International Journal of Physical Sciences Vol. 7(16), pp. 2478 - 2485, 16 April, 2012
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS12.010
ISSN 1992 - 1950 ©2012 Academic Journals

Full Length Research Paper

Friction and wear behaviours of medical grade UHMWPE at dry and lubricated conditions

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Accepted 29 March, 2012

In this investigation the friction and wear performance of GUR 1020 medical grade ultra-high molecular weight polyethylene (UHMWPE) polymer under dry sliding, distilled water and egg albumen lubrication conditions were evaluated. The sliding experiments were carried out on a pin-on-disc tribometer. The contact configuration used was a polymer pin on a rotating AISI 304L stainless steel disc. Wear tests were carried out for 30 min duration at room temperature with 50, 100 and 150 N applied load values and at 0.50, 1.0 and 2.0 m/s sliding speeds condition. The results show that the coefficient of friction for GUR 1020 medical grade UHMWPE polymer is more significantly influenced by applied load and sliding speed values under dry sliding condition rather than lubricant media condition. Furthermore, the coefficient of friction and specific wear rate increases with the increase in applied load and speed values. This increase is much pronounced under dry sliding condition. Moreover, for the range of load and speed values of this study the specific wear rate using egg albumen lubricant registered lower values than that of the distilled water lubricant and the dry conditions. Finally, the specific wear rate values for GUR 1020 medical grade UHMWPE polymer under dry, water lubricant and egg albumen lubricant conditions are at the levels of $8x10^{-14}$, $1.4x10^{-14}$ and $0.5x10^{-14}$ m^2/N respectively.

Key words: Medical Grade UHMWPE, tribology, distilled water, wear.

INTRODUCTION

In prosthesis technology, knee replacements are usually the only solution for patients whose joints are totally worn out. In this field, technology for the production of knee prostheses and total knee arthroplasty has improved notably, but these devices last no longer than 15 years with a poor performance compared to a natural knee. Viewing the physical nature of the knee, the loads inserts on the knees can reach peak values of three times the body weight during normal walking conditions and can peak between four to five times the body weights during more stressful surfaces activities (Morrison, 1970). This is of concern as contact stresses can exceed the compressive yield stress of the insert material (Bartel et al., 1985). Apart from high stresses, the tribological behavior of prostheses material is also important and wear should be low and the debris produced must not be toxic. The main consequences of the presence of debris particle between the contacting surfaces are both the loosening of the prosthesis components and the concentration of those particles inside macrophages that remain in the joint. The first leads to the replacement of the worn out element, while the other problem increases the concentration of immunological cells that could cause infectious focuses and an excessive bony resorption. Excessive friction can cause the prostheses to work loose within the bone, resulting in pain and instability while excessive wear reduce life and increase the instability of the prostheses (Davim et al., 2001).

Ultra-high molecular weight polyethylene (UHMWPE) is useful thermoplastic polymer both for industrial and biomaterials applications. The material has been used successfully as a bearing material in engineering applications as well as for total joint replacements. This is due to its excellent properties, such as bio-compatibility, chemical stability, high impact strength, high wear

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Table 1. Properties of GUR 1020 UHMWPE polymer used in this study.

Property	Unit	Value
Average molecular weight (average molecular mass)	g/mol	Approx. 5×10^6
Tensile stress at yield (tensile strength)	MPa	> 21
Tensile stress at break (ultimate tensile strength)	MPa	> 35
Tensile modulus	MPa	approx. 720
Elongation at break	%	> 300
Shore-Hardness D, 15 s value	-	60 - 65
Water absorption at 23°C until saturation	%	< 0.01
Sterilization, ethylene oxide	-	Yes
Sterilization, gas plasma	-	Yes
Sterilization, gamma (inert atmosphere)	-	Yes
Sterilization, superheated steam 121/134°C	-	No

