ROLLING CONTACT FATIGUE OF BEARING STEEL IN HYDROGEN ENVIRONMENT

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INTRODUCTION
In the future renewable energy systems where hydrogen is used as secondary energy carrier, bearings, seals, and valves may operate in hydrogen. It is important in ensuring reliability and safety to know any deviation of their tribological behaviors from those in normal atmosphere. It is well known that hydrogen causes embrittlement in many of commercially available steels, and the bearing steels are not the exception.

Hydrogen affects rolling contact fatigue even in normal environment. Rounds [1] suggested that thermal cracking of oil produced hydrogen in rolling element bearings, which caused hydrogen embrittlement. Grunberg [2] indicated that the penetration of hydrogen accelerated pitting failure, and that lubricant additives affected the penetration of hydrogen. Recently, establishment of steels of higher purity has afforded longer fatigue life, though ultra-long life fatigue occurs at lower stresses than the conventional fatigue limit. On the other hand, in shorter cycle fatigue in rolling element bearings, hydrogen embrittlement is often associated with the extremely fine crystal grains of ferrite named white etching area, WEA. In order to see how hydrogen causes such crystallographic changes, fatigue tests are often conducted with specimens that are chemically charged with hydrogen. However, little work has been reported in the literature on rolling contact fatigue in hydrogen environment except for the four-ball tests by Ciruna and Szieleit [3], and Endo et al. [4].

In this study, rolling contact fatigue of bearing steel is studied with three-ball-on-disk tests. Fatigue life in hydrogen is compared with those in air and in nitrogen under a range of contact conditions.

EXPERIMENTAL
A three ball-on-disk type apparatus shown in Fig.1 is used. Balls and disks are made of JIS SUJ2 steel, which is equivalent to AISI 52100. Disk specimen is mounted on the upper rotating shaft, while the ball specimens are guided by a race of a thrust ball bearing which is fixed at the bottom of a chamber. The chamber is pushed upward by a loading arm such that normal load is applied between the balls and the disk. Test conditions are shown in Table 1. In all the tests, a paraffinic mineral oil P60 is used. The oil is filled in the chamber either to ‘low level’ so that the balls are half immersed in the oil, or to ‘high level’ so that both the balls and the upper disk are submerged in the oil. The upper disk surfaces are finished either by polishing or grinding, which give the dimensionless film thickness \( \Lambda \) of 3 and 0.3, respectively. Hydrogen, air and nitrogen are used as test gases. The gases are blown in the lower part of the chamber and vented out from the upper part of the chamber. Purge with nitrogen and then with the test gas

Table 1 Experimental conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Series A</th>
<th>Series B</th>
<th>Series C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A ratio</td>
<td>3.0</td>
<td>3.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Maximum Hertzian pressure [GPa]</td>
<td>4.0 5.0 5.5 6.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Oil level</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Temperature of lubricant</td>
<td>333 K</td>
<td></td>
<td>P60 @ 333 K</td>
</tr>
<tr>
<td>Lubricant</td>
<td>P60 @ 44 mm/s @ 333 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas flow</td>
<td>30 m/min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational speed</td>
<td>1500 rpm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact track diameter</td>
<td>43 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ball diameter</td>
<td>6.35 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
is carried out for one hour before each test. Vibration sensor detects the occurrence of flaking on the specimen surfaces. At least three tests in the same condition are conducted.

RESULTS AND DISCUSSION

Effect of contact pressure with low oil level

In the case of the Hertzian contact pressure of 4 GPa, which gives elastic contact between the specimens, no flaking occurs for 1.4×10^5 cycles in all the three environmental gases. Flaking occurs as the contact pressure increases.

Under the Hertzian contact pressure of 5 GPa, air gives slightly longer fatigue life than other gases. Differences in fatigue life for the three gases are much clearer at Hertzian pressures of 5.5 and 6 GPa, where air gives the longest fatigue life and nitrogen gives the shortest. Figure 2 shows the Weibull plot of fatigue life in the Hertzian contact pressure of 6 GPa. In most of the tests, flaking has occurred on the upper disk specimens.

The shorter life in hydrogen than in air agrees with the results by Endo et al. [4], and can be ascribed to the generally accepted effect that some crystallographic changes in the solids by hydrogen accelerate fatigue crack growth. However, it is rather striking to see that nitrogen gives the shortest life; nitrogen has been chosen in this study as an inert gas. In order to understand these differences in the fatigue life, other relevant processes regarding lubrication by the oil in combination with the environmental gases have to be investigated. Firstly, how much are the environmental gases dissolved in the oil? Under the ambient pressure, the solubility in the oil depends on the gas. Also, even in the tests in nitrogen and in hydrogen, a small amount of contents of air has been found to remain in the oil. Secondly, how the dissolved gases affect fluid flow in the chamber and hydrodynamic film formation? Thirdly, how the gas contents in the oil adsorb and react with the contacting surfaces to affect lubrication and surface damages? Oxide formed on the surfaces may work as boundary film and at the same time promote or prevent crack initiation.

![Figure 2](image-url)

**Figure 2**  Weibull plot of fatigue life for Series A at the Hertzian pressure of 6GPa

Effect of oil level

In order to see if there is any effect of the amount of the oil, tests with ‘high oil level’ are conducted. Figure 3 shows the results at 6 GPa. Fatigue life in nitrogen in this set of tests is significantly longer than that with the low oil level, and is almost the same with that in air as anticipated. Hydrogen gives shortest fatigue life among the three test gases.

The difference in the fatigue life with different amount of oil suggests the difference in the condition of lubrication, particularly in the cases with nitrogen. Further work is in progress to investigate what and how nitrogen, and residual oxygen, do in fluid and/or boundary film formation.

![Figure 3](image-url)

**Figure 3**  Weibull plot of fatigue life for Series B

Effect of surface roughness

In order to look at fatigue under severer mixed lubrication conditions, tests at Λ=0.3 are conducted at 6 GPa. In the case of Λ=0.3, the fatigue life in all gas is less than 1.0×10^6 cycles, which is far shorter than those at Λ=3 in air and hydrogen. In addition, no significant difference in fatigue life can be found for three gases. The cracks appear to propagate along ground trace on the disk surfaces, which implies that these failures have originated at the surfaces. It is likely that, in such severe conditions, asperity interaction predominates in causing the flaking failure over the other possible effects by environmental gas.

CONCLUSIONS

The rolling contact fatigue of the bearing steel are studied in hydrogen, nitrogen and air with the three-ball-on-disk machine. Fatigue life is shorter in hydrogen than in air at Λ=3 and the contact pressure higher than 5GPa. There is negligible gas effect at Λ=0.3. Environmental gases affect fatigue life not simply through the changes in material properties as hydrogen embrittlement, but also through changes in lubrication conditions.

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REFERENCES