Very high cycle fatigue for GCr15 steel with smooth and hole-defect specimens

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Abstract Very high cycle fatigue (VHCF) properties of a low temperature tempering bearing steel GCr15 with smooth and hole-defect specimens are studied by employing a rotary bending test machine with frequency of 52.5 Hz. Both smooth and hole-defect specimens break in VHCF regime with some difference in fatigue crack initiation. For smooth specimens, a fine granular area (FGA) is observed near the grain boundary in the fracture surface of the specimens broken after 10^7 cycles. But no FGA is observed in the hole-defect specimens broken in VHCF regime, and the VHCF crack does not initiate from the small hole at the surface as it does at low or high cycle fatigue regime. Internal stress is employed to explain the VHCF behavior of these two types of specimens. At last, an advanced dislocation model based on Tanaka and Mura model is proposed to illustrate the internal stress process and to predict fatigue crack initiation life with FGA observed in the fracture region.
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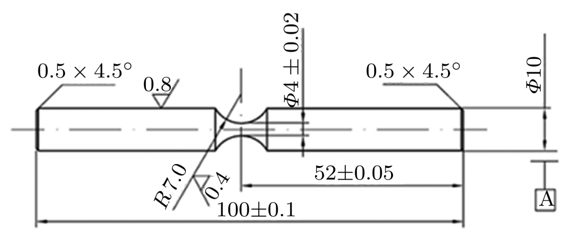
Keywords Very high cycle fatigue, GCr15, FGA, hole-defect, experimental research

Very high cycle fatigue (VHCF) has been confirmed to exist in more than 58 types of metallic materials at least.[1] This fact suggests that the conventional fatigue limit defined at 10^7 cannot provide safety design data for mechanical structures with the life longer than 10^7 cycles. However, there is a need for many engineering structures to be used for long period, such as aircrafts, automobiles, ships, railway, and so on.[2] Therefore, it is an urgent necessity to clarify the behavior and mechanism of VHCF.

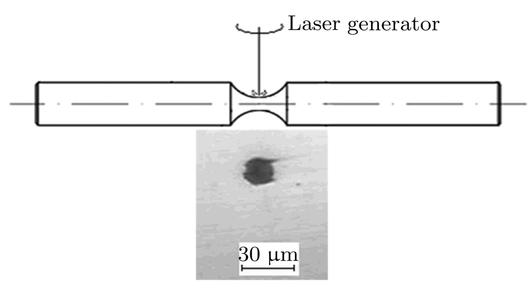
VHCF crack tends to initiate from interior inclusions of specimen as reported in many papers.[3–5] In the vicinity of the inclusion, a fine granular area[6] (FGA) can be observed by scanning electron microscope (SEM). The stress intensity factor (SIF) range at the periphery of the FGA (ΔK_{FGA}) corresponds to the threshold value (ΔK_{th}) for stable crack propagation,[7] so FGA is assumed as fatigue crack initiation region which consumes more than 90% of VHCF life.[3] GBF[8] and ODA[9] are also used as the same region as FGA in other studies.

However, FGA finishes in the interior of the specimen, which makes it difficult to seize the fatigue crack growth behavior directly. In this paper, VHCF tests for smooth and hole-defect specimens of a bearing steel, are performed by a rotary bending machine operating at a frequency of 52.5 Hz. The size of the hole is between 15 and 20 μm, and it is aimed to obtain the crack initiation behavior of FGA from the small holes.

Material used in this study is a high-carbon-chromium bearing steel (GCr15 in China).The specimens are heated at 1 118 K for 2 h in vacuum, then oil-quenched and tempered for 2.5 h in vacuum at 423 K with furnace-cooling. The Vickers hardness and tensile strength are 818 and 2 372 MPa, respectively. The shape and size of the smooth specimens for fatigue testing are shown in Fig. 1(a). The hole-defect specimens used for this study have the same shape and size except for a small hole fished by fiber lesser at the surface of the minimum cross section, as shown in Fig. 1(b). The diameter and the depth of the holes are about 20 μm.



(a) Smooth specimen



(b) Hole-defect specimen

Fig. 1. Schematic of specimen (mm).

