Improvement of Wear Characteristics of Metal-on-Metal Artificial Hip Joint by Means of Magnetic Field* (Influence of Alternating Current Magnetic Field)

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The possibility of wear control in Metal-on-Metal artificial joints has been investigated by using a uni-directional sliding tester and a reciprocating pin-on-plate tester. The mechanism to reduce the amount of wear was the promotion of oxidization of bearing surfaces by means of externally applied magnetic field. Bearing materials were austenitic stainless steel (SUS304, SUS316) which are paramagnetic materials. In uni-directional wear tests of SUS304 sliding on SUS304 and SUS316 on SUS316 in atmosphere of air, the reduction in the amount of wear was observed by means of magnetic field, if the influence of the magnetic field horizontal to the surfaces, which enhances wear rate, could be avoidable. The magnetic field, however, deteriorated the wear characteristic or obstructed the severe to mild transition in the tests where sliding materials were SUS304 on SUS316 and SUS316 on SUS304. The influence of magnetic field, which reduces the amount of wear of SUS316 on SUS316, was confirmed in water-based lubrication (distilled water, saline solution with and without proteins) and reciprocated sliding. The influences of magnetic field were varied by the constituents of lubricant (chlorine ion, proteins).

Key Words: Magnetic Field, Paramagnetic Material, Severe Wear, Mild Wear, Oxidation, Metal-on-Metal Artificial Joint, Mixed Lubrication, Proteins

1. Introduction

Total joint replacement has been crowned with great success in orthopedic surgery, which can remove functional disorder and pain derived from skeletal lesion and arthritis. Once osteolysis induced by wear particles has been recognized as one of the major causes of long-term failure in total joint replacement⁽¹⁾⁻⁽³⁾, a new call was made for the development of a better understanding of the wear processes

in implants and even greater reductions in the wear rates of sliding pairs in implants⁽⁴⁾⁻⁽¹¹⁾.

In recent studies concerned with the clinical wear behavior of metal-on-metal hip joint replacements⁽¹¹⁾, metal-on-metal articulation has taken some important steps of improvement in friction and wear mechanisms. The authors^{(13),(14)} studied the tribological characteristics of metal-on-metal joints and concluded that the adsorbed layer of proteins on metallic bearing surface acted as the boundary lubricating film and reduced the wear.

The core of the present paper is the wear of metallic bearing surface in the condition where considerable local contacts between two bearing surfaces cannot be avoided. Adhesive wear is one of the representative wear mode, and this can be divided broadly into two categories; severe wear and mild wear.

The effectiveness of technique of applying an magnetic field to bearing surfaces has been already

* Received 29th March, 1999. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 64, No. 626, C (1998), p. 3952-3958 (Received 22nd December, 1997)

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confirmed for the controlling of wear in the application for industrial use. Hiratsuka et al.⁽¹⁵⁾ investigated the magnetic field effects on wear of ferromagnetic materials (Fe, Ni), and showed that the magnetic field accelerated the severe to mild wear transition in air. The result was explicated by the mechanism that the magnetic field activated the chemisorption of oxygen to the metals. Kumagai et al.⁽¹⁶⁾ proposed the another mechanism, in which the magnetic field produced fine wear particles because of both promotion of oxidation and attraction of the particles to bearing surfaces. Although the effectiveness of the magnetic field depended on the sliding velocity^{(17)–(19)}, the effects were confirmed even in sliding pair of stainless steel (SUS304 or SUS316) which was paramagnetic material^{(20),(21)}.

In general, the magnetic field does not affect the wear of demagnetised bearing surfaces, but there are the conditions where the magnetic field deteriorates the wear characteristic in bearing material combination between ferromagnetic and paramagnetic materials. Kumagai et al.⁽²²⁾ investigated wear characteristics for various metallic pins sliding on the rotator fabricated from a stainless steel (SUS304), and indicated that the balance of Vickers hardness between the bearing surface and the wear particle decided whether the magnetic field increases or decreases the wear. The magnetic field effects have been also observed in lubricated condition. Yamamoto et al.⁽²³⁾ examined the magnetic field effects on boundary lubricating performance of carbon steel with oils containing polar substances, and showed that the resistance of the boundary films to thermal disturbance was enhanced in the presence of the magnetic field.

