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Inclusion size evaluation and fatigue strength analysis of 35CrMo alloy railway axle steel

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ABSTRACT

The axial loading fatigue tests of 35CrMo alloy railway axle steel were carried out with the untreated specimens and those treated by nitrocarburization. It is found that the untreated 35CrMo steel specimens fracture from surface, while those of the treated specimens fracture from internal inclusions. In order to investigate the inclusion size in the material, the ultrasonic fatigue tests were conducted for the 35CrMo steel by applying large risk volume specimens with straight section after nitrocarburization. The results show that the cracks of all the specimens initiate from the internal inclusion. The statistics of extreme values (SEV) method was applied to evaluate the maximum inclusion size in the large volume material and the full-scale axle. Based on the evaluated maximum inclusion sizes and the fracture mechanics, different fracture behaviors of axial loading specimens and full-scale axle as well as the effect of inclusion size on fatigue strength of full-scale axles were analyzed based on the fracture mechanics.

1. Introduction

For case hardened steel and high-strength steel the fatigue crack generally initiates from a larger non-metallic inclusions and the fracture surface displays a fish-eye pattern. When the steels fracture from the internal inclusion, the fatigue properties of it are significantly affected by the inclusion size [1–4]. Therefore, it is important to investigate the inclusion size in the material. The traditional methods for the characterization of inclusions are techniques based on surface analysis by optical microscopy. However, this method is time-consuming and the results are affected by the preparation of samples [4]. Meanwhile, it has been reported that the inclusion size measured by this method is smaller than full size due to the fact that the inclusion section on the polished surface is not always the maximum one [5].

In recent years the ultrasonic testing system is developed and it is applied to investigate the inclusion size. The major advantage of ultrasonic tests is that a large volume can be assessed to decrease the chances of missing large harmful exogenous inclusions compared with conventional techniques. Besides, it has been reported that the effect of risk volumes is relatively high when the specimens fracture from internal inclusion [6,7]. The risk volume is the size of the region in which high stress acts in a fatigue test specimen or a machinery part, so the effect of risk volume is a type of size effect. The risk volumes of the ultrasonic fatigue testing specimens normally tend to be small, while it can be increased largely by introducing a straight section [8].

In addition, the size of the maximum inclusion size in a large volume of steel has to be predicted through data from a small sample. This requires predictions based on the size distribution curve with statistical analysis. The estimation of the maximum inclusion size in larger volumes of steel will be helpful both for the estimation of the potential danger caused by the worst inclusion and for the control over the inclusion size in the steel making process. Recently, the statistics of extreme values (SEV) method based on the statistics of extremes has been developed by Murakami and co-workers [8–15] The SEV methods allow data on inclusion sizes in small samples to be used to predict the maximum inclusion size in a large volume of steel.

The previous study shows that under rotary bending loading the 35CrMo alloy axle steel cannot fracture from internal inclusions, while they can fracture from the internal inclusions after nitrocarburization [16]. Besides, it is reported that the 30NiCrMoV12 alloy axle steel cannot fracture from internal inclusions with small rotary bending specimens under rotary bending loading, while the full-scale specimens revealed a sub-surface 'fish-eye' pattern with a small non-metallic inclusion at the fracture origin [17]. The difference between the fracture behaviors is considered to be caused by the scale effect due to the large stress gradient in the small specimens. Given the fact that the mechanical properties of 30NiCrMoV12 axle steel are similar to those of the 35CrMo steel, it is considered that the full-scale

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35CrMo axles are likely to fracture from the internal inclusion, thus, it is dangerous to design the full-scale axles based on results obtained from the small specimens. Therefore, it is necessary to conduct the tests under axial loading, evaluate the inclusion size in full-scale axles and analyze the effect of inclusion size on fatigue strength of full-scale axles.

In this study, the axial loading fatigue tests of 35CrMo steel were carried out with the untreated specimens and those treated by nitrocarburization. Meanwhile, the ultrasonic fatigue tests were conducted for 35CrMo steel by using large risk volumes specimens with straight section. Usually, the ultrasonic fatigue specimens are cooled by compressed air to suppress any temperature increase during the testing process, while it is difficult to cool the specimens by air when the straight section is introduced. So in this test, the specimens were treated by nitrocarburizing and then cooled them by water during the tests. The inclusion sizes in the specimens were investigated and the maximum inclusion size in large volume and full-scale axles were estimated. The different fracture behaviors of small specimens and full-scale axle as well as the effect of inclusion size on fatigue strength of full-scale axles were analyzed based on the fracture mechanics.

