

A new testing method for investigating the shear-mode fatigue crack growth behavior in hydrogen environment

Y Akaki¹, T Matsuo^{2,3}, Y Nishimura⁴, S Miyakawa⁴ and M Endo^{2,3}

¹Graduate School of Engineering, Fukuoka University, 8-19-1 Nanakuma, Jonan-ku, Fukuoka 814-0180, Japan

²Development of Mechanical Engineering, Fukuoka University, 8-19-1 Nanakuma, Jonan-ku, Fukuoka 814-0180, Japan

³Institute of Materials Science and Technology, Fukuoka University, 8-19-1 Nanakuma, Jonan-ku, Fukuoka 814-0180, Japan

⁴Materials Engineering R&D Division, DENSO CORPORATION, Japan, 1-1 Syowa-cho, Kariya, Aichi 448-8661, Japan

E-mail: tmatsuo@fukuoka-u.ac.jp

Abstract. Ball bearing is widely used in a variety of machines including the transportation equipments of the automobiles and airplanes. Flaking failure is a common problem for ball bearing and it is caused by shear-mode fatigue crack growth under cyclic shear stress. Further, it is known that the premature flaking is attributed to the combined effect of hydrogen penetration into the material and cyclic shear stress during the operation. Therefore, in order to ensure the integrity of ball bearing, it is necessary to clarify the effect of hydrogen on shear-mode fatigue crack growth behavior, in particular, the threshold behavior. The evaluation of the shear-mode crack growth behavior is not easy because mode I crack branching occurs easily. Our previous studies revealed that it is required to apply static compression in the direction of specimen axis to attain a stable shear-mode fatigue crack growth. In addition, successive hydrogen supply to the specimen is essential for the evaluation of hydrogen effect on the fatigue threshold because hydrogen emits from the specimen during the fatigue test. In other words, the hydrogen-precharging method, commonly used for the research on hydrogen embrittlement, is not appropriate for the evaluation of fatigue threshold. In this study, to solve these problems, we have developed a novel, easy-to-use experimental method to evaluate the threshold behavior of shear-mode fatigue crack in the presence of hydrogen. The fundamental principle of the method is introduced in this paper.

1. Introduction

A premature flaking called white structure flaking (WSF) is a crucial problem in roller ball bearings especially for automobile components, wind turbine gearboxes, etc. This WSF is attributed to rolling contact fatigue, i.e. the crack growth from a surface defect or a subsurface inclusion under the combination of cyclic shear stress and compressive stress. Some previous studies [1-10] reported that invasion of hydrogen, derived from decomposition of lubricants in operation, into the bearing steel plays a key role in WSF. Most of them conducted a rolling contact fatigue test to investigate the WSF [1-7]. On the other hand, to the authors' best knowledge, there is only a few papers [8-10] that investigate the essential shear-mode fatigue crack growth behavior in the presence of hydrogen by



utilizing torsional fatigue test. In order to understand the essential mechanism of WSF, it is necessary to clarify the effect of hydrogen on the shear-mode fatigue crack growth behavior.

Shear-mode fatigue crack initiation and growth behavior has often been investigated in torsional fatigue tests with round bar specimens. However, it is required to apply a static compression in the direction of specimen axis to attain the stable shear-mode fatigue crack growth since the Mode I branching occurs easily in pure torsional fatigue test. Fujita et al.[10] investigated the shear-mode fatigue characteristics of hydrogen-precharged bearing steel by cyclic torsion fatigue test with a static compression, and they figured out that Mode II (i.e. in-plane shear mode) crack growth rate was higher in hydrogen-precharged specimens than in uncharged specimens, involving the local microstructural change. In the fatigue test using hydrogen-precharged specimen, however, hydrogen outgassing from the specimen occurs in parallel with crack initiation and growth, and consequently, hydrogen effect cannot be evaluated precisely in a long-term fatigue test. To avoid this problem, a few institutes employ the testing in high pressure hydrogen environment. However, this method is technically difficult and expensive for most others because high-pressure gas equipment such as high-pressure vessel, piping and so on needs to be installed in a laboratory.

