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The potential significance of microalloying with niobium in governing very high cycle fatigue behavior of bainite/martensite multiphase steels

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ABSTRACT

We elucidate here the effect of microalloying with niobium (Nb) on very high cycle fatigue (VHCF) behavior in high-strength C–Mn–Si–Cr bainite/martensite (B/M) multiphase steels studied through ultrasonic fatigue testing. The tensile strength (R_m) and fatigue limit strength after 10^9 cycles (σ_{w9}) and in the non-failure condition of the steel microalloyed with Nb were 1640 MPa and 900 MPa, respectively. Thus, the value of σ_{w9}/R_m exceeded in comparison to conventional steels and was approximate 0.55. Three types of failure modes were observed in Nb-bearing steels depending on the surface condition, inclusion, and the matrix microstructure, i.e., surface defect-induced failure mode (S-mode), inclusion-induced failure mode (I-mode), and non-inclusion induced failure mode (N-mode). Only two failure modes were observed in Nb-free steels, the S-mode and the N-mode. The study clearly suggests that Nb had a distinct effect on the VHCF properties of B/M steels. The VHCF limit of Nb-bearing steel was enhanced by 200 MPa because of refinement of the microstructure and pinning of dislocations by randomly distributed nanometer-sized Nb(C, N) precipitates. It is underscored that microalloying with Nb is a potential approach to enhance VHCF properties in advanced high-strength steels.

1. Introduction

The continued demand for superior automobile components has led to increased life expectancy of certain components that experience fatigue process, such as engine and suspension springs, besides other automotive components. This necessitates the study of fatigue behavior in very long life cycle regime, beyond 10^7 cycles [1]. Fatigue of various structures continues to be a practical problem, for instance in the case of aircrafts, cars, cranes, bridges, offshore structures, etc. This situation is a consequence of several developments associated with new types of structures, reduction in the weight of the structure, new production methods and materials. Safety and economic considerations are also important, especially in view of a more intensive and longer utilization of structures in service [2–4]. Very high cycle fatigue behavior of advanced high-strength steels is viewed as an important subject. The fatigue limit and the associated damage mechanism in the very high cycle regime are governed by mechanical properties (e.g. strength, toughness and hardness etc.) and microstructure (e.g. morphology, volume fraction, and nature of microstructure) of the steel [5,6]. Based on this viewpoint, the VHCF performance of steels can be enhanced through optimization of the microstructure. Moreover, homogenization and refinement of microstructures are beneficial to the VHCF behavior of steels.

Numerous approaches have been used to improve the mechanical properties, including the use of thermo-mechanical control processing (TMCP) [7] and the addition of carbide forming elements such as niobium, vanadium, and titanium [8,9]. Among them, the effect of Nb on the microstructure and mechanical properties has been intensively studied in low carbon low alloyed steels. Based on previous studues, the austenite grain growth can be retarded by the solute drag effect induced by Nb in solid solution during the heating process before hot rolling, and further impeded by the pinning force exerted by Nb(C, N) precipitates during subsequent dynamic recrystallization or static

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recrystallization during thermo-mechanical processing [10–12]. As a consequence, the mechanical properties of steels with ferrite [13] or bainite microstructure [14] were optimized through the refinement of prior austenite grain size and precipitation strengthening.

Although the addition of Nb has profound effect on strengthening through grain refinement and precipitation strengthening in high-strength low alloy steels [15,16], there is no quantitative data on the effect of Nb on VHCF properties of low carbon bainite/martensite (B/M) steels. Thus, the present study is mainly focused on the effect of microalloying with Nb on the microstructure and VHCF properties of B/M steels.

2. Experimental procedure

Two experimental steels abbreviated as EU20Si (Nb-free) and EU20SiNb (microalloyed with Nb) were studied. The composition of the studied steels are listed in Table 1. Mn was added to avoid austenite to ferrite transformation at high temperature.

The steels were melted in a vacuum induction furnace, followed by electroslag remelting, with the objective to decrease the size and number density of non-metallic inclusions in steels. Electroslag remelting has large impact on very high cycle fatigue properties of materials (please see Section 3.2). Each ingot of 30 kg was reheated at 1200 °C and forged to 30 mm thickness with a finish-forging temperature of ~950 °C. The forged plate was then annealed at 900 °C followed by furnace cooling.

The dilatometer experiment was carried out to determine continuous cooling transformation (CCT) diagram using 4 mm diameter × 10 mm cylindrical specimens using a Bähr D805L quenching device equipped with quartz push-rods. The temperature was monitored by a S-type thermocouple spot welded on the surface of the specimen. Nitrogen was used as quenching medium.