The S–N curves for smooth and hole-defect specimens are shown in Fig. 2. Many failures occur after 10^7 cycles. For smooth specimens, surface crack initiation often occurs at the fatigue life less than 10^7 cycles while interior crack initiation is dominant in VHCF regime.

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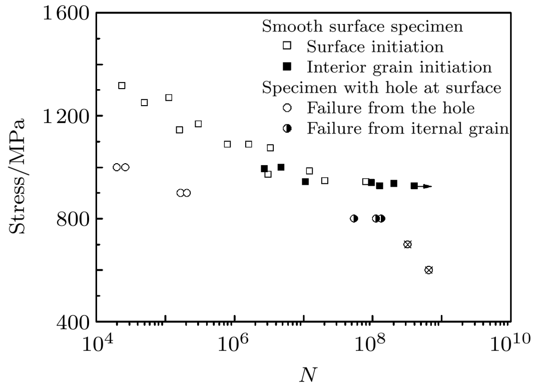
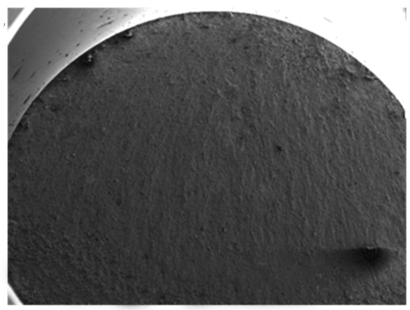
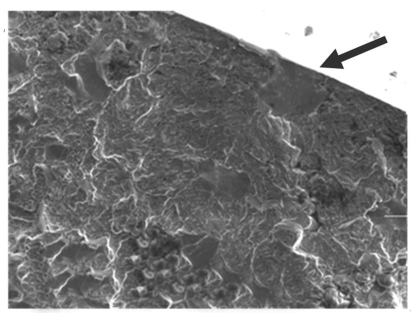


Fig. 2. S–N curves of GCr15 steel with smooth and hole-defect specimens.

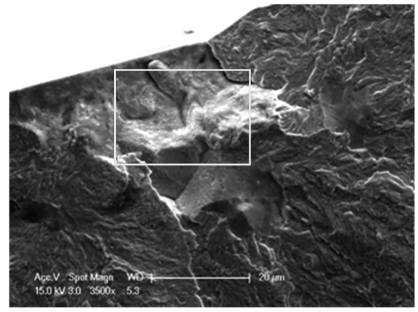


(a)

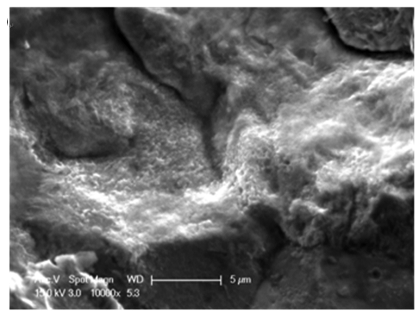


(b)

Fig. 3. Fracture morphology of a smooth specimen. $\sigma = 1\,089$ MPa, $N = 7.98 \times 10^5$.

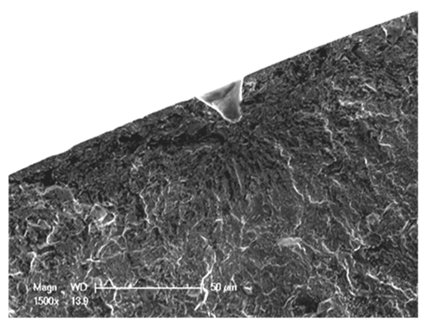


(a)

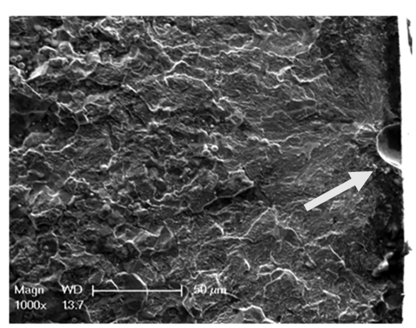


(b)

Fig. 4. VHCF fracture morphology of smooth specimen. $\sigma = 937$ MPa, $N = 2.03 \times 10^8$.



