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Effect of tribochemical reaction on wear of silicon carbide for joint prostheses

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While silicon carbide has excellent properties for ceramic-on-ceramic joint prostheses, the wear rate is affected by tribochemical reaction. In this study, wear of silicon carbide was investigated in water whose dissolved oxygen density is controlled. According to the result, wear rate in oxygen rich or oxygen poor water is higher than the wear rate in normal water. The major mechanism of wear in oxygen rich environment is tribochemical reaction while third body abrasion is predominant in oxygen poor condition. It is found that moderate tribochemical reaction contributes to keeping wear low in an artificial joint of silicon carbide.

Key words: Artificial joint, Ceramic-on-ceramic joint, Silicon carbide, Tribochemical reaction, Third body abrasion, Dissolved oxygen density.

Introduction

High density polyethylene is widely used to total joint prostheses because it has high wear resistance, high biocompatibility and high chemical stability. However, as wear particles of polyethylene are also stable in a human body, they sometimes stay long near the joint causing biological reaction, born resorption and loosening of the joint [1]. Therefore, metal-on-metal or ceramic-on-ceramic total hip prostheses have been developed and applied to young patients because they are expected to survive longer than joints of polyethylene. For an all metallic joint, we must take care of the ions dissolve in the body fluid after replacement [2]. An all-ceramic joint has different problem. When the motion of the joint exceeds the assumed range, the edge of the acetabular cup impinges on the neck of the femoral stem. Concentrated contact stress at the impinging region may cause fracture or abrasion possibly because alumina is a brittle material. Joint dislocation also causes stress concentration between the edge of the socket and the femoral head.

Most of ceramic-on-ceramic total hip joint are made of alumina [3, 4] because alumina has high wear resistance, bio-compatibility and chemical stability. Silicon carbide is another potential material for all-ceramic joint [5-7] not only because it has high wear resistance but also it is harder and less brittle than alumina. However, wear process of silicon carbide accompanies tribochemical reaction. Wear rate in a joint prosthesis of silicon carbide may be higher than experimental prediction because the time period of wear test is shorter than the lifetime of an artificial joint. The purpose of this study is to investigate the effect of synovial fluid on the wear of silicon carbide in terms of tribochemical reaction.

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Materials and Method

An end-face friction apparatus (Fig. 1) is used to investigate the wear properties between a couple of ceramic specimens of silicon carbide. Table 1 lists the properties of the silicon carbide (KYOCERA: SC211). Figure 2 shows that one of the specimens is a hollow cylinder while the other is a circular disk. Centerline average roughness of the end faces was about 0.033

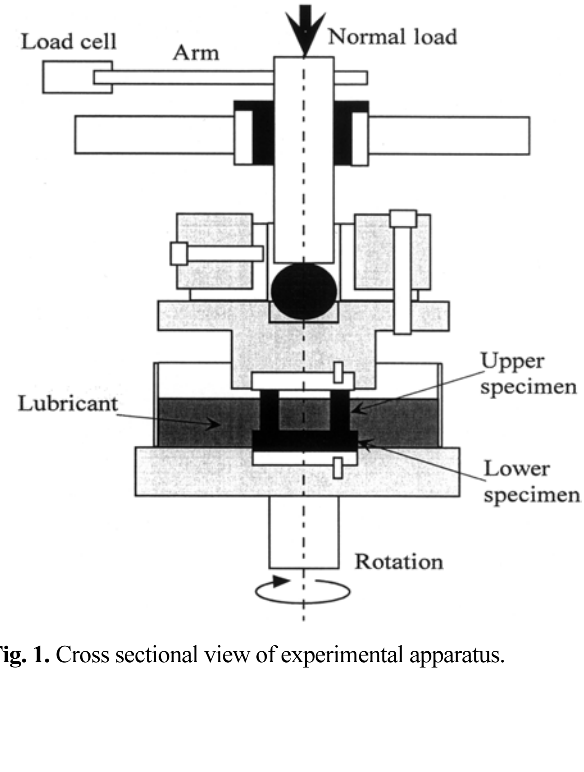

Fig. 1. Cross sectional view of experimental apparatus.

