Tribological Behaviours of Lotus-Type Porous Cast Iron

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Tribological behaviours of lotus-type porous cast iron under oil lubrication were investigated with reciprocal motion friction testing equipment. Lotus-type porous cast iron was fabricated by unidirectional solidification in mixture gas of hydrogen and argon at high pressure up to 2.8 MPa. The porosity is controlled by partial pressures of hydrogen and argon during melting and solidification. The friction coefficient was improved by about 20%, and the seizure resistance was also improved by about double, and the abrasion resistance was decreased by about 20%, compared with that of non-porous cast iron. Thus, such improvement of wear resistance and seizure resistance of lotus cast iron may be attributed to the hardness and tribological behaviour of lotus-type porous cast iron.

Keywords: tribological behaviour, cast iron, porous metals, friction coefficient, seizure resistance, lotus-type metals

1. Introduction

Environmental problems are very important issues on the earth, and the reduction of carbon dioxide is executed worldwide. In each industry, various measures are carried out against such problems. For example, reduction of vehicle weight, air resistance and friction of slide parts have been taken for the purpose of improvement in fuel consumption of automobiles. Many sliding parts in the automobile, such as gears and pistons are rubbed under oil lubrication. Under oil lubrication, the slide material, the condition of material surface and the lubrication are mentioned as factors which influences the tribological behaviour. Many studies, such as adaptation of low friction material, concavo-convex processing to the surface¹,²) and an increasing of the amount of lubrication oil, have been made to improve and control the tribological behaviour.

Porous metal contains the countless pores and huge surface area which are not involved in the usual bulk metals. Therefore, it is apparent that surface and lubrication conditions of porous metals are very different from those of the usual bulk metals. Recently, porous metals were fabricated by various methods, such as casting, powder metallurgy process, and electroplating method³,⁴) They have been developed for the application such as impact-absorbing material, a heat exchanger, sound absorption material, artificial bone, etc.

Most of porous metals have isotropic properties because of their spherical pores. Those would be easy to generate cracks by stress concentration if the load was applied. However, the porous metals called as lotus-type ones which Shapovalov⁵) and Nakajima⁶) developed, have pores aligned in the direction of solidification. The lotus-type porous metals exhibit strong anisotropy in the mechanical properties. The strength parallel to the pore growth direction is much higher than that perpendicular, whose specific strength does not change by pore existence. This is because no stress concentration occurs. Thus, the strength of the lotus metals is superior to that of foamed metals and sintered metals. By the way, the light weight materials with small inertia are expected for slide parts in the vehicle engine cylinders. The lotus metals may be suitable candidate for such slide parts with large load. The lotus-type porous metals can be fabricated by utilizing the hydrogen solubility gap between solid phase and liquid phase.⁵,⁶) Various lotus-type porous metals, for example, copper, nickel, magnesium, aluminum, etc.⁷) were fabricated until now. Although various properties such as mechanical properties, sound absorption, vibration-damping, thermal conductivity, electrical conductivity, biocompatibility etc., have been studied, investigations of tribological behaviour have not been studied until now.

In this study, the tribological behaviour of porous cast iron under oil lubrication was investigated and the adaptation possibility of lotus metal to the slide parts is discussed.

2. Experimental Procedure

2.1 Fabrication of porous cast iron

The chemical composition of cast iron is listed in Table 1. This material is normally used to automobiles. Figure 1 shows a schematic drawing of the unidirectional solidification casting apparatus for fabricating a lotus-type cast iron. The apparatus consists of a melting part and a mold part, and both of them are installed in a high-pressure chamber. The melting part consists of the radio-frequency induction coil for heating and the iron in the alumina crucible. On the other hand, the mold part consists of a water-cooled copper chiller bottom and a stainless steel side wall with 0.1 mm thickness.

The cast iron was put into the alumina crucible in the chamber and melted by radio-frequency heating in a vacuum at 10⁻³ Pa. After the cast iron was completely melted and the temperature rose up to 1673 K, the mixture gas of hydrogen and argon was introduced into the chamber to a given pressure. After holding the cast iron melt at 1673 K for 300 s to dissolve hydrogen uniformly, the melt was poured into the mold by rotating the chamber by 90 degrees as shown in Fig. 1(b).

<p>| Table 1 Chemical composition of cast iron (mass%). |</p>
<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.23</td>
<td>2.09</td>
<td>0.81</td>
<td>0.03</td>
<td>0.05</td>
<td>0.46</td>
<td>0.30</td>
<td>bal</td>
</tr>
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</table>
The dimensions of the ingot were about 25 mm in diameter and 30 mm in height. The ingots contained various level of porosity that was controlled by the partial pressures of hydrogen and argon. The conditions of gas pressure are listed in Table 2. The ingots were cut in halves with a wire electrical discharge machine in order to observe the structure of cross section plane parallel to the solidification direction. Then the half pieces were cut perpendicular to the solidification direction at the position 2 mm from the bottom. In order to determine the porosity, this cross section was analyzed using a personal computer with an image processing program (Winroof, Mitani Corp.). The cross sections were observed under an optical microscope (Model PMG3, Olympus Co.), and micro Vickers hardness (Model AVK, Akashi Seisakusyo Co.) was measured under a load of 98 N.