This paper is intended as an investigation of the wear-control of Metal-on-Metal sliding pair by means of the magnetic field in mixed lubrication regime. This paper takes notice of the following three essential points. The first point to be discussed is the wear characteristic of a paramagnetic material (stainless steel) in the presence of the magnetic field. The next point is the influence of proteins on wear characteristic of a stainless steel. The final point is the influence of the water-based lubrication containing synovial fluid constituents on the magnetic field effects.

2. Materials and Methods

2.1 Influence of magnetic field on wear characteristics in unlubricated condition

Effect of the magnetic field on wear characteristic of paramagnetic materials (stainless steels) was investigated by using a uni-directional pin on plate

Table 1 Test conditions (uni-directional motion)

Load [N]	17.6 , 27.4
Sliding velocity [mm/s]	8.4 ~ 70
Offset [mm]	2.5 ~ 10
Lubricating condition	Dry, Distilled water
Temperature [°C]	22 ± 2
Magnetic-flux density [mT]	0 , 4 (60Hz)

Fig. 1 Schematic representation of pin on plate tester (1) (uni-directional motion)

tester shown in Fig. 1. The test conditions are listed in Table 1. To make the magnetic field effects clear, both a constant contact pressure and a constant uni-directional sliding velocity were applied in unlubricated condition. The offset value indicated the radius of weartrack center. The pin was fastened into a magnet coil and jutted out at 7.5 mm length. The magnet coil generated the external alternative current (AC) magnetic field whose frequency was 60 Hz. The magnitude of the field on the pin surface (without contact with the plate) was 4.0 mT.

2.2 Influence of water-based lubrication on magnetic field effects

Figure 2 shows a reciprocating pin-on-plate tester. The test conditions are listed in Table 2. The AC magnetic field (60 Hz) whose magnitude was 1.5 mT was generated by a couple of magnet coils (Helmholtz coil). The bearing surface after the test was analyzed through EPMA (Electron Probe Microanalysis, Energy Dispersive X-ray spectroscopy, acceleration voltage: 25 kV).

2.3 Bearing materials

Figure 3 shows geometries of test specimens. The bearing materials were two kinds of austenitic

Table 2 Test conditions (reciprocating motion)

Load [N]	3.92 ~ 68.6 (0.2 ~ 3.5 MPa)
Stroke [mm]	20
Period [s]	1
Lubricating condition	<ul style="list-style-type: none"> • Dry • Distilled water • Saline solution • Saline solution of Proteins (1.0wt% albumin + 0.3wt% γ-globulin)
Temperature [°C]	22 ± 2
Magnetic-flux density [mT]	0, 1.5 (60Hz)

Fig. 2 Schematic representation of pin on plate tester (2) (reciprocating motion)

Fig. 3 Test specimens

stainless steels. One was SUS304 (JIS, HV : 185) that contained 18Cr-8Ni, another was SUS316 (JIS, 18Cr-12Ni-2.5Mo, HV : 190). Although Co-Cr alloy are ordinarily used as bearing material in current metal-on-metal joint prostheses, the stainless steel (SUS316) provided in this and previous studies^{(13),(14)} has almost the same composition except carbon content as the prosthetic material (SUS316L) that is clinically used. A carbon steel (S45C, JIS, 0.45C-

Fig. 4 Influence of magnetic field on wear characteristics of S45C on S45C

0.75Mn-0.25Si, HV : 199) which was a ferromagnetic material was also used as a screening material. The bearing surfaces were polished to a surface finish of $R_{rms}=0.02 \mu\text{m}$.

3. Results and Discussion

3.1 Influence of magnetic field on wear characteristics in sliding pair of S45C

Figure 4 shows the results in sliding pair of carbon steels (S45C) in uni-directional sliding and unlubricated conditions. If ferromagnetic materials are used as both bearing materials, the attraction between the surfaces comes into play. The attraction in this test, however, was not so obvious because the magnetic-flux density was low (4 mT). Remarkable decrease in wear was observed in the presence of the magnetic field in both two sliding speed and offset conditions, indicating that the pin on plate tester fulfilled the function for investigation of unsolved subjects about magnetic field effects on paramagnetic bearing materials.