Cylindrical specimens of dimensions 12 mm diameter × 80 mm length were subjected to heat treatment. The EU20Si specimens were austenitized at 900 °C for 45 min, followed by oil cooling to ambient temperature, and then tempered at 280 °C for 2 h. Oil was used as a quenching medium to ensure the formation of bainite during cooling (the average cooling rate was ~15 °C/s). Hence, the heat treatment is called bainite-based quenching and tempering treatment (BQ&T).

Table 1
Chemical composition of experimental steels.

No.	C	Si	Mn	Cr	Nb
EU20Si	0.21	1.74	2.20	0.62	–
EU20SiNb	0.23	1.73	2.24	0.68	0.042

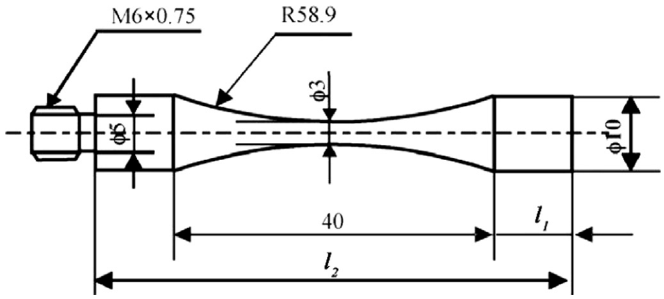

Fig. 1. Geometry of specimen for VHCF test (length l_1 and l_2 depends on the elastic modulus and density of steels, l_1=9.5–10.5 mm).

It is necessary to pre-treat EU20SiNb steel to take Nb into solution. According to the solubility product of Nb(C, N) in austenite [17], the temperature at which Nb goes into solution is given by:

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

where $[Nb]$ and $[C]$ are concentration of Nb and C in austenite, in wt%. T is the solution temperature, in Kelvin. The calculated dissolution temperature of EU20SiNb steel according to Eq. (1) is 1236.5 °C. Thus, the heat treatment process for EU20SiNb steel was as follows: the specimens were solution treated at 1240 °C for 30 min, water cooled to the ambient temperature, and then austenitized at 900 °C for 45 min, followed by oil cooling to the ambient temperature, and finally tempered at 280 °C for 2 h. Through the combination of solution treatment and BQ&T process, the nanometer-sized Nb(C, N) precipitates were nucleated (please see Fig. 6), which aided the refinement of microstructure.

Standard tensile tests were conducted using tensile specimens of 5 mm diameter and 25 mm gage length using SUNS 5305 tensile testing machine. Impact tests were performed with standard Charpy v-notch specimens ($10 \times 10 \times 55$ mm^3) using a JB-30A impact test instrument. Three specimens were tested for each heat treatment and their average values were determined.

Fatigue specimens of geometry presented earlier [18] (Fig. 1) were prepared with longitudinal axis along the rolling direction of the initial bar, resulting in fracture surface perpendicular to the rolling direction. After heat treatment, all samples were polished to mirror-like finish in the longitudinal direction. The fatigue test was conducted using ultrasonic fatigue testing equipment (SHIMADZU USF-2000, Japan) at a frequency of 20 kHz up to and beyond 10^9 cycles in an open environment and at ambient temperature with constant stress ratio R of -1. Compressed air was introduced to eliminate possible "self-heating" in specimens during testing.

Microstructure and fracture surface were observed by scanning electron microscopy (SEM, ZEISS-EVO18, 20 KV) and transmission electron microscopy (TEM, FEI TECNAI G20, 200 KV). The retained austenite (RA) fraction was measured by X-ray diffraction (XRD, Rigaku Smartlab, Cu Kα radiation). To study the microstructure, 2% nital solution was used to distinguish bainite and martensite. TEM observations were carried out using thin foils electropolished using a solution of 4% perchloric acid. The size of GBF area was analyzed by Photoshop 7.0 software.

3. Experimental results

3.1. Microstructure and mechanical properties

The continuous cooling transformation (CCT) diagrams of the two steels determined by dilatometer tests are presented in Fig. 2.

It can be seen from the two CCT diagrams, that Nb significantly shifts ferrite transformation temperature to the left and bainite transformation slightly to the upper left. Thus, the effect of Nb on bainite transformation is weaker than the ferrite transformation. In addition, Nb can raise M_s but has little impact on M_f temperature. Lee [19] suggested that solute Nb strongly segregates at the γ/α interphase boundary and reduces ferrite growth rate because of solute drag effect. Nb(C, N) precipitation in austenite accelerates ferrite transformation because they act as potential nucleation sites [20]. In this study, the ferrite transformation occurred at high temperature in the EU20SiNb steel with 0.042% Nb, but not in Nb-free EU20Si steel. Thus, it is concluded that Nb(C, N) precipitates play an important role in the formation of ferrite formation at high temperature.

The mechanical properties of EU20Si and EU20SiNb variants