

Influence of Relative Densities on Tribological Characteristics of Various Artificial Joint Materials

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Abstract

Improving the tribological characteristics of artificial joints is crucially important for people who use such joints. In order to increase the durability of the artificial joint, it is necessary to prevent loosening and limit wear on the sliding planes. Thus, with the objective of improving the tribological characteristics of materials for artificial joints, the present study used varying densities of Ti-6Al-4V, ZrO₂, and GAP-M in combination with high density polyethylene (HDPE) and investigated their respective tribological characteristics. As the result, Ti-6Al-4V, ZrO₂, and GAP-M with a low relative density showed an improvement in tribological characteristics.

Keywords: tribological characteristics, artificial joint material, relative density

1 Introduction

There are people who suffer from serious joint disorders that hinder ordinary mobility. Artificial joint replacement surgery is of great benefit to such people and significantly improves their quality of life (QOL). Because the artificial joints are man-made, however, they have limited durability. The breakdown is caused mainly by wear between the artificial joint sliding surfaces and loosening of the stem and cup. This sliding surface friction and loosening is also closely related. Recent research has identified wear debris from ultra-high molecular weight polyethylene (UHMWPE), the material used for artificial joints, as a major factor in loosening. Extending the service life of artificial joints, therefore, depends crucially on preventing loosening by reducing wear between the artificial joint sliding surfaces.

In this study, varying densities of titanium alloy (Ti-6Al-4V), ceramic zirconium dioxide (ZrO₂), and hydroxyapatite (GAP-M), all high-biocompatibility metals and ceramics used as biomaterials, were used as sliders of opposing materials. The tribological characteristics of the artificial joint using combinations of these materials with high density polyethylene (HDPE) were investigated. In addition, a fundamental review was performed with the objective of improving the tribological characteristics.

2 Experimental details

2.1 Specimens

The HDPE used in this study (J-Rex·HD SS5003B powder) was extruded in an extruder and machine-finished into a cylindrical shape with an outside diameter of 23mm, inside diameter of 19mm, and height of 35mm. #1200 emery paper was used to provide a final finish on the HDPE frictional surface to an arithmetic mean roughness of approximately 0.04 – 20.06µm.

2.2 Apparatus and experimental procedure

The sliders used were made of (1) Ti-6Al-4V powder (TSA150) with an average particle diameter of 62µm, (2) ZrO₂ (ZrO₂-Y₂O₃ 3mol%) powder (OZC-3Y) with an average particle diameter of 63 - 68µm, and (3) GAP-M with an average particle diameter of 200µm. Each powder was individually sintered using the spark plasma sintering method in a spark plasma sintering machine (DR.SINTER Model SPS1030). The relationships between the relative density and sintering pressure/sintering temperature for each sintered material are shown in Tables 1, 2, and 3. The sintered compact was disk-shaped with a diameter of 30mm and height of 4 – 12mm. The frictional surfaces of the sliders were finished with #1200 emery paper.

The experimental apparatus used was the thrust washer type wear tester shown in Fig. 1. It was modified to enable oscillating motion (oscillation angle 90°).

Purified water (PW) and physiologic saline (PS) were used as lubricants, and the test conditions are shown in Table 4.

Table 1 Sintering conditions and relative densities of Ti-6Al-4V

Material	Ti-6Al-4V			
	Sintering pressure	1.4MPa	14.7MPa	29.4MPa
Sintering temperature	850°C	700°C	700°C	1100°C
Relative density	65.3%	75.2%	86.9%	98.9%

Table 2 Sintering conditions and relative densities of ZrO₂

Material	ZrO ₂			
Sintering pressure	29.4MPa			
Sintering temperature	1050°C	1080°C	1150°C	1200°C
Relative density	60.4%	73.9%	82.3%	92.4%

Table 3 Sintering conditions and relative densities of GAP-M

Material	GAP-M			
Sintering pressure	39.0MPa	29.4MPa	20.0MPa	10.5MPa
Sintering temperature	800°C	900°C	1000°C	1100°C
Relative density	82.6%	95.4%	96.4%	98.5%

