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Effects of intermittent loading on fatigue life of a high strength steel in very high cycle fatigue regime

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ABSTRACT

An intermittent loading path (i.e. a pause duration follows after a loading pulse) is broadly employed in a ultrasonic fatigue test to minimize the effect of self-heating in specimens. The exact influence of such intermittent loading strategy remains elusive. We report here a significant fatigue life improvement of a high strength steel in very high cycle fatigue regime subjected to intermittent loading, in contrast to that without the pause duration although the crack initiation mechanism remains the same. This phenomenon is attributed to the strain aging by the numerous low stress amplitude cycles under intermittent loading, which strengthens the local region ahead of the initiated crack tip by the former high stress amplitude cycles and improves the fatigue life.

1. Introduction

Ultrasonic fatigue technique has been widely used to evaluate the fatigue performance of metallic materials in very high cycle service because its high frequency loading greatly reduces the testing time and cost [1–5]. One significant concern regarding the validity of ultrasonic fatigue test (USFT) systems is that the difference in strain rate and the internal heat generation between USFT loading and that in real engineering practice, which may lead to inaccurate evaluation of very high cycle fatigue (VHCF) behavior of materials.

To alleviate the effect of internal heat generation, researchers usually adopt a pulse-pause mode (i.e. an intermittent loading) in USFT, and also use cold air or water to cool down the specimens during the test so that the temperature rise in the specimen is not significant [6–8]. It is noted that the internal heat generation is greatly material and loading-path dependent: A low ratio of pulse to pause duration in USFT should be chosen especially for materials with lower strength. For example, Guennec et al. [9] conducted USFT for a low carbon steel with 110 ms pulse and 2500 ms pause and found that the fatigue strength obtained by ultrasonic frequency (20 kHz) differed dramatically from that by conventional frequency (from 0.2 to 140 Hz). Nonaka et al. [10] used a longer pause duration from 3 to 10 s with loading period from 35 to 150 ms for a medium carbon steel, for which the specimen temperature was controlled under 35 °C. In their results, it was shown that the increase of fatigue strength in USFT might be mainly due to the increase of the yield strength by the rapid straining, correspondingly higher strain rate.

Peng et al. [11] conducted the USFT for a high strength steel under four different intermittent pause times. They showed that the intermittent time had a certain impact on the fatigue life, and that the mean fatigue life increased as the pause time increased, which was attributed to the relative lower temperature at a longer intermittent time. The results by Yu et al. [12] also indicated that the larger intermittent time led to the higher fatigue strength of bainite/martensite dual phase steels in USFT, which was explained by the self-heating effect, i.e. longer intermittent time led to lower temperature of specimens.

Although the intermittent loading can be effectively used to control the specimen temperature along with the cold air or water cooling in many cases, the intermittent loading differs very much from the regular loading method, which is indeed a variable loading spectrum. There are important issues for the application of USFT in metallic materials: How does the intermittent loading influence the fatigue life of materials compared to the loading without intermittence? To what level could such influence be? By far, per the best knowledge of the authors, there is no report to show the effects of the loading types (the intermittent loading and the loading without intermittence) themselves.

The objective of this work is to demonstrate the effects of intermittent loading in USFT on the fatigue life of high strength steels in VHCF regime. The crack initiation mechanism under the intermittent loading is also compared to that under the loading without intermittence.

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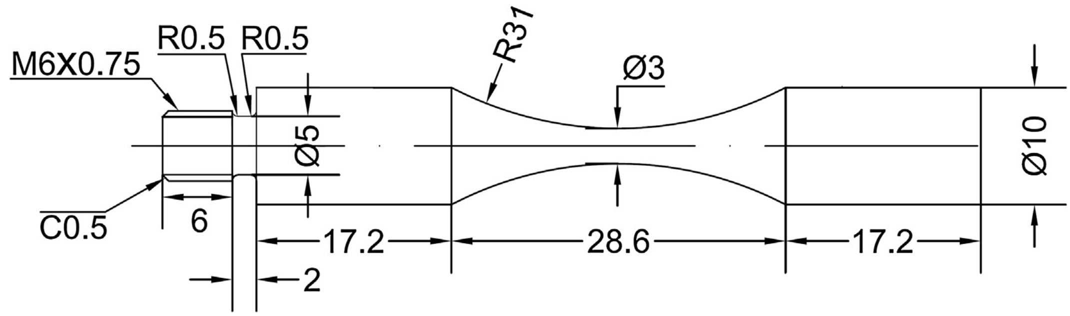

Fig. 1. Shape and dimensions (in mm) of specimens for fatigue test.

