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Effects of strength level and loading frequency on very-high-cycle fatigue behavior for a bearing steel

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

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

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ABSTRACT

Rotating bending (52.5 Hz) and ultrasonic (20 kHz) fatigue tests were performed on the specimens of a bearing steel, which were quenched and tempered at 150 °C, 300 °C, 450 °C and 600 °C, respectively, to investigate the influence of strength level and loading frequency on the fatigue behavior in very-high-cycle regime. Influences on fatigue resistance of materials, characteristics of *S*–*N* curves and transition of crack initiation site were discussed. The specimens with higher strength showed interior fracture mode in very-high-cycle regime and with slight frequency effect, otherwise cracks all initiate from the surface and the fatigue strength was much higher under ultrasonic cycling.

1. Introduction

In many industries, the required design lifetime of some components exceeds 10^7 loading cycles, such as aircrafts (gas turbine disks 10^{10} cycles), ships (big diesel engine 10^9 cycles), railways (high speed train 10^9 cycles), and automobiles (car engine 10^8 cycles) [1]. It is well known that the *S*–*N* curves of low-strength steels usually tend to a limit at 10^7 cycles by which the fatigue limit is defined, i.e. a stress level below which fatigue failure does not occur and it has been used as a design stress for machine components. However, in recent years, it has been reported that the fatigue failure of some high-strength steels and case-hardened steels still occurs at stress levels below the conventional fatigue limit in the life region greater than 10^7 cycles [2–11]. Therefore, it is no longer safe to use the conventional fatigue design standard, especially for high-strength steels.

For low and medium strength steels, fatigue cracks tend to initiate from specimen surface and there is a common relation between fatigue limit and tensile strength: $\sigma_w = \sigma_b/2$ [6,12]. The data collected by Abe et al. [12] show that for those low alloy steels of $\sigma_b \leqslant 1200$ MPa, the relation is quite applicable. However, while $\sigma_b > 1200$ MPa, the ratio of fatigue limit to tensile strength is relatively low and the fracture tends to initiate from internal defects such as inclusions or cavities.

A classical method to determine the infinite fatigue life is to use Gaussian functions [1,13]. The fatigue limit is given by the average alternating stress σ_w, and the probability of fracture is given by the standard deviation of the scatter (s). It is said that the values of $\sigma_w - 3s$ gives a probability of fracture close to zero, where s is generally taken as 10 MPa. Then the true infinite fatigue limit should be σ_w minus 30 MPa. However, the study by Bathias et al. [7] showed that for many materials, the difference between the fatigue strength at 10^6 and 10^9 was larger than 50 MPa, especially for high-strength steels. Sometimes the difference could even reach to 200 MPa. The reason why the change of strength level has such a great effect on very-high-cycle fatigue (VHCF) behavior of materials is not clear.

In recent years, some researchers apply piezoelectric fatigue systems to accelerate testing of specimens at a frequency of 20 kHz, namely ultrasonic fatigue testing [14–18]. From 52.5 Hz to 20 kHz, there is an increase in strain rate of 2–3 orders of magnitude. Whether the data acquired from ultrasonic testing can be equivalent to those obtained by conventional frequency testing is dubious.

Laird and Charsley [19] gave an overview of frequency effect on cyclic plastic deformation, dislocation movement, damage localization and fatigue crack growth in pure fcc and bcc metals, and Mayer [20] gave a more detailed review. For pure fcc metals, the critical shear stress is low and insensitive to strain rate, for which slip systems are still active under high frequencies, thus the increase of frequency has little influence on them. For pure bcc metals, due to high dislocation activation energy and high critical shear stress, the slip systems tend to be suspended under high frequency, so the frequency effect is obvious. The frequency effect is also correlated with stress level and tends to show up at large plastic strain

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

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Nomenclature

$2a$	fish-eye dimension in direction perpendicular to specimen surface
A	$\mu/[(2\pi(1-\nu)]$
$(area)^{1/2}$	the size of FGA or inclusion
$2b$	fish-eye dimension in direction parallel to specimen surface
D^*	Deborah factor
f	loading frequency
F_I^M	correction factor of crack shape
k	resistance of dislocation movement
k_w	w_i/w_s
ΔK	stress intensity factor
ΔK_{th}	threshold value of ΔK for fatigue crack growth
ΔK_{tr}	value of ΔK at transition point from Paris law
l	grain radius
L	dislocation moving distance
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
r_p	plastic zone size at crack tip
R_1	radius of fish-eye on fracture surface under ultrasonic loading
s	the standard deviation of the scatter
τ	stress applied on dislocations
τ_0	stress required to give a dislocation velocity v_0 = 1 cm/s
$\Delta\widetilde{U}$	dimensionless unit increment of energy
w_i	surface energy related to subsurface crack initiation
w_s	surface energy related to surface crack initiation
μ	shear modulus
ν	Poisson's ratio
$\Delta\sigma$	applied stress amplitude
σ_b	ultimate tensile stress
σ_w	fatigue limit or fatigue strength at $N = 10^7$
$\Delta\sigma_{fs}$	fatigue strength difference between $N = 10^7$ and $N = 10^9$
φ	$0.5\Delta\sigma/k$
ψ	r/l