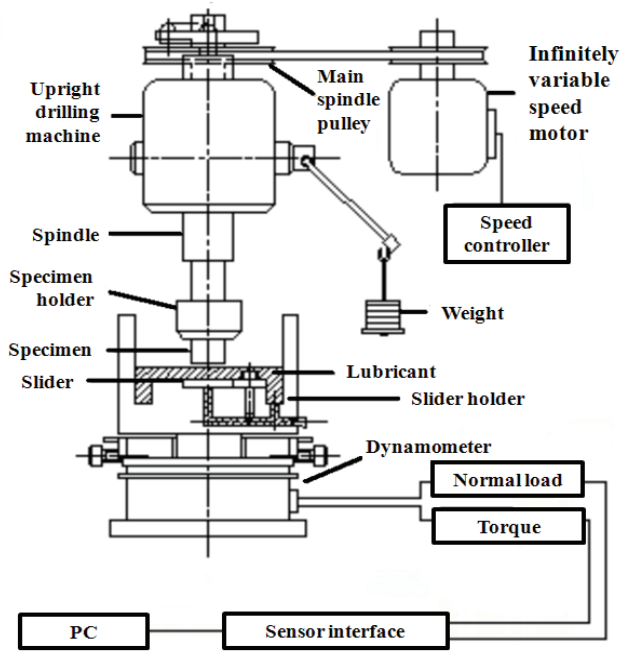


Fig. 1 Principal part of experimental apparatus

Table 4 Experiment conditions

Contact pressure		4.0MPa
Sliding velocity (average)		0.06m/s
Sliding distance		1000m
Air-conditioned atmosphere	Temperature	23±1°C
	Humidity	50±2%
Lubricating fluid		PW · PS
Temperature of Lubricating fluid		Uncontrolled
Driving method		Oscillating motion
Oscillating angle		90°

3 Results and discussion

3.1 Tribological characteristics

Figure 2 shows the relationship between the relative density and friction coefficient for Ti-6Al-4V. The friction coefficient value for all relative densities was about 0.1, and almost no differences were observed between densities. In regards to differences in the friction coefficient resulting from the use of different lubricants, physiologic saline resulted in a slightly larger value. The greater corrosive effect on the frictional surface by physiologic saline compared to purified water is believed to account for the higher value. The frictional surface is shown in **Fig. 8**.

Figure 3 shows the relationship between the relative density and friction coefficient for ZrO₂. The friction coefficient value for all relative densities was slightly less than 0.1, and no significant differences observed either between the various densities or lubricants.

Figure 4 shows the relationship between the relative density and friction coefficient for GAP-M. The friction coefficient value for all relative densities was about 0.15, and almost no differences in the friction coefficient were observed between the relative densities. In regards to the differences in the friction coefficient resulting from the use of different lubricants, purified water had a slightly larger value.

From **Figs. 2, 3, and 4**, it is believed that nearly no lubricant-related differences in the friction coefficients for ZrO₂ and GAP-M were observed because they are ceramics. Ti-6Al-4V and ZrO₂ exhibited friction coefficient values of 0.1, and GAP-M had a value of 0.15.

Figure 5 shows the relationship between the various densities of Ti-6Al-4V and the HDPE wear rate. The wear rate increased as the relative density increased, but it was smaller at a relative density of 98.9% compared to 86.9%. Here, the area of contact with corroded areas increases because the true area of contact increases along with the relative density. This accounted for much of the corrosion transferring to the HDPE. This resulted in wear between the HDPE and the Ti-6Al-4V, which led to the lower wear rate.

Figure 6 shows the relationship between the various densities of ZrO₂ and the HDPE wear rate. The wear rate exhibited a value between approximately 7 to 9 × 10⁻⁸mm³·N/m, and it also increased as the relative density increased. Purified water resulted in a smaller value compared to physiologic saline.

Figure 7 shows the relationship between the various densities of GAP-M and the HDPE wear rate. The wear rate exhibited a value between approximately 0.1 to 2.0 × 10⁻⁸mm³ · N/m. In regards to lubricant-related differences, physiologic saline resulted in a larger value as the relative density increased. For purified water, a value of approximately 1.0 at a relative density of 82.6% was exhibited. Following this, the value decreased before increasing to 2.0 at a relative density of 98.5%.

From **Figs. 5, 6, and 7**, it can be seen that the wear of Ti-6Al-4V was higher when using physiologic saline

compared to purified water, and it became approximately six times greater than that of ZrO_2 . The black wear debris that appeared on the frictional surface is believed to account for the high wear. This black wear debris was likely the result of wear fragments mixing with corrosion that peeled from the corroding Ti-6Al-4V.

