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Ultra-high cycle fatigue property of a multiphase steel microalloyed with niobium

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A R T I C L E I N F O

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A B S T R A C T

The effect of microstructure on the ultra-high cycle fatigue behavior of a high strength steel microalloyed with niobium (Fe-0.23C-1.73Si-2.24Mn-0.68Cr-0.042Nb) was investigated through ultrasonic fatigue test. The ferrite and martensite (F/M) multiphase structure was obtained by air-cooling treatment, while the bainite and martensite (B/M) multiphase structure was obtained by oil-cooling treatment. The ultra-high cycle fatigue limit (10^9 cycles, σ_{w9}) of steel with F/M multiphase structure was 750 MPa, while the σ_{w9} of steel with B/M multiphase structure was 900 MPa. In the high cycle regime, cracking occurred at the non-inclusion site in the steel with F/M structure. However, half the specimens cracked at the non-inclusion site, the others cracked at inclusions in the steel with B/M structure. The study clearly underscores that the microstructure had a distinct impact on the ultra-high cycle fatigue behavior of high strength steels. Moreover, the present work demonstrates that the fatigue properties of steel can be optimized by using appropriate heat treatment, which is related to the change in the F/M microstructure to B/M microstructure in an advanced Nb-microalloyed steel.

1. Introduction

Industrial development and environmental protection have led to increased demand for steel with high strength, excellent ductility and toughness. Microalloyed high strength steels can undoubtedly meet these requirements. Among potential low alloyed high strength steels, Nb-microalloyed steel has attracted significant attention. The addition of Nb can improve the performance of steel because of grain refinement and precipitation strengthening effect [1].

Nowadays, industries are demanding components with a longer service life. A number of components and structures of vehicles, bridges, railways and aircraft are expected to exhibit cyclic loading greater than 10^8 cycles. Thus, there is a growing attention in ultra-high cycle fatigue ($\geq 10^7$ cycles) behavior of metallic materials, and ultra-high cycle fatigue performance is becoming a significant part for modern material design and sometimes the first design criteria.

In general, inclusion is the main cause for crack initiation in steels experiencing ultra-high cycle fatigue. Hence, studies on ultra-high cycle fatigue behavior of high strength steels are being pursued in the direction of increasing the ultra-high cycle fatigue properties by modifying the size and reducing density of inclusion in steels [2–5]. However, reducing inclusions increases the manufacturing costs. Thus, processing steels with high tolerance for inclusions is a potential route.

Recently, Chai et al. [6] observed that the crack initiated at subsurface (non-defect area) or matrix in martensitic-ferritic low-alloyed steel and martensitic-austenitic stainless steels. Non-inclusion induced crack initiation (NI-mode) was also observed in some austenitic stainless steels under cyclic uniaxial loading at low temperatures [7] and in some steels that were modified by super-rapid induction heating and quenching under rotation bending loading [8]. Our earlier work showed that NI-mode was the dominant failure mode in ultra-high cycle fatigue regime of multiphase steels [9–12]. Obviously, in this case (NI-mode), ultra-high cycle fatigue performance is no longer controlled by inclusions (size or geometry), but is controlled by the matrix microstructure.

The effect of inclusions and surface condition on ultra-high cycle fatigue properties has been extensively studied in a number of kinds of steels. But the effect of microstructural factors on ultra-high cycle fatigue properties is limited, and the ultra-high cycle fatigue behavior in multiphase steels is not yet fully explored. In the present study, a Nb-containing steel was selected, and different heat treatments were carried out to obtain varied microstructure. Finally, ultrasonic fatigue test

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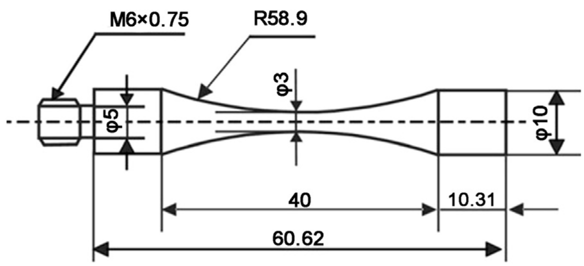

Fig. 1. Specimen for ultra-high cycle fatigue testing.

was carried out to reveal the effect of microstructural factors on ultra-high cycle fatigue performance.

2. Experimental procedures

The steel selected for the study was a Mn-Si-Cr low alloyed steel, with nominal composition of Fe-0.23C-1.73Si-2.24Mn-0.68Cr-0.042Nb (wt%), and is abbreviated BM-Nb steel. In order to obtain clean steel for the study described here, BM-Nb steel was prepared by two steps: melting in a vacuum induction furnace as ingots, following by electroslag remelting (ESR). Subsequently, each ingot of 30 kg was forged to a square bar of 30 mm thickness and 1000 mm length. All the experimental studies were carried out on samples machined from the forged bars.

According to the solubility product of Nb(C,N) in austenite [13], the temperature at which Nb goes into solution is given by:

$$\text{Log}\{[\text{Nb}][\text{C}]\} = 2.96 - 7510/T \quad (1)$$

where [Nb] and [C] are the concentration of Nb and C in austenite, in wt%, T is the solution temperature. Thus, the heat treatment process for Nb-bearing steel was as follows: the specimens were solution treated at 1200 °C for 30 min, and cooled to the ambient temperature. After solid solution treatment, the BM-Nb-A specimens were austenitized at 900 °C for 45 min, followed by air-cooling. The BM-Nb-B specimens were austenitized at 900 °C for 45 min, followed by oil-cooling. Next, they were tempered at 280 °C for 2 h.