2. Materials and experimental procedures

The material used in this research is a high carbon chromium bearing steel GCr15 with the chemical compositions (wt%) of: 1.00 C, 1.52 Cr, 0.31 Mn, 0.21 Si, 0.0086 P, 0.016 S and balance Fe. The machined specimens are heated at 850 °C for 60 min in vacuum furnace, then oil-quenched and tempered for 2 h in air at 200 °C. The microhardness of the heat-treated specimen is 812 kgf/mm^2. The ultimate strength is 2375 MPa, and the yield strength is 1760 MPa. The geometry of specimen for USFT is illustrated in Fig. 1. The round notch surface is finally polished by the grade 400, 800, 1500 and 2000 abrasive papers to eliminate machining scratches before fatigue test.

The ultrasonic fatigue test is conducted on a Shimadzu USF-2000 with a frequency of 20 kHz at room temperature in air. The stress ratio R is -1. Two loading types are used. The one is loading without intermittence and the other is intermittent loading (200 ms pulse and 200 ms pause). Fig. 2 shows the stress of the small section of a specimen versus the time under the intermittent loading type. The stress of the small section of the specimen is calculated by measuring the displacement of its free end using a laser displacement sensor LK-H025. As illustrated in Fig. 2, the maximum stress (stress amplitude) gradually damps during the pause duration after a loading pulse. It takes about 200 ms for the stress amplitude dropping to zero. This process repeats until the specimen fails. Due to intermittence, the variable low stress amplitude is introduced under the intermittent loading type, which is different from the loading type without intermittence (i.e. constant amplitude loading). The loading cycles during the damping period are not counted for the fatigue life.

All the specimens are cooled down by the cold air blowing on the small section of specimens through two nozzles from an air compressor

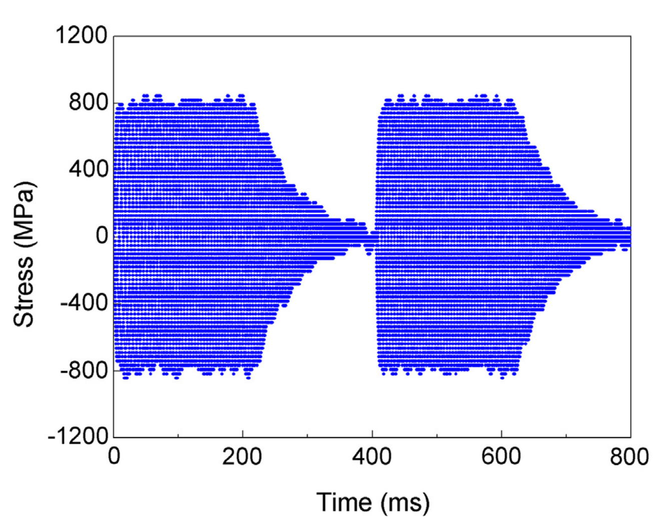

Fig. 2. Variation of the stress at the small section of a specimen versus the time under the intermittent loading.

