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Surface vs. interior failure behaviors in a structural steel under gigacycle fatigue: Failure analysis and life prediction

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ABSTRACT

The failure behaviors of a structural Cr–Ni–W steel under gigacycle fatigue were investigated, and a life prediction method based on the crack growth was proposed. The discovery of two failure phenomena, including the coexistence of surface and interior cracks and the coexistence of multiple fish-eyes, verifies the possibility of competing failure. The developed interior crack growth model reveals the failure progress at a slow rate below 10^{-10} m/cycle within the fish-eye induced by the inclusion or the inhomogeneous matrix area. The validity of the life prediction method is proved by the good agreement between the predicted and the experimental lives.

1. Introduction

In recent years, along with the never-ending reports of fatigue failures of structural materials in the longer life regime beyond 10^7 cycles, the gigacycle fatigue, also called very high cycle fatigue, has been an active subject [1–3]. A series of special international conferences [4] were hold to present and discuss the latest experimental and theoretical researches on the gigacycle fatigue properties of structural materials, but some fundamental but novel problems such as duplex or step-wise *S–N* properties [2,5] and competing failure mechanisms from surface and interior [6], are not yet well understood. Also, there is still much to be desired in the appreciable methods of damage evaluation and life prediction in the gigacycle fatigue regime [7]. To a certain extent, this can be attributed to the variable failure behaviors, especially the complex crack nucleation and growth behaviors, reflected by some structural materials in the gigacycle fatigue regime, especially under the influences of some uncertain factors such as surface finish [8,9], test environment [10,11], and microstructure including grain size [12], precipitation condition [12,13] and material discontinuities [14–17].

As the commonly used structural materials, high strength steels [1–3,5,6,8,10,14] often present two failure modes, i.e. surface crack induced failure in the shorter life regime and interior crack induced failure in the longer life regime. The material discontinuities, including nonmetallic inclusions [14], second-phase particles [15] and some inhomogeneous microstructures [16,17], play an important role in causing interior crack nucleation. Generally speaking, only one failure mode can be reflected from the fracture morphology, surface or interior, and only one fish-eye can be observed for the interior failure. However, we cannot help wondering such problems: whether surface and interior cracks can coexist on a fracture surface, and whether the multiple fish-eyes can occur just like the commonly observed multiple surface crack nucleation sites at the higher stress level. In theory, they are highly possible. Furthermore, studies [1,2,5–7] have shown that a granular bright facet (GBF) can occur in the vicinity of the inclusion or the second-phase particle when fatigue life is larger than about 10^6 cycles. However, for some inhomogeneous microstructures induced failure, the GBF sometimes occurs [15] and sometimes does not occur even if fatigue life exceeds 10^8 cycles [16]. Only from the viewpoint of experimental phenomena, several typical failure modes of high strength steels in the gigacycle fatigue regime still need to be verified, and summarized as follows:

- The coexistence of surface and interior cracks on a fracture surface.
- The occurrence of multiple interior crack nucleation sites, i.e. the formation of multiple fish-eyes.
- The occurrence of the GBF in the vicinity of the inhomogeneous microstructure.

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Compared with surface crack, the interior crack is extremely difficult to be directly observed and measured during testing. The analysis based on the fracture morphology is a common way of investigating interior failure mechanism. Some theoretical models including the "polygonization and debonding" [1], the "depressive decohesion of spherical carbide" [2], the "hydrogen embrittlement-assisted cracking" [3], the "continuously compression between the crack faces" [10] and the "grain refinement and localized decrease of threshold value" [11] had been developed to clarify the interior crack nucleation mechanism, especially the GBF formation mechanism. However, there is still a great of disagreement among them and the consensus is yet to be reached. As a result, the evaluation of crack nucleation life in the gigacycle fatigue regime is still a difficult task [12]. On the other hand, studies [13,14] show that the crack still can propagate even if the relative stress intensity factor below the traditional threshold value controlling macroscopic crack growth, and in vacuum the crack growth rates of some steels can be reduced to about 5×10^{-13} m/cycle [14]. Also, the similar fractographic morphology to the GBF in fracture surface of crack growth specimen tested in vacuum is observable [10]. In view of the fact that the interior-induced failure takes place in vacuum, therefore, some researchers [10,14] proposed that the gigacycle fatigue life could be characterized by the crack growth process with a very slow rate. Some theoretical models based on *S*–*N* data [15] or threshold condition for crack non-growth [12,16,17] are used to predict the crack growth life on the premise of the GBF existence. However, for the inhomogeneous microstructure induced failure without the GBF, obviously these models are not suitable. This is also growing demand for the development of new ideas and methods that can characterize the interior crack growth in the gigacycle fatigue regime.

