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Investigation of crack initiation and propagation behavior of AISI 310 stainless steel up to very high cycle fatigue

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ABSTRACT

Fatigue behavior up to very high cycles for AISI 310 stainless steel has been investigated. The fatigue crack initiated from the surface of the material. It was found that up to 10^6 cycles, cracks initiated from the carbide precipitates at grain boundaries. However, above 10^6 cycles, the cracks initiated from persistent slip bands found at the surface of the specimen. At lower stress levels, slip bands were developed without initiating the cracks. The horizontal asymptote S–N curve from 10^6 to 10^9 cycles was attributed to the development of slip bands all over the surface of the specimen, before crack initiation.

1. Introduction

The fatigue crack initiation and growth in metallic materials is now well-understood. Fatigue cracks initiate at stress concentrating features within a structure. An area of fatigue assessment is still under investigation, however, is how cracks are initiated from surface and subsurface regions at very low stress levels in the very high cycle fatigue (VHCF). It is believed that the fatigue life of numerous aerospace, locomotive, automotive and biomedical structures may go beyond 10^8 cycles [1]. Hence, better understanding of the long life fatigue behavior is extremely important for efficient design of the components and structures, especially between the 10^7 and 10^{10} cycles. The VHCF behavior of materials has attracted more attention in recent years after the establishment of the fact that there is no fatigue limit in many cases. Most current engineering designs are based on the assumption that any cyclic stress below fatigue limit yields the infinite life. Recent studies, however, pointed out that most materials experience failure up to 10^{10} cycles or above at low stress levels, and concept of infinite fatigue life is conservatie [1–5].

The VHCF behavior of metallic materials is generally divided in two types, based on the crack initiation region [1–7]. In first type, the difference in fatigue strength from 10^6 to 10^9 cycles is found more than 50 MPa, and the cracks are initiated from the internal defects of the material. A fish-eye region is obtained at the crack initiation and a stair-case type S–N curve is obtained [1]. In second type, the cracks are initiated from the surface of the material due to the surface defects, heterogeneities, pores and absence of inclusions and microstructural defects [1]. In this type of materials, the S–N curve between 10^6 and 10^9 cycles show horizontal asymptote without any transition at 10^7 cycles [2,3]. The difference in fatigue strength from 10^6 to 10^9 cycles is found less than 50 MPa.

The materials which show surface crack initiation have been studied earlier as well [8–17]. It was concluded that the fatigue cracks were initiated due to the plastic deformation developed during cyclic loading. At microscopic level, the plasticity around surface defects and pores [7], planar slip bands [9,12,15] and grain boundaries [18] were found as the potential stress concentration regions for the fatigue crack initiation.

The VHCF behavior of the materials without inclusions and microstructural defects exhibit surface crack initiation phenomenon [8–11]. The surface crack initiation was attributed to the Persistent Slip Bands (PSBs), developed in the form of intrusions and extrusions. The S–N curve between 10^6 and 10^9 cycles decreased monotonically without transition at 10^7 cycles [3]. One typical example of the materials which show surface based crack initiation is high temperature grade stainless steel alloy AISI 310. The alloy is used in moist conditions offering resistance to corrosion such as heat exchangers, pipes and machinery parts. The alloy is considered effective for prevention of oxidation at elevated temperatures. It is subjected to pressure cycles, temperature cycles and many start up and shut down cycles during service life and hence, expected to serve for large number of loading cycles. However,

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there is no such study, to the best of authors' knowledge, which details the behavior of fatigue crack initiation phenomenon especially up to very high cycle fatigue domain. Hence, it is important to be able to assess the very high cycle fatigue behavior of the material.

Multiple conclusions were made about the surface crack initiation in earlier studies. Tokaji et al. [8] and Yang et al. [9] investigated the fatigue behavior of Mg alloys and found that the cracks initiated from the surface of specimen. Miura and Takahashi [10] observed surface cracks and found radial pattern of lines and markings on the fracture surface in 316 stainless steels. Stocker et al. [11] observed the surface cracks in Ni based super alloys and attributed the surface roughening and strength mismatch between matrix and precipitates for the surface crack initiation. Chai [12] concluded that the crack initiation was a competition process for the occurrence of plastic deformation, and attributed the surface crack initiation to micro-cracks formed due to the extrusion and intrusions. Marines et al. [13] and Park et al. [14] observed surface cracks initiation in different steel alloys and attributed it to the surface roughness of the specimen. Xu et al. [15] studied the crack initiation mechanism of the forged Mg alloy and observed different stages of the fatigue crack initiation and attributed it to the intrusions and extrusions Bollenhagen et al. [16] attributed the local and global plastic deformation for the fatigue crack initiation in VHCF region. Stanzl-Tschegg and Mayer [17] studied polycrystalline copper in VHCF and found PSBs even at lower stress levels. Man et al. [19] and Polak et al. [20,21] observed the PSBs in stainless steel and found difference in the topography of slip bands for FCC and BCC materials. In these studies the surface defects, local plasticity due to the fatigue loading and surface roughness were attributed to the surface crack initiation. It was concluded that any of these parameters or combination may initiate the cracks from the surface. In addition, the crystallographic surface facets play an important role in the surface crack initiation. The difference in FCP and HCP based crystal structure in different metals generated various topographies of PSBs. Hence, experimental investigation of the crack initiation region and slip and basal planes for the materials is considered essential.