amplitudes [15]. The loading frequency can change the fatigue mechanism of bcc metals. Under high frequencies, the dislocations are hardly to be activated and the fracture modes tend to transit from ductile to brittle. The behavior of hcp metals is very similar to bcc ones. Due to high dislocation activation energy, the frequency effect of hcp metals is also obvious. For most alloys, they have relatively higher strength and the dislocation movement is strongly impeded by interstitials, second phases and inclusions. In brief, the influence of frequency on the fatigue properties of metallic materials is rather complicated and till now has not any theoretical explanation been proposed. Therefore, the effect of loading frequency needs further investigation.

In the present study, fatigue testing of a high carbon chromium bearing steel (GCr15) quenched then tempered at four different temperatures, was performed with rotating bending and ultrasonic fatigue testing machines to clarify the effect of strength level and loading frequency on fatigue behavior.

2. Experimental procedure

2.1. Material and specimens

The material used in this investigation is a high carbon chromium bearing steel (GCr15). The chemical composition (mass percentage) of this steel is: 1.01 C, 1.45 Cr, 0.35 Mn, 0.28 Si, 0.015 P, 0.01 S and balance Fe. From the annealed steel bar, specimens were machined into hourglass shape with a certain amount of finishing margin. The specimens were heated at 845 °C for 2 h in vacuum, then oil-quenched and tempered for 2.5 h in vacuum at 150 °C, 300 °C, 450 °C and 600 °C with furnace-cooling, respectively. The final geometries of specimens are shown in Fig. 1. Before fatigue testing, the round notch surface was polished by the grade 400, 800, 1500 and 2000 abrasive papers.

Before fatigue testing, tensile testing was conducted on an MTS 810 system with cylindrical specimens of 6 mm in diameter at a strain rate of 10^{-4}. Hardness measurement was performed using a Vickers hardness tester at a load of 50 g with the load holding time of 15 s.

2.2. Fatigue testing methods

The conventional frequency fatigue test was performed at room temperature in air by using a four-axis cantilever-type rotating bending machine, which was operated at 3150 rpm (f = 52.5 Hz), and the stress ratio was $R = -1$. The ultrasonic fatigue testing was conducted on a Shimadzu USF-2000 at a resonance frequency of 20 kHz at room temperature in air, with a resonance interval of 100 ms per 500 ms and the stress ratio $R = -1$. Compressive air was used to cool the specimens during ultrasonic fatigue testing. After the fatigue testing, the fracture surfaces of all fractured specimens were examined by using a field-emission type scanning electron microscope (FE-SEM).

3. Experimental results

3.1. Microstructure and mechanical properties

The microstructure observations on etched specimen are shown in Fig. 2. Big residual spheroidal carbides are observed on the four groups of specimens. The number and size of cementite particles precipitated during tempering increased as tempering temperature increased. The microstructure of specimens tempered at 150 °C and 300 °C is tempered martensite. From SEM photographs, it is seen that small martensite blocks present, with the measured average lamellar width of 378 nm. The carbon content in martensite is about 0.2% for specimens tempered at 150 °C and 0.06% for specimens tempered at 300 °C. For specimens tempered at 450 °C, the microstructure is troostite in which ferrite still has the shape of martensite and the carbon content in ferrite is lower than 0.02%. When tempered at 600 °C, recovery and recrystallization occurred in the ferrite matrix. The dislocation density and carbon content in ferrite decrease greatly.

The austenite grain size is about 13.8 μm, obtained from 1638 grains of intergranular fatigue fracture surface of specimens tempered at 150 °C and 300 °C. In the following text, T.T. is used for the abbreviation of tempering temperature, R.B. stands for rotating bending, and UL stands for ultrasonic loading.

Table 1 lists the mechanical properties of the four groups of specimens. It is seen that the ultimate tensile strength decreases as the tempering temperature increases.

3.2. S–N curves

Fig. 3 presents the S–N curves for the four groups of specimens tested in rotating bending and ultrasonic fatigue testing. It is noted that for specimens with the highest strength (T.T. 150 °C) the