Table 1. Material properties of silicon carbide

Material	Silicon carbide
Commercial name	SC211
Chemical composition (wt%)	SiC > 94
Production process	Pressureless sintered
Grain size (μm)	–
Density (g/cm^3)	3.2
Porosity (%)	≒ 0
Young's modulus (GPa)	431
Vickers hardness (Hv)	2400
3-point bending strength (MPa)	539
Fracture toughness (MN/m$^{3/2}$)	6
Thermal conductivity (cal/ (cm · sec · °C))	0.15

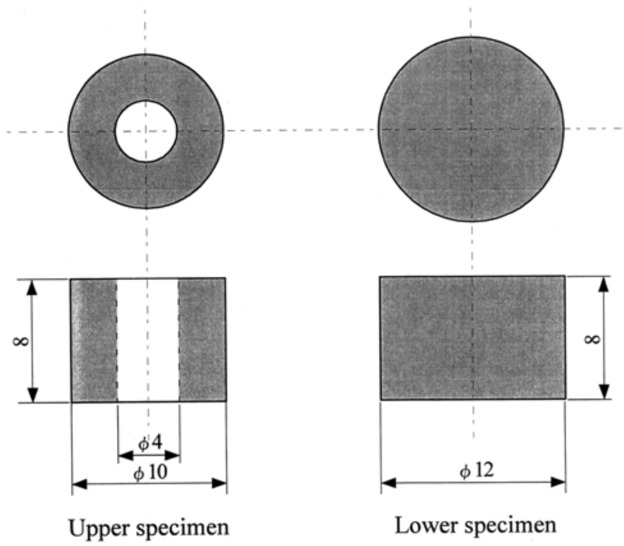

Fig. 2. Specimens of silicon carbide.

μm. The cylindrical specimen is attached to the upper shaft and vertical load of 607 N is applied to the top of the shaft with dead weights. The disk specimen is attached to the lower shaft and rotates with the water vessel. In the wear test, contact pressure was 9.2 MPa, mean velocity was 40 mm and total sliding distance was 21 km. Ambient temperature was controlled at 25 degrees. The tests were performed in normal distilled water, water with 3% hydrogen peroxide, water with 20% hydrogen peroxide, water with oxygen gas supply by means of bubbling and water bubbled with nitrogen gas.

Water temperature and pH values were monitored during the test. Surface roughness, wear loss and dissolved oxygen density were measured before and after the test. Specific wear rate was calculated by the following equation.

$$S_w = \frac{v}{f \times l} \tag{1}$$

Where S_w is specific wear rate, v is wear volume, f is applied load and l is sliding distance.

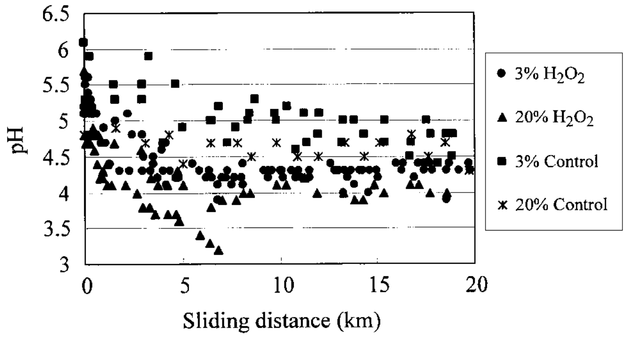

Fig. 3. Transition of pH value in water.

Result

Figure 3 shows that pH value of the water with hydrogen peroxide falls, in other words, the water is acidified during the wear test. In the figure, 'control' denotes the case that the specimens are immersed simply in water at the same temperature. The pH value drops rapidly for water with dense hydrogen peroxide while rate of acidification is very low for the controls. Saturation density of oxygen dissolved in water is about 8 mg/l at 25 degrees. Figure 4 shows that the normal water is almost saturated with dissolved oxygen.

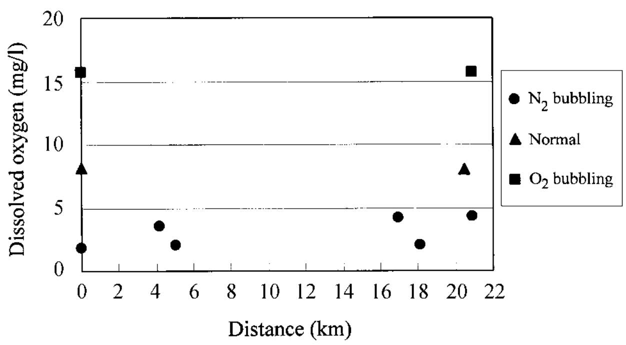

Fig. 4. Transition of dissolved oxygen density in normal water, water bubbled with oxygen gas and water bubbled with nitrogen gas.