The objective of the present paper is to establish an easy-to-use yet reasonable method for evaluation of hydrogen effect on the shear-mode fatigue crack growth behavior. A new testing system was designed to continuously circulate hydrogen charging solution in a specimen with a through-hole in the axial direction during torsional fatigue testing and its capability was discussed.

2. Experimental set-up

2.1 Developed testing method

In order to realize continuous hydrogen-charging for the round bar specimen with a through-hole during torsional fatigue test, hydrogen-charging solution was circulated in a specimen with a through-hole using a pump, flexible tubes and special jigs, which are shown in Figure 1 and Figure 2. Hydrogen charging solution was pumped into the specimen not directly but via a L-joint, and owing to this, screw holes do not need to be introduced on the specimen surface. This is an important consideration because the screw hole on the side surface of specimen would cause combined effect of stress concentration and direct exposure to hydrogen-charging solution, and would lead to failure from itself. In addition, the through-hole was on the neutral axis where the shear stress by torque is zero, and thus the effect of the through-hole on the stress field near the test part (i.e. the side surface of specimen) can be regarded as negligible. The L-joints which are exposed directly to hydrogen-charging solution were made of type 316L austenitic stainless steel (JIS-SUS316L), a material being non-susceptible to hydrogen embrittlement.

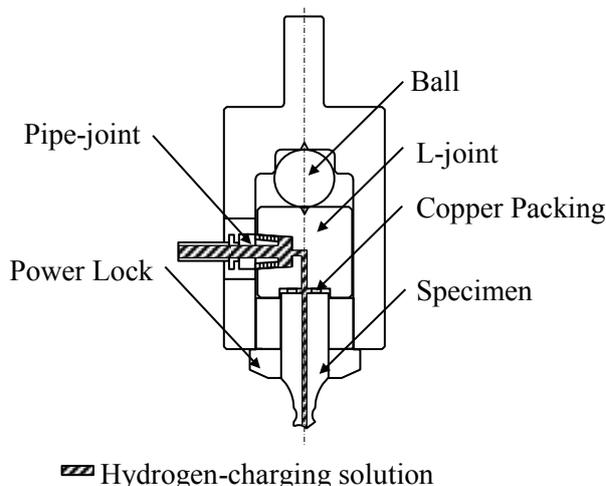


Figure 1. Cross-section view of assembled jigs.

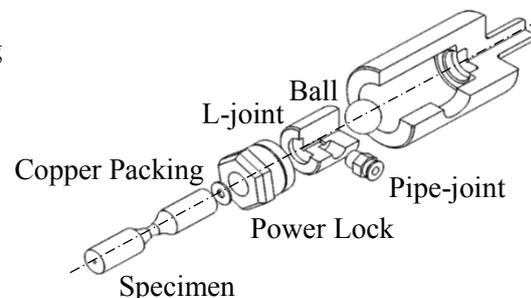


Figure 2. 3D image of jigs.

The friction-type fastener, called Power-Lock, was used to fasten the specimen to the jig. The specimen and the jigs except the Power-Lock were attached on the test machine, and a static compression was applied to them. Then, the specimen was fastened to the jig by Power-Lock. Consequently, the Power-Lock which is vulnerable to axial thrust load transmits only the torque to the specimen. A copper packing was set to prevent the leakage of solution from the space between the L-joint and the specimen by utilizing the test compression load.

2.2 Material and specimen

The material used in this study is a bearing steel, JIS-SUJ2, which is basically the same material as the ball used in a ball bearing. The shape and the dimensions of specimen are shown in Figure 3. As seen in this figure, to circulate a hydrogen-charging solution, a through-hole of 2 mm in diameter was introduced in the direction of specimen axis. Also, a shallow notch with the radius of 6.5 mm and the depth of 0.75 mm was introduced in order to localize the crack initiation. The stress concentration factor of the notch was $K_t = 1.48$ for axial loading and $K_t = 1.06$ for torsion. The notched region of the specimen was finished by buffing and electro-polishing following polishing with emery papers up to #2000. Residual stresses were measured using the X-ray diffraction method. Measurements were performed at the root of the notch before fatigue testing. The residual stresses were smaller than 5.0 MPa.

