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Influence of microstructure and surface defect on very high cycle fatigue properties of clean spring steel

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ABSTRACT

Very high cycle fatigue (VHCF) properties of a newly developed clean spring steel were experimentally examined under rotating bending and axial loading. As a result, this steel represents the duplex *S–N* property only for surface-induced failure under rotating bending, whereas it represents the single *S–N* property for surface-induced failure and interior inhomogeneous microstructure-induced failure under axial loading. Surface small grinding defect-induced failure is the predominant failure mode of this steel in VHCF regime. The surface morphology of the interior inhomogeneous microstructure with distinct plastic deformation is much rougher than that of the ambient matrix, which means the stress concentration resulted from the strain inconsistency between the microstructural inhomogeneity as soft phase and the ambient matrix as hard phase plays a key role in causing interior crack initiation. Considering the effect of surface compressive residual stress, the threshold stress intensity factor for surface small defect-induced crack propagation of this steel is evaluated to be 2.04 $MPam^{1/2}$, which means that the short crack effect plays a key role in causing the surface small defect-induced failure of this steel in the VHCF regime. From the viewpoint of defect distribution, surface and interior failure probabilities are equivalent under a fixed characteristic value of defect density. If the interior defect size is less than or even equal to the surface defect size, surface defect-induced failure will become the predominant failure mode in VHCF regime, especially under rotating bending.

1. Introduction

Based on two failure modes consisting of surface-induced failure and interior-induced failure, some high strength steels with tensile strength exceeding 1200 MPa usually represent a characteristic *S–N* property called the duplex *S–N* property or the stepwise *S–N* property in the very high cycle fatigue (VHCF) regime [1–3]. This characteristic *S–N* property is mainly embodied in the transition of failure mode from the surface-induced failure corresponding to high stress amplitude and short fatigue life to the interior-induced failure corresponding to low stress amplitude and long fatigue life. Generally, the interior non-metal inclusion-induced failure is the predominant failure mode of high strength steel in the VHCF regime.

Recently, with higher cleanness of steel upgraded steadily, studies show that there may be a critical inclusion size [4,5], below which fatigue crack causing failure of high strength steel in the VHCF regime does not initiate from the interior inclusion but may initiate from some interior inhomogeneous microstructures [6–14]. These interior inhomogeneous microstructures are mainly generated during the process of heat treatment, closely relating to the quenching and the tempering temperature. For some steels with tempered martensite structure [6,7], the inhomogeneous microstructure causing interior crack initiation is mostly the bainite derived from the imperfect transformation of the austenite during quenching. For some duplex-phase steels such as the bainite/martensite steels [8–11], ferrite/pearlite steels [12,13] and ferrite/austenite steels [14], the inhomogeneous microstructures causing interior crack initiation may be the coarse bainite [8–11], the occasionally generated ferrite grain [8] and or the ferrite grain as matrix [12–14], corresponding to the soft phase in the microstructure of steel. Furthermore, it should be noted that the “fine granular area” (FGA) [15] sometimes can be observed in the vicinity of these homogeneous microstructures [8–10,14] but sometimes cannot be observed even in the life regime beyond 10^8 cycles [6,7,11,12]. Apparently, the interior crack initiation and propagation mechanisms induced by the inhomogeneous microstructure are different from that induced by the inclusion, which will have to be discussed further.

In addition, surface small grinding defects such as scratches and cavities or surface small inclusion can also induce crack ini-

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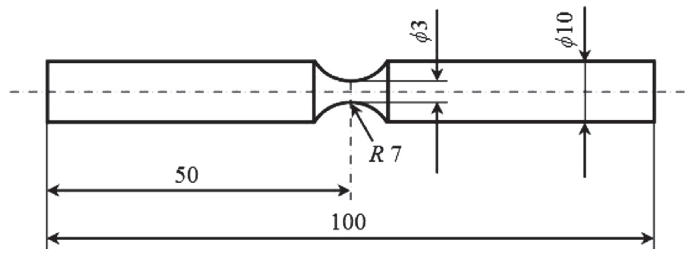
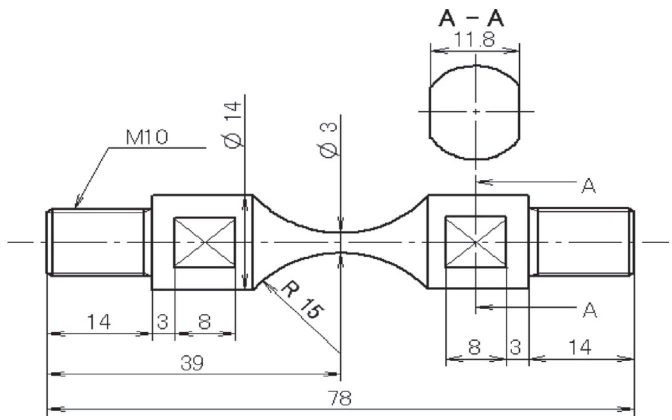