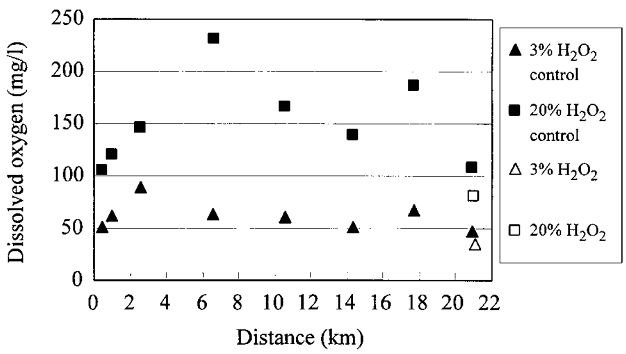

Fig. 5. Transition of dissolved oxygen density in water with hydrogen peroxide, 'control' denotes the case without sliding.

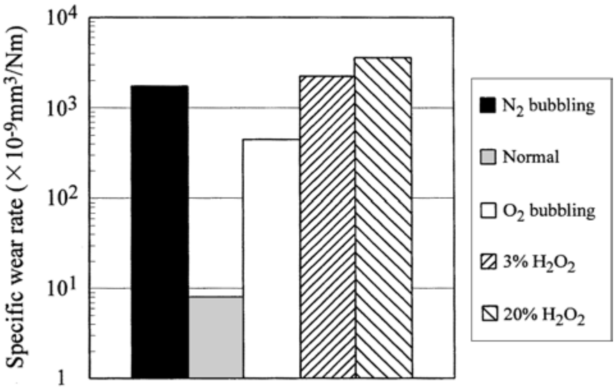

Fig. 6. Effect of dissolved oxygen on specific wear rate.

When oxygen gas is bubbled, dissolved oxygen density is about twice of the density in normal water, while it is kept at one third of the normal water when nitrogen gas is bubbled. For the water with hydrogen peroxide (Fig. 5), dissolved oxygen density is kept very high in sliding or resting condition. Figure 6 shows that specific wear rate is lowest for the test in the normal water. Wear rate increases drastically for the test with hydrogen peroxide solution, oxygen gas bubbling and nitrogen gas bubbling. The water turned cloudy and white during the test in oxygen rich water. On the other hand, sharp wear particles were observed in the water after the test with nitrogen gas bubbling.

Discussion

Tribochemical reaction of silicon carbide with oxygen [8] is expressed as follows.

$$SiC + 2O_2 \rightarrow SiO_2 + CO_2 \quad (2)$$

Further, in water environment, carbon dioxide dissolves and changes to carbonic acid by the following reaction.

$$CO_2 + H_2O \rightarrow H_2CO_3 \quad (3)$$

The decrease of pH value is due to the production of carbonic acid as shown by the equation (2) and (3). A rapid acidification results from a high concentration of dissolved oxygen because oxygen is necessary for the tribochemical reaction. Thus, the increase of wear rate in the water bubbled with oxygen gas or in the water added with hydrogen peroxide confirms that the main mechanism of wear is tribochemical reaction in oxidizing environments.

However, wear rate increases in the case of bubbling with nitrogen gas too, though the tribochemical reaction is less active in this case. The major mechanism of wear in oxygen poor water seems to be the third body abrasion with sharp wear particles. In water, silicon dioxide is hydrated as expressed by the following equation [8].

$$SiO_2 + 2H_2O \rightarrow Si(OH)_4 \quad (4)$$

Silicon dioxide and its hydrate act as solid lubricants because they are softer than silicon carbide. Accordingly, the shape of the surface profile and the wear particles becomes milder and wear rate is reduced by moderate tribochemical reaction. This is the reason why specific wear rate is lowest for the test in the normal water.

Though the density of oxygen dissolved in synovial fluid is not known in the author's knowledge, it is believed that the oxygen density inside of the joint capsule is lower than the oxygen density of water in the atmospheric condition. Therefore, rapid wear due to tribochemical reaction is unlikely to arise in a joint prosthesis in clinical use. On the other hand, severe abrasive wear is also unlikely to arise because hydrodynamic lubrication and boundary lubrication with synovial fluid will assist lubrication and contribute to reduce wear. However, as it is shown in this paper that wear of silicon carbide is affected by tribochemical reaction, further investigations including *in vivo* study is necessary in order to predict wear rate more exactly.

Conclusion

The conclusion from the wear tests with silicon carbide in various dissolved oxygen densities is as follows;

1. Wear rate was lowest for the test in normal distilled water because moderate tribochemical reaction prevented severe abrasive wear.
2. In oxygen-rich water, wear rate increases due to tribochemical reaction with dissolved oxygen.
3. In oxygen-poor environment, third body abrasion is the major wear mechanism because hard wear particles are produced by lack of tribochemical reaction.

Acknowledgement

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