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Propensities of crack interior initiation and early growth for very-high-cycle fatigue of high strength steels

Youshi Hong *, Zhengqiang Lei, Chengqi Sun, Aiguo Zhao

State Key Laboratory of Nonlinear Mechanics (LNM), Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

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ABSTRACT

Fatigue tests of a high carbon chromium steel were performed using rotating bending and ultrasonic axial cycling. Fatigue crack initiated at specimen interior for very-high-cycle fatigue (VHCF) with fish-eye pattern embracing fine-granular-area (FGA) originated from inclusion. The fatigue life from FGA to fish-eye and from fish-eye to the critical crack size was respectively calculated, so as to estimate the fatigue life contributed by FGA. The crack extension rate within FGA was also estimated. Our results demonstrated that the formation of FGA is responsible for a majority part of total fatigue life.

1. Introduction

The topic of very-high-cycle fatigue (VHCF), i.e. the process of fatigue failure beyond 10^7 cycles of loading, has attracted an increasing number of investigations in recent years. The progress of the research on this topic has been summarized in the recent reviews [1–5]. On one hand, this trend is driven by the modern engineering requirement that the design lifetime of many components exceeds 10^7 loading cycles. On the other hand, the behavior of VHCF process, especially the propensities of crack initiation and early growth, differs from what prevail in low-cycle and high-cycle fatigue regimes, and has yet to be clearly understood.

It is known that for VHCF of high strength steels, cracks are prone to initiate at specimen subsurface or interior with a distinct feature of so-called “fish-eye” embracing “fine-granular-area (FGA)” [6–8] (also called “optical-dark-area” [9] or “granular-bright-facet” [10]) originated from an inclusion. (Acronym FGA is used in what follows.) The formation of FGA and fish-eye, i.e. the stage of crack initiation and early growth of VHCF, almost dominates the fatigue life [11–15]. During this ultra-long period of cycling, the crack extension rate at its initiation and early growth is estimated as the order of magnitude between 10^{-11} and 10^{-12} m/cycle [9,12].

Based on the premise that the fracture mechanics parameter of stress intensity factor is applicable for fish-eye and FGA, there is an interesting tendency that the values of stress intensity factor range for fish-eye and FGA almost keep constant for high strength steels [6,8,13,16–18], with the latter comparable to the threshold value of fatigue crack initiation [6,17,18].

The investigations of VHCF behavior were therefore based on the essential characteristics related to fish-eye and FGA so as to explain the dominative mechanism of VHCF damage, and to predict the fatigue strength and fatigue life for the fatigue process containing VHCF regime [11,19–24]. Some models have correlated the fatigue strength to the sizes of FGA and inclusion from which the crack originates [11,19,20], some have taken into account the plastic zone size at the front of initial crack [21,22] and some have been based on the probability or cumulative concept for the simulation [22–24]. Although these models were empirical, they reflected, to some extent, the mechanism of crack initiation and early growth for VHCF.

In this paper, fatigue tests on a high carbon chromium steel were performed with rotating bending and ultrasonic fatigue testing methods for the further investigation on the propensities of crack initiation and early growth for high cycle and VHCF. The fractography of broken specimens was examined via scanning electron microscopy, showing that fatigue crack initiated at specimen interior for VHCF with fish-eye pattern embracing FGA originated from inclusion. The fatigue life from FGA to fish-eye and from fish-eye to the critical crack size was respectively calculated, so as to estimate the fatigue life contributed by FGA. The values of stress intensity factor range at FGA and fish-eye were calculated, and the crack extension rate within FGA was estimated. Combined with our previous results [8,17,21,22,25] and those available in literature [13,16,20,26], we explained that the crack growth process in the early stage of VHCF, namely the formation of FGA, is responsible for a majority part of total fatigue life. The very small value of crack extension rate within FGA was further discussed in the light of

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* Corresponding author. Tel.: +86 10 82543966; fax: +86 10 62561284.
E-mail address: hongys@imech.ac.cn (Y. Hong).

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Tanaka–Mura model [27]. Lastly, the large scattering of fatigue life was also discussed.

2. Experimental procedure

The test material of this investigation is a high carbon chromium steel with the main chemical compositions of 1.06%C and 1.04%Cr (Fe balance). Two types of hour-glass shape specimens were machined from the annealed material bar. The dimensions of the specimens are shown in Fig. 1. The hour-glass shape specimens enable the calculation and the control of the applied stress at the minimum section where the fatigue failure is always located. Such specimens were heat-treated: austenitized at 845 °C for 2 h in vacuum, then oil-quenched and tempered for 2.5 h in vacuum at 150 °C and 180 °C, respectively. The two groups of specimens are named as TT150 (tempered at 150 °C) and TT180 (tempered at 180 °C). The surface of the diameter reduced part for each specimen was ground and polished to a smooth finish in order to eliminate the machining scratches. The average ultimate tensile strength is 2163 MPa for TT150 and 1849 MPa for TT180, which were obtained from the tensile tests on four specimens (Ø5 mm) per group with the same heat-treatment procedure.

Fatigue tests were performed with two loading schemes, namely rotating bending (RB) and ultrasonic axial cycling (UL).

TT180 specimens were tested via RB method which was accomplished by using a “Giga-Quad” machine at room temperature with the rotating speed of 3150 rpm, i.e. the loading frequency being 52.5 Hz. The machine possesses four loading ends and is capable of allowing four specimens to be tested simultaneously. A weight was loaded to the end of each specimen through a fixture as a cantilever type loading with the stress ratio of -1. The applied maximum stress ($\sigma_{\max}$) for TT180 specimens ranged from 730 MPa to 1150 MPa, so as to gain the whole spectrum of *S–N* data for the test material.

