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Small internal fatigue crack growth rate measured by beach marks

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ABSTRACT

Internal fatigue crack growth rates were measured using the beach marks created by repeated two-step fatigue tests on a high-strength steel. This material revealed internal fractures originating from oxide-type inclusions whose sizes ranged from 14 to 40 µm. Large and small beach marks were observed depending on the conditions under which the repeated two-step fatigue tests were carried out. Small beach marks indicated small internal cracks just after crack initiation, while large beach marks indicated internal cracks in the final stages. The small internal cracks showed extremely slow growth rates that were much smaller than the lattice length: the measured growth rates were very close to those calculated using fracture mechanics. The large internal cracks showed conventional growth rates, larger than the lattice length, and the border between the large and small internal cracks was almost equal to the threshold stress intensity range ΔK_{th}. These results show the validity of evaluating the fatigue lives by calculating the crack propagation lives of the small internal cracks as in the Tanaka-Akiniwa model. However, it has been suggested that the Tanaka-Akiniwa model overestimates the effects of inclusion sizes, meaning that the Tanaka-Akiniwa model has room for improvement. To correct this problem, we propose a new model, based on a new crack growth law, in which the crack growth rate also depends on crack size. The new model generates more realistic predictions.

1. Introduction

Gigacycle fatigue occurs in high-strength steels whose tensile strength exceeds approximately 1200 MPa [1]. In spite of the surface fractures seen in conventional fatigue, gigacycle fatigue of high-strength steels that is caused by internal fractures mostly originates from inclusions [2–8]. These internal fractures occur even at low stress levels below conventional fatigue limits and even in long-life regions of over 10^7 cycles, resulting in disappearance of the fatigue limits. High-strength steels thus reveal fatigue failures in gigacycle regimes exceeding 10^9 cycles. This means that evaluation of internal fracture properties is necessary to predict the gigacycle fatigue strength of high-strength steels.

Internal fractures show different properties from a conventional surface fracture. Although the disappearance of the fatigue limits is one of these dissimilarities, there are differences also in hydrogen effects [9] and size effects [10,11]. Moreover, the sizes of the inclusions at which internal fractures originate have major effects on fatigue strength [2,12]. Any evaluation of internal fracture properties needs to take these differences into account. A new mathematical model is thus required to evaluate the properties of internal fractures.

Fracture mechanics is suitable as a basis for the mathematical model, since the effects of the inclusion sizes can be taken into account as initial crack sizes. One approach based on fracture mechanics is to use a threshold value at which the fatigue crack stops growing. Murakami's equation [2] is typical of this approach. Although it leads to fatigue limits that disappear with internal fractures, Murakami et al. claim that the disappearance of the fatigue limits can be described by using the optically dark area (ODA) [13,14]. This is why many researchers are investigating ODAs [15–17]. However, the nature of ODAs is still unclear and a growth law for ODAs has yet to be established.

The other approach estimates the crack propagation life by integrating the fatigue crack growth law. This approach is applicable if the crack propagation life is dominant over the total fatigue life. Tanaka and Akiniwa first applied this approach to internal fractures [18]. Although it relies on internal crack propagation rates, which are very difficult to measure, Tanaka and Akiniwa proposed a method for reverse-calculating the internal crack growth rates by using conventional fatigue test results which measure only total fatigue lives and the inclusion sizes of the crack origins. A simpler version of this reverse calculation was then proposed by Omata [19]. This concept is called the Tanaka-Akiniwa model in this report.

A problem with the Tanaka-Akiniwa model is the validity of the calculated internal crack growth rates. The Tanaka-Akiniwa model calculates extremely slow crack growth rates, which are much smaller than the lattice length, while the lower limit of the fatigue crack growth rate is regarded as being near the lattice length, i.e., the validity of this

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extremely slow crack growth rate has yet to be experimentally confirmed. For this reason, some researchers claim that crack initiation life is dominant in internal fractures [20,21]. Even if this were indeed the case, however, no plan has been proposed for predicting fatigue strength, since the effects of inclusion sizes are difficult to take into account.

Measurement of the internal crack growth rate is therefore required in research into the gigacycle fatigue of high-strength steel. The validity of the extremely slow crack growth rate is a specific issue in that measurement. It is expected to take place just after crack initiation when small cracks are present. The small internal cracks could be as small as the ODA, so the extremely slow crack growth might be connected with the mechanism of ODA formation. The measurement of the extremely slow crack growth rate is thus a key for solving the problem of internal fractures.

Internal cracks, however, unlike normal surface cracks, cannot be observed directly. The author, therefore, established a method of visualizing small internal fatigue crack growth by using the beach marks created by repeated two-step fatigue tests [22]. Beach marks are a feature of a fracture surface that results from irregular loading during fatigue. The repeated two-step fatigue tests created controlled beach marks which reveal the traces of crack growth. As the result of a huge number of pre-tests, the author identified which conditions in the repeated two-step fatigue tests would create fine beach marks. These created beach marks were precise enough to disclose small internal cracks just after crack initiation. It was moreover found that the small internal cracks just after crack initiation had asymmetric shapes which required three-dimensional modeling. The extremely slow crack growth was attributable to these asymmetric crack shapes.