resistance, and low friction (Saikko, 1993; Briscoe et al., 2002; Brach Del Prever et al., 2009; Jin et al., 2006; Kurtz et al., 1999; Dangsheng and Shirong, 2001). Thus, understanding, enhancing tribological and mechanical properties of UHMWPE will be important to prolong the longevity of joint replacement components and alleviate pain of the patients. In past, studies had been carried out on characteristics of UHMWPE polymer. Some were as a general reviews (McGloughlin and Kavanagh, 2000; El-Domiaty and El-Fadaly, 2002; Walker et al., 1981) and some others were extensive studies to improve UHMWPE wear resistance by tailoring the material with fiber reinforcement (Chang et al., 2000; Fang et al., 2005; Dangsheng, 2005), cross-linking (Lewis, 2001; Kurtz et al., 2002) and grafting (Moro et al., 2004). Although, these factors are important in influencing the tribological characteristics of UHMWPE polymer, but other factors such as applied load, sliding speed and lubrication are also important (Chandrasekaran and Loh, 2001; Gispert et al., 2006; Stewart et al., 1995; Gang et al., 2008).

The purposes of this investigation are to clarify the tribological characteristic of GUR 1020 medical grade UHMWPE polymer sliding against stainless steel under dry sliding, distilled water and egg albumen lubricated conditions and to evaluate the level of influence of applied load and sliding speed values. Friction and wear tests against AISI 304L stainless steel disc were carried out on a pin–on–disc arrangement. These tests were at room temperature under 50, 100 and 150 N load values and at 0.5, 1.0 and 2.0 m/s sliding speeds.

EXPERIMENTAL DETAILS

Materials

Flat-ended pins with 6 mm in diameter of GUR 1020 medical grade UHMWPE polymer were used in this investigation. AISI 304L stainless steel discs were machined to 10 mm thickness and 100 mm diameter, and was grind to 0.09 µm Ra surface roughness and with a hardness value of 297 HV. Material properties and the specific wear test conditions (that is, materials, ambient temperature, speed and humidity) are summarised in Tables 1 and 2.

The tribometer and tests

A pin-on-disc apparatus connected to a computer was used to evaluate the friction coefficient of the GUR 1020 medical grade UHMWPE polymer against steel under dry sliding, water and egg albumen lubricated conditions. Before each tests the flat-ended polymer pins and AISI 304L stainless steel discs were cleaned with alcohol and acetone and then installed in the pin-on-disc apparatus. The friction and wear tests were performed at room temperature, sliding speeds of 0.5, 1.0 and 2.0 m/s and applied load values from 50 to 150 N. These wide ranges of test condition were decided to cover severe working condition of knee joint such as jogging. These tests were carried out under dry sliding, distilled water and egg albumen lubricated conditions. The lubricants were added to the rubbing surfaces at a rate of 20 drops per minute to ensure the presence of lubricant media during the test period. Figure 1 shows a schematic diagram of the pin-on-disc wear test apparatus that was designed and used for this work. As shown in this figure, the rig consists of a stainless steel table which is mounted on a turntable, a variable speed motor which provides the rotational motion to the turntable, hence to the disk sample and a pin sample holder which is rigidly attached to a pivoted loading arm. This loading arm is supported in bearing arrangements to allow loads to be applied to the specimen. During the test, friction force was measured by a transducer mounted on the loading arm. The friction force readings were taken as the average of 35 readings every one sec for a period of a 30 min test time which ensures the sufficient sliding distance within the steady state wear region. For this purpose a microprocessor controlled data acquisition system was used. Finally, the specific wear rates were calculated from mass loss and the represented. Sliding wear data is the average of at least three runs.

RESULTS AND DISCUSSION

Figure 2 illustrates the variation of friction coefficient for GUR 1020 medical grade UHMWPE polymer with sliding distance at dry and water lubricated conditions under 100 N load and 1.0 m/sec sliding speed value. It is clear from

Table 2. Test parameters.

Ambient temperature (°C)	Applied load (N)	Sliding speed (m/s)	Humidity, RH (%)	Dropping velocity of water and egg albumen (10 g/l) (drops/min)
19±2	50, 100, 150	0.5, 1.0, 1.5, 2.0	52±2	20

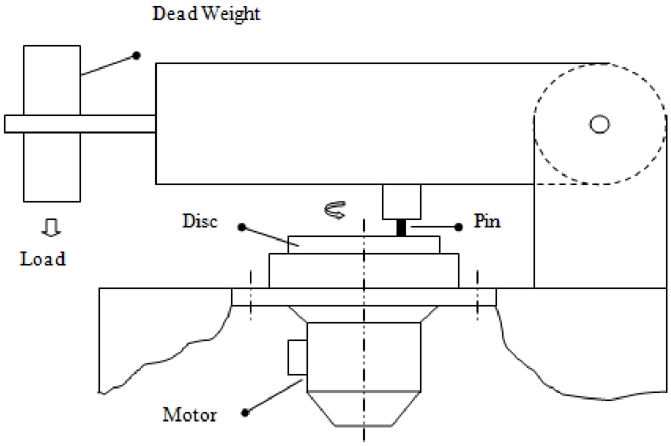


Figure 1. Schematic diagram of wear test apparatus.

