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A model to predict *S–N* curves for surface and subsurface crack initiations in different environmental media

Guian Qian, Chengen Zhou, Youshi Hong *

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

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ABSTRACT

The influence of environmental media on crack propagation of a structural steel at high-cycle and very-high-cycle fatigue (VHCF) regimes was investigated with the fatigue tests in air, water and 3.5% NaCl aqueous solution. The fatigue strength in water and 3.5% NaCl solution is significantly decreased and the cracking morphology due to different driving forces is presented. A model is proposed to explain the influence of environmental media on fatigue life, which reflects the variation of fatigue life with applied stress, grain size, inclusion size and material yield stress. The model prediction is in good agreement with experimental observations.

1. Introduction

Very-high-cycle fatigue (VHCF) [1], (also named ultra-high-cycle fatigue [2], ultra-long-life fatigue [3], or gigacycle fatigue [4]) of metallic materials is generally regarded as fatigue failure at stress levels below conventional fatigue limit and the corresponding fatigue life beyond 10^7 loading cycles. Lots of modern engineering structures and components, such as airplanes, turbines, nuclear structures, automobiles and high speed trains are expected to have fatigue life in the range of 10^7 to 10^{10} load cycles.

One typical feature of VHCF for high strength steels is that the *S–N* curve consists of two parts corresponding to subsurface and surface crack initiation, resulting in a stepwise or duplex shape [5–11]. Generally, the crack initiation in VHCF regime is observed as fisheye pattern on fracture surface, which is located at specimen subsurface region and originated from a nonmetallic inclusion for high strength steels [3,5–16]. Since the pioneering work performed by Naito et al. [17,18] and by Atrens et al. [19], there have been a variety of studies on the VHCF behavior for different materials. Among these studies, the crack initiation mechanism in VHCF attracted most of the attention. Murakami et al. [3] attributed the mechanism of subsurface crack initiation to the interaction of hydrogen embrittlement with cyclic damage. Bathias and Paris [4] found that subsurface crack initiation originated from either nonmetallic inclusions or other microstructural inhomogeneities, e.g. perlite colonies and long platelets. They [4] argued that the probability of finding a sufficient stress concentration inhomogeneity is much higher in the interior of the material than at the surface. Nishijima and Kanazawa [15] attributed the reason why the fatigue life for internal failure is longer than that for surface failure to the fact that the stress intensity factor for flaws with the same size in the material interior is smaller than that at the surface. The influence of some factors, such as loading frequency [12,14,20,21], surface finishing condition [8,16,22], material microstructure state [23–25] and environmental media [10,11,26], on the VHCF properties of high strength steels has been widely studied. Among them, the effect of ultrasonic frequency on the estimated fatigue strength has been intensively studied in order to make sure that the fatigue results obtained by using ultrasonic testing and conventional fatigue equipment with a low frequency are comparable. Stanzl-Tschegg and Mayer [20] showed that the frequency influences might be divided into intrinsic and extrinsic. The former one is related to strain rate, dislocation structures, crack formation and propagation. Whereas, the latter influence includes the correlation of test frequency with environmental effect, influence of creep, specimen heating during ultrasonic testing, etc. However, Furuya et al. [14] found that the loading frequency does not have significant impact on the VHCF behavior of a high strength steel. Recently, Zhao et al. [12] showed that loading frequencies do have effect on fatigue strength of materials, but for materials with some specific microstructure the resultant of the effect may defer. Loading frequencies have little influence on specimens with high strength, while for the specimens with low tensile strength the fatigue resistance is markedly high in ultrasonic testing.

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

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Nomenclature

a	crack depth
CIS	critical inclusion size
E	Young's modulus
F	geometrical factor for stress intensity factor calculation
HV	Vickers hardness
k	resistance of dislocation movement, corresponding to material yield stress
k_w	w_i/w_s
K_I	stress intensity factor
K_{IC}	fracture toughness of material
l	grain radius
N_f	fatigue failure cycles
N_i	fatigue cycles required for crack initiation at subsurface
N_s	fatigue cycles required for crack initiation at surface
n_i	normalized fatigue cycles required for crack initiation at subsurface
n_s	normalized fatigue cycles required for crack initiation at surface
r	inclusion radius
r_p	plastic zone size
$\Delta\widetilde{U}$	dimensionless unit increment of energy
ΔU_i	unit increment of energy for subsurface crack initiation
ΔU_s	unit increment of energy for surface crack initiation
w_i	surface energy related to subsurface crack initiation
w_s	surface energy related to surface crack initiation
α	0.813 for surface, 0.528 for subsurface and 0.969 for interior inclusions
σ_{max}	maximum applied stress
σ_s	yield stress
σ_a	applied stress
σ^w_{max}	applied maximum stress for the tests in fresh water
σ^s_{max}	applied maximum stress for the tests in 3.5% NaCl aqueous solution
σ^a_{max}	applied maximum stress for the tests in laboratory air
$\Delta\sigma$	stress amplitude
φ	$0.5\Delta\sigma/k$
ψ	r/l
ν	Poisson's ratio
μ	shear modulus