2. Experimental procedures

2.1. Experimental material

The material used in this study was 35CrMo alloy railway axle steel (Chinese standard), the chemical composition (mass%) of it is given in Table 1. The 17 mm diameter steel bars were machined from the blank axle which is in rolled condition and austenitised at 860 °C for 0.5 h, quenched in oil, then tempered at 580 °C for 0.5 h and air-cooled. The microstructure of the heat-treated materials is temper sorbite and the mechanical properties of the material are given in Table 2. After the heat treatment, the axial loading specimens were machined into the shape and dimensions as shown in Fig. 1a. The round notch surface of the axial loading specimen was mechanically polished by emery paper with a mesh of 400–2000, which removed about 25 μm mechanical hardening layer. Besides, in order to investigate the fracture behaviors after surface treatment, part of the axial loading specimens were gas nitrocarburized at 570 °C for 2 h with a gas mixture of NH_3, O_2 and additive organic gas at 0.11 MPa in a gas multi-elements penetrating equipment and then cooled in air [18]. Hereafter, for the axial loading fatigue test, the nitrocarburized specimen is referred to as treated specimen and the specimen without surface treated as untreated specimen in this paper. Meanwhile, the surfaces of the treated specimens were mechanically polished off by about 15 μm by emery paper with a mesh of 2000 to remove the surface oxide layer.

Table 1
Chemical composition (mass%).

C	S	P	Cr	Ni	Mn	Si	Cu	Mo
0.35	0.015	0.016	0.90	0.06	0.55	0.27	0.08	0.20

Table 2
The mechanical properties of the material.

Young's modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Area reduction (%)
215	863	982	22.1	56.3

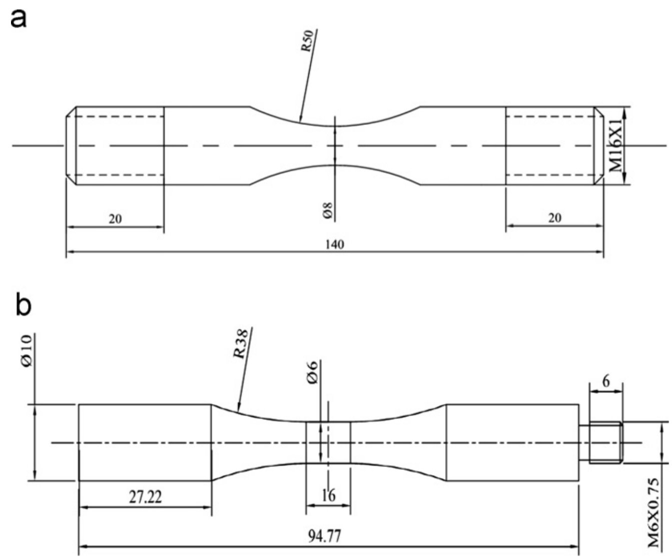

Fig. 1. Specimen shape and dimensions for (a) axial loading fatigue test; (b) ultrasonic fatigue test (unit: mm).

The specimens used for the ultrasonic tests were machined from the blank axle which was in rolled condition and heat-treated in the same condition with the axial loading specimens. The specimens were machined into the shape and dimension as shown in Fig. 1b and the specimens have a straight section of 6 (diameter) × 16 mm in the middle. In order to ensure that the specimen fractures from internal inclusion and to protect them from corrosion, which is induced by the cooling water, the specimens were nitrocarburized in the cyanate salt bath at 560 °C for 1 h. After that the samples were cooled in water; then they were exposed to further post-oxidation in nitrate–nitrite salt bath at 350 °C for 10 min and then cooled in water to room temperature.

2.2. Fatigue experiments

The axial loading fatigue tests were performed under constant amplitude fully reversed loading ($R = -1$) on Rumul 250 kN at the frequency of 94 Hz and the run-out stress cycles were set up to 10^7 cycles due to the fact that in rotary bending tests the specimen cannot fracture after 10^7 cycles and the GBF area was not observed in the very high cycle regime [16]. The ultrasonic fatigue tests were conducted on a Shimadzu USF-2000 ultrasonic testing system with a resonance frequency of 20 kHz, a resonance interval of 200 ms and a stress ratio of $R = -1$. During the ultrasonic fatigue testing process, specimens were cooled by water to suppress any temperature increase. The tests were carried out by applying the specimens to as many as 10^9 cycles at every applied stress amplitude, which was increased by an increment of 20 MPa each time from the starting point of 600 MPa until the failure.

In order to identify the crack initiation behavior, all the fracture surfaces were observed by Scanning Electron Microscopy (SEM) after the specimens ruptured.

3. Results

3.1. *S–N* curve of 35CrMo steel

The *S–N* curves obtained from the rotary bending tests with treated and untreated specimens are given in Fig. 2 [16]. It can be