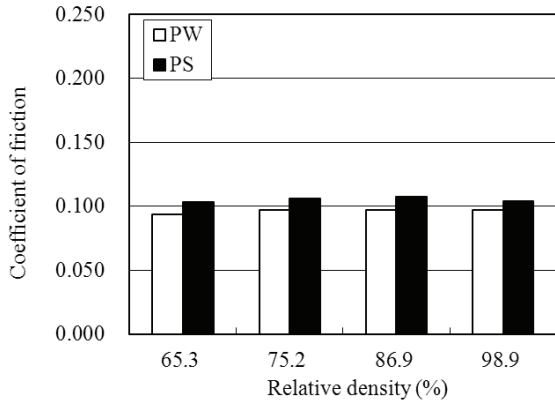


Fig. 2 Relationship between coefficient of friction and various relative densities of Ti-6Al-4V

Wear was likely promoted by the corrosion of this frictional surface. The value for GAP-M wear when using physiologic saline was less than approximately 1/20th of that for Ti-6Al-4V and less than approximately 1/5th of that for ZrO_2 .

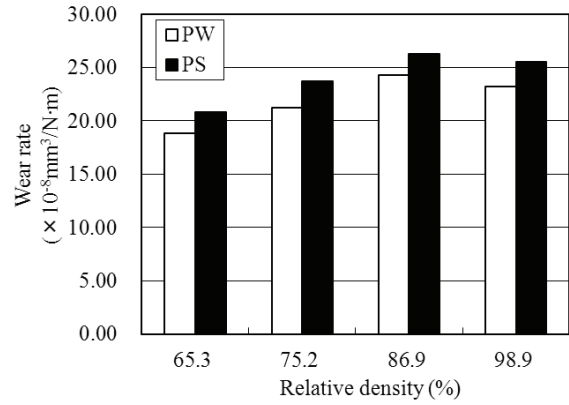


Fig. 5 Relationship between wear rate and various relative densities of Ti-6Al-4V

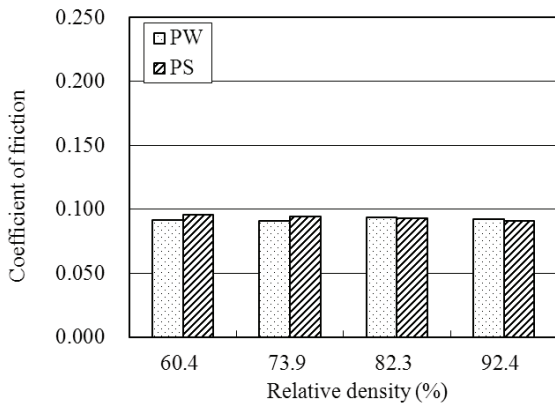


Fig. 3 Relationship between coefficient of friction and various relative densities of ZrO_2

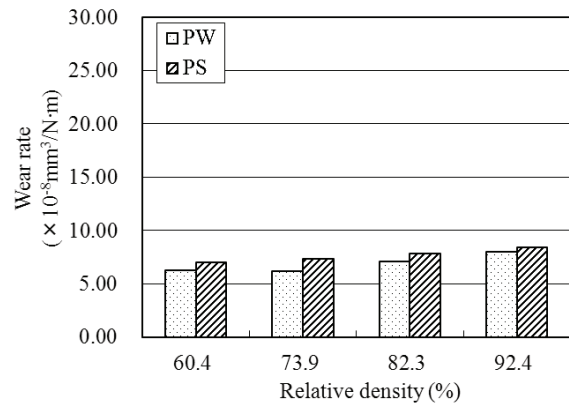


Fig. 6 Relationship between wear rate and various relative densities of ZrO_2

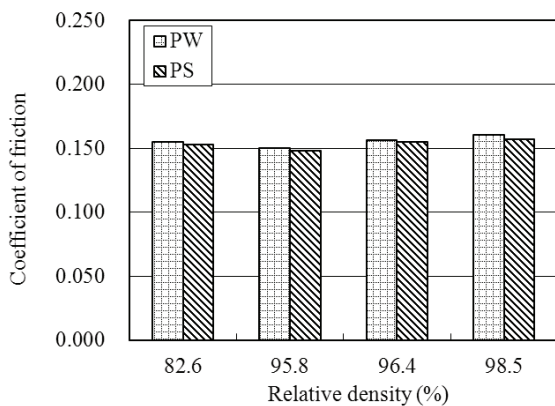


Fig. 4 Relationship between coefficient of friction and various relative densities of GAP-M

