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Tribology for all-ceramic joint prostheses

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Ceramic on ceramic total hip prostheses are developed to apply to young patients because lifetime of polyethylene joint prostheses is limited by loosening due to biological response. As mating faces of all-ceramic joint must be highly conformed to reduce stress concentration, wear properties of flat surfaces are investigated in this study. Through wear tests at 2 MPa of contact pressure and 36 mm/s of sliding velocity, alumina and silicon carbide keep low wear rate, high hardness and smooth surface. Soft surface film was detected after the test in bovine serum. This suggests that boundary lubrication is effective to reduce wear in all-ceramic joint.

Key words: All-ceramic joint prosthesis, Wear of ceramics, End-face friction apparatus, Wear rate, Boundary lubrication, Tribochemical reaction.

Introduction

In most of the joint prostheses, one of the sliding surfaces is made of ultra-high molecular weight polyethylene (UHMWPE) because of its chemical stability and high wear resistance. According to radiographic measurement of a hip joint, wear depth of polyethylene socket is usually less than 0.1 mm per year. However, Biological response to wear particles of polyethylene causes bone absorption though the polyethylene is a bio-inert material in a block shape. Thus, lifetime of artificial joints is limited by loosening of the joint due to bone loss [1]. It is likely that a human body has poor function to discharge polyethylene wear particles because the human being had not encountered polyethylene during the history of evolution.

For this reason, metal on metal and ceramic on ceramic total hip prostheses have been developed. Though it is thought that toxicity of Co, Cr and Mo is low, we must be aware of the effect of the ions from a joint prosthesis on human health.

Ceramic on ceramic joint prostheses have different problem [2]. As ceramics are brittle and their elastic moduli are high, stress concentration may lead to cracking and abrasive wear. Therefore, high geometric conformity is required for sliding surfaces in ceramic on ceramic joint prostheses. Hence, wear properties of highly conformed ceramic surfaces must be investigated to develop joint prostheses for permanent use [3-6]. The purpose of this study is to investigate tribological properties of ceramics between highly conformed surfaces.

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Materials and Method

Figure 1 shows the end-face friction apparatus used to investigate wear properties of ceramics. Vertical load is applied to the upper part with dead weights while the lower part rotates with a water vessel. Friction torque is measured with a load cell. The upper specimen shown by Fig. 2 is ring-shaped and the lower specimen is a circular disk. The specimens slide to each other in the vessel filled with fluids. The mating faces of the specimens are nominally flat and their centerline average roughness is less than 0.01 μm before the test. Mean contact pressure is 2 MPa and sliding velocity is 36 mm/s. Alumina and zirconia have the same quality with joint prostheses, while silicon carbide and silicon nitride are industrial materials.

The water vessel is filled with distilled water, water with 1% albumin, water with 1% hyaluronic acid or 30% bovine serum. Temperature of the fluids was

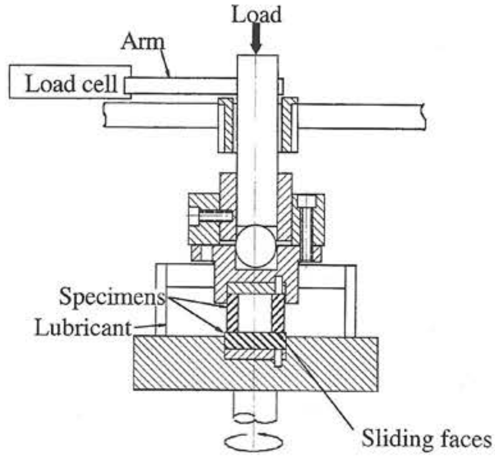

Fig. 1. Schematic of end-face friction apparatus.

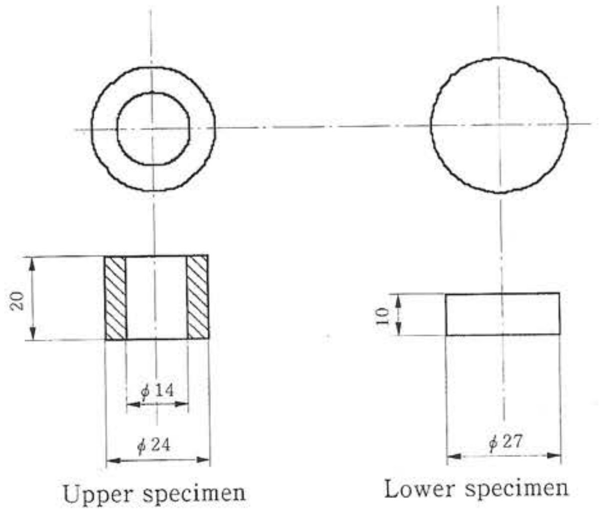

Fig. 2. Shapes and dimensions of specimens of alumina, silicon nitride, silicon carbide and zirconia with 4.5~5.4 mol% Y_2O_3.

heated to 37°C during the test. 0.02% of sodium azide and 0.005% of phenylmethylsulfonyl fluoride were added to albumin and bovine serum as antibacterial agents.