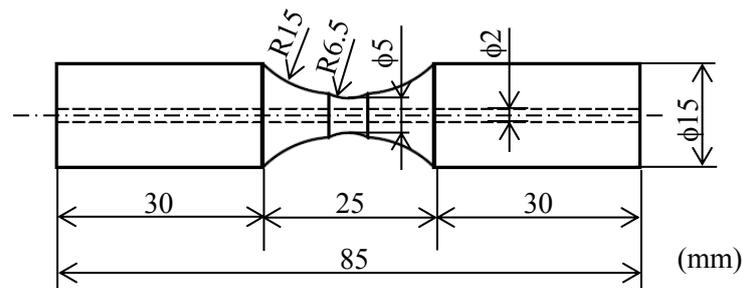


Figure 3. Fatigue test specimen.

2.3 Hydrogen-charging method

Hydrogen-charging was performed by circulation of an aqueous solution of 20 mass% NH_4SCN in a specimen. In order to achieve stable hydrogen distribution inside the specimen, hydrogen charging was started 48 h prior to fatigue testing.

2.4 Experimental condition

Fatigue tests were carried out in air at room temperature by a servo-hydraulic combined axial/torsional loading fatigue testing machine. A single specimen was used for each test under the conditions in presence and absence of hydrogen. The nominal shear stress amplitudes in cyclic torsion was $\tau_a = 1000$ MPa. A nominal static compressive axial stress of $\sigma_s = -1200$ MPa was simultaneously applied to attain a stable shear-mode fatigue crack growth. The test frequency was $f = 2$ Hz and the stress ratio was $R = -1$. Surface cracks were observed using the replica method at every scheduled number of cycles to measure the crack length.

3. Results and discussion

Several cracks were observed on the root of notches regardless of hydrogen-charging, and one of them continued propagation as a main crack. The propagation of main crack was observed successively by the replica method, which is shown in Figures 4 and 5. For both the uncharged specimen and the specimen subjected to continuous hydrogen-charging, Mode II cracks propagated axially up to a several hundred micrometers long (see Figures 4(b)-(d) and 5(b)-(d)), and then a branching from

Mode II to Mode I occurred (see Figures 4(e) and 5(e)). As shown in Figure 4(e) and 5(e), macroscopically, Mode I crack propagated in the about 45° direction with respect to the axial direction after branching and the Mode I crack eventually propagated until the final failure of specimens. Figure 6 shows the relationship between the crack length of Mode II fatigue crack, $2a$, and the number of cycles, N , for both the uncharged specimen and the continuously hydrogen-charged specimen. The number of cycles to crack initiation of continuously hydrogen-charged specimen was smaller than that of uncharged specimen. In other words, hydrogen facilitated crack initiation. In addition, the final length of Mode II crack, i.e. the crack length at the moment of Mode I branching was $256 \mu\text{m}$ for the