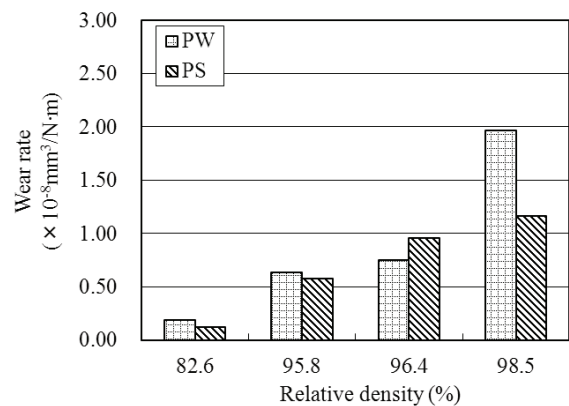


Fig. 7 Relationship between wear rate and various relative densities of GAP-M

3.2 Photographs of the frictional surfaces

Figures 8 and 11 show the pre- and post-experiment condition of the frictional surface of 98.9% relative density Ti-6Al-4V immersed in physiologic saline. Some scratching on the pre-experiment surface after grinding can be observed. Vacancies appearing as black spots with a diameter of a few μm can also be observed. The post-experiment frictional surface has

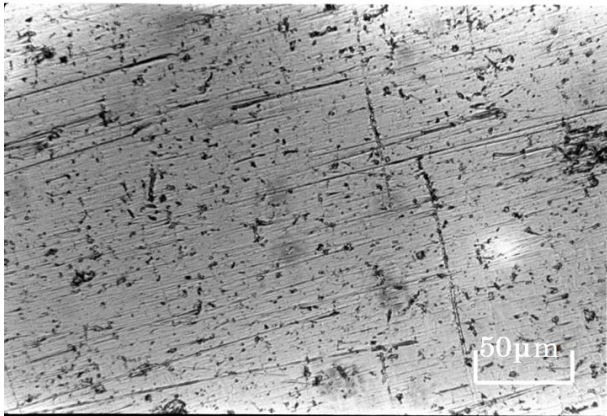


Fig. 8 Pre-experiment photograph of relative density 98.9% Ti-6Al-4V

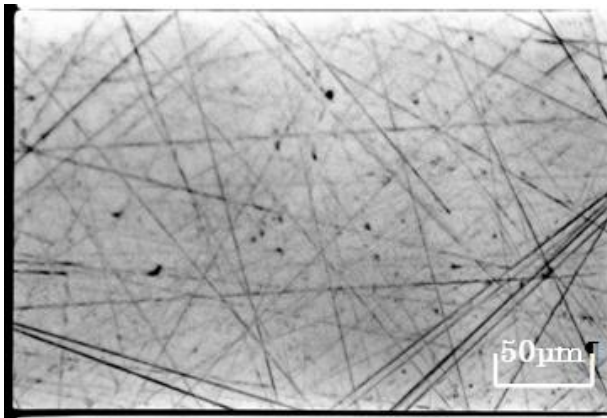


Fig. 9 Pre-experiment photograph of relative density 92.4% ZrO₂

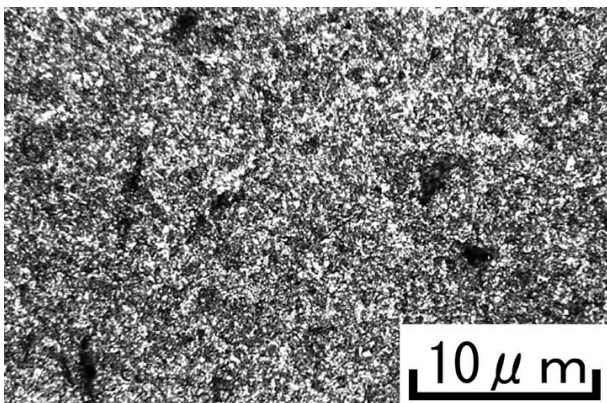


Fig. 10 Pre-experiment photograph of relative density 96.4% GAP-M

been discolored to black. This is believed to be corrosion. Specimen transfer to the frictional surface in the direction of the wear can also be seen.

Figures 9 and 12 show the pre- and post-experiment condition of the frictional surface of 92.4% relative density ZrO₂ immersed in physiologic saline. Some scratching on the pre-experiment surface after grinding can be observed.