Weight loss of the specimens was measured after 20 km of sliding to obtain specific wear rate *Sw* defined by the following equation.

$$Sw = \frac{v}{Pl} \tag{1}$$

Where v is wear volume in cubic millimeters, P is load in newtons and l is sliding distance in meters.

Before and after the test, centerline average roughness Ra was measured. Dynamic hardness is measured with Dynamic Ultra Micro Hardness Tester (DUH-201) by Shimadzu. The indenter is a triangular pyramid with 115 degrees apex angle. According to the instructions, dynamic hardness *DH* is defined by

$$DH = 37.8\frac{P}{D^2} \tag{2}$$

Where P is load in gram force and D is indentation depth in micrometers.

Result

Figure 3 compares specific wear rates of the ceramics sliding in the fluids. Wear of silicon nitride is exceptionally high in every fluid and wear of zirconia is second highest. Wear of alumina and silicon carbide are very low in every fluid.

Figure 4 shows that surface roughness increases rapidly in the early stage of the test. Then, the roughness takes constant value with further increase of sliding distance. Roughness of silicon nitride and zirconia become much larger than the ones of alumina and silicon carbide.

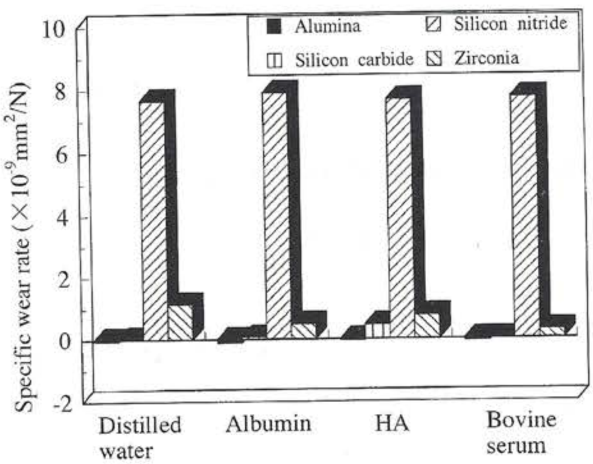

Fig. 3. Specific wear rate of ceramics.

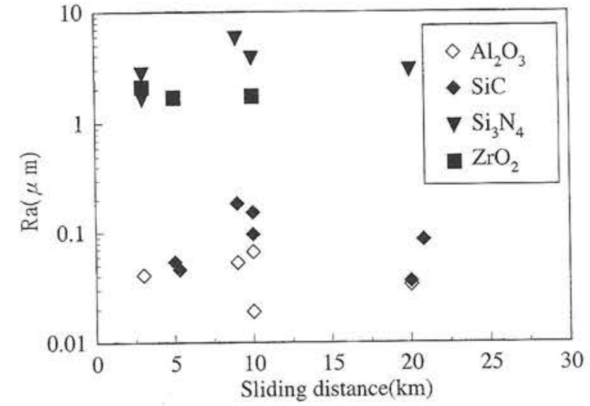

Fig. 4. Change of centerline average surface roughness with sliding distance.

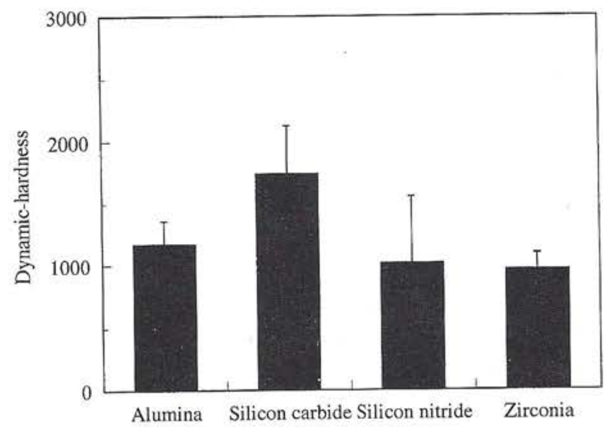

Fig. 5. Dynamic hardness of original surface in micro scale.

