Very high cycle fatigue of surface carburized CrNi steel at variable stress ratio: Failure analysis and life prediction

Abdelhak Nehila, Wei Li, Ning Gao, Xinxin Xing, Hongqiao Zhao, Ping Wang, Tatsuo Sakai

ABSTRACT

High cycle fatigue and very high cycle fatigue properties of a surface-carburized CrNi steel were examined under axial loading with stress ratios of −1 and 0. The positive stress ratio overcomes the effect of carburized layer and promotes crack initiation from the carburized layer. The morphology of fine granular area (FGA) is more distinct under the negative stress ratio with more obvious crack closure effect. Two models concerning the inclusion-fish-eye failure and the inclusion-FGA-fish-eye failure are proposed. The predicted fatigue lives based on the concept of crack initiation are in good agreement with experimental results.

1. Introduction

In view of the fact that the fatigue failure under cyclic loading is more easily induced from the surface, some surface strengthening techniques, such as carburizing, shot peening, nitriding, etc., are still widely used to improve the fatigue resistance of structural materials [1,2]. Recently, with the occurrence of very high cycle fatigue (VHCF), studies show that sometimes the surface strengthening has no effect on the improvement of fatigue strength of structural materials in the VHCF regime [3,4]. This is mainly due to the transition of crack origin from the surface in the high cycle fatigue (HCF) regime to the interior in the VHCF regime [5–13]. Although some VHCF studies about the duplex or step-wise S-N curve characteristics [8,10], the interior crack nucleation and propagation behavior [9,10,12,13] and the life prediction approaches [3,6,14] are done, the fundamental failure mechanisms of structural materials in the VHCF regime are not yet well understood.

For high-strength steels, the interior or subsurface failure is mainly caused by the interior metallurgical defects such as non-metallic inclusions [3–6,8–13] or small inhomogeneous microstructures [7]. As a typical feature of interior failure, a propagating crack shaped like a fisheye can be observed on the fracture surface. Sometimes, a special region can occur in the vicinity of inclusion, which is named as “fine granular area (FGA)” by coauthor Sakai [8], or “optically dark area (ODA)” by Murakami [9] and or “granular bright facet (GBF)” by Shiozawa [10], respectively. Herein, the term FGA is used throughout the paper. Correspondingly, three classical models such as “polygonization and debonding” [8], “hydrogen embrittlement-assisted cracking” [9] and “depressive decohesion of spherical carbide” [10] are also developed to explain the FGA formation process from the different aspects. Recently, with the improvement of attention to the interior failure mechanisms in the VHCF regime, some new models or ideas about FGA formation are proposed on the basis of classical models, mainly including: “formation of nanograins by repeated pressing under negative stress ratios” [11], “continuous grain refinement and crack propagation” [12], “cyclic compression between crack faces in vacuum environment” [13] and “matrix fragmentation and local volume rotation” [15], etc. Furthermore, some researchers used the artificial surface defect in vacuum environment to simulate the subsurface defect served as crack nucleus, the FGA can be reproduced [16]. Through the assessment of plastic zone size at the FGA border, the crystallographic charter of FGA formation was revealed [17]. Although there is no consensus on this highly concerned issue, researcher agree that the crack initiation process or small crack growth process [18,19] within the FGA is considered to play a critical role in governing the VHCF properties of high-strength steels.

Recent studies show that about 90% of fatigue life is spent in crack initiation and early crack growth stages in the VHCF regime [19]. From the viewpoint of crack growth, the results show that crack still can propagate even if the stress intensity factor at the crack tip is less than the traditional threshold value [20]. In vacuum environment, the crack growth rate of high strength steels can be reduced to about $10^{-14}$ m/cycle [13]. Furthermore, on the fracture surfaces tested in vacuum, the similar crack morphology to the FGA was observed [13,17]. Based on this, some researchers proposed that VHCF life can be estimated from...
the viewpoint of crack growth. According to the $\sqrt{area}$ parameter model [21] concerning small discontinuities that are identical to existed cracks, some models associated with inclusion size [22], material properties such as tensile strength [23], accumulative damage [24], etc. are proposed to predict the fatigue life in the VHCF regime. By contrast, the approaches or models for predicting the VHCF life based on the concept of crack initiation are relatively rare. It is mainly attributed to the lack understanding of crack initiation mechanisms. For high strength steels with high crack propagation rate and low fracture toughness, the fatigue life in the VHCF regime should be governed by the crack initiation. Thus, the VHCF life prediction approach related to the crack initiation mechanism need to be further discussed.

In this study, the axial loading tests for stress ratios $R$ of $-1$ and $0$ [25] were performed to clarify the failure mechanisms of a carburized high strength alloy steel in the HCF and VHCF regimes. Based on the discussion of $S$-$N$ curve properties, the two and three dimensional observation of fracture surfaces, the evaluation of characteristics crack size and the evaluation of stress intensity factor at the crack tip, the failure mechanisms in the HCF and VHCF regimes were elucidated. Combined with the definition of transition crack sizes and the microstructure-scale parameters, a crack initiation life prediction model was developed to predict the VHCF life associated with failure mechanism.