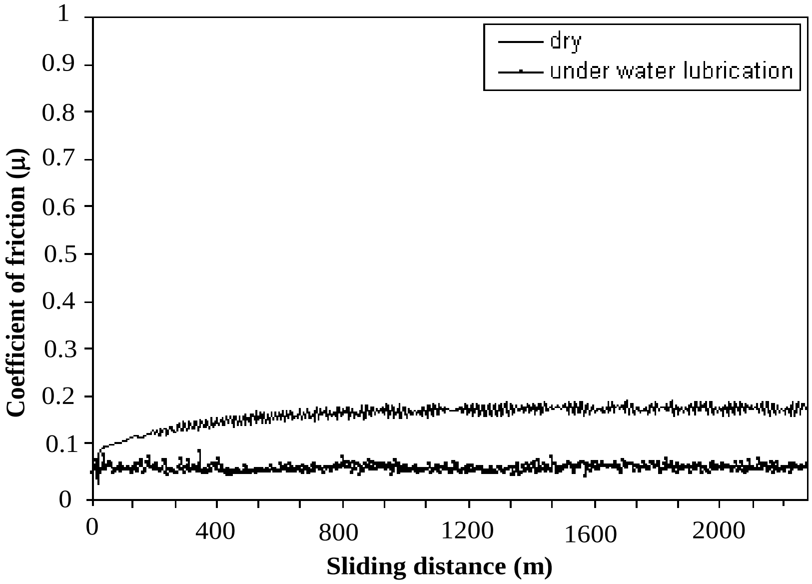


Figure 2. The relationship between coefficient of friction and sliding distance of UHMWPE polymer at dry sliding and under water lubrication conditions. Applied load = 100N, sliding speed=1.0 m/s.

this figure that for dry sliding condition, there is a running-in stage of about 400 m sliding distance followed by a steady state condition while there is not a clear running-in stage under water lubricated test condition. The presence of clear running-in stage under dry condition might be explained by the effect of some peaks of the surface roughness which were smoothened after some sliding distance. This is not pronounced in water lubricated condition because of the presence of the lubricant media. Figure 3 illustrates the variation of friction coefficients of

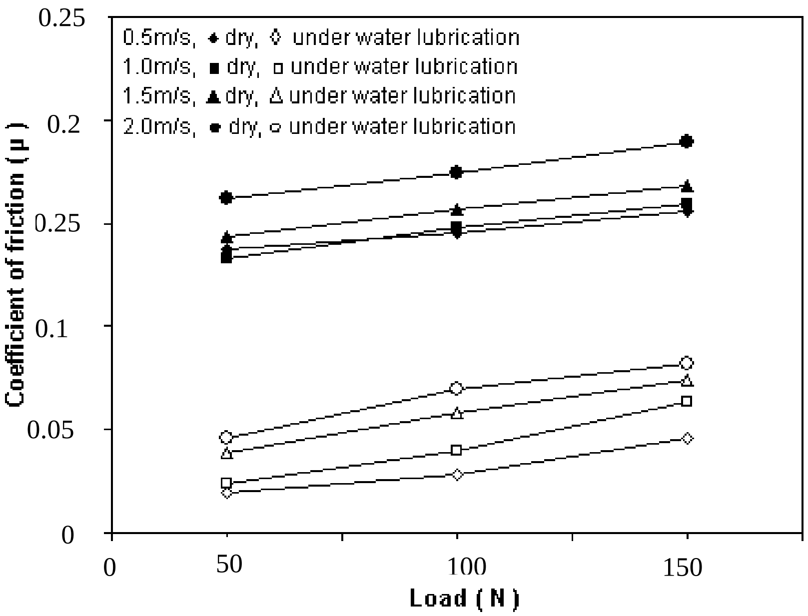


Figure 3. The relationship between coefficient of friction and applied load values of UHMWPE polymer at dry sliding and under water lubrication conditions.