Shiozawa and Lu [16] found that for surface shot-peened specimens, due to the surface residual stress induced by shot peening subsurface crack initiation dominated. We [8] studied the influence of surface notch on VHCF behavior of a structural steel, which revealed that surface notch decreases the fatigue strength and the possibility of subsurface crack initiation. Krupp et al. [25] studied the effect of the microstructure of an austenitic–ferritic duplex steel on the VHCF behavior and revealed that the formation of slip bands caused by fatigue damage in VHCF regime leads to the initiation and propagation of microstructurally short cracks in a very localized manner. Lei et al. [5] found that the inclusion size and location has a significant impact on VHCF behavior for high strength steels. The degradation of VHCF strength caused by the increase of inclusion size is ascribed to the decrease of the critical stress of fine-granular-area (FGA) formation for large inclusions. We [10] investigated the effect of environmental media on the fatigue strength and crack initiation of a high strength steel in VHCF regime and the decrease of fatigue strength in environmental media is reported. However, the crack initiation and propagation process of high strength steels in environmental media in VHCF regime is still not clear.

In addition to experimental investigations, theoretical or empirical models for fatigue strength and life prediction in VHCF regime are of significant importance for both scientific and engineering applications. Murakami et al. [3] developed a model to predict fatigue strength in VHCF regime based on crack initiation site, crack area and material hardness. Hong et al. [6] demonstrated that the formation of FGA is responsible for a majority part of total fatigue life. It is shown in [27–29] that in VHCF regime the crack growth constitutes insignificant portion of the total fatigue life. Instead, the importance of fatigue crack initiation stage has been repeatedly emphasized.

Chapetti et al. [30] showed a relation between the FGA size, the inclusion size and the fatigue life by fitting the experimental data of high strength steels. Liu et al. [31] proposed an expression in the form of Basquin equation for predicting the *S*–*N* curves based on the fatigue strengths at 10^6 cycles and at 10^9 cycles. Lai et al. [32] presented a unified model, which provides the prediction of fatigue behavior of hardened steels in different regimes, that is, low cycle fatigue regime quantified by the tensile strength, high cycle fatigue regime obeying Basquin's law and VHCF regime featured by the fisheye and FGA surrounding an initiating inclusion on the fracture surface. A combination of the deterministic model with a stochastic model describing the inclusion size distribution allows prediction of fatigue strength and the associated reliability of a steel component. Sun et al. [33] developed a model for estimating the fatigue life of high-strength steels in high cycle and VHCF regimes with fisheye mode failure based on the cumulative fatigue damage, which takes into account the inclusion size, FGA size and tensile strength of materials. We [9,10] developed a model to investigate the competition between surface and subsurface crack initiation at VHCF regime, and showed that high strength steels with fine grain size tend to initiate crack in the subsurface, whereas surface notch and environmental medium will lead to surface crack initiation. However, models to predict *S*–*N* curves in VHCF regime in different environmental media are still lacking due to the complicated crack initiation mechanisms. Recently, new models have been further proposed to predict or estimate the fatigue life for high cycle and VHCF regimes by taking into account the failure mechanism and cumulative damage characteristics [34–37].

In this paper, the process of crack initiation and propagation for a high strength steel in environmental media in VHCF regime is investigated. The specimens of a structural steel were subjected to rotary bending up to VHCF regime in the environments of laboratory air, fresh water and 3.5% NaCl aqueous solution, respectively. The influence of environmental media on the variation of fatigue strength and cracking process is presented. Based on the experimental observations, a model is proposed to study the *S*–*N* curves of the material in high cycle and VHCF regimes in different media.

2. Material and experimental method

In this paper, hour-glass type specimens (Fig. 1a) of a structural steel 40Cr (main compositions: 0.4% C and 1% Cr) were tested with a rotary bending machine operating at a frequency of 52.5 Hz and the testing environments were of three types: laboratory air, fresh water and 3.5% NaCl aqueous solution, respectively, so as to investigate the influence of environmental medium on the variation of fatigue strength and cracking process. The average size of original