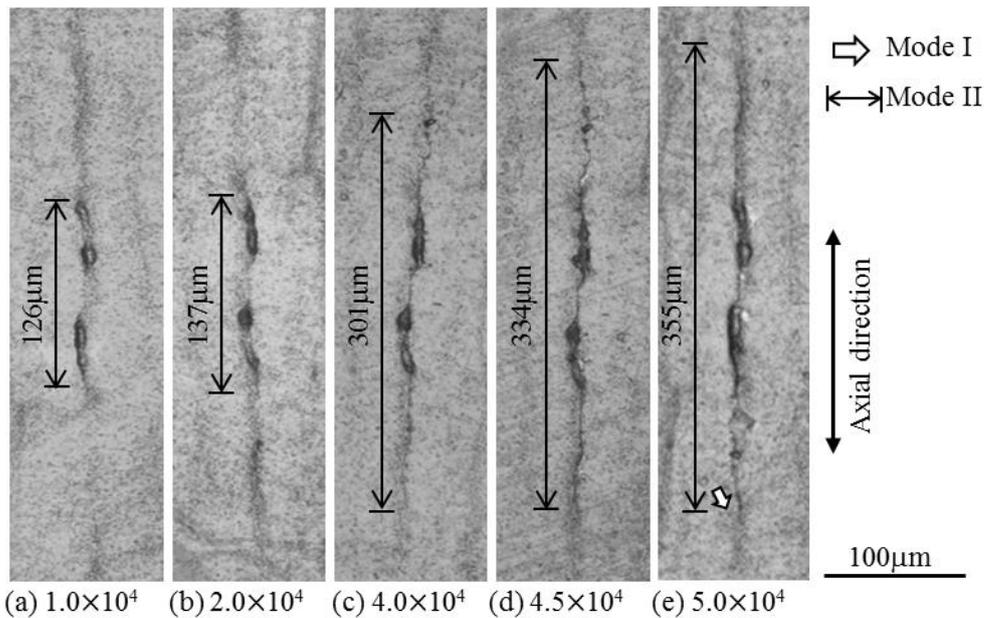


Figure 4. Mode II crack growth behavior in the continuously hydrogen-charged specimen. ($\sigma_s = -1200 \text{ MPa}$, $\tau_a = 1000 \text{ MPa}$, $f = 2 \text{ Hz}$)

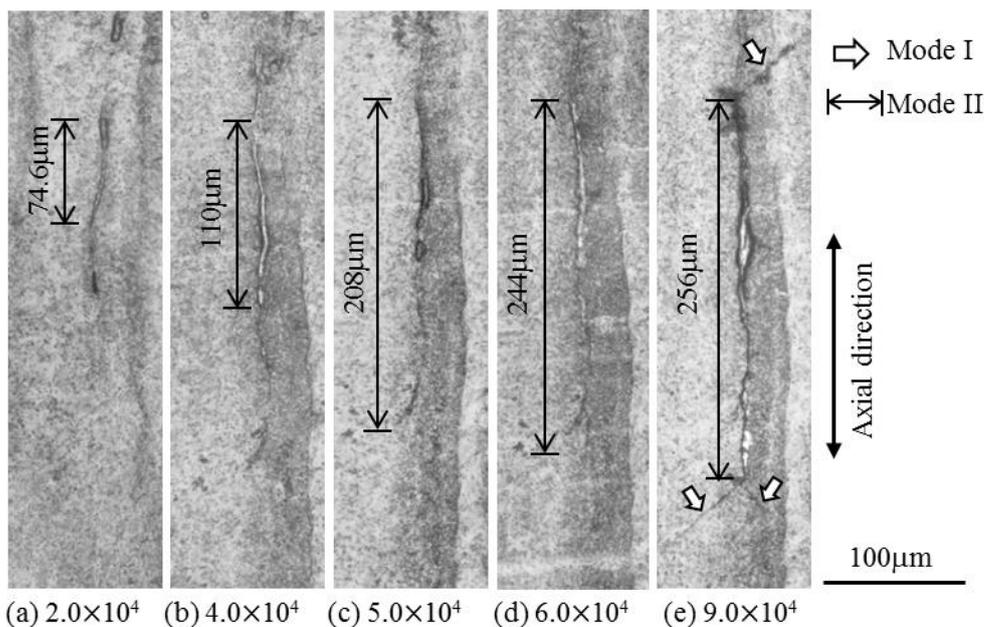


Figure 5. Mode II crack growth behavior in uncharged specimen. ($\sigma_s = -1200 \text{ MPa}$, $\tau_a = 1000 \text{ MPa}$, $f = 2 \text{ Hz}$)