(a) $\sigma = 900$ MPa, $N = 1.68 \times 10^5$

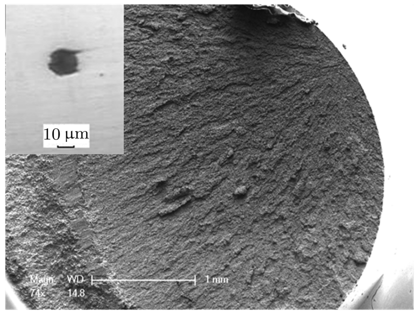


(b) $\sigma = 900$ MPa, $N = 2.07 \times 10^5$

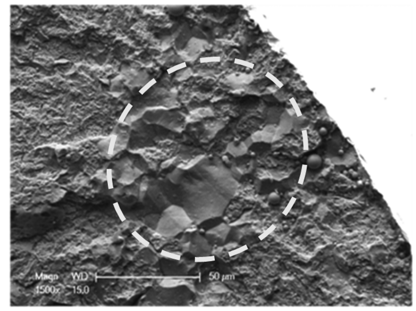
Fig. 5. SEM observations of crack initiation site for hole-defect specimen.

Both surface and interior grain initiation exist at about 940 MPa. The S–N curves are not a stepwise shape as reported by many other papers.[6] For hole-defect specimens, the tendency of the S–N curve is similar to that of the smooth ones. In low cycle fatigue regime, fatigue crack started from the hole at the surface, but in VHCF regime fatigue crack initiated from the interior grain boundary. For a given fatigue life, there is a significant decrease in fatigue strength for the hole-defect specimens.

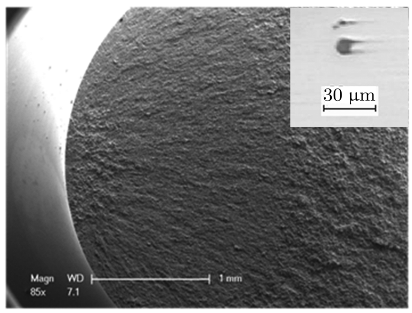
According to the results of SEM observations, the fatigue crack initiation site of smooth specimen is classified into two typical modes: the fatigue crack initiates



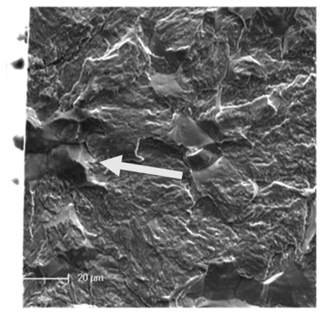
(a) $\sigma = 800$ MPa, $N = 5.40 \times 10^7$



(b) $\sigma = 800$ MPa, $N = 5.40 \times 10^7$



(c) $\sigma = 800$ MPa, $N = 1.14 \times 10^8$



(d) $\sigma = 800$ MPa, $N = 1.14 \times 10^8$

Fig. 6. VHCF fracture morphology of hole-defect specimen.

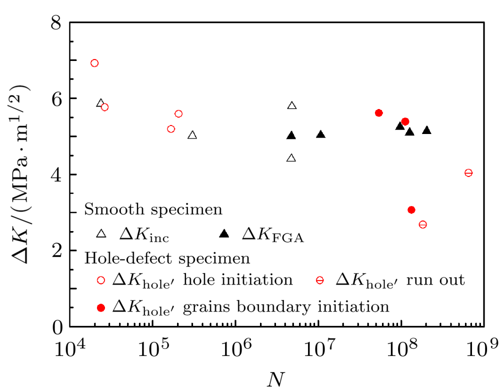


Fig. 7. Relationship between ΔK and N.

at the specimen surface and the fatigue crack initiates in the interior of the specimen at relative lower stress level. Figure 3 shows typical fracture morphology of surface crack initiation. Figure 4 is a typical example of VHCF failure with FGA. It is noticeable that the fatigue crack initiates mostly from the prior austenite grains boundary at this heat treatment in rotary bending test condition as shown in Fig. 2.

