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Low cycle fatigue behavior of Cr–Mo–V low alloy steel used for railway brake discs

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ABSTRACT

The cyclic stress–strain response and the low cycle fatigue (LCF) behavior of Cr–Mo–V low alloy steel which was used for forged railway brake discs was studied. Tensile strength and LCF properties were examined over a range from room temperature (RT) to 600 °C using specimens cut from circumferential direction of a forged disk. The fully reversed strain-controlled LCF tests were conducted at a constant total strain rate with different axial strain amplitude levels. The cyclic strain–stress relationships and the strain–life relationships were obtained through the test results, and related LCF parameters of the steel were calculated. The studied steel exhibits cyclic softening behavior and behaves Masing type, especially at higher strain amplitudes. At higher than 600 °C, carbide particles aggregated and a decarburized layer developed near the specimen surface. Micro voids distribute within the depth of 50 μm from the specimen surface could coalesce with fatigue cracks. Multiple crack initiation sites were observed on the fracture surface. The oxide film that generated at 600 °C covered the fatigue striations and accelerated the crack propagation. Final fracture area with bigger and deeper dimples showed better ductility at higher temperature. The investigated LCF behavior can provide reference for brake disc life assessment and fracture mechanisms analysis.

1. Introduction

Cr–Mo–V low alloy steels which have high hardenability, favorable strength and toughness are widely used material for many applications that include the mechanical, transportation and petroleum industries. Some of the reasons for this are that the relatively low percent volume of alloying elements make the steel more economical and the toughness and ductility can be further improved by keeping low impurities content through the use of electroslag refining [1,2]. With appropriate heat treatment, such as quenching and tempering (Q&T), it is possible to achieve a high level of strength and toughness along with a high degree of heat-resistance. A further advantage of Cr–Mo–V low alloy steel is that it has relatively high heat conductivity, low thermal expansion coefficient and good heat shock resistance [3]. This enables the material to operate at high temperatures for long durations and make it an ideal material for railway brake discs [4–6].

In railway transportation industries, brake discs are essential safety components, especially for high speed trains. During braking, the brake pads press against the friction surface of brake discs and transform the kinetic energy of the railway vehicles into heat. The friction heat generated during braking causes significant temperature variation on brake discs. In a typical railcar, the peak temperature on the surface of brake disc can reach in excess of 600 °C. As the trend in transportation is towards an increasing of maximum speed and braking loads, the higher level of thermal and friction loadings during braking can induce thermal stress and local plastic strains near the friction surface [7–11]. Because of repeated heating and cooling caused by braking process, several issues are of concern. The first is that the thermal fatigue cracks may appear under the action of the complex thermal–mechanical load. The heat shock and crack propagation of brake discs become common issues for railway transportation field these years [8–10,12]. The thermal fatigue of brake discs, which is essentially a low cycle fatigue (LCF) progress, may lead potential danger to the brake discs. However, high fatigue resistance and LCF behavior of brake disc materials is also of great significance and it may essentially decide the lifespan.

There have been large amount of studies that have been conducted to investigate the friction properties of the braking pairs. Findik [13–15] investigated the friction behavior of brake linings made of various ingredients. The effect of the friction environment, pressure and temperature on the pads was discussed. Furthermore, LCF behavior of different kind of brake disc materials is also a hot topic. Since 1997, Samrout and El Abdi [5,6] have started researches on the fatigue behavior of 28CrMoV5-8 brake disc steel, which had been used in French high speed trains for many years.

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A series of isothermal and anisothermal experiment were conducted at strain range 1.4% under cyclic uniaxial tensile and compressive load. An anisothermal fatigue damage model based on the Manson–Coffin relationship was presented, as well. Singh et al. [16] evaluated the effect of Q&T heat treatment on the LCF behavior of a traditional French steel 15CrMoV6 at RT. The fatigue resistance of the steel after Q&T process was lower than as-received condition because of a reduction of the fracture toughness. Šamec et al. [17] conducted a series of monotonic test and strain-controlled LCF experiments on studying the cast iron EN-GJS-500-7 used for brake disc material and the LCF behavior was investigated from RT to 400 °C. The basic LCF parameters of the cast iron were proposed in his work. LCF behavior of Cr–Mo–V steels used for other industry applications was also investigated. Zhang et al. [18] conducted a series of LCF tests at room temperature to investigate the LCF behavior of a Cr–Mo–V high-speed steel, which is used for cold forging tool. The microstructure of the steel was investigated and the brittle phases were found to be the source of the fatigue cracks. The cracks could initiate from both the specimen surface and the interior area. Kneifl et al. [19] proposed a model describing the life of Cr–Mo–V and Cr–Ni–Mo–V steels at combination of LCF and creep and elaborated a computational method to calculation the fatigue life. Luo et al. [20] evaluated the LCF life of a micro-alloyed high strength steel using energy-based prediction method. Plastic strain energy per cycle was considered to be an important parameter for lifespan evaluation.

