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Very high cycle fatigue properties of bearing steel under axial loading condition

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ABSTRACT

It has been observed to appear a step-wise or duplex *S–N* curve under the test of rotary bending fatigue using high strength steel. This behavior was caused by the transition of fracture mode from surface-induced fracture to subsurface inclusion-induced fracture. The aim of this study is to clarify the *S–N* characteristic under an axial loading fatigue in the very high cycle fatigue regime. In order to investigate the mean-stress effects, fatigue tests were carried out in air at room temperature under three applied stress ratios of -1, 0 and 0.5 using a hour-glass shaped specimen of high carbon–chromium bearing steel, JIS SUJ2. From the results, three types of fracture mode were observed on the fracture surface, such as surface-induced fracture, subsurface inclusion-induced fracture without granular bright facet (GBF) area and that with GBF area around an inclusion. Fatigue lifetime for transition in the fracture mode depended on the applied stress ratio. Shape of the *S–N* curve was a smooth and continuous under three testing conditions in spite of the occurrence on the three types of fracture. Detail discussion for fatigue fracture behavior was made through the observation of fracture surface and from point in view of the fracture mechanics. In addition, an effect of residual stress in the specimen surface layer on the transition of fracture mode was discussed and compared with the experimental results.

1. Introduction

In recent years, attention has been given to the fatigue behavior of materials in the very high-cycle region, because of a requirement for high efficiency and reliability for machines and structures. An increasing interest of this topic is reflected by the fact that the international conference is already held four times since 1998 as a series of “Very High Cycle Fatigue Conference” [1]. It has been reported by some researchers that a step-wise or a duplex *S–N* curves occurs for high-strength steels tested under a rotary bending fatigue [1–12]. This distinctive behavior is appeared by change in crack initiation site from a surface to a subsurface defect, depending on applied stress amplitude. That is, one of two *S–N* curves appears at high-stress amplitude level and low number of cycles, and is governed by a surface fracture mode. The fatigue limit appears at critical stress amplitude where the initiated surface microcracks are arrested. Another *S–N* curve appears at low-stress amplitude level and high number of cycles, and is governed by an internal crack initiation and growth. On the fracture surface resulting from internal crack initiation and propagation, a white-bright facet area was found in the vicinity of a non-metallic inclusion at fracture origin inside the fish-eye zone by SEM observation. This area revealed a very rough and granular morphology in comparison with the area inside the fish-eye [2–4,13], and the authors have named this a “granular-bright-facet” (GBF) [2]. The formation of the GBF area during the high cycle fatigue process controls the internal fracture mode and is an important factor clarifying fatigue behavior in the very high cycle regime, and ensuring the long durability of machine elements and structures [14–16]. Mechanism for the GBF formation was discussed in detail through the experimental facts obtained by the rotary bending fatigue test and proposed as ‘dispersive decohesion of spherical carbide’ model by the authors [15,16]. It is important to confirm the justification of this model under the other loading conditions.

Now, actual mechanical components of machine and structure are operated under various type of service loading, such as rotary bending, plane bending, axial loading, torsional loading and combined these loadings. It is important for establishment of high safety and reliability fatigue design method of machine elements to obtain fundamental characteristic and data under each of the above loading conditions. Experimental study for fatigue properties under axial loading [17–19] is very few compared with that under rotary bending. The aim of this study is to clarify the effect of applied stress ratio on fatigue behavior of high strength steel in very high cycle regime. Axial loading fatigue tests were carried out under three applied stress ratios using hourglass-shaped specimens of high carbon–chromium bearing steel, and *S–N* characteristic and

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fatigue fracture mode were discussed based on the fracture mechanics.

2. Experimental procedures

2.1. Testing material and specimen

The material used in this study was a high carbon–chromium bearing steel, JIS SUJ2. The chemical composition (mass percentage) of this steel is shown in Table 1. Hourglass-shaped specimens with a minimum diameter of 3 mm and round notch radius of 15 mm with a flange, as shown in Fig. 1, were machined. The specimens were heated for 2400 s in a vacuum at 1008 K and oil-cooled, tempered for 1200 s in a vacuum at 453 K and then air-cooled. The round notch surface was polished by an emery paper having a mesh of #2000 and buff polishing. The elastic stress concentration factor of this specimen is 1.029.

Fig. 2 shows the microstructure of the heat-treated material observed by an SEM, which was prepared with micro-etching by Nital (a) and electro-etching (b). It can be seen from the photographs that many spherical carbide particles are distributed in the matrix which is a tempered martensite structure composing of an average prior-austenitic grain size of 5.7 μm. Size of the carbide particle distributed in the range of 0.2–2.0 μm and the average was 0.8 μm. The tensile strength and the Vickers hardness of the heat-treated material are 2316 MPa and HV749, respectively.