3.2 Influence of magnetic field on wear characteristics in sliding pair of SUS304

Figures 5 and 6 show the results in the pair of stainless steels (SUS304). The magnetic field decreased the wear of pins and, in particular, the severe to mild wear transition was confirmed in the offset value of 2.5 mm (Fig. 6). The wear of plate seemed to be decreased by the magnetic field in the offset value of 2.5 mm, but the magnetic field increased or did not affect the wear of plate in offset value of 5 mm (Fig. 5).

As shown in Fig. 4, it is known that the externally applied magnetic field vertically to the bearing surfaces accelerates the severe to mild wear transition of ferromagnetic metals. In contrast, it is also apparent that the magnetic field horizontal to the surfaces enhances the specific wear^{(17),(18)}. Stainless steel is,

Fig. 5 Influence of magnetic field on wear characteristics of SUS304 on SUS304 (1)

fundamentally, paramagnetic material, implying that it is not magnetized. If the sliding process causes the stress-induced martensitic transformation, it is possible that the stainless steel surface is magnetized. Thus the magnetic field effects on wear characteristic seemed to be observed in sliding pair of stainless steels⁽²⁰⁾. The transformed layer into the martensitic structure on the stainless surface is thought to be thin, so that the wear characteristic may be subject to the effect of the magnetic field horizontal to the bearing surfaces in the application of the multidirectional magnetic field. In the uni-directional tester shown in Fig. 1, the magnetic field was generated by the magnet coil which fixed a pin specimen. Therefore, the magnetic field was applied vertically to the worn surface of the pin, whereas the magnetic fields seemed to be applied both vertically and horizontally to the wear track on the rotating plate. It might be the reason why the increase in wear of plate was often observed in the application of the magnetic field.

3.3 Influence of magnetic field on wear characteristics in sliding pair of SUS316

Figure 7 shows the results in the pair of stainless steels (SUS316). The SUS316 pin gave a wear which is larger than that of SUS304 pin (Fig. 6). The wear of SUS316 plate was slightly smaller than that of SUS304 plate. These results suggest that SUS316 and SUS304 differ in the oxidative character in rubbing condition; SUS316 may have a poorer oxidative ability than SUS304 in the severe rubbing condition where the pin bearing surfaces suffers. However, SUS316 has a better oxidative ability than SUS304 in the mild

Fig. 6 Influence of magnetic field on wear characteristics of SUS304 on SUS304 (2)

Fig. 7 Influence of magnetic field on wear characteristics of SUS316 on SUS316

rubbing condition where the plate bearing surfaces suffers. These hypotheses serve as explanations of the magnetic field effects. The oxidation of the pin bearing surface was promoted by the application of magnetic field, so that the wear was decreased. The plate bearing surface formed the sufficient oxidized layer even in the absence of magnetic field, so that the magnetic field effects were not so obvious.

As shown in Fig. 7(B), once more increase in the wear of pin was observed after the end of severe-mild wear transition in the presence of magnetic field. The reason may be that the oxidized layer on the bearing surfaces in sliding pair of SUS316 is not always steady⁽²⁰⁾.

3.4 Influence of magnetic field on wear characteristics of SUS316 against SUS304

Wear characteristics of SUS316 sliding against SUS304 with or without the magnetic field are plotted in Fig. 8. The magnetic field effects seemed to be dependent on the sliding velocity. This dependency was more evident for SUS316 pin sliding on SUS304 plate. In 20 mm/s, the magnetic field accelerated the severe to mild wear transition (Fig. 8(C)). In contrast, the magnetic field interfered with the transition

Fig. 8 Influence of magnetic field on wear characteristics of SUS304 on SUS316 and SUS316 on SUS304

in 35 mm/s (Fig. 8(D)). The wear characteristic of SUS316 pin in 35 mm/s was similar to that for the Cu pin sliding on Fe disk⁽²⁰⁾. These results suggest that magnetic field sometimes interfered the sever to mild wear transition in the sliding pair of two different bearing materials. The mechanical and chemical properties of a stainless steel depend on its compositions, suggesting that the characteristic of the oxidized layer is also affected. Although both SUS304 and SUS316 are the austenitic and paramagnetic materials, each oxidized layer may not be the same. The interaction between the different oxidized surfaces seemed to be enhanced by the sliding condition such as the sliding velocity, the degree of chemisorption of oxygen or the externally applied magnetic field. Furthermore, the magnetic field might change the contact potential difference or the mechanical properties between bearing surfaces^{(24)–(26)}. Thus variation of wear characteristic was observed.