2.2 Tribological tests

Specimens for tribological tests were fabricated in the mixture gas of 0.5 MPa of hydrogen and 1.5 MPa of argon. The dimensions of ingot were about 100 mm in diameter and 20 mm in height. The ingot was cut into specimen with a wire electrical discharge machine. The dimensions of specimen were 15 mm in width, 65 mm in length and 1 mm in height. The surface of specimens was polished by emery papers in order to keep the given roughness.

It is known that the surface roughness may affect the tribological behaviour under the lubrication. For this reason, the surface roughness of test pieces was set constant, while the pin test pieces were 0.1 \( \mu m \) \( R_a \), and the block test pieces were 0.6 \( \mu m \) \( R_k + Rpk \). The roughness index \( R_k \) and \( Rpk \) are based on the standard (ISO13565-2), where \( R_k \) shows the depth of the roughness core profile, and \( Rpk \) shows the average height of protruding peaks above the roughness core profile. \( R_k + Rpk \) shows the surface roughness in the area excluding the pores. The surface roughness of the porous cast iron measured using \( R_a \) is larger than that of contact surface, because the depth of pore influences the calculation of \( R_a \). For this reason, \( R_k + Rpk \) were adopted as a surface roughness of the porous cast iron.

The tribological behaviours were investigated with the reciprocation type friction tester, as shown in Fig. 2. The tribological tests were performed using the block test piece of porous iron, and the pin test piece of low-carbon steel. The block test piece was fixed to the block holder which reciprocates at given rotation frequency, while the pin test piece was fixed to a pin holder, and applied the given load by spring. The applied load was measured with a load cell. The friction force of the pin was measured with a load cell behind the pin holder, and friction coefficient was the division of friction force by load.

In this study two types of tribological tests were performed. A friction coefficient and abrasion resistance were measured by the friction test, while a seizure resistance was measured by the seizure test. Both tests were carried out under oil lubrication.

The friction test was performed at ambient temperature (298 K), where the applied load was 98 N. The rotation frequency was 500 rpm, which corresponded to a slide speed of 0.67 m/s. The test was carried out for 1800 s. The friction coefficient was determined by the average during the test. The maximum depth of wear track was compared as an abrasion resistance.

The seizure test was conducted at ambient temperature (298 K), and the applied load was increased 49 N at every 180 s from initial load 49 N to final load 490 N. Other conditions were the same to those of the friction test. The test was finished, when the seizure occurred or applied load was increased to the final load 490 N. The seizure load was compared as a seizure resistance.

3. Results and Discussion

3.1 Dependence of porosity on gas pressure

Figure 3 shows the optical photographs of the cross

Table 2 Condition of total pressure \( P_{total} \), partial pressure of hydrogen \( P_{H_2} \), and partial pressure of argon \( P_{Ar} \) in this study.

<table>
<thead>
<tr>
<th>Method</th>
<th>Unidirectional Solidification Casting</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{total}/MPa )</td>
<td>0.5 1.0 2.0 2.5 2.8 2.0 2.0 2.0 2.0 2.0</td>
</tr>
<tr>
<td>( P_{H_2}/MPa )</td>
<td>0.5 0.5 0.5 0.5 0.5 0 2.0 0.5 0.3 0.1</td>
</tr>
<tr>
<td>( P_{Ar}/MPa )</td>
<td>0 0.5 1.5 2.0 2.3 2.0 2.0 0 1.5 1.7 1.9</td>
</tr>
</tbody>
</table>

Fig. 1 Schematic drawing of the unidirectional solidification casting apparatus for fabricating the lotus-type cast iron (a) during melting and (b) after solidification.

Fig. 2 Schematic drawing of the apparatus for reciprocation type friction test.
The lotus-type porous cast iron with high carbon content was made with hydrogen gas. Figure 4 shows the porosity of lotus-type porous cast iron as a function of partial pressure of argon at a given hydrogen pressure of 0.5 MPa. The porosity was found to be affected by the partial pressure of argon. The porosity decreases with increasing partial pressure of argon, and can be controlled from 1 to 40%.