Figure 5 shows that dynamic hardness of the ceramics is in the range between 1,000 and 1800 before the wear test. The corresponding indentation depth estimated by equation (2) is in between 0.46 micrometers and 0.62 micrometers. Thus, hardness of thin surface layer can be measured by this method. In addition, it is expected that the film adsorbed by the surface can be detected. After the test in distilled water (Fig. 6),

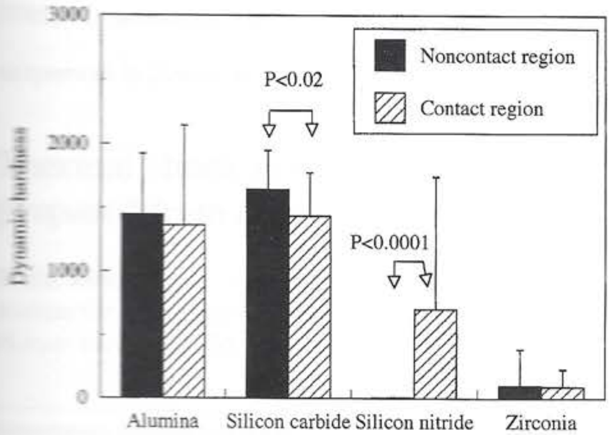

Fig. 6. Dynamic hardness after wear test in distilled water.

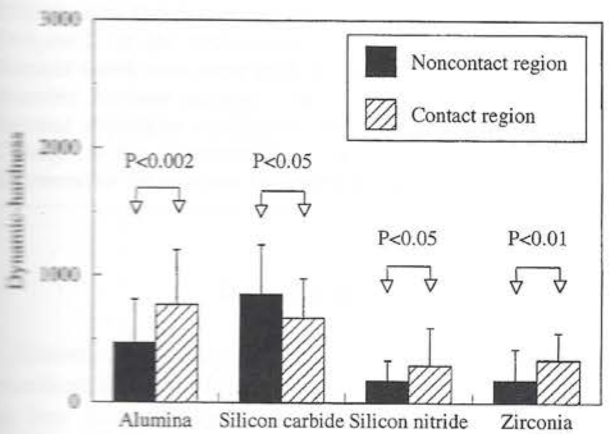

Fig. 7. Dynamic hardness after wear test in bovine serum.

change of hardness is not remarkable for alumina and silicon carbide. Hardness of non-contact region of silicon nitride becomes close to zero. Hardness of zirconia decreases both in the non-contact region and the contact region. After sliding in bovine serum (Fig. 7), dynamic hardness of each ceramic surface becomes about half of the initial value.

Discussion

Among the four ceramics tested in this study, alumina and zirconia have been applied to joint prostheses, while only alumina is used for ceramic on ceramic hip joints.

Wear rate of silicon nitride is very high in water environments. Its excessive wear is followed by a rapid increase in centerline average roughness to 3 micrometers. Its high wear rate and rapid roughening is caused by tribochemical reaction to water through which silicon dioxide is produced [7]. After the test, dynamic hardness is very low in the non-contact region because wear particles of silicon nitride and silicon dioxide accumulate. Decrease of hardness is not remarkable in the contact region because wear particles are removed from the surface through wear process before the soft layer is formed.

Though zirconia has excellent tribological properties when it is combined with polyethylene, its surface may be roughened during sliding with hard materials. The specimens are made of partially stabilized zirconia with 4.5-5.4 mol % Y_2O_3. For this material, phase of crystal may transform from tetragonal to monoclinic [8] by high contact pressure during sliding. The authors suppose that the reason of roughening is non-uniform surface strength as a result of phase transformation.

Alumina and silicon carbide show low wear rate keeping smooth and hard surfaces during sliding in distilled water. Therefore, it may be concluded that silicon carbide is a candidate material in addition to alumina that has been applied to ceramic on ceramic total hip prostheses.

It is likely that decrease of hardness after the test in bovine serum is due to formation of soft surface film. As bovine serum includes proteins and phospholipids, they are adsorbed by the ceramic surface. The surface film contributes to boundary lubrication and reduction of wear. As synovial fluid includes proteins and phospholipids as well as serum does, surface film will be formed in a ceramic on ceramic joint prostheses in clinical use. The boundary lubrication promoted by the surface film will reduce wear in total joint prostheses.

Conclusions

Wear properties of nominally flat ceramic surfaces are investigated for alumina, zirconia, silicon nitride and silicon carbide. The conclusions are as follows.

(1) Among the four ceramics, alumina and silicon carbide can be applied to ceramic on ceramic joint prostheses because they keep low wear rate, smooth surface and high hardness during sliding in water environments.

(2) Surface film formed on the ceramic surface may contribute to boundary lubrication in a ceramic on ceramic joint prostheses.

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