In this study, the above method was applied to measurement of the small internal fatigue crack growth rate. Based on the results, the mechanism and the mathematical model were discussed based on the internal fracture of a high-strength steel.

2. Experimental method

2.1. Materials

Table 1 shows the chemical compositions of the tested steel, which comprised hot-rolled round bars of JIS-SCM440 low-alloy steel. The heat treatments applied were quenching and tempering. The quenching conditions were oil-cooling after holding at 1153 K for 30 min, and the tempering conditions were air-cooling after holding at 473 K for 60 min. These heat treatments were conducted on round bars 12 mm in diameter. The Vickers hardness after heat treatment was 604 HV1, and the microstructure, as seen in Fig. 1, was tempered martensite..

2.2. Fatigue testing

Fig. 2 shows the waveform of the repeated two-step fatigue tests. The fatigue tests were basically conducted at a stress ratio of R=0, in which the mean stress σ_m was equal to the stress amplitude σ_a. During these fatigue tests, irregular loadings of a stress amplitude $\sigma_{a,\ IL}$ for a cycle number $N_{i,\ IL}$ were inserted every N_i cycles. The mean stress of the irregular loadings was equal to that of the test stress, i.e., σ_m. Although the stress amplitude of the irregular loadings is higher than that of the test stress in Fig. 2, in actuality there were also conditions under which the stress amplitudes of the irregular loadings were lower.

Table 1
Chemical compositions of the tested steel.

Steel	Element (mass%)						
	C	Si	Mn	P	S	Cr	Mo
SCM 440	0.40	0.21	0.71	0.009	0.009	0.96	0.16

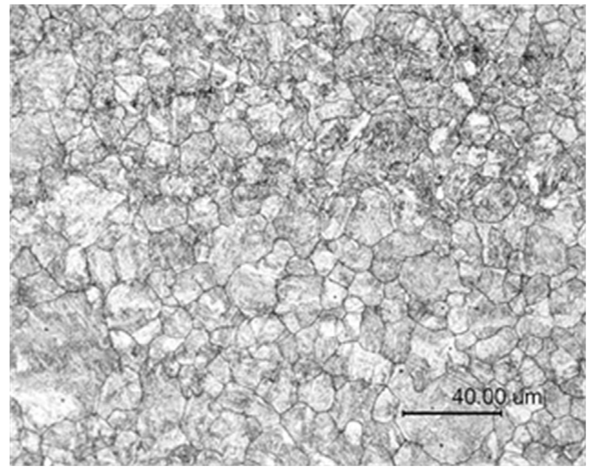

Fig. 1. Microstructure of the tested steel.

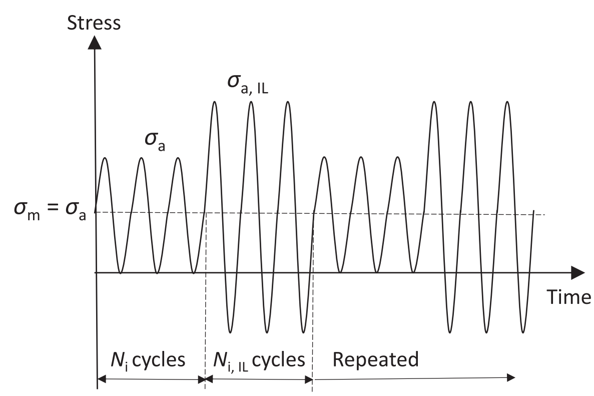

Fig. 2. Waveform of the repeated two-step fatigue tests.

Fatigue tests were conducted by ultrasonic fatigue testing at 20 kHz [23–27]. The ultrasonic fatigue testing machine used in these tests was a commercial model (Shimadzu USF2000), while the software for controlling the testing machine was modified to conduct the repeated two-step fatigue tests. The ultrasonic fatigue testing machine has a load frame for superimposing the tensile mean stress. An air-cooling system is built into this system to suppress any temperature increase of the specimens. The specimen's surface around the narrowest section was finished with 1-μm grit powder to completely eliminate any machining flaws (Fig. 3). The frequency, although very high, had a negligible effect on internal fractures. Past studies have shown that 20-kHz test results

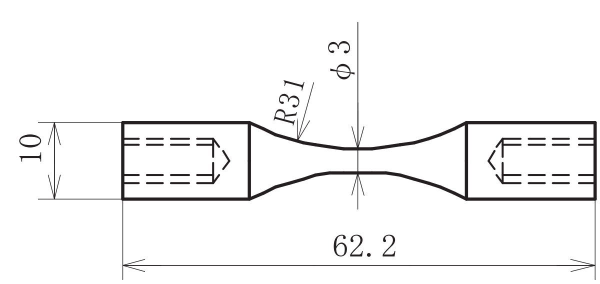

Fig. 3. Profiles of the fatigue test specimens in millimeters.