For hole-defect specimens, the fatigue crack initiation site could also be classified into two typical modes. In low cycle fatigue regime, fatigue crack starts from the hole at the surface due to the stress concentration effect. Figure 5 shows the microscopic fracture surface of two hole-defect specimens subjected to 900 MPa. Here, we use the parameter $\sqrt{\text{area}}$ to describe the size of the hole, and ΔK_{hole} is about $4.27\ \text{MPa}\cdot\text{m}^{1/2}$, which is close to the threshold of traditional crack growth threshold $5\ \text{MPa}\cdot\text{m}^{1/2}$ of this material. The value of ΔK_{hole} is calculated by the following formula[10]

$$\Delta K_{\text{hole}} = 0.65\sigma_{\text{m}}\sqrt{\pi\sqrt{\text{area}_{\text{hole}}}}, \tag{1}$$

where σ_{m} is the maximum stress in the cross section. VHCF did occur for hole-defect specimens as shown in Fig. 6, and no FGA was observed in the fracture surface which was distinguished with smooth ones. Figure 6(a) shows a specimen with a 15.4 μm hole at the surface fractured at $\sigma = 800$ MPa, $N = 5.40 \times 10^7$, and the fatigue crack started from the grain boundary as shown in Fig. 6(b). Figures 6(c) and 6(d) are other examples of VHCF failure for hole-defect specimens with the similar crack initiation site.

SIF ranges for inclusions and FGA are calculated with Eq. (1) by changing the modification factor as the following formula

$$\Delta K = 0.5\sigma_{\text{m}}\sqrt{\pi\sqrt{\text{area}}}. \tag{2}$$

Figure 7 shows the relationship between ΔK and number of cycles to failure. For hole-defect specimens VHCF crack starts from the grains boundary without FGA when $\Delta K_{\text{hole}} \le \Delta K_{\text{th}}$. To be more precise, when the stress is below 900 MPa, fatigue crack of hole-defect specimens initiates from interior grains boundary instead of the hole. It indicates that endurance limit for subsurface crack is lower than surface crack. Sadananda et al.[11] suggested that preexisting internal stresses is the main reason, which was induced by inclusions, voids or inhomogeneities in deformation. Furthermore, the fatigue strength of the hole-defect specimens decreased as Fig. 2 shows because of the much higher stress intensity factor of the hole in high cycle fatigue regime. And the VHCF strength for hole-defect specimens is also decreased although the fatigue crack dose not initiate from the hole. How and what the influence of this hole-defect on the interior crack initiation is not clearly understood.

For smooth specimens, $\Delta K_{\rm FGA}$ is about 5 $\rm MPa\cdot m^{1/2}$ which is close to $\Delta K_{\rm th}$ of this material. Zhao et al.[7] have confirmed this phenomenon and believed that FGA is finished when the plastic zone size of the micro crack exceeds the lower bound of the martensite width $l_{\rm m}$. Since martensite is a key factor for FGA formation,[12] we introduce $l_{\rm m}$ into the Tanaka and Mura model as used for VHCF crack initiation life prediction in many studies.[3,13] Thus we have the following modified formation

$$N_{\rm i}\cdot\pi\left(\tau-\kappa\right)^2 l_{\rm m}^2/G = C\cdot\sigma_{\rm b}\cdot {\rm area}_{\rm FGA,net}, \tag{3}$$

where $\sigma_{\rm b}$ is the tensile strength of the material, ${\rm area}_{\rm FGA,net}$ is the value of $({\rm area}_{\rm FGA} - {\rm area}_{\rm Inc})$, and C is a correction coefficient which shows the relationship between the strength of the martensite and tensile strength of material.

Based on the rotary bending fatigue tests for the GCr15 steel with smooth and hole-defect specimens, the following conclusions are drawn:

VHCF failure occurs after 10^7 cycles for low temperature tempering GCr15 steel. For smooth specimens, VHCF crack tends to start from interior grain boundary with FGA at the initiation site by rotary bending test. The stress intensity factor range of FGA also keeps constant about the threshold value for stable crack propagation as it did when VHCF crack started from inclusion.

Fatigue endurance limit exists for small hole at the surface, but the interior defects such as inclusions and large grains could be a VHCF crack origining with the same nominal stress intensity factor, for the reasonably lower endurance limit of subsurface crack.

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