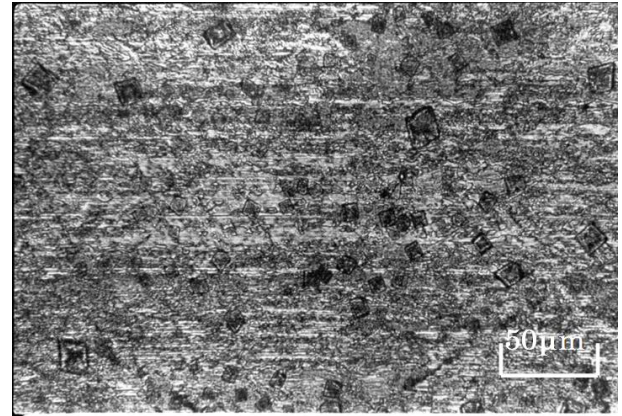


Fig. 11 Post-experiment photograph of relative density 98.9% Ti-6Al-4V

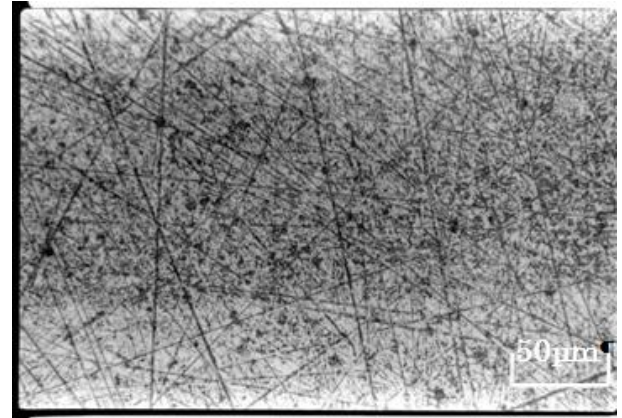


Fig. 12 Post-experiment photograph of relative density 92.4% ZrO₂

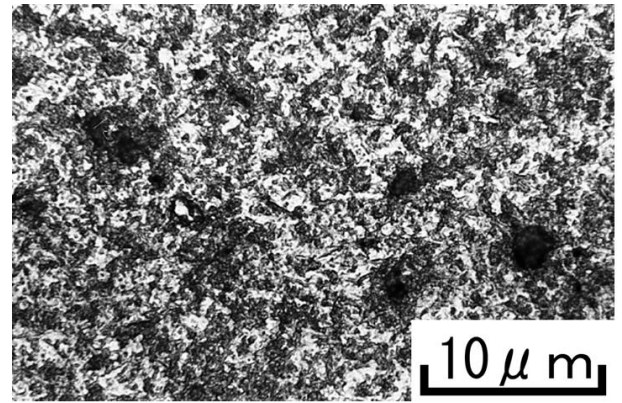


Fig. 13 Post-experiment photograph of relative density 96.4% GAP-M

Vacancies appearing as black spots with a diameter of a few μm can also be observed. The post-experiment frictional surface has been discolored to black. This is believed to be corrosion. Specimen transfer to the frictional surface in the direction of wear is barely discernible. There is nearly no change between the pre- and post-experiment conditions of the surfaces.

Figures 10 and 13 show the pre- and post-experiment condition of the frictional surface of 96.38% relative density GAP-M immersed in physiologic saline. Because the image is enlarged compared to the photographs for the pre-experiment Ti-6Al-4V and ZrO_2 , in reality there is little difference in the vacancy diameters. Because the particle diameters are about three times that of Ti-6Al-4V and ZrO_2 , the vacancy edges appear wide open. It is believed that a squeeze effect occurred due to large amounts of lubricant collecting in the vacancies.

3.3 Summary of results

Wear rate decreased as the relative density decreased for all materials. At lower relative densities, there are considerably more vacancies. These vacancies retain lubricant, resulting in the formation of a squeeze film effect. This is believed to reduce direct contact with the frictional surface, decreasing the true area of contact, and therefore reducing wear.

4 Conclusions

The following conclusions have been drawn from the results.

1. The results of the wear experiments using two types of lubricants, purified water and physiologic saline, showed that for Ti-6Al-4V and ZrO_2 , lubricants approximating that of body fluid, such as physiologic saline, resulted in higher wear with HDPE than purified water. For GAP-M, physiologic saline had lower wear, except at 96.4% relative density.
2. It was shown that when using physiologic saline as a lubricant, ceramics such as ZrO_2 and GAP-M corrode less than metals such as Ti-6Al-4V, therefore reducing HDPE wear.
3. It was shown that when the relative density of each material was varied, even in the same material, the number of vacancies increased significantly as the relative density decreased. This led to the formation of a squeeze film effect, which resulted in a decrease in HDPE wear.

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