Materials Science and Engineering A 528 (2011) 6381–6386

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

The study of crack-propagation behaviors and dislocation structures in cyclically deformed polycrystalline IF steel

Chia-Chang Shih[a,*], Ding-Hao Yeh[a], New-Jin Ho[a], Hsing-Lu Huang[b]

[a] Institute of Materials Science and Engineering, National Sun Yat-Sen University, Kaohsiung, Taiwan
[b] Department of Mechanical Engineering, Chinese Military Academy, Kaohsiung, Taiwan

ARTICLE INFO

Article history:
Received 5 July 2010
Received in revised form 9 March 2011
Accepted 17 April 2011
Available online 22 April 2011

Keywords:
Interstitial-free steel
Loop patches
Dislocation cells
Grain boundary

ABSTRACT

Strain controlled fatigue experiments were employed to evaluate automotive-grade interstitial-free ferrite steels (IF steels). This study demonstrates that the loop-patch structure, dislocation walls and dislocation cells larger than 2 μm have no significant effect on fatigue failure. The cracks prefer to grow near grain boundaries while dislocation cells smaller than 2 μm tend to develop along the grain boundaries and triple junction of the grains. Once the dislocation cells smaller than 2 μm develop from grain boundaries to grain interior, the cracks will propagate near the grain boundaries and through the grain interior simultaneously.

1. Introduction

Compared with cyclically deformed copper, fatigued body-centered cubic (BCC) metals have received less attention concerning the fundamental fatigue mechanisms. It is well known that the dislocation-cell structure rapidly develops at higher strain amplitudes for cyclically deformed BCC metals. However, for the lower strain amplitudes, people merely plotted out the cyclic hardening curve or observed the gliding behaviors of dislocations in early or saturated stage of cyclic deformation at most [1–7]. Recently, Majumdar et al. [8], Narasaiah et al. [9] and Endo and Murakami [10] have shown that crack initiation could also occur while the strain amplitudes are kept below the fatigue limit, but these cracks would not propagate, and are thus called non-propagating cracks. Additionally, Majumdar et al. [8] indicated that the cracks tend to propagate along grain boundaries when strain amplitude is just above the fatigue limit. They also found that the cracks will propagate near the grain boundaries and through the grain interior simultaneously if the strain amplitudes are much higher than fatigue limit. Therefore, we believe that the occurrence of these phenomena should be influenced by the dislocation developments. Since the relationship between fatigued microstructures and crack growth (i.e. failure mechanism) in pure BCC metals remains unproven, hence it will be the main interest in this study.

2. Experimental

A hot rolled polycrystalline interstitial-free steel plate with a chemical composition of C < 50 ppm, N < 50 ppm, S < 120 ppm, B ≈ 2 ppm, Mn ≈ 0.15 wt%, Ti ≈ 0.04 wt% and balance Fe was used in this study. The material was annealed at 800 °C for 2 h and then cooled in a furnace to obtain an average grain size of about 80 μm in diameter. The preparation of specimens followed the ASTM E606 specification. In order to observe the surface cracks, the specimen geometry is necessary to be modified, where the tested specimens with gage width and thickness both are 7 mm (i.e. square cross-section of $7 \times 7\,mm^2$) were used. The gage surfaces were all ground with No. 4000 silicon carbide sandpaper, polished with 1 μm diamond suspension prior to fatigue tests. A computerized Instron 8801 hydraulic testing machine was employed at a testing strain rate of $4 \times 10^{-3}\,s^{-1}$ with $R = 0$ at room temperature. The tests on IF steels were performed with total strain amplitudes ($\Delta\varepsilon/2$) ranging from 0.1% to 0.2%. The fatigue test data for different strain amplitude were summarized in Table 1. The specimens for microstructure observations were ground to a thickness of about 0.3 mm using abrasive paper and punched into 3 mm-diameter discs. The 3 mm discs were twin-jet polished using a solution of 90% methanol diluted with 10% perchlorate at 15 V and −40 °C.

* Corresponding author. Tel.: +886 7 5252000; fax: +886 7 5254099.
E-mail address: ccshih095@gmail.com (C.-C. Shih).

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doi:10.1016/j.msea.2011.04.048

Table 1
The fatigue test data at different strain amplitude.

Sample	Total strain amplitude ($\Delta\varepsilon/2$) (%)	Number of cycles (N)	Failure
A1	0.1	4×10^5	No
B1	0.125	10,000	No
B2	0.125	2×10^5	Yes
C1	0.2	200	No
C2	0.2	35,000	Yes

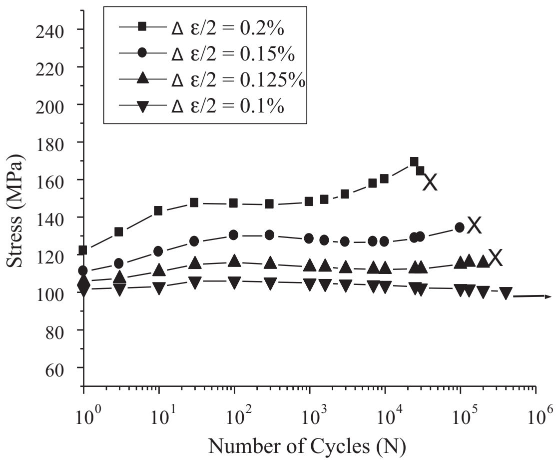

Fig. 1. The curve of stress versus number of cycles in low cycle fatigue at various strain amplitudes, where mark x is for fatigue failure and arrow for no failure.

A scanning electron microscope (SEM) of Philips Quant200 SEM under backscattering electron image (BEI) mode and secondary electron image (SEI) mode was employed to obtained observations of microstructure and surface crack, respectively.

