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The formation mechanism of characteristic region at crack initiation for very-high-cycle fatigue of high-strength steels

Youshi Hong [*], Xiaolong Liu, Zhengqiang Lei, Chengqi Sun

LNM, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

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ABSTRACT

For high-strength steels, the crack initiation of very-high-cycle fatigue (VHCF) is commonly at the interior of material with fish-eye (FiE) morphology containing a fine-granular-area (FGA) surrounding an inclusion as crack origin, and FGA is regarded as the characteristic region of crack initiation. Here, we carefully examined the micro-morphology of FGA and FiE for two high-strength steels. The results revealed that the microscopic nature of FGA is a thin layer of nanograins. Then we proposed the formation mechanism of FGA: Numerous Cyclic Pressing (NCP) between originated crack surfaces, which causes grain refinement at originated crack wake and therefore the formation of FGA. The results of second set experiment showed that the cases with negative stress ratios exhibit the prevalence of nanograin layer in FGA region and the nanograin layer vanishes for the cases with positive stress ratios, which is a verification of the proposed NCP model.

1. Introduction

Fatigue failures of metallic materials may happen beyond 10^7 loading cycles under a relatively low cyclic stress below conventional fatigue limit [1–4]. This is the new research topic of very-high-cycle fatigue (VHCF) that receives increasing research attentions due to not only engineering requirements but also scientific interests [5–10]. The key aspect of the scientific significance is to understand the mechanism of crack initiation and early growth for VHCF, which is basically different from that for low-cycle fatigue (LCF) and high-cycle fatigue (HCF). For LCF and most of HCF cases, the fatigue failure is basically initiated by persistent slip bands from the surface of metallic materials.

For high-strength steels as an instance, the process of VHCF is commonly caused by subsurface or interior crack initiation with the morphology of so-called fish-eye (FiE) containing a rough region of fine-granular-area (FGA) surrounding an inclusion or other defect as crack origin [11–15]. FGA is also called optical dark area (ODA) [11] or granular bright facet (GBF) [16]. Although the size of FiE is just hundreds of microns and that of FGA is only tens of microns, the region of FGA, as crack initiation characteristic region, consumes larger than 95% of total fatigue life [17,18]. To reveal the formation mechanism of this crack initiation characteristic region is extremely essential for understanding the unique behavior of VHCF and predicting the fatigue life of VHCF for high-strength steels. Several mechanisms have been proposed for this aspect, including “hydrogen assisted crack growth” [11,19], “decohesion of spherical carbide” [20], and “formation and debonding of fine granular layer” [2,21].

For the mechanism of “hydrogen assisted crack growth” [11,19], it was stated that the formation of FGA was assisted by the locally concentrated hydrogen. The existence of hydrogen trapped by an inclusion induced the discrete crack growth at a very slow rate during crack initiation and produced a rough fracture surface. When the size of FGA reached the critical value, crack growth occurred without the assistance of hydrogen.

For the mechanism of “decohesion of spherical carbide” [20], it was proposed that the formation of FGA was due to the existence of spherical carbides and their decohesions from the matrix to cause crack initiation in the vicinity of an inclusion. The coalesced crack was along the boundary between spherical carbides and the matrix with the generated roughness to form an FGA region. After the formation of a certain size for FGA, the crack propagation was independent of the spherical carbide decohesion.

For the mechanism of “formation and debonding of fine granular layer” [2,21], it was regarded that FGA was caused by the debonding of the fine granular layer and the matrix to form the rough morphology, and the fine granular layer was generated (before crack initiation) by the intensive polygonization in the vicinity of an inclusion during the long sequence of cyclic loading. It was supposed that when a penny-shape crack of FGA was formed

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

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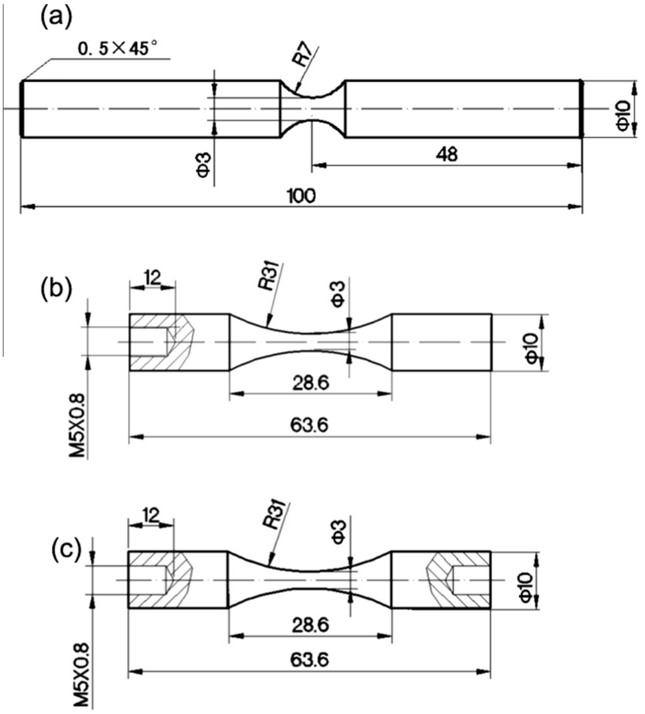

Fig. 1. Three types of specimens used in fatigue testing: (a) for rotary bending, (b) for ultrasonic axial cycling without mean stress, and (c) for ultrasonic axial cycling with superimposed mean stress (dimensions in mm).

around the inclusion, the size of FGA was terminated and the crack growth tended to Paris crack regime.