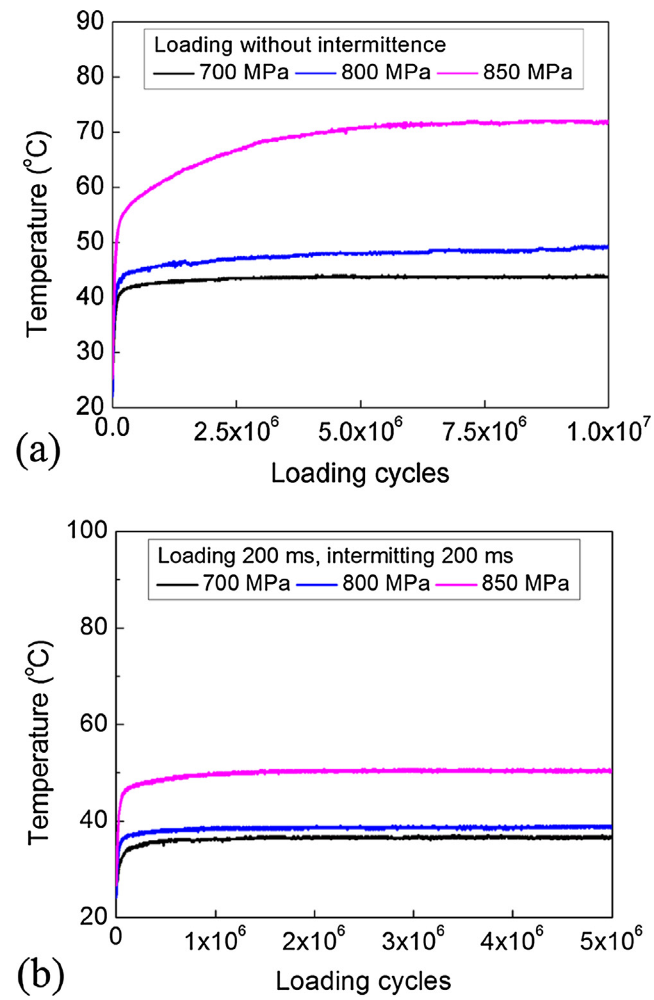

Fig. 3. Surface temperature of the small section of specimen with loading cycles. (a) Under the loading without intermittence; (b) under the intermittent loading.

during the fatigue test. A thermocouple is used to measure the surface temperature of the small section of several specimens. The thermocouple is adhered to the surface of the small section of specimens by using the YK-607 high-temperature adhesive so that the thermocouple contacts well with the specimen surface. Fig. 3 shows the variation of temperature of the small section of a specimen versus the loading cycles under different stress amplitudes for the two loading types. It is seen that the surface temperature of the small section is strongly dependent on the stress amplitude for both loading types, which increases with the increase of stress amplitude. At the same stress amplitude, the temperature under the loading without intermittence is higher than that under the intermittent loading. In order to eliminate the influence of temperature and the difference of specimens, all the specimens are tested under a relative low stress level (σ_a = 800 MPa). The stable temperature is 39 °C under intermittent loading and is 49 °C under the loading without intermittence. The difference of the stable temperature is 10 °C, and both of them are a little higher than the room temperature. Therefore, the effect of self-heating in specimens on the fatigue life is negligible.

Seven specimens are tested for each loading type by the consideration that at least seven specimens are needed for the explanation of fatigue experiment at a stress level from the Chinese standard [13].

The fracture surfaces of failed specimens are observed by a scanning electron microscope (SEM), and the fine granular area (FGA) size, which is defined as the square root of the FGA area including the projection area of the crack origin, is measured by using Image-Pro Plus (IPP) software by Media Cybernetics, Inc.

3. Results and discussion

For both the loading types, all specimens fail from the interior fatigue cracking originated from grains/grain boundaries and exhibit fish-eye patterns. FGA features are also observed surrounding the crack initiation site. No difference is found from the SEM observation for the crack initiation sites and the morphologies of the fracture surface under the intermittent loading and the loading without intermittence. The typical morphology of the fracture surface under the two loading types is shown in Fig. 4. It is seen that the whole region of crack initiation (FGA) and early propagation resembles the fish-eye pattern. Out of the fish-eye, it is an intergranular/transgranular morphology, and the fast crack growth morphology.

The FGA region is a characteristic of samples failed in VHCF regime, because it consumes more than 90% of the total fatigue life although the size of FGA is usually only several tens of microns [14]. Here, the FGA size of the specimens subjected to different loading types is also compared, as shown in Fig. 5. It is observed that the FGA size under the intermittent loading is slightly bigger than that under the loading without intermittence. The mean value of the FGA sizes under the intermittent loading is 50.1 μm, which is 19% bigger than the value (42.2 μm) under the loading without intermittence. The standard deviation is 4.0 under the intermittent loading and is 7.4 under the loading without intermittence.