3.5 Magnetic field effects in uni-directional sliding with distilled water lubrication

Experimental results are shown in Fig. 9. Lubricating condition appeared to change significantly both wear behavior and magnetic field effect. Although the decrease in wear of pin by means of magnetic field was observed in unlubricated condition, it was not so evident in lubricated condition, where wear amount of pin became small even without

Fig. 9 Influence of magnetic field on wear characteristics in different lubricating condition

magnetic field. However, the improvement of wear characteristic such as the sever to mild wear transition by magnetic field was observed for plate in the lubricated condition. The result suggests that the improvement of wear characteristic by means of magnetic field is expected even in the water-based lubricated condition if the sliding condition is adjusted.

3.6 Influences of contact pressure and lubricant constituent on frictional and wear characteristics of stainless steel (SUS316)

In this section, preliminary experiments were performed to elucidate the influences of proteins on wear of a stainless steel. Figure 10 shows the results of the reciprocating wear tests (Fig. 2 and Table 2). Addition of proteins in saline solution reduced friction in the same manner as the previous studies^{(13),(14)}. Saline solutions both with and without proteins recorded almost the same wear for plate, and the wear of plates was extremely lower than that of pins. The main reason is that the rubbed area on the plate surface appeared to be replenished with provided lubricant, because the contact zone of plate under the pin surface was continuously shifted in one stroke. Proteins extremely increased the wear of pins. The result is inconsistent with the result performed in previous studies at higher contact pressure^{(13),(14)}, in which proteins adsorbed on bearing surfaces acted as a protective boundary lubricant.

The metallic surface such as a stainless steel forms the oxidized layer which ordinary reduces friction and wear⁽²⁷⁾. The rubbing motion appears to break, more or less, the oxidized layer. Under mild condition, the base metal exposed to lubricant is oxidized again usually at unloaded phase during rubbing motion, so that low friction and wear can be maintained. But under sever condition, the friction and wear characteristics seem to be deteriorated, because the excessive demolition of the oxidized layer

Fig. 10 Influence of protein and contact pressure on friction and wear characteristics of SUS316 on SUS316

was caused and the oxidization of the exposed base metal is not sufficiently expected. The exposed base metal is the chemically active surface, so that proteins also adsorb onto that surface. This indicates that it is necessary to take the relationship between the oxidization and the adsorbed proteins on the exposed base metal into consideration for friction and wear processes of metallic bearing surfaces.

The series of tests clarified that proteins lowered friction, and this was independent of contact pressure and pattern of pathway, for example uni-directional or reciprocating motion. The most likely explanation is that the adsorbed proteins on the metallic (both oxidized and exposed) surfaces prevented the direct contacts and reduced shearing force between the bearing surfaces.

The adsorbed proteins on the bearing surfaces, however, gave rise to two contrasting wear behaviors; an increase and a decrease in wear.

Under the high contact pressure adopted in previous studies (39 MPa – 240 MPa), the adhesive action seemed to be dominant in the wear processes because the excessive demolition of the oxidized layer was

caused and the oxidization of the exposed base metal was not so expected. In such a condition, the adsorption of proteins onto the exposed base metal prevents the adhesion between metallic bearing surfaces, so that the wear is reduced.

Under the low contact pressure conducted in this study (0.2 MPa – 3.5 MPa), the exposed base metal is easily oxidized again during rubbing motion in lubricant without proteins. In such low contact pressure condition, the adsorbed layer of proteins appeared to increase wear because of the obstruction to the oxidization of the exposed base metal. The deterioration in wear may be relevant to the influence of proteins on the corrosion of metallic implants, such as Charge Neutral Corrosion Model⁽²⁸⁾, and there is room for further investigation.