UHMWPE polymer with applied load tested at 0.5, 1.0, 1.5 and 2.0 m/s sliding speeds and at dry sliding and water lubrication conditions. It was clear from Figure 3 that the coefficient of friction values for UHMWPE polymer at dry sliding and water lubrication conditions increases with the increase in applied load values. In case of lubricant media, the increase in coefficient of friction values with the increasing load value could be explain that the high load causes it to squeeze the lubricant out of contact surfaces (Gispert et al., 2006). This figure also show that there is an average of 15% increase in friction coefficient value for a 200% change in load values under dry sliding condition while this increase is about 50% under water lubrication condition. As it is known that GUR 1020 medical grade UHMWPE polymer is a visco-elastic material, the variation of friction coefficient with the load follows the equation $\mu = K N^{(n-1)}$, where μ is the coefficient of friction, N is the applied load, K is a constant and n is also a constant, with value between 2/3 and 1. According to this equation, the friction coefficient decreases with load increase. But when the load increases to the critical load value of the GUR 1020 medical grade UHMWPE polymer, the friction and wear will increase sharply. This behavior can be attributed to the fact that the frictional heat raises the temperature of the friction surfaces, which lead to relaxation of polymer molecule chains. Furthermore, the friction coefficient of GUR 1020 medical grade UHMWPE polymer was lower under water lubricated conditions than dry sliding condition because the water as a lubricant might function to significantly hinder induced thermal effect of friction.

Figure 4 illustrate the variation of specific wear rate of UHMWPE polymer with sliding speed, tested at 50, 100 and 150 N applied loads at dry sliding and water lubricated conditions. This figure shows that the specific wear rate values increases with the increasing in sliding speed. This is in agreement with the results of Wang and Li (1999). As the sliding speed is increased by 300%, from 0.5 to 2.0 m/s, there is an average of 66 and 50% increase in specific wear rate of UHMWPE polymer at dry sliding and water lubricated conditions respectively. In addition, the average specific wear rate value under dry sliding condition was 50% higher than that of the underwater lubricated conditions. This result illustrates the influence of the lubricant. To illustrate the influence of different lubricant media on the friction coefficient and specific wear rate for of UHMWPE polymer (Figures 5 and 6). It is clear from these figures that the coefficient of friction reaches the lowest levels using of water lubricant. This is followed by egg albumen and dry conditions. This behavior could be explained due to the less presence of transfer film for egg albumen which most of it was quickly rubbed away by the egg albumen lubricant. This is quite clear in the optical microscopy results of the disc worn surface examination. In fact, the presence of the egg albumen avoids the adhesion and transfer film of UHMWPE (Gispert et al., 2006). Figure 7 present the variation of coefficient of friction and specific wear rate with combined pressure and speed effect known as PV factor. It is clear from this figure that the coefficient of friction and specific wear rate for GUR 1020 medical grade UHMWPE polymer is increasing with the increase

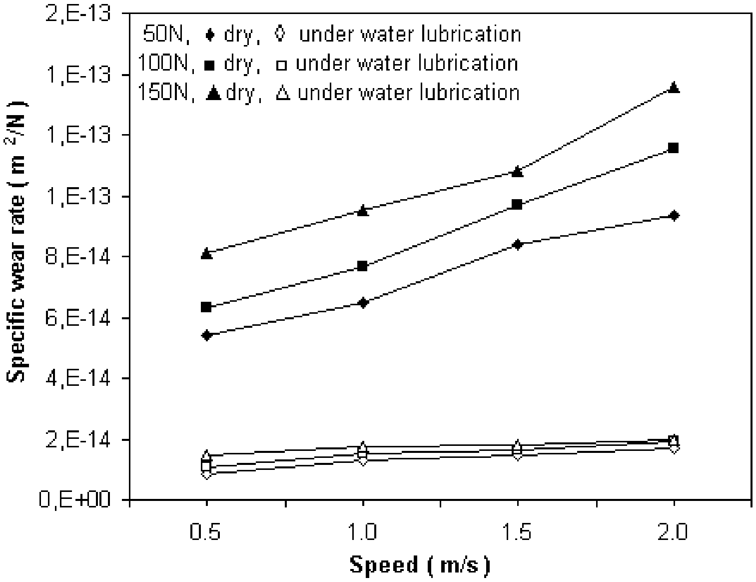


Figure 4. The relationship between specific wear rate and sliding speed values of UHMWPE polymer at dry sliding and under water lubrication conditions.

