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Study on fatigue failure mechanism at various temperatures of a high-speed railway wheel steel

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ABSTRACT

The fatigue life and limit of the wheel rim and the wheel web position of a high-speed railway wheel steel at various testing temperatures (−60 to 60 °C) were investigated. Both microstructures and fracture morphologies were observed in details. The fatigue failure mechanism at various temperatures was discussed. The results demonstrated that the wheel rim had a longer fatigue lifetime and a higher value of fatigue limit than the corresponding properties of the wheel web due to various microstructural distributions. The temperature, microstructure and stress amplitude had a significant impact on the fatigue initiation and propagation. The typical features including the propagation zone of regular fan-like shapes, the fatigue step, the gray wear facets and the fatigue striation were observed on the fracture surface, which were related to the failure mechanism transition.

1. Introduction

The railway wheel serves as a vital component of high-speed railway vehicles, which the corresponding safety and economy have usually gained an increased public attention [1]. The ferrite-pearlite steel is the widely utilized material in the railway wheel manufacturing industry, which has an adequate strength with high ductility. In recent years, the operation speeds increase has aggravated the issue of railway wheel damage in terms of safety and economy. A high number of railway wheel steel types were newly developed for the strict demands of high-speed railway to be met, which contain high contents of Si and Mn and low contents of Cr [2]. In order for the long service life time to be met, it is proven necessary for the fatigue performance and study of fatigue failure mechanism of railway wheel steels to be evaluated. Furthermore, under strict service conditions, such as low temperature and high load amplitude, the fatigue performance and failure mechanism will be different. The microstructure distribution effect, the fatigue life, the fatigue limit and the temperature condition effect on the fatigue failure mechanism, remain as questions that were discussed in this paper.

The fatigue life usually contains both the fatigue initiation and the propagation life. Extensive literature studies [3–5] exist, reporting that the microstructure plays an important role in both fatigue crack initiation and propagation. Also, the temperature, stress amplitude and loading mode (such as stress ratio, loading frequency) on the fatigue crack initiation and propagation exist. Zhu [6] demonstrated that the railway wheel rim steel displays differences in the microstructural evolution related to the testing temperatures, including the slip system, the dislocation structure, the austenite transformation and the sub-grains, which led to significant changes in the strain dissipation mechanism and the fatigue behavior. The Fatigue Ductile-Brittle Transition (FDBT) is a phenomenon similar to the ductile to brittle fracture transition, where the fracture mode of the fatigue cracks changes from ductile transgranular to cleavage and/or grain boundary separation. The fatigue at temperatures below the FDBT displays a quite different crack growth rate than the fatigue beyond that temperature [7,8]. Moody et al. [9] reported that the crack growth rates were observed to decrease initially as the temperature decrease for all alloys. At a certain temperature below the ductile-brittle transition temperature, the trend reversed due to enhanced cleavage bursts. Verkin et al. [10] investigated the effects of low temperatures on both fatigue life and fatigue limit of various crystal lattice types of both metals and alloys. The results demonstrated that the temperature had a significant effect on both size and character of the plastic strain within a surface region of smooth samples and in the region of microcracks of Kth subthreshold values.

According to the aforementioned results, the fatigue failure modes changed under various testing temperatures. Moody [9] pointed out that when cleavage appeared from ductile failure modes, the dislocation models derived specifically for striation mechanisms demonstrated

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Table 1
Steel chemical composition (mass %).

C	Si	Mn	Cr	Ni	Mo	Cu
0.54	0.95	0.95	0.14	0.068	0.015	0.07
P	S	O	N	Ti	V	Fe
0.0076	0.0022	0.0013	0.0045	0.011	< 0.005	Balance