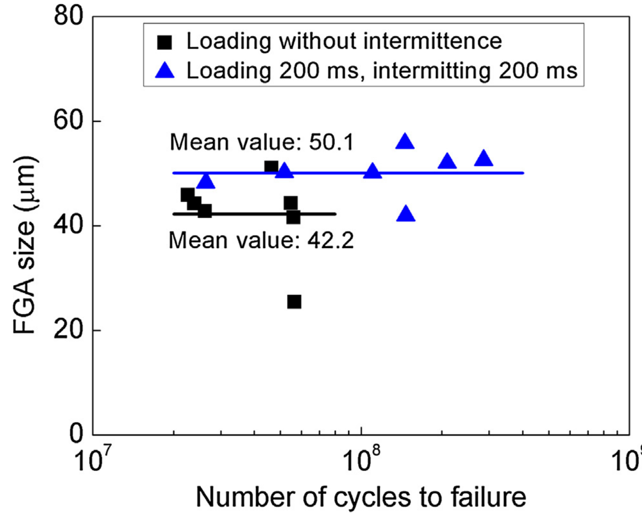

Fig. 5. FGA size versus fatigue life under different loading types.

For clarifying the effect of the intermittent loading on the fatigue life, the cumulative probability of the fatigue life is calculated. The values of fatigue life in logarithm of base 10 are considered and ranked from the shortest, and labeled as $\log_{10}N_{f,1} \leqslant \log_{10}N_{f,2} \leqslant \cdots \leqslant \log_{10}N_{f,n}$, in turn. The cumulative probability of fatigue life no larger than $N_{f,i}$ is calculated by $F(\log_{10}N_f) = (i-0.3)/(n+0.4)$ [13], where n is the number of specimens, and i = 1, 2, …, n is the sequence number. A comparison of the fatigue life is given in Fig. 6, which indicates that the scatter of fatigue life is larger under intermittent loading and the fatigue life under the intermittent loading is much larger than that under the loading without intermittence. The maximum value of the fatigue life is