In 2012, an investigation by Grad et al. [22] reported that an average grain size of about 70 nm was observed in the FGA layer for a high-strength steel and proposed the FGA formation mechanism of “local grain refinement at the crack tip”. In fact, this model is very similar to the model of “formation and debonding of fine granular layer” by Sakai [2]. It should be noticed that the model by Sakai [2] and later by Grad et al. [22] stated that the fine grain layer is produced *before* crack formation or at the head of crack tip. A very recent publication by Chai et al. [23] presented that the occurrence of cyclic localized plastic deformation during VHCF near the subsurface defect leads to the formation of fine granular layer.

One may notice that each of the above proposed mechanisms could explain an individual experimental phenomenon, but every one of them encountered difficulties in the explanation of more general cases. The following lists some examples.

For the cases of VHCF of medium-carbon structural steels, fatigue cracks are initiated from the interior of specimen with FiE fracture mode but without FGA morphology, and for the cases of VHCF of high-strength steels at different stress ratios, crack interior initiation is with FiE but without FGA at positive stress ratio conditions. For example, in the case of VHCF for a medium-carbon structural steel tested by rotary bending (52.5 Hz) in laboratory air with the stress ratio of $R = -1$, fatigue crack initiated from the subsurface or the interior of specimen with FiE pattern but without FGA morphology [24]. A similar case is the VHCF for a medium-carbon structural steel tested by ultrasonic axial cycling (21 kHz) in laboratory air with the stress ratios of $R = -1$ and $R = 0$, for which cracks nucleated at non-metallic inclusions in the interior of specimen with FiE morphology but FGA was not visible on fracture surfaces [25]. Another interesting case [26] is that, for a high-carbon bearing steel with axial cycling (50 Hz) under the stress ratios of $R = 0$ and $R = 0.5$, fatigue cracks initiated from the interior of specimen with FiE pattern and FGA morphology at the failure cycles of 6.22×10^7 at $R = 0$, whereas the initiation region was with FiE but without FGA morphology at the failure cycles of 2.57×10^5 at $R = 0$. A recently reported case [27] of VHCF for a martensitic 12% Cr steel (0.117% C), for which the specimens were tested by axial cycling (20 kHz) in laboratory air at the stress ratios from −1 to 0.7, showed that FGA was observed in the specimens at $R = -1$ but never found in the specimens fatigued at $R = 0.1$, 0.5 and 0.7. It is obvious that the presence or the absence of FGA in the crack initiation process of VHCF in above cases cannot be explained or reconciled by the existed proposed mechanisms. It should be emphasized that, FGA is a characteristic region at crack initiation for VHCF of high-strength steels and its size is the characteristic dimension for crack initiation, which is responsible for a majority part of larger than 95% of total fatigue life [17,18]. Therefore the revelation of the formation mechanism for the crack initiation region of FGA is a key point not only for understanding the physical process of VHCF crack initiation but also for predicting the fatigue life containing VHCF regime.

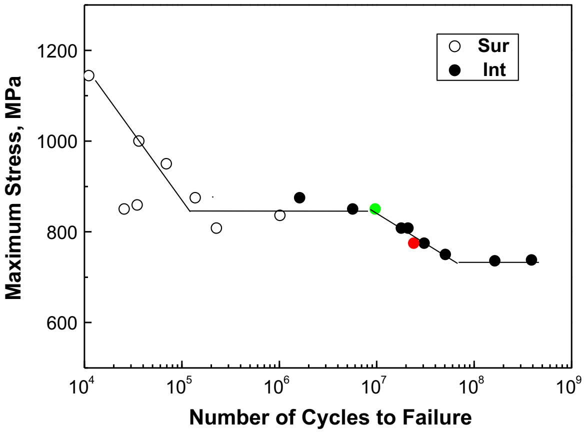

Fig. 2. S–N data of material A, showing fatigue strength decreases with the increase of loading cycles, and for fatigue life (N_f) beyond 2×10^6 cycles, failure caused by crack initiation at the interior of specimen. Sur: crack initiation at surface, Int: crack initiation at interior, red point: specimen A1, green point: specimen A2.

Thus one sees an unclear issue in the understanding of the formation mechanism for the characteristic region of crack initiation for VHCF of high-strength steels. What is the microscopic nature of FGA? What is the real formation mechanism of this characteristic area? The present paper is aiming at the answer to these two challenging questions.

For this purpose, we carefully examined the micro-morphology of crack profile at FGA and FiE regions for a high-strength steel by transmission electron microscopy (TEM) and scanning electron microscopy (SEM) with the samples prepared by ion beam cross section polishing (IBP) and focused ion beam (FIB) cutting, showing the microstructure features of FGA and FiE regions together with reflected electron selected area diffraction (SAD) patterns. The observations revealed that the microscopic nature of FGA is a thin layer of nano-sized grains. Based on this unique revelation, we proposed that the formation mechanism of crack initiation characteristic region of FGA is due to the numerous cyclic pressing (NCP) at originated crack surfaces simultaneously with crack growing, which causes the grain refinement at the wake of originated crack. Then a second set investigation was carried out for a similar high-strength steel with ultrasonic axial cycling at different stress ratios of $R = -1$, −0.5, 0.1 and 0.3. The results showed that the test cases of negative stress ratios exhibit the prevalence of nanograin layer in the FGA region and this tendency vanishes for the test cases of positive stress ratios, which is a verification of the proposed NCP