Table 1
Chemical composition of tested materials (mass%).

C	Si	Mn	P	S	Cr	Cu	Ni	Mo	[O]
1.01	0.23	0.36	0.012	0.007	1.45	0.06	0.04	0.02	8 ppm

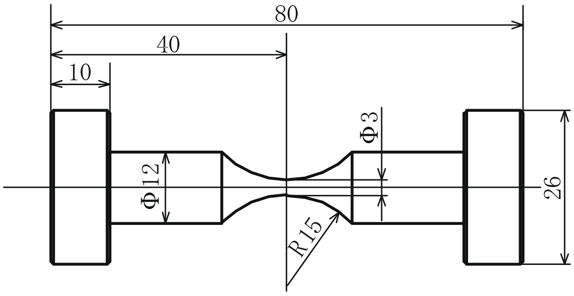


Fig. 1. Shape and dimension of specimen used.

2.2. Fatigue testing method

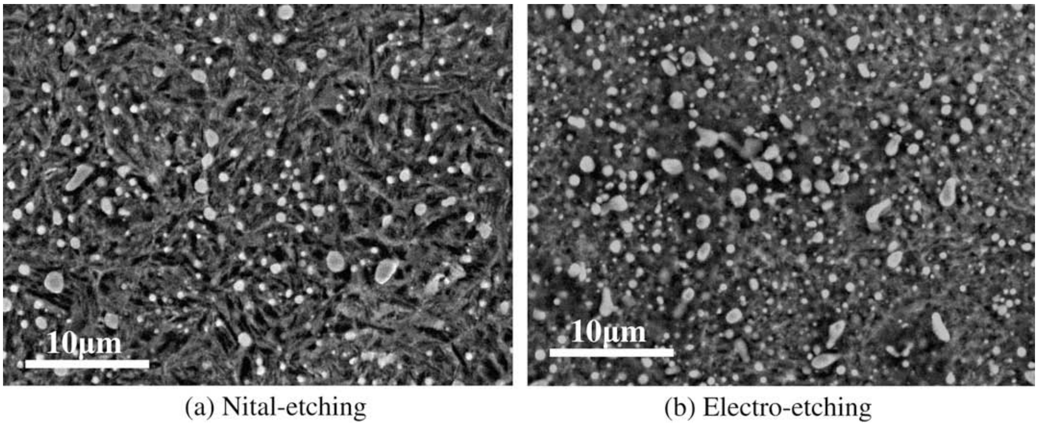
Fatigue tests were performed using a newly developed multi-type fatigue testing machine in axial loading [20,21]. This testing machine can simultaneously perform fatigue tests for four different specimens at the frequency of 80 Hz, using a special hydraulic system with rotary valve to distribute high-pressure oil into the respective actuators. The loading capacity for each specimen is ±10 kN and the applied load can be given independently to the individual specimen. In this study, force-controlled fatigue tests under axially-reversed loading of sinusoidal wave type were carried out at three applied stress ratios, R, of -1, 0 and 0.5 in an open environment at room temperature.

3. Experimental results

3.1. ***S–N*** Curve

The *S–N* curve obtained from the axial loading fatigue tests under different applied stress ratio is shown in Fig. 3a. As observation result of the fracture surface by SEM, fatigue fracture mode was classified into two types, such as surface fracture mode resulting from the surface crack initiation and growth (referred to as S-mode) and subsurface non-metallic inclusion-induced fracture mode with a fish-eye. Also, the subsurface fracture mode was divided two types of fracture mode; One was formed the GBF area in the vicinity of a non-metallic inclusion at the fracture origin inside the fish-eye zone for the specimens ruptured at the high cycles of a lifetime of more than 10^6 cycles (IG-mode), plotted by solid mark in Fig. 3a. The other was not formed the GBF area at short lifetime bellow 10^6 cycles plotted by half-solid marks (I-mode).

Fig. 3b shows the comparison between the *S–N* curve obtained from the axial loading fatigue test under the stress ratio of -1 and that from the cantilever-type rotary bending fatigue test using hourglass-shaped specimens with a minimum diameter of 3 mm [2]. It can be seen from the figure that the *S–N* curve depends on the applied loading mode. Even though the results obtained from the rotary bending fatigue test shows the step-wise *S–N* curve or a duplex *S–N* curve, shape of *S–N* curve obtained from the axial loading fatigue tests is a smooth and continuous in spite of the occurrence of the three types of fracture mode. The fatigue life in surface-induced fracture mode can be found to have no difference between loading modes. However, the fatigue life in subsurface-induced fracture mode obtained from the axial loading fatigue test is shorter than that from the rotary bending fatigue test. It is suggested that a reason of the difference in lifetime between them is



(a) Nital-etching (b) Electro-etching

Fig. 2. Microstructure of tested materials, JIS SUJ2.