For the new generation of Metal-on-Metal joint prostheses, numerous attempts have been made by scholars^{(4)–(6)} to demonstrate the full fluid film lubrication mechanism, and there is fairly agreement that the full fluid film lubrication is possible with sufficient quality surface finish and high conformation between bearing surfaces. The lubrication mode of the prostheses that possesses both large radius and small clearance will be mixed lubrication with low contact pressure when a full fluid film is not present. The experimental results, however, showed that lowered contact pressure sometimes deteriorates the wear characteristic. It is obvious that the key to reduce the amount of wear of Metal-on-Metal sliding pair is the promotion of oxidization of the metallic bearing surfaces.

3.7 Influence of lubricants on magnetic field effects in reciprocating sliding condition

Wear characteristics of stainless steel (SUS316) under various lubricating conditions are shown in Fig. 11. In unlubricated condition, the magnetic field effect that reduces wear was also confirmed for both pin and plate.

In the distilled water lubrication, the decrease in wear was observed for both pin and plate compared with the unlubricated condition, but the severe to mild wear transition was confirmed only for the plate. The magnetic field reduced the wear of plate alone. These wear characteristics were similar to those in uni-directional sliding tests, indicating that the magnetic field effect was affected by lubricated condition rather than sliding condition. The reason might be that oxygen supply was insufficient in lubricating condition in comparison to unlubricated condition⁽¹⁵⁾ or that interference of wear debris between bearing surfaces was changed by lubrication.

Wear of plate in saline solution was lower than that in distilled water. The magnetic field effect that was not evident in distilled water for pin was

Fig. 11 Influence of magnetic field on wear characteristics of SUS316 on SUS316 in different lubricating conditions

confirmed in saline solution. The difference between two lubricating conditions is the concentrations of sodium and chlorine ions in lubricant. Therefore the chlorine ions may act as an extreme pressure agent and ease rubbing severity. Under milder rubbing condition, the oxidization of metallic surface appeared to improve, so that the magnetic field effect for pin was observed in saline solution. However, the reaction product between chlorine ion and bearing surface was not detected through EPMA analysis.

Although the effectiveness of the magnetic field was also observed in saline solution of proteins, the effect for pin was smaller than that in saline solution. The main reason is that proteins increased the wear in the contact pressure of 0.28 MPa (Fig. 10). The results through EPMA analysis on the bearing surface after each test (Fig. 11(D)) are shown in Fig. 12. Although improvement of oxidization on the bearing surface by rubbing motions was confirmed, the improvement by the magnetic field was observed only for plate. As shown in Fig. 11(D), wear of pin was increased like a straight line with sliding distance, suggesting that the pin was in the severe wear condition. Therefore the detection of the magnetic field effect for pin was difficult through EPMA analysis under the lubricated condition where oxygen supply was insufficient in comparison to unlubricated condition.

Fig. 12 Element analysis of sliding surfaces with EPMA (Test condition : Fig. 11(D), Accelerated voltage : 25 kV)

4. Conclusion

The fundamental and experimental investigations for improvement of wear characteristic of Metal-on-Metal artificial hip joint have been demonstrated in simplified sliding conditions. Important features are summarized below :

1. Effects of magnetic field on wear characteristics of stainless steel (SUS304 and SUS316) in unidirectional sliding and unlubricated conditions ;

1-1) Reduction in wear was observed by the magnetic field vertical to the bearing surfaces for SUS304 sliding on SUS304 plate or SUS316 on SUS316 plate.

1-2) In sliding pair of SUS304 and SUS316, the magnetic field deteriorated wear or interfered with severe to mild wear transition in some cases.

2. Effects of magnetic field on wear characteristics of stainless steel (SUS316) in reciprocated sliding and lubricated conditions ;

2-1) Effect of magnetic field was also confirmed in reciprocated sliding condition.

2-2) The magnetic field effect was affected by the constituents of lubricants.

Acknowledgment

The authors wish to express their appreciation to Mr. T. Gohara, undergraduate student at Kyushu University (present affiliation: Ishikawajima-Harima Heavy Industry Corp.) for his cooperation. EPMA analysis was conducted at the Center of Advanced Instrumental Analysis, Kyushu University. This research was supported by Grants-in-Aid for Scientific Research ((A): 07558256 and 8543) of Ministry of Education, Science, Sports and Culture, Japan.

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