Figure 5 shows the diameter of pore as a function of partial pressure of argon at a given hydrogen pressure of 0.5 MPa. The diameter of pore decreases with increasing partial pressure of argon. Nakajima and co-workers explained the relation between porosity and gas pressure from the Sieverts’ law about the gas solubility in metal, and the Boyle’s law about pressure and volume of gas. The volume of pore, \( V \), can be described as

\[
V = \frac{4\pi r^3}{3},
\]

where \( r \) is the diameter of pore. The pressure dependence of porosity observed in Fig. 4 is understood by eq. (4). The pressure dependence of diameter of pore observed in Fig. 5 is understood by eqs. (3).

\[
\frac{\partial V}{\partial P_{H_2}} = \frac{2}{P_{H_2}} \left( \frac{(k_1 - k_s)}{P_{H_2} + P_{Ar}} \right) \frac{1}{3},
\]

where \( k_1, k_s, P_{H_2}, P_{Ar}, R \) and \( T_n \) are the equilibrium constant in the liquid phase and in solid phase, partial pressure of hydrogen and argon, the gas constant and the temperature at which liquid phase change into solid and gas phase by the gas-crystallization reaction. The form of a pore is assumed to be a sphere. The volume of pore, \( V \), is described as

\[
V = \frac{4\pi r^3}{3},
\]

where \( r \) is the diameter of pore. The pressure dependence of porosity observed in Fig. 4 is understood by eq. (4). The pressure dependence of diameter of pore observed in Fig. 5 is understood by eqs. (3).
3.2 Tribological behaviour

Table 3 shows the tribological behaviour of lotus-type porous cast iron and non-porous cast iron under oil lubrication. It is clear that the friction coefficient of lotus-type porous cast iron is lower than that of non-porous cast iron. The friction coefficient of porous cast iron is 0.069, which is 20% smaller than that of non-porous cast iron. As shown in Table 3, the wear depth of lotus-type porous cast iron is 0.88 μm, while that of non-porous cast iron is 1.10 μm. The abrasion resistance of lotus-type porous cast iron is superior by 20% to that of the non-porous iron. The seizure load of lotus-type porous iron is 490 N, which is about double of non-porous iron. Therefore, the seizure resistance of porous cast iron is superior to that of the non-porous cast iron.

The microstructure of porous cast iron is mixed structure of cementite and pearlite as shown in Fig. 6, where graphite flakes is not found. On the other hand, non-porous cast iron has only pearlite and graphite. The hardness of porous cast iron is 570 Hv, which is about 2.5 times of non-porous cast iron. Thus, the improvement of wear resistance and seizure load may be attributed to the increase in hardness due to change of the microstructure and an improvement of the lubrication state by lubricating oil held by pores. At present, it is not apparent to distinguish which effect is dominant.

The lubrication state can be divided roughly into three; the fluid film lubrication through lubricating oil, the boundary lubrication which an oil film breaks off and solid contact is occurred, and the mixed lubrication. Generally, it is well known that the friction coefficient is the lowest under the fluid film lubrication, while the highest is under the boundary lubrication.

Slide speed is one of the important factor which influences the lubrication state. The lubrication state becomes severe when slide speed is slow. In this study the coefficient of friction is measuring the static friction at the time of the pin beginning to slide. For this reason, the lubrication state of this part is severe. Under the severe lubrication state, it is presumed that the lubrication oil held in pore was supplied to the sliding surface. The presumed mechanism is shown in Fig. 7. Lubrication oil on the surface of porous cast iron is held in pores. The pin specimen applies pressure to the oil held in the pore during the test.

The oil held in pores supplies to the surface lubricates the pin specimen. Thus, the lubrication state is improved and this is why the lotus-type porous cast iron showed low friction and high seizure resistance on the same slide conditions as compared with non-porous cast iron. The improvement of tribological behaviour was reported also in the study of mechanical seal.\(^\text{10}\) It was reported that domain of fluid film lubrication spreads on the porous surface. Although this study is inadequate, it can be supposed that tribological behaviours change with the porosity and the diameter of pores. The research by Wang and Yokoi\(^\text{11}\) investigated the influence of porosity and diameter of pore on the friction between tool and metals. The lubricating effect of the pores become larger\(^\text{11}\) with increasing porosity or decreasing pore size.

It can be expected that tribological behaviour of porous cast iron improves further, when the diameter of a pore and the porosity were controlled to suitable value. Although further investigations are necessary in order to find lower friction characteristics under oil lubrication using the lotus-type porous cast iron, it is expected from the present study that the application of lotus metals to sliding parts and other parts will be possible.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Friction coefficient</th>
<th>Wear depth (μm)</th>
<th>Seizure load (N)</th>
</tr>
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<tbody>
<tr>
<td>Porous (porosity 10%)</td>
<td>0.069</td>
<td>0.88</td>
<td>490</td>
</tr>
<tr>
<td>Non-porous</td>
<td>0.086</td>
<td>1.10</td>
<td>220</td>
</tr>
</tbody>
</table>

Fig. 6 Optical micrograph of (a) non-porous cast iron (b) lotus-type porous cast iron.

Fig. 7 Schematic drawing of oil supply mechanism.
4. Summary

Lotus-type porous cast iron was fabricated by unidirectional solidification method in a mixture gas of hydrogen and argon gases. Tribological behaviours of lotus-type porous cast iron under oil lubrication were investigated. The results are as follows:

(1) The friction coefficient of lotus-type porous iron decreased by 20% as compared with that of non-porous iron.
(2) The seizure load of lotus-type porous cast iron was double of the non-porous cast iron.
(3) The wear resistance of lotus-type cast porous iron was superior to that of non-porous by about 20%.

REFERENCES