(a) Under rotating bending



(b) Under axial loading

Fig. 1. Shapes and dimensions of specimens (units: mm).

tiation of high strength steel in the VHCF regime. Unfortunately, this failure mode does not arouse popular attention in previous studies, even though it was observed during the experiment. This is probably attributed to the very low probability of this failure mode in the VHCF regime due to the presence of larger inclusions or the special surface treatment of specimen. However, with the development of clean steels with the inclusion control, this failure mode also becomes a research subject worthy of attention. Akiniwa et al. [16] found that slip due to shear deformation played an important role in this crack initiation mechanism for their investigated steel, and the size of straight slip region was very small and was closed to the prior grain size. Shiozawa et al. [17] founded that the minimum stress intensity factor for surface small defect-induced crack propagation for their investigated steel is only 2.5 $MPam^{1/2}$. Mayer et al. [18] pointed out that the plausible small crack effect should be responsible for this crack propagation mechanism controlled by the small stress intensity factor based on the experimental result of their investigated steel, which was in agreement with the result reported by Tanaka et al. [19]. Furthermore, Marines et al. [20] pointed out that the crack propagation following initiation induced by surface small grinding defect was a small portion of total life if over 10^7 cycles. However, the detailed crack initiation mechanism induced by surface small grinding defects in the VHCF regime is not yet completely understood so far and still needs to be further verified by means of more test results of other high strength steels under different loading condition.

In the present study, fatigue tests under rotating bending and under axial loading were carried out to clarify fatigue properties of a newly developed clean spring steel in the VHCF regime, the emphasis was put on the *S*–*N* property, the crack initiation and propagation mechanisms, and the statistical evaluation of inclusion size, fatigue limit and competing failure mode.

2. Experimental procedure

2.1. Material and specimen

Material used in this study is a newly developed clean spring steel (JIS-SUP7-T450), whose chemical composition (mass percentage) is: 0.6 C, 2.0 Si, 0.9 Mn, 0.014 P, 0.019 S. Firstly, specimens were machined into the shape of hourglass with a certain amount of finishing margin, and then quenched in vacuum (1173 K $\times$ 20 min + oil cooling) and tempered (723 K $\times$ 60 min + air cooling). The surfaces of specimens under rotating bending and axial loading were all grinded in a direction perpendicular to the axis of specimen by the grade 600–2000 abrasive paper to the final shapes, as shown in Fig. 1. The minimum diameter d for these two kinds of specimens is all 3 mm, and the round-notched radius γ of specimens is 7 mm for rotating bending and 15 mm for axial loading, respectively. The corresponding elastic stress concentration factors K_t are evaluated to be 1.06 and 1.04, respectively. The Vickers hardness (HV) distribution along the cross-section of specimen is almost uniform, about 485 kgf/mm^2. The tensile strength is evaluated to be 1586 MPa.

Based on the observation by means of scanning electronic microscope (SEM), the microstructure of heat-treated material is the tempered sorbite structure, in which a number of fine granular carbides are dispersedly distributed in the matrix of ferrite, as shown in Fig. 2a. Furthermore, the prior austenite grain size is measured to be about 9.4 μm, as shown in Fig. 2b.

2.2. Fatigue testing method

A cantilever-type fatigue testing machine (RB4-3510-V2) at frequency of 52.5 Hz and a multi-type fatigue testing machine (PMF4-10) at frequency of 80 Hz were used to carry out the VHCF tests of SUP7-T450 spring steel under rotating bending and axial loading, respectively. Fatigue tests were all performed in an open