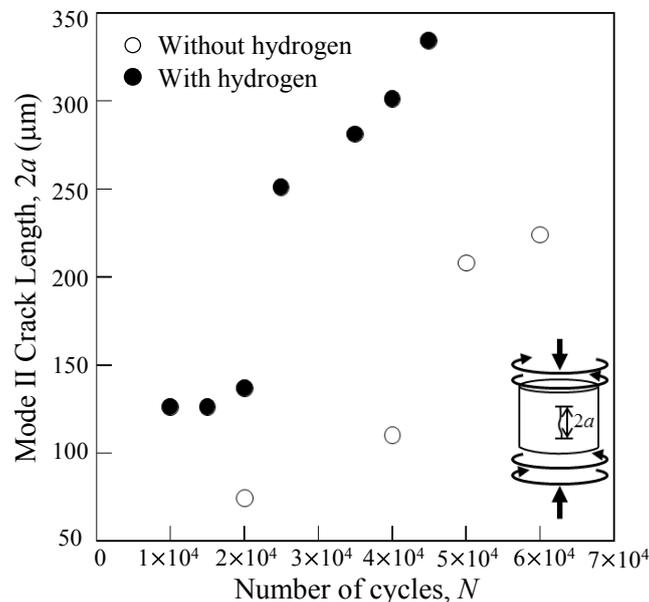


Figure 6. A comparison of Mode II crack growth behaviors between continuously hydrogen-charged and uncharged specimen. ($\sigma_s = -1200$ MPa, $\tau_a = 1000$ MPa, $f = 2$ Hz)

uncharged specimen and 355 μm for the continuously hydrogen-charged specimen as shown in Figures 4(e) and 5(e). This result suggests that hydrogen would inhibit the Mode I branching and/or enhance the stable Mode II crack growth. Regarding the Mode II crack growth rate, however, there is no remarkable hydrogen effect. As seen in Figure 6, it appears that the Mode II fatigue crack growth rate was slightly faster for the continuously hydrogen-charged specimen than for the uncharged specimen, but it is hard to say that there is the marked difference in crack growth rate between these two specimens because of the short crack growth distance, i.e. a small number of data. In contrast, regarding Mode I crack growth after Mode I branching, the crack growth rate was markedly accelerated by hydrogen. Unfortunately, no crack growth data was obtained because the extremely fast crack growth caused the unexpected failure of the hydrogen-charged specimen.

Fujita et al. [10] conducted torsional tests with a static axial compression using hydrogen-precharged specimens and they pointed out the crack initiation was earlier and the Mode II and Mode I fatigue crack growth rate was higher for the hydrogen-precharged specimen than for the uncharged specimen. According to their results, additionally, it can be seen that the final length of Mode II fatigue crack in the hydrogen-precharged specimen was slightly longer than that in the uncharged specimen, though they did not remark it. This result obtained using hydrogen-precharged specimen by Fujita et al. is similar to that obtained in this study using continuously hydrogen-charged specimen. Therefore, it can be concluded that the novel testing method developed in this study has a capability comparable to a conventional precharging method. In case of a long-term test such as a fatigue test to evaluate a fatigue threshold and a test at extreme low frequency, the new testing method may have an advantage over the conventional precharging method, because the effect of hydrogen outgassing from a specimen during a test is not negligible in the conventional precharging method.

4. Conclusions

A new testing method of torsional fatigue test with a superposed static compression using continuously hydrogen-charged specimen was developed. The following conclusions are drawn up:

1. The number of cycles to crack initiation for continuously hydrogen-charged specimen was smaller than that for uncharged specimen.
2. It appears that the Mode II fatigue crack growth rate was accelerated slightly by continuous hydrogen-charging.
3. The final length of Mode II crack, i.e. the crack length at the moment of Mode I branching, was 256 μm for uncharged specimen and 355 μm for hydrogen-charged specimen. Hydrogen would inhibit the Mode I branching and/or enhance the stable Mode II crack growth. However, Mode I crack growth after mode I branching was markedly accelerated by hydrogen.
4. The newly developed testing method in evaluating hydrogen embrittlement has a capability comparable to or would rather be better than the conventional precharging method.

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