The dimensions of the smooth hour-glass type specimens for ultra-high cycle fatigue testing are shown in Fig. 1. The fatigue test was conducted using ultrasonic fatigue testing equipment at a frequency of 20 kHz up to 10^9 cycles at room temperature. The stress ratio R of -1 was selected. Microstructure of steel and fracture surface of specimen subjected to fatigue test were observed by optical microscope (OM), scanning electron microscopy (SEM), electron backscattered diffraction (EBSD), and transmission electron microscopy (TEM).

3. Results

3.1. Microstructure and general mechanical properties

Microstructure of steels was observed by OM as shown in Fig. 2. The microstructure of two steels was uniform and fine, and no apparent inclusions were observed in the field of view. From Fig. 2, it can be stated that Nb-bearing steel was very clean that was processed by combination of vacuum induction melting + electroslag remelting. Thus, the influence of inclusions on ultra-high cycle fatigue performance is expected to be greatly reduced, and microstructural factors may dominate the ultra-high cycle fatigue behavior. After air-cooling, the microstructure comprised of grain boundary allotriomorphic ferrite and martensite (Fig. 2(a)). From Fig. 2(b), it can be seen that the sample after oil-cooling was characterized by typical bainite and martensite multiphase microstructure.

The general mechanical properties of BM-Nb-A and BM-Nb-B steels are listed in Table 1. Both steels can be considered to be characterized by high-strength-toughness combination. The tensile and yield strength of BM-Nb-B steel was greater than BM-Nb-A steel, whereas the yield strength ratio and toughness of BM-Nb-B steel was slightly greater than BM-Nb-A steel. The amount of retained austenite (RA) was less as compared to similar steel without Nb [10], which was because of consumption of carbon by Nb(C,N) precipitation. The reason for lower strength of air-cooled sample is related to addition of Nb that led to ferrite formation from austenite during air-cooling.

3.2. The ultra-high cycle fatigue behavior

The *S-N* curves of the two steels are presented in Fig. 3. Solid square symbols represent the specimens that broke prior to 10^9 cycles and fatigue crack initiated at the surface defect (S-mode). Solid five-star-symbols represent samples in which the crack initiated in the interior matrix (NI-mode), and solid circles represent specimens where crack initiated at the interior inclusion (I-mode). From Fig. 3, it can be seen that one plateau existed in the *S-N* curves for the two steels. Using "up-and-down" method [14], the ultra-high cycle fatigue endurance limit (σ_{w9}) was determined to be 750 MPa for BM-Nb-A steel (Fig. 3(a)) and 900 MPa for BM-Nb-B steel (Fig. 3(b)). The tensile strength (R_m) of BM-Nb-A and BM-Nb-B steels were 1446 MPa and 1640 MPa, respectively. Thus, the ratio of fatigue limit to tensile strength (σ_{w9}/R_m) for the two steels was 0.52 and 0.55, respectively. Meanwhile, the calculated values of σ_{w9}/R_p of two steels were 0.65 and 0.68, respectively (Table 2). The values of σ_{w9}/R_m and σ_{w9}/R_p of studied steels were higher than steels reported in the literature [15–17].

Fig. 4 shows two types of fracture surface of BM-Nb-A steel. Fig. 4(a)-(c) is the specimen with S-mode of failure. The crack initiated

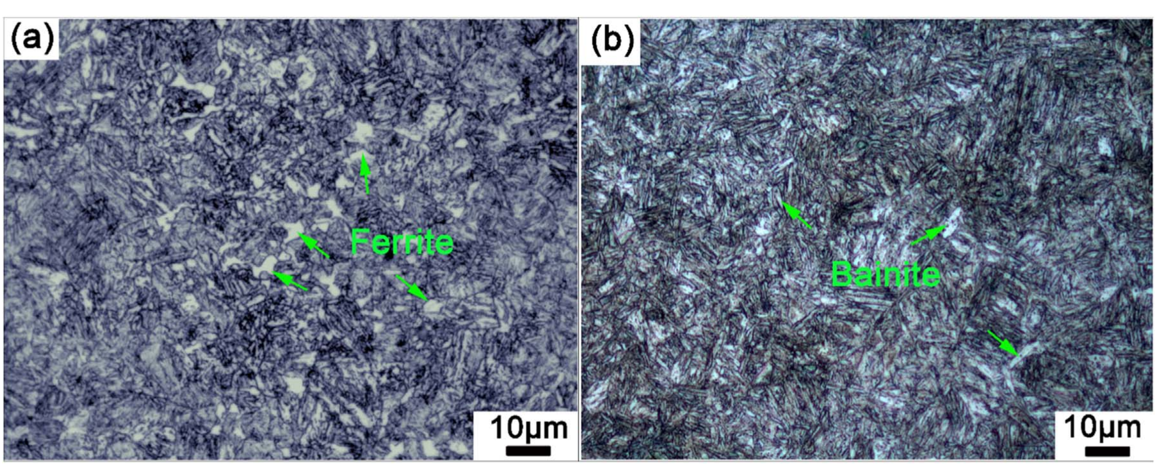

Fig. 2. Light micrographs of Nb-bearing steels of (a) BM-Nb-A specimen, and (b) BM-Nb-B specimen.