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Experimental and theoretical investigation of environmental media on very-high-cycle fatigue behavior for a structural steel

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Abstract

Rotary bending fatigue tests were performed in laboratory air and 3.5% NaCl aqueous solution to investigate the influence of environmental media on fatigue properties of a structural steel in high-cycle and very-high-cycle fatigue regimes. The results show that the fatigue strength of the structural steel in 3.5% NaCl solution is remarkably degraded compared with the case tested in laboratory air. The fracture surfaces of specimens tested in different environments were examined to reveal the fatigue crack initiation characteristics. It shows that for specimens tested in 3.5% NaCl solution, cracks originate via multiple surface initiation modes and cracking is intergranular; in addition, widespread secondary cracks feature on the fracture surface. Based on fatigue tests and fractography observations, a numerical model of crack initiation is proposed to describe the transition of fatigue initiation site from subsurface to surface for specimens tested in air and 3.5% NaCl solution. The model reveals the influences of load, material strength, grain size, inclusion size and surface environmental media on the crack initiation site transition. It agrees well with the experimental observations.

Keywords: Very-high-cycle fatigue; Aqueous environment; Fatigue strength; Fatigue crack initiation; Structural steel

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 commonly regarded as fatigue failure at stress levels below conventional fatigue limit and the relevant fatigue life beyond 10^7 loading cycles. The research of VHCF has become a new horizon in the field of metal fatigue since the early work of Naito et al. [5,6], who reported the occurrence of fatigue failure at loading cycles beyond 10^7 and even longer than 10^8 with specific fatigue characteristics for carburized steels. In recent years, the investigation of VHCF on metallic materials has attracted an increasing number of investigators in the fatigue research field (e.g. [7–22]) due to the growing requirements of engineering applications, including aircraft, automobile, ship, railway, bridge, etc., for which the metallic components and structures need to endure a fatigue life larger than 10^7 or 10^8 loading cycles, and even requiring 10^{10}–10^{11} life cycles of endurance in some vital cases.

One typical characteristic of VHCF for high-strength steels is that the *S–N* curve includes two parts corresponding to subsurface and surface crack initiation, resulting in a stepwise or duplex shape [7–9]. Another distinct feature of crack initiation for VHCF is identified as a fisheye pattern on the fracture surface, which is mostly located at the specimen subsurface region and originates from a nonmetallic inclusion [3,8–10]. Murakami et al. [3] reported that the mechanism of subsurface crack initiation and the formation of the fisheye pattern are associated with the interaction of hydrogen embrittlement and cyclic damage. Bathias et al. [4] found that subsurface crack initiation can start from nonmetallic inclusions and microstructural inhomogeneities, e.g. perlite colonies and long platelets. The study [4] revealed that the probability of finding a sufficient stress concentration inhomogeneity is much bigger in the interior of the material than at the surface.

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Nomenclature

E	Young's modulus
k_w	w_i/w_s
k_W^a	w_i^a/w_s^a
k_W^s	w_i^s/w_s^s
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
r	inclusion radius
$\Delta\tilde{U}$	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^a	surface energy related to subsurface crack initiation in air
w_i^s	surface energy related to subsurface crack initiation in 3.5% NaCl solution
w_i	surface energy related to subsurface crack initiation
w_s	surface energy related to surface crack initiation
w_s^a	surface energy related to surface crack initiation in air
w_s^s	surface energy related to surface crack initiation in 3.5% NaCl solution
σ_{max}	maximum applied stress
$\Delta\sigma$	stress amplitude
φ	$0.5\Delta\sigma/k$
ψ	r/l

Nishijima and Kanazawa [11] attributed the reason why the fatigue life for internal failure is longer than that for a surface failure to the fact that the stress intensity factor for flaws in the interior is smaller than that at the surface for the same size defect. Some factors, such as loading frequency [12,13], surface finishing condition [14,15], microstructure state [16–18], etc., may affect the VHCF properties of high-strength steels. Results in Ref. [12] show an influence of loading frequency on fatigue strength for several cast aluminum alloys. The fatigue strength tested at a frequency of 20 kHz is much higher than that tested at 75 Hz. Furuya et al. [13] found that the loading frequency does not have any significant impact on the VHCF behavior of a high-strength steel. Shiozawa and Lu [14] found that for surface shot-peened specimens, subsurface crack initiation dominated due to the surface residual stress induced by shot peening. Itoga et al. [15] investigated the influence of surface notch on VHCF behavior of a structural steel. The studies revealed that surface notch decreases the possibility of subsurface crack initiation. Krupp et al. [18] studied the effect of the microstructure of austenitic–ferritic duplex steels on the fatigue damage of VHCF. It revealed that fatigue damage in the VHCF regime causes the formation of slip bands followed by initiation and propagation of microstructurally short cracks in a very localized manner and the plastic slip occurred firstly in the softer austenite phase of the material. Of these factors, the investigation of environmental media, i.e. environmentally induced fatigue resistance difference (corrosion fatigue) in VHCF regime, is not only of scientific interest, but also of obvious engineering importance since engineering components are inevitably subjected to the environment with an extent of corrosiveness. However, there are few experimental results [7,19] on the effect of environmental media on VHCF behavior of high-strength steels. In addition, the mechanism of surface and subsurface crack initiation for specimens tested in air and environmental media is still not clear.

Therefore, in this article, the VHCF behaviors of a structural steel were tested with a rotary bending machine operating at a frequency of 52.5 Hz; the testing environments were laboratory air and 3.5% NaCl aqueous solution, so as to investigate the influence of environmental media on the variation of fatigue strength and cracking process. According to the fatigue testing data and scanning electron microscopy (SEM) observations of fracture surfaces, the effect of environmental media on the fatigue behavior at high-cycle and VHCF regimes was examined. The mechanism of crack initiation and propagation was discussed. Based on the fatigue tests and the observations, a crack initiation model was proposed to describe the transition of fatigue initiation site from subsurface to surface for specimens tested in various environmental media.

2. Material and experimental method

The material tested in this investigation is a structural steel (40 Cr), which has a chemical composition (wt.%)

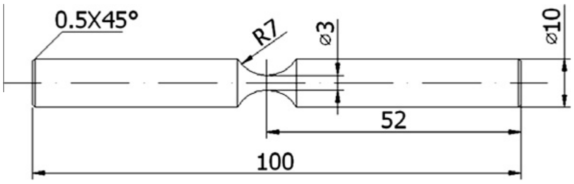

Fig. 1. Schematic drawing of an hourglass-shape specimen for rotary bending fatigue test (dimensions in mm).