The lifespan and operational safety issues of brake discs are of great significance. Brake discs are subject to severe temperature variations during its lifetime, the LCF behavior of brake disc steel at different temperature levels must be established prior to its application in the railway vehicles. However, there has only a few research conducted on LCF behavior of railway brake disc steels. In this study, a kind of indigenously-developed Cr–Mo–V low alloy steel for railway brake discs was used as an example for LCF behavior investigation. The studied steel, having composition similar to 28CrMoV5-8 steel but with higher carbon content, has been developed following the electroslag refining (ESR) process and kept in low impurity contents.

The aim of this study is focused on the LCF behavior and fracture mechanism of the brake disc steel. The LCF tests were conducted under strain-controlled condition at RT and elevated temperatures. Basing on the Manson–Coffin–Basquin and Ramberg–Osgood equations, the strain–life relationship and cyclic stress–strain behavior of the material were all obtained by the test results. Moreover, in order to get a better understanding of crack initiation and propagation mechanism of the studied steel during LCF process, metallographic and fractographic observations are necessary. The related methods and test results in this study can provide basic reference for life assessment of brake discs basing on the elastic and plastic strain methods. The micro-mechanism of crack initiation and propagation can be used for comparison with type of failure of brake discs, as well as other components working with frequently temperature variation.

2. Experimental procedure

In this study, LCF properties of a low alloyed brake disc steel were studied. The steel contains 0.32% C (weight percent) and other chemical composition is close to 28CrMoV5-8 brake disc steel. The material was produced by electroslag remelting process and the gas and impurities content of the steel was strictly controlled within a low level. The casting ingot was firstly forged into a disc having a 615 mm diameter and 55 mm thickness. The initial forging temperature was 1150 °C and ended at 880 °C. Then small bars were cut along the circumferential direction from the forged disk and then machined into monotonic tensile and LCF tests specimens. After that, a Q&T heat treatment process, which included oil quenching after austenitizing at 880 °C for 1 h and air cooling after tempering at 660 °C for 2 h, was applied to the specimens before finishing machining.

Prior to performing the LCF tests, monotonic tensile tests at different temperatures were conducted to evaluate the mechanical properties of the material. Tensile tests were conducted using an electronic universal testing machine CMT5105 with a load capacity of 100 kN that was equipped with a resistance heating furnace. The tensile tests were performed at room temperature (RT), 200 °C, 400 °C, 600 °C, and 800 °C with three replications at each temperature level. All tensile test specimens (Fig. 1) were designed and machined in accordance with the Chinese National Standard GB/T 4338-2006 ‘‘Metallic materials – Tensile testing at elevated temperature’’ [21]. The working section of the cylindrical specimens had a diameter of 4 mm. Strain was measured continuously with an extensometer of gauge length of 20 mm and travel length of 10%.

The LCF tests were carried out using a 250 kN capacity servo-hydraulic machine (MTS-810) equipped with an electric resistance heating furnace. The LCF test specimens (Fig. 2) were machined according to Chinese National Standard GB/T 15248-2008 ‘‘The Test Method for Axial Loading Constant Amplitude Low-Cycle Fatigue of Metallic Materials’’ [22]. The specimens with a diameter of 6.35 mm and gage length of 25 mm were finely polished before testing to ensure a consistent surface finish. Temperature calibration was conducted before the fatigue tests. Three thermocouples were fixed on the top, middle and bottom sections of a specimen, respectively. These thermocouples were used to measure surface temperatures of the specimen to ensure an uniform temperature distribution. The temperatures were controlled in a constant value and temperature differences between the specimen and the target temperature were strictly controlled within ±2 °C.

The strain controlled LCF tests were carried out at RT, 200 °C, 400 °C and 600 °C, respectively. The total axial strain amplitudes were controlled at different levels of ±1.0%, ±0.8%, ±0.6%, ±0.4%, and a lower level from 0.25% to 0.35%. Two replications were tested at each strain amplitude with a fully push–pull mode (minimum to maximum strain ratio, $R = -1$). A triangular waveform signal with a constant strain rate of $5.0 \times 10^{-3}\ \mathrm{s}^{-1}$ was used. The longitudinal strain was measured continuously with an extensometer during each of the LCF test. The cyclic stress–strain data was recorded and the hysteresis loops were obtained. The plastic strain range was measured from the width of the monitored hysteresis loop. The stress ranges were examined by the peak and valley stress values during each strain cycle which were determined from the tips of the hysteresis loop. The number of cycles which leads to a drop of 25% of the tensile stress was taken as fatigue life and the mid-life cycle was taken as stable hysteresis loop.

After the tests were completed, selected specimens were examined by scanning electron microscope (SEM) on their microstructures and fracture features. The thin sections for metallographic analysis were cut off from the monotonic test specimens

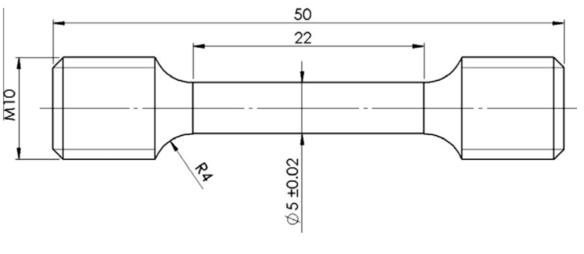

Fig. 1. Geometry of the monotonic tensile test specimen (unit: mm).