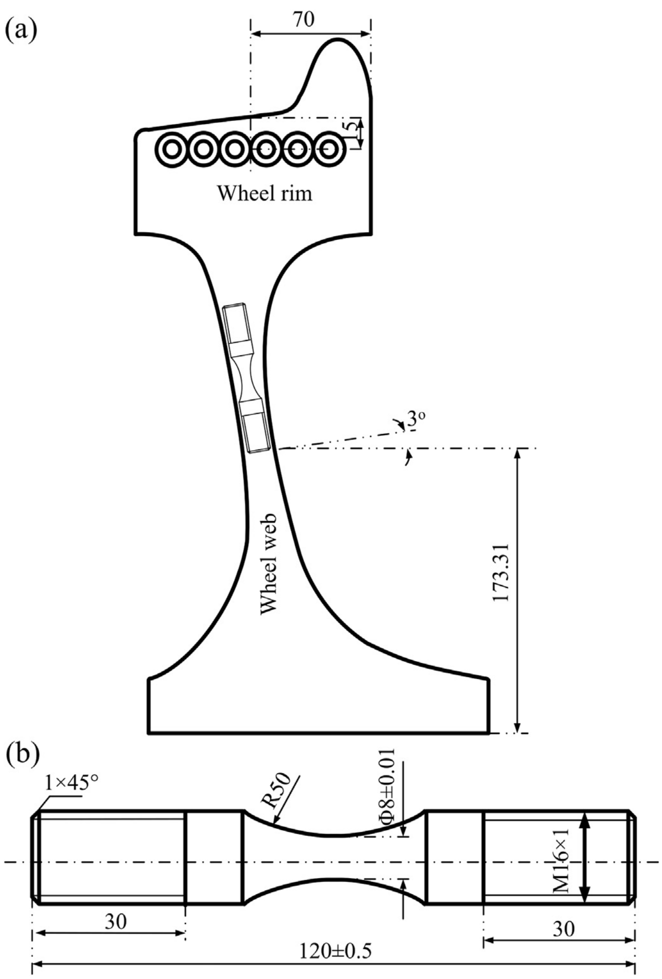

Fig. 1. Schematic of (a) specimen position, and (b) specimen geometry for fatigue tests.

a weakness in the accelerated growth rates prediction. An improved agreement was obtained when the models accounted for the cyclic cleavage failure modes. He et al. [11] investigated the effects of temperature on the low cycle fatigue behavior of a directionally solidified nickel-base superalloy. The results demonstrated that the fracture modes could be divided into three types: the crystallographic plane the facets fracture (shear fracture) at a low temperature region (< 600 °C), the mixed fracture mode at a middle temperature region (600–700 °C) and the non-crystallographic fracture (*I* type fracture) at a higher temperature region (> 700 °C).

In this paper, the high-speed railway wheel steel was selected, whereas both the fatigue life and the fatigue limit for the wheel rim and the web position under various testing temperatures were investigated. Furthermore, the effects of microstructure and temperature on the failure mechanism were discussed in details.

2. Experimental procedure

2.1. Materials

The as-received material was the *ER8C* railway wheel steel, which was utilized in the high-speed railway manufacturing industry. The steel chemical composition, in weight percent, is listed in Table 1. The steel was rolled and the following heat treatments were executed for various positions, including the wheel rim and the web of the railway wheel for the service properties to be met. The wheel rim was heated to 850 °C, tempered for one minute, quenched in water, in order for high hardness and wear resistance to be obtained. Consequently, it was heated to 500 °C, tempered for 4 h, whereas following cooled down inside the furnace to an ambient temperature, in order for the entire wheel to obtain an adequate toughness and for the residual stress to be released. The microstructures of both the wheel rim and the web were observed by an optical microscope (OM; Auto-Montage) and a scanning electron microscope (SEM; JSM-6610 LV). The phase percentage and inter-lamellar spacing were calculated by statistical software (Video Test-Master Structure) as follows: Firstly, the microscope images were taken at various positions. Subsequently, the images were opened by the Video Test-Master Structure software, where both the ferrite and the pearlite phases were identified due to various gray levels, respectively. Finally, the various gray levels area ratios were calculated and simultaneously, the inter-lamellar spacing was calculated by the line sections. In order for the statistical results reliability during the counting to be ensured, five specimens were prepared and five maps at various positions in each specimen were obtained and counted, whereas consequently the mean values were calculated.

2.2. Fatigue tests

The pull-push stress-controlled fatigue tests were performed on a high frequency fatigue machine (25t RUMUL) at various temperatures in air. A sinusoidal wave loading was selected with a stress ratio of −1 and a loading frequency of approximately 90 Hz. The specimens of both the wheel rim and the web were severed from the railway wheel as presented in Fig. 1(a), whereas Fig. 1(b) presents the specimen geometry for the fatigue tests.

In order for the S-N relations and the fatigue limit of the materials to be accurately obtained, the group method [12] and the up-and-down method for small samples [13,14] were employed at a constant temperature of −40 °C, respectively. Furthermore, the fatigue life of a single specimen at various temperatures under constant stress amplitude was tested. The testing temperatures were selected as −60 °C, −50 °C, −40 °C, −30 °C, −20 °C, −10 °C, 0 °C, 10 °C, 20 °C, 30 °C, 40 °C, 50 °C and 60 °C, respectively. The constant stress amplitudes were focused at 440 and 400 MPa for both the wheel rim and the web, respectively. The testing temperature was controlled with the assistance of an environmental chamber and thermocouples.

2.3. Fracture morphology observations

Following fatigue testing, all fracture surfaces were observed by SEM. The composition analyses of the inclusions in the fracture surface were performed by an energy dispersive X-ray spectroscopy system (EDS). The area ratio from the ultimate fracture to the crack propagation was also calculated by statistical software.

3. Results

3.1. Microstructure characterization

The investigated material was a typical ferrite-pearlite steel. It is utilized for the new generation of high-speed railway wheels. No significant differences in the microstructures were observed for both