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Microscopic and nanoscopic study on subsurface damage and fatigue crack initiation during very high cycle fatigue ☆

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ABSTRACT

"Fish eye" is a typical phenomenon of fatigue crack initiation at a subsurface defect such as inclusion during very high cycle fatigue. The formation of a fine grained area and micro-debonding is believed to cause fatigue crack initiation. This paper provides a basic study on the formation of the fine grained area in a martensitic stainless steel during very high cycle fatigue using scanning electron microscopy, SEM, focused ion beam technique, FIB, electron backscatter diffraction, EBSD, and electron channeling contrast imaging, ECCI. The results show that the formation of a fine grained zone is a local behavior. The fine grained zone is very near the fatigue crack initiation origin. In the transversal direction (cross section), the depth of the fine grained zone is only few micrometers. In the longitudinal direction (crack propagation direction), the depth of the fine grain zone is about one micrometer. ECCI analysis shows that in the fine grained area with high retained strain, high plastic deformation can be found. Dislocation slip bands can be observed. They interact with grain boundaries and cause the formation of damage due to impingement cracking. The results indicate that occurrence of plastic deformation in metallic material during very high cycle fatigue is very localized, mainly near the front of the crack tip or a defect.

1. Introduction

In the last decade, very high cycle fatigue (VHCF) in metallic materials has become an important subject to guarantee the safety and reliability of structures during a long term service. The VHCF behaviors in different materials have been widely investigated [1–5]. It has been found that fatigue crack initiation in metallic material can shift from surface defects, subsurface defects to subsurface matrix with decreasing applied stress or increasing fatigue life [1,4,6–8]. Subsurface fatigue crack initiation has been mostly reported to initiate from subsurface defects such as inclusions, pores and microstructure inhomogeneity [4]. Surface treatments like shot peening, case hardening and surface nitriding can prevent the surface fatigue crack initiation, and cause a shift to a subsurface fatigue crack initiation at relatively higher stress amplitudes, and therefore improve the fatigue life and fatigue strength of the material [7]. Recently, another type of subsurface crack initiation, namely subsurface non-defect fatigue crack origin (SNDFCO), has been reported [6–8]. These crack origins were observed in the material fatigue tested for a very high fatigue life, and start in some phase or matrix of the material and are not associated with pre-existing defects.

Fine granular area, FGA, is usually formed around a subsurface defect during VHCF [9]. A relatively rough surface area can be observed in the vicinity around the inclusion. High resolution SEM investigation shows that this area has a fine granular microstructure, and was therefore called fine granular area or FGA [9–13] (fine grained area used in this paper). Several mechanisms have been proposed. Sakai et al. [10] proposed that the formation of FGA includes the following three stages; (I) Formation of fine granular layer, (II) Nucleation and coalescence of micro-debonding, and (III) Completed formation of fine granular area. The paper has not provided the explanations how these three stages occurred. Murakami et al. [11] proposed a hydrogen embrittlement assisted cracking model. The rough surface formed around the inclusion is due to hydrogen embrittlement assisted fatigue crack growth. This theory may only be limited to the material that contains hydrogen. For the material containing carbides, Shiozawa et al. [12] proposed a decohesion model. Multi microcracks can be initiated by decohesion of carbides from the matrix around an inclusion. The roughness of the fracture surface depends on the

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Table 1
Chemical composition (wt%) and conventional tensile properties of the material used.

C	Si	Mn	Cr	Mo	$\sigma_{p0.05}$ (MPa)	σ_{UT} (MPa)	E-modulus (GPa)	Density (g/cm^3)	Hardness (HRC)
0.38	0.4	0.6	13.5	1.0	1300	1650	215	7.7	53

$\sigma_{p0.05}$: is the proof strength with 0.05% strain, and σ_{UT}: is the tensile strength.

carbide size. According to this model, FGA should cover the whole specimen, but it is not the case in some observations [10]. Fatigue in metallic materials is cyclic plastic deformation process in nature [1,2,14]. In this investigation, fatigue damage and crack initiation behavior and mechanism at a stress well below the bulk yield strength will be investigated in a martensitic steel using scanning electron microscopy, SEM, electron channel contrast image, ECCI technique and transmission electron microscopy, TEM. The purposes are to get a better understanding of the mechanisms of the formation of FGA using a combination of dislocation theory and fracture mechanics.

2. Material and experimental

The specimen used was a martensitic steel with a chemical composition and mechanical properties as shown in Table 1. It consists of a few micrometers fine-grained martensitic matrix with evenly distributed chromium carbides. The material in the tempered condition has a high strength and hardness.