In this study, the VHCF behavior of Stainless Steel AISI 310 was investigated through the ultrasonic fatigue testing. In fatigue cycles, a horizontal asymptote of S–N curve was found without any step at 10^6 cycles. Surface crack initiation was found irrespective of the stress level. It was found that up to 10^6 cycles, the cracks initiated from carbide precipitates present on the grain boundaries. However, beyond 106 cycles, PSBs were developed at the surface of the specimen which acted as the fatigue crack initiation sites. Below a certain stress threshold, the PSBs were observed but declared as non-damaging. It was concluded that the PSBs were developed due to higher fatigue cycles instead of higher stresses.

2. Materials and experimental methods

Cold rolled cylindrical rods of 12 mm diameter of AISI 310 were used in this study. AISI 310 is a commonly used material in heat exchangers, pipes and machinery parts. The material exhibits excellent high temperature properties with good ductility and weldability. It resists oxidation at elevated temperature and corrosion in moist conditions and dry environments.

Metallographic sample were prepared up to 0.05 μm finish and etched with diluted Aqua Regia Reagent (15 mL HCl + 5 mL HNO_3 + 100 mL H_2O) for 120 s. The grain size of the material was determined by quantitative metallography and was found to be ~10 μm as shown in Fig. 1. The grains were equiaxed and showed a random orientation. Carbide precipitates were obtained on the grain boundaries of the material. Elastic–plastic properties of the material were obtained by tensile testing according to the ASTM

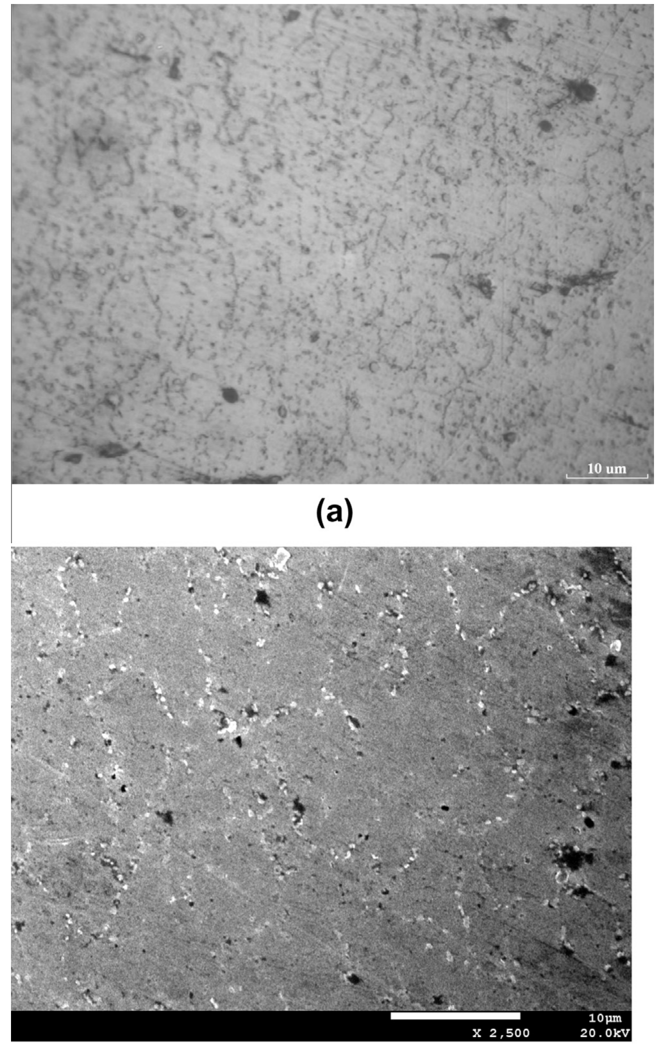

Fig. 1. Micrographs of the material (a) optical micrograph and (b) SEM micrograph shows carbide precipitates grain boundaries.

standard E8 and are given in Table 1. Vickers microhardness tester was used at 200 g load. The average Vickers hardness of the material was found as 370 HV.

The chemical composition of the material is shown in Table 2. X-ray diffraction (XRD) was used to obtain the details of the diffracting planes of the material. A Bruker DX-1000 advance X-ray diffractometer was used. Measurements were carried out at room temperature in step scan mode with step size of 0.06 at 2θ angular interval 20–80. Cu Kα (1.54056 Å) radiation filtered with Ni was used with 40 kV and 25 mA without monochromator. Diffraction planes (1 1 1), (2 0 0) and (2 2 0) were obtained for the material as shown in Fig. 2a.

The crystallographic orientation of various common diffracting planes was measured by XRD. The texture pattern was determined and represented in terms of the pole figures. A scan size of 8 mm × 8 mm was used in the measurement to ensure that information on the crystallographic texture pattern was obtained from large number of grains. As shown in Fig. 2b, no such texture or preferred orientation was obtained for the material apart from the (2 2 0) plane in which intensity reached to 1.6, which was negligible.

The VHCF testing samples were designed to resonate longitudinally at 20 kHz with the ultrasonic fatigue testing system at load ratio $R = -1$. To avoid the heating during the ultrasonic fatigue