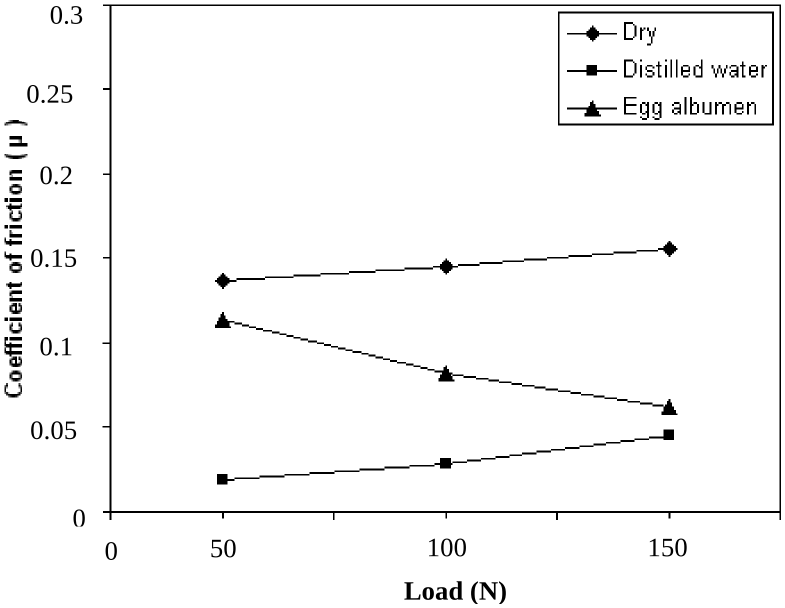


Figure 5. The relationship between coefficient of friction and applied load values of UHMWPE polymer at dry sliding, under water and egg albumen lubrication conditions.

in pressure velocity (PV) factor values. There is an increase of 100% in coefficient of friction and specific wear rate for a 1000% increase in PV factor at both dry and water lubricated conditions. It can be deduced from this figure that medical type UHMWPE polymer is sensitive to conditions with varying load and speed under both dry and lubricated conditions. The dry behavior of UHMWPE is in agreement with the results obtained by Wang and Li (1999).

The optical microscopy examination of worn surfaces of

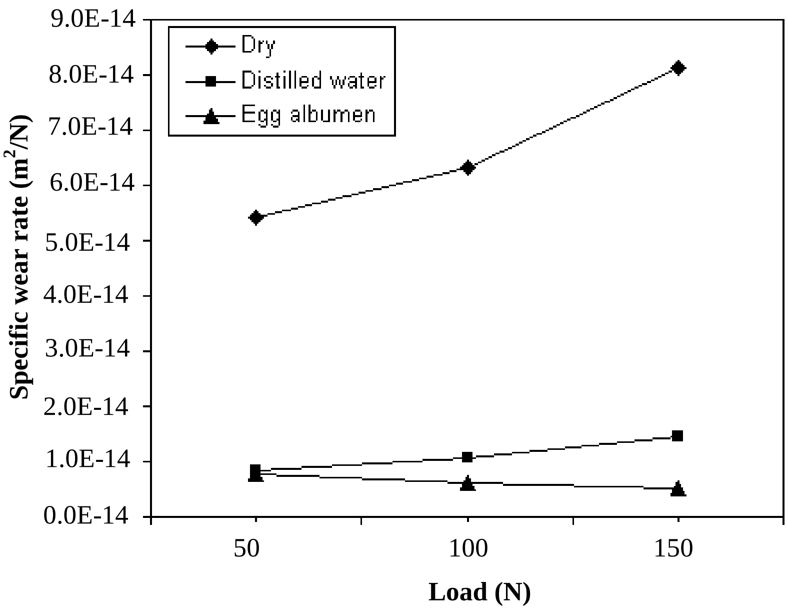


Figure 6. The relationship between specific wear rate and applied load values of UHMWPE polymer at dry sliding, water and egg albumen lubrication conditions.