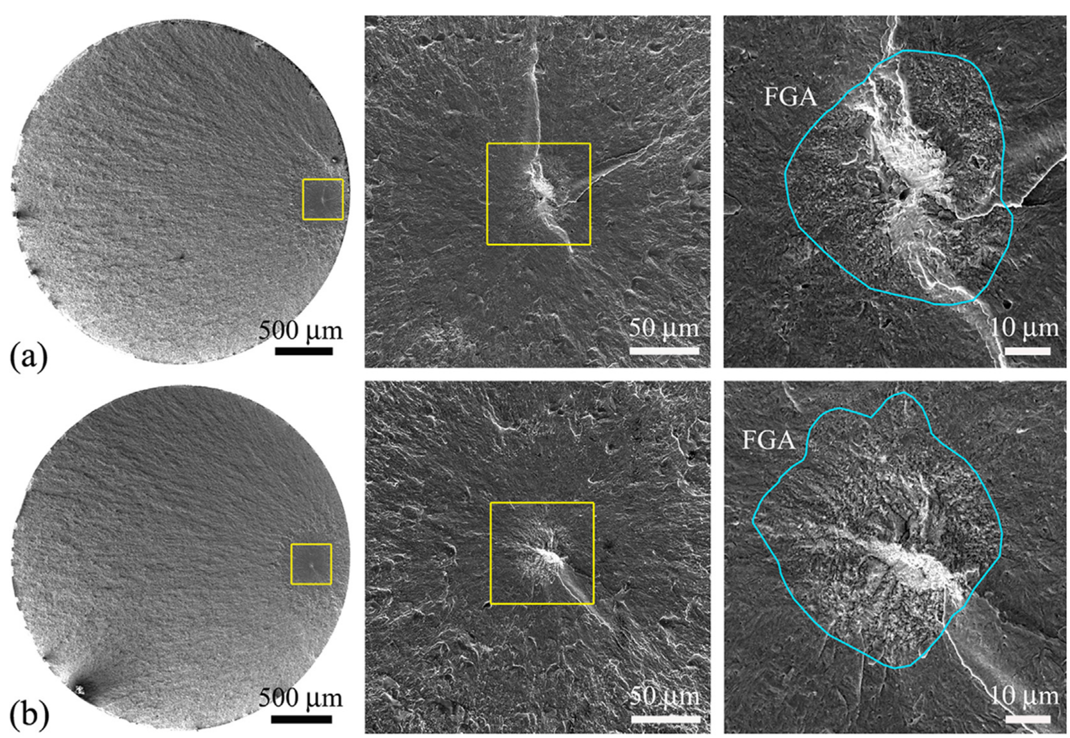

Fig. 4. Comparison of the fractographs of the high carbon chromium bearing steel GCr15 after ultrasonic fatigue test. (a) SEM images of the specimen failed at $N_f = 4.63 \times 10^7$ cycles under the loading without intermittence. (b) SEM images of the specimen failed at $N_f = 1.47 \times 10^8$ cycles under the intermittent loading.

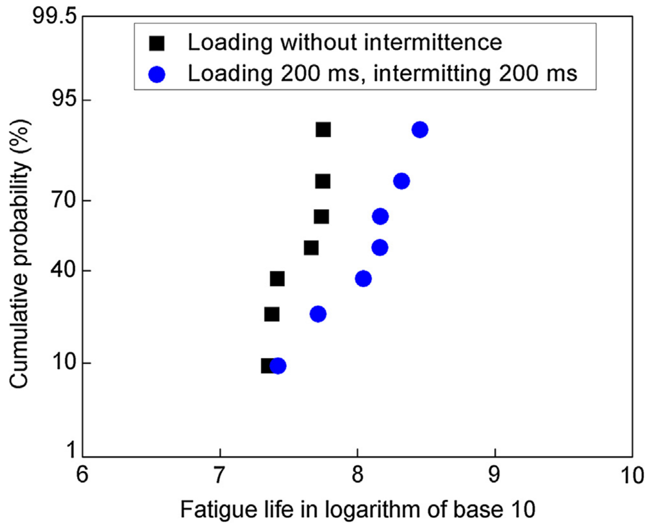

Fig. 6. Cumulative probability of fatigue life under intermittent loading and the loading without intermittence.

5.65×10^7 under the loading without intermittence, while more than 70% of the fatigue life (five out of seven tests) is larger than 1.1×10^8 under the intermittent loading. Further, it is assumed that the fatigue life in logarithm scale follows the normal distribution. The median fatigue life under the intermittent loading is increased by 189% compared to that under the loading without intermittence, and the fatigue life at 90% survival probability under the intermittent loading is increased by 74% compared to that under the loading without intermittence. This indicates that the intermittent loading type greatly improves the fatigue life of the present high strength steel in VHCF regime.

According to the work by Nakagawa & Ikai [15] and Wilson & Tromans [16], strain aging occurred in the fatigue process for carbon steels, which could improve the fatigue strength by suppressing dislocation multiplication or by increasing the constraints imposed on regions of plastic strain concentration. For the intermittent loading, the specimen experiences more time of cycling for the same fatigue cycles than that under the loading without intermittence since the loading cycles during the damping period are not counted in the fatigue life. During the damping period, a large number of low stress amplitude cycles after each pulse could not induce the further crack initiation or crack growth. Moreover, the crack initiation region (i.e. FGA region) is very small for high strength steels in VHCF regime, which is only several tens of microns [14]. The crack growth rate in FGA is much lower than 10^{-10} m/cycle, and it consumes more than 90% of the total fatigue life in FGA. So, it is thought that this phenomenon is due to the strain aging by the numerous low stress amplitude cycles after each pulse under intermittent loading, which strengthens the local region ahead of the initiated crack tip by the former high stress amplitude cycles and improves the fatigue life especially for the fatigue life in FGA.

4. Conclusions

In conclusion, the present results suggest that the intermittent loading type does not change the crack initiation mechanism but improves the fatigue life of high strength steels in VHCF regime compared to those under the loading without intermittence. In contrast to the loading without pause duration, the median fatigue life is increased by 189%. This phenomenon is ascribed to the strain aging by the numerous low stress amplitude cycles under intermittent loading. The difference between the intermittent loading type and the loading without intermittence observed in the USFT is vital for better understanding VHCF behavior of high strength steels.

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