The fatigue test with a stress ratio $R = -1$ was performed using an ultrasonic fatigue test machine with a frequency of 20 kHz. In this investigation, a flat specimen with as-received surface condition was used. The design according to fracture mechanics was described in Ref. [15]. The specimen was produced from a 1 mm thick strip. A waist shape specimen was used as shown in Fig. 1. Its smallest cross-section had 3 mm width. The specimen during the fatigue testing was cooled using compressed air with a temperature of 5 °C and a pressure of 2 bar. A special fixture was used to avoid the buckling as described by Ref. [15].

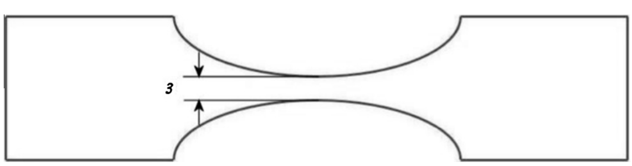

Fig. 1. Schematic diagram of the specimen used in the very high cycle fatigue test.

Table 2
Information of the fatigue tested specimen used in this study.

Stress amplitude (MPa)	N_f cycles	Crack initiation origin	Size $\sqrt{area}$[b] (μm)
±650	2.0×10^8	Hole after inclusion[a]	9

[a] The origin was an inclusion; the hole was formed after the specimen was broken during the fatigue testing where the inclusion dropped away.
[b] The area measured according to Murakami method [16].

In this paper, only one fatigue tested specimen was used to study the damage mechanism during very high cycle fatigue. Table 2 shows the information of the specimen.

In order to study the damage and fracture mechanism, the failure surface was investigated using a ΣIGAM/VP FEG–SEM. The fracture surface in nano-size was studied. Fig. 2a shows the fatigue crack initiation. The fatigue crack initiated at a subsurface inclusion, type of oxide. The fatigue crack initiation origin is a hole where the inclusion was dropped away after the separation of the specimen. To study the phenomenon of the fine grained area, FGA, in the fatigue initiation origin (Fig. 2b), cross-sections were prepared from two different areas, using Focused Ion Beam (FIB). One cross section was from an area between zone I and zone II according to Sakai et al. [9,10], zone I is the fine grained area (FGA). The other was near the end of zone II, as shown in Fig. 2b. The microstructures in these two FIB cross sections were studied using the electron channel contrast image (ECCI) technique.

To study the microstructures between zone I, a lamella intended for transmission electron microscopy (TEM) was taken out in the FIB, using the in-situ lift out technique. The lamella was taken just beside the first area in Fig. 2b. As a last step the sample was cleaned using a lower ion acceleration voltage of 5 kV to reduce beam damage from the preparation. The microstructures were studied using TEM and transmission EBSD. The TEM investigation using an acceleration voltage of 200 kV was performed in order to study the micro deformation and damage behavior.

3. Results and discussion

3.1. Fine grained area

Fig. 3a shows the fracture near the fatigue crack origin. The fracture surface is relatively rough with small granular area in sizes from several hundred nano meter up to about one micro meter.

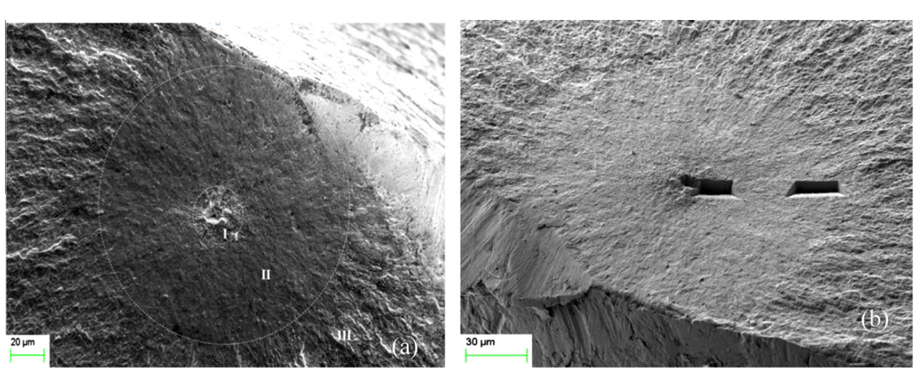

Fig. 2. Fatigue fracture. (a) Fatigue crack initiation and propagation, zones I, II and III are defined according Sakai et al. [9,10]. (b) FIB cross sections.