TT150 specimens were tested via UL method which was conducted by using a Shimadzu USF-2000 at a resonance frequency of 20 kHz at room temperature, with a resonance interval of 100 ms per 500 ms (the testing process interrupted with an interval of 100 ms for every 500 ms) and the stress ratio being -1. Compressive air was used to cool specimen surface during UL testing. The applied maximum stress for TT150 specimens was within a small range between 860 MPa and 880 MPa. This was aimed to examine the scattering characteristics of fatigue strength for the test material.

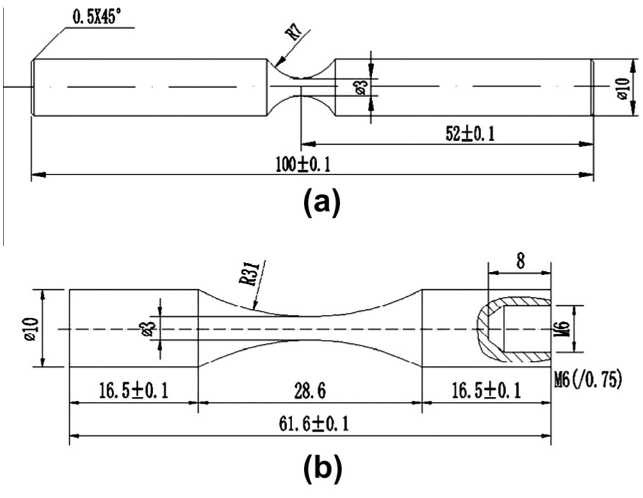

Fig. 1. Shapes and dimensions (in mm) of two types of specimens for fatigue tests, (a) for rotating bending test, the part of 52 mm for loading, and (b) for ultrasonic axial cycling test.

Fracture surfaces of failure specimens were examined by using a field-emission type of scanning electron microscope (SEM). Local regions of crack initiation were carefully examined. Characteristic dimensions for crack initiation region, i.e. sizes of inclusion, FGA and fish-eye, were measured from SEM photos.

3. Experimental results

The SEM photos shown in Fig. 2 are an example of the typical morphology of interior crack initiation for a TT180 specimen experienced VHCF subjected to RB loading, for which the dimensions are: inclusion equivalent diameter $2a_{\mathrm{Inc}} = 35.3$ μm, FGA equivalent diameter $2a_{\mathrm{FGA}} = 66.3$ μm, and fish-eye equivalent diameter $2a_{\mathrm{fish\text{-}eye}} = 206.2$ μm. To obtain these results, we used $2a_{\mathrm{Inc}} = \sqrt{area_{\mathrm{Inc}}}$, $2a_{\mathrm{FGA}} = \sqrt{area_{\mathrm{FGA}}}$, and $2a_{\mathrm{fisheye}} = \sqrt{area_{\mathrm{fisheye}}}$, with the values of *area* being measured from SEM photos. Since RB loading leads to the largest stress at specimen surface, the crack initiation of fish-eye formed underneath the surface, grew towards the surface, and then transitioned into the next stage of crack growth. For UL axial cycling of TT150 specimens, the sites for interior crack initiation were randomly distributed in the cross-section of specimen. The SEM photos of Fig. 3 show the fractography of a TT150 specimen subjected to UL cycling.

Table 1 lists the measured data of the characteristic dimensions for crack initiation of the two groups of specimens together with the values of the applied maximum stress and the fatigue life (N_f). The fatigue life is defined as the number of loading cycles to the complete failure of the specimen. Fig. 4 shows the results of *S–N* data for the two groups of specimens, in which the symbol styles indicate the crack initiation mode at surface or from interior of specimen. It is shown in Table 1 and Fig. 4 that, for TT180 specimens subjected to RB cycling, the fatigue life ranged from 10^4 to 4×10^8; the *S–N* data present a duplex or step-wise tendency. It is noted that the stress concentration factor is 1.06 at the minimum section of the specimens used for the rotating bending test, and this value is included in the calculation of applied maximum stress for such specimens. For TT150 specimens subjected to UL cycling at almost the same level of the maximum stress (860–880 MPa), the results show a very large scattering of data distribution. The difference of the fatigue life is as large as three orders of magnitude, ranging from 10^5 to 10^8. The large scattering of fatigue life from this test has been specifically investigated in our recently published paper [28].

Fig. 5 shows the measurements of both FGA and fish-eye sizes as a function of the applied maximum stress. It is shown from Table 1 and Fig. 5 that the FGA sizes are within a relatively small range between 40 and 100 μm and the fish-eye sizes are distributed in a large range between 100 and 300 μm.

The values of stress intensity factor range at the periphery of inclusion (ΔK_{Inc}), FGA (ΔK_{FGA}) and fish-eye ($\Delta K_{\mathrm{fisheye}}$) are calculated by using the following equation [10]:

$$\Delta K = 0.5\sigma_{\max}\sqrt{\pi\sqrt{area}} \qquad (1)$$

where $\sigma_{\max}$ is the maximum applied stress and $\sqrt{area}$ is the equivalent size of inclusion, FGA or fish-eye. For the inclusion on the fracture surface of the specimen experienced rotating bending test, the maximum applied stress was calculated via $\sigma_{\max}(1 - d_{\mathrm{Inc}}/R)$, where R is the radius of the cross section, d_{Inc} is the depth of the inclusion from the surface of specimen, and $\sigma_{\max}$ is the maximum stress at specimen surface. The values for FGA and fisheye were calculated via the same procedure. The calculated values of ΔK_{FGA} are shown in Fig. 6, in which most data are between 5 and 6 MPa m$^{1/2}$. The values of ΔK_{Inc} are also shown in Fig. 6, which are below that of ΔK_{FGA}, displaying a slightly decreasing trend with respect to failure life.