In the present study, the axial loading fatigue test was performed to examine the gigacycle fatigue properties of a structural steel. Based on the evaluation of threshold condition controlling crack non-propagation or unstable propagation, the surface and interior crack growth behaviors with a very low rate were modeled. From a viewpoint of crack growth, a method was proposed to predict fatigue life of high strength steel associated with surface and interior failures in the gigacycle fatigue regime.

2. Material and experimental method

Material used in this study is a structural Cr–Ni–W steel, and its chemical composition (wt%) is 0.16 C, 0.19 Si, 0.33 Mn, 1.55 Cr, 4.22 Ni, 0.97 W, etc. The raw specimens were machined into the hourglass-shape with a certain amount of finishing margin, and then they were quenched and tempered as follows: (1) first quenching: 950 °C × 30 min + air cooling; (2) secondary quenching (i.e. subcritical quenching): 850 °C × 30 min + air cooling; (3) tempering: 170 °C × 180 min + air cooling. After heat treatment, all the specimen surfaces were grinded in a direction of perpendicular to the axis of specimen by the grade 600–2000 abrasive paper to the final shapes shown in Fig. 1. The minimum diameter and the round-notched radius of specimen, *d* and *R*, are 4.5 mm and 60 mm, respectively. The corresponding elastic stress concentration factor, K_t, is about 1.02 based on the book on stress concentration factors [18]. The tested Vickers microhardness, HV, over the cross-section of specimen is basically uniform and the average value is about 503 kgf/mm^2. By means of the scanning electronic microscope (SEM), the mainly observed microstructure of heat-treated steel is tempered martensite, and the lath ferrite generated from the subcritical quenching is also distributed in the structure. The average grain size is about 11.5 μm, as shown in Fig. 2(a). Furthermore, combined with the analysis of energy dispersive X-ray spectrometer (EDS), some non-metallic inclusions of Al_2O_3 are found in the steel matrix, as shown in Fig. 2(b).

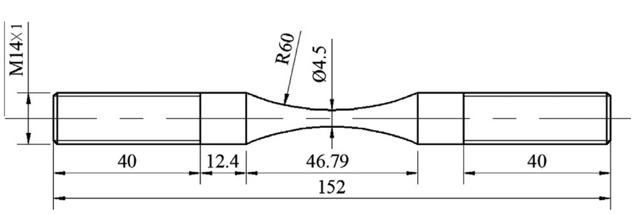

Fig. 1. Shape and dimensions of specimens (units: mm).

An electromagnetic resonant fatigue testing machine at frequency of 100 Hz was used to perform the gigacycle fatigue test of the steel under axial loading. Fatigue tests were all performed in an open environment and at room temperature with the constant stress ratio of −1. After the experiment, fracture surfaces of all the failed specimens were carefully observed by the SEM.

3. Experimental results and discussions

3.1. S–N property

The gigacycle fatigue *S*–*N* diagram of Cr–Ni–W steel under axial loading is shown in Fig. 3. Based on the observation of crack nucleation sites, fatigue failures of specimens can be divided into two modes on macroscopic perspective: surface induced failure and interior induced failure. The surface induced failure mainly occurs at high stress region (about $\sigma_a > 750$ MPa) with short fatigue life ($N_f < 10^5$ cycles), whereas the interior induced failure mainly occurs at low stress region (about $\sigma_a \leqslant 700$ MPa) with long life ($N > 10^6$ cycles). However, it should be noted that there exists an intermediate stress region (about $750 \geqslant \sigma_a > 700$ MPa), and the surface or interior induced failure may all occur in this region. Considering the overall failure tendency, the intermediate stress region can be regarded as a transition stress region from surface to interior failure.

In consideration of the difference of failure modes, two *S*–*N* curves, respectively corresponding to the surface and interior induced failures, are proposed to represent the gigacycle fatigue *S*–*N* property of Cr–Ni–W steel under axial loading, as indicated by a dashed line and a solid line in Fig. 3. With respect to the surface induced failure, this steel presents the common *S*–*N* property with an obvious surface fatigue limit. Based on the fitting curve equation, the surface fatigue limit is evaluated to be about 730 MPa, which is also the value of transition stress from surface to interior failure. With respect to the interior induced failure, this steel presents the continuously descending *S*–*N* property, and no obvious interior fatigue limit can be found in the life range of 10^9 cycles. Compared with the experimental results of other high strength steels [1,2,6], the duplex *S*–*N* property of this steel under axial loading is not so obvious. The life range in the transition stress region is only about 10^5–10^6 cycles, much less than that for other steels with about 10^4–10^7 cycles [1]. To some extent, this should be attributed to the size difference of defect causing failure. The detailed analysis will be given in the following sections.

3.2. Crack nucleation modes

As above mentioned, fatigue failure of specimen is composed of the surface induced failure and the interior induced failure. For the surface induced failure, fatigue crack is mainly induced from the nonmetallic inclusion or the surface machining flaw, as shown in Fig. 4(a and b). By contrast, the inclusion plays a more important role in causing the surface crack nucleation. No matter inclusion