3. Results and discussion

The relation of cyclic responding stress versus the number of cycles shown in Fig. 1 clearly demonstrates that fatigue failure would not occur if the strain amplitude is controlled at $\Delta\varepsilon/2 = 0.1\%$ and fatigued to 4×10^5 cycles (sample A_1) at least, since no significant cyclic hardening has taken place. When strain amplitudes are controlled above $\Delta\varepsilon/2 = 0.125\%$, a secondary cyclic hardening will occur prior to fatigue failure.

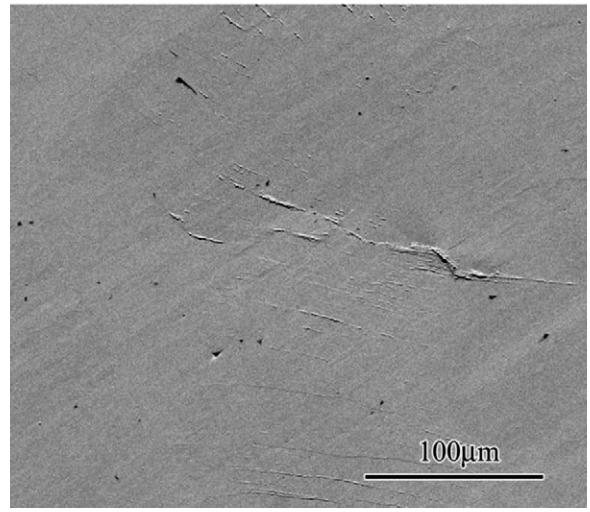

Fig. 3. Surface observation in sample B_1 (after 10,000 cycles at $\Delta\varepsilon/2 = 0.125\%$).

Fig. 2 shows a few slip bands can be found on sample surface for sample A_1, where the obvious cracks are absent. Fig. 3 shows the similar surface morphology with sample A_1 when strain amplitude is controlled at $\Delta\varepsilon/2 = 0.125\%$ and cycled to 10,000 cycles without failure (sample B_1). The slip bands in sample B_2 shown in Fig. 4 had rapidly developed and fatigue cracks tend to propagate near the grain boundaries (i.e. intergranular cracks). For sample C_1, Fig. 5 exhibits an alike surface morphology with samples A_1 and B_1. Fig. 6(a) shows the surface observation of sample C_2. Fig. 6(b) and (c) reveals the detailed observation of mark I and mark J in Fig. 6(a), respectively, where the intergranular cracks (cracks propagate near grain boundaries) and transgranular cracks both can be found in sample C_2.

The dislocation structures after 4×10^5 cycles at $\Delta\varepsilon/2 = 0.1\%$ (sample A_1), as shown in Fig. 7(a)–(c) (where Fig. 7(b) and (c) show marks S and T in Fig. 7(a) at high magnification), are mainly composed of loop patches, though, in addition, a few dislocation walls and dislocation cells larger than 2 μm also can be found. Fig. 7(b) and (c) shows marks S and T in Fig. 3(a) at high magnification. However, dislocation cells smaller than 2 μm are too scarce to be found. Fig. 8(a) reveals the loop-patch structure is also the main structure after 10,000 cycles at $\Delta\varepsilon/2 = 0.125\%$ (sample B_1). Additionally, as shown in Fig. 8(b) and (c), some dislocation

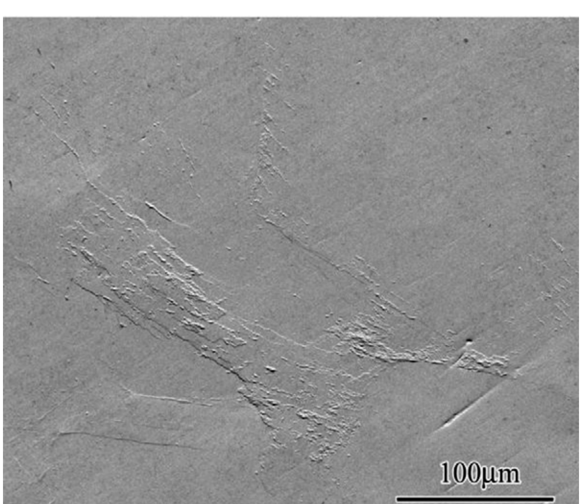

Fig. 2. Surface observation in sample A_1 (after 4×10^5 cycles at $\Delta\varepsilon/2 = 0.1\%$).

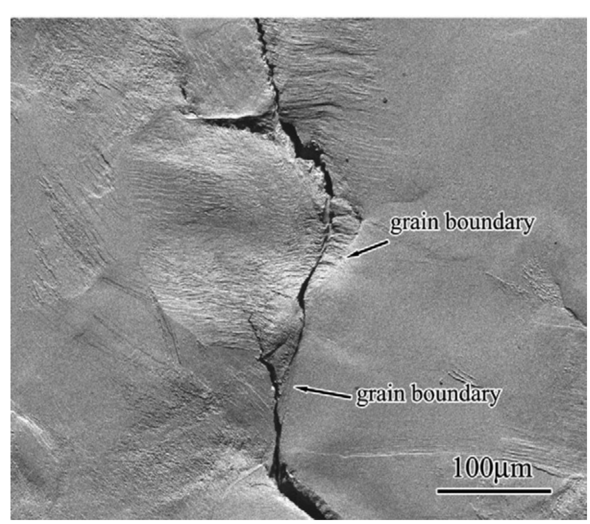

Fig. 4. Surface observation in sample B_2 (after 2×10^5 cycles at $\Delta\varepsilon/2 = 0.125\%$).