2. Materials and methods

2.1. Material and specimen

The material investigated in this study is a high strength CrNi gear steel, its chemical composition is presented in Table 1. From the annealed steel bar with a diameter of 18 mm, specimens were first machined into the shape of hourglass with a certain amount of finishing margin, and then ground in a direction parallel to their axis by using grades 400–2000 abrasive paper to their final shapes, as shown in Fig. 1. The minimum diameter and the corresponding stress concentration factor of specimen are 6 mm and 1.03, respectively.

2.2. Carburizing and microstructure

Specimens were put into a container filled with the carburization powder consisting of charcoal, calcium carbonate and barium carbonate with 12:1:5. A vacuum furnace was used to heat the container with 12:1:5. A vacuum furnace was used to heat the container to the carburizing temperature of 930 °C. The carburizing time approaches the carburizing temperature of 930 °C. The carburizing time for the carburizing process, the direct quenching and tempering were performed. The furnace temperature is stepped down to 860 °C for 30 min prior to quenching in oil, followed by tempering at 200 °C for 2 h.

After heat treatment, through a series of measurements including grinding, polishing and etching with 4% alcohol nitric acid solution, the microstructure of carburized specimen in cross-sectional area was observed by using optical microscopy (OM) or scanning electron microscopy (SEM), as shown in Fig. 2(a). It can be seen from Fig. 2(a) that there is an obvious divide between the carburized layer and the matrix region, the thickness of carburized layer is evaluated to be about 800 μm. Under a higher magnification inspection, the acicular martensites with high carbon and partial residual austenites is observed in the carburized layer (seen in Fig. 2(b)), whereas the lath martensites with low carbon is observed in matrix region (seen in Fig. 2(c)). Moreover, some non-metallic inclusions can be found in the microstructure, as shown in Fig. 2(d). Based on the analysis of energy dispersive X-ray spectrometer (EDS), the main chemical composition of inclusion is Al$_2$O$_3$. In addition, based on the monotonic tension test, Young’s modulus $E$, Poisson’s ratio $\nu$, and tensile strength $\sigma_t$ of CrNi steel are given as 205 GPa, 0.3 and 1510 MPa, respectively. Based on the Ref. [26], Young’s modulus and Poisson’s ratio of inclusion, $E_{inc}$ and $\nu_{inc}$, are around 390 GPa and 0.25, respectively.

2.3. Fatigue testing method

The axial loading tests of CrNi steel under $R = -1$ and 0 in the life regime of $10^5$–$10^9$ cycles were performed by using an electromagnetic resonant fatigue testing machine. It was operated at the frequency about 100 Hz in an open environment with room temperature. The total number of specimens was 41, roughly 2 or 3 specimens were tested at each load level. After experiment, fracture surfaces were observed using SEM and OM, particularly paying attention to crack initiation and propagation mechanisms. Moreover, based on a computer-aided LAMOS imaging processor, the three-dimensional (3D) fracture morphologies of fracture surfaces were analyzed to emphatically clarify crack initiation mechanism.

3. Results and discussion

3.1. Vickers hardness and residual stress

Along the direction from the edge to the center on the surface shown in Fig. 2(a), the micro-hardness of carburized CrNi steel was in turn measured by using an instrumented nano-indenter. Results show that the variation of hardness is gradient, mainly limited in the carburized layer. The hardness value is the maximum. With the increasing of depth, it tends to decrease and gradually approaches a constant value within the matrix region, about 505 kgf/mm².

Based on the sin$^2$ method with CrKα-radiation, the residual stress on the round surface was measured along the axis of specimen by using X-ray diffraction, and determined by taking the mean value of 4 measurement points on the surface. It can be found that the maximum compressive residual stress on the surface is about 150 MPa.

3.2. S-N diagram

The data of applied stress amplitude $\sigma_a$ versus fatigue life $N_f$ for carburized CrNi steel under axial loading with stress ratios of $-1$ and 0 in the life regime of $10^5$–$10^9$ cycles are shown in Fig. 3(a). By means of observation of crack initiation sites, only the interior failure of specimen takes place in this study. Obviously, to a great extent it is mainly

Table 1

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
<th>Al</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>CrNi</td>
<td>0.16</td>
<td>0.05</td>
<td>0.50</td>
<td>0.004</td>
<td>0.001</td>
<td>1.62</td>
<td>1.50</td>
<td>0.29</td>
<td>0.10</td>
<td>0.036</td>
<td>0.032</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Fig. 1. Shape and dimensions of specimen (units: mm).
دریافت فوری
متن کامل مقاله
امکان دانلود نسخه تمام متن مقالات انگلیسی
امکان دانلود نسخه ترجمه شده مقالات
پذیرش سفارش ترجمه تخصصی
امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
امکان دانلود رایگان ۲ صفحه اول هر مقاله
امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
دانلود فوری مقاله پس از پرداخت آنلاین
پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات

ISI Articles
مرجع مقالات تخصصی ایران