	2	2
Critical shear stress	(MPa)	91	80
Shear stress	(GPa)	94	81

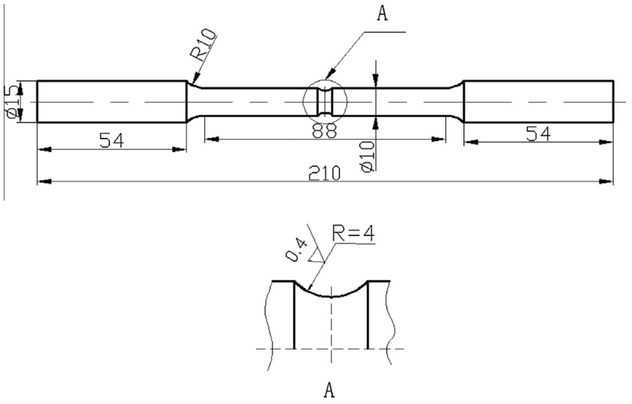

Fig. 1. Size and shape of specimen.

3. Simulation procedure

3.1. Overview

The simulation procedure included microstructure generation, basal energy assignment, crack initiation, crack propagation, crack coalescence and interference. The microstructure of low carbon structure steel model was generated by correctional Voronoi-polygons. Before the simulation, different basal energy was randomly assigned for the microstructure on the model to simulate the inherent microstructure's energy to cracking. The crack initiation and propagation were simulated based on incremental energy method. Every slip-band and grain boundary was set for an incremental energy for driving force per cycle. The incremental energy for slip-band and grain boundary was based on different model. The energy in our simulation was normalized and had not units. Crack coalescence criterion was established based on the crack tip plastic zone, which was a small circle whose center was the crack tip. Crack coalescence occurred when the crack tip plastic zones met. Crack interference was simulated in a specified zone defined by a circle area whose diameter was the line connecting the two endpoints of a crack. A self-written program was developed based on simulation procedure. The detail simulation procedure was listed below.

3.2. Microstructure generation of material

The microstructure on the notched surface of the specimen of the low carbon structural steel was modeled with regard to grain size, grain orientation and the percentage of pearlite and ferrite. The simulation area was restricted to $0.32 * 0.96\ \text{mm}^2$ and contained 1350 grains. About 20% grains with banded arrangement were randomly selected to simulate pearlite grains and other 80% grains were used to simulate ferrite grains. The orientation of each ferrite grain was generated by assigning $3 * 3$ random direction matrix. The dark polygons shown in Fig. 6 stand for pearlite grain and the light ones stand for ferrite grain. The dashed shown in green zoom box of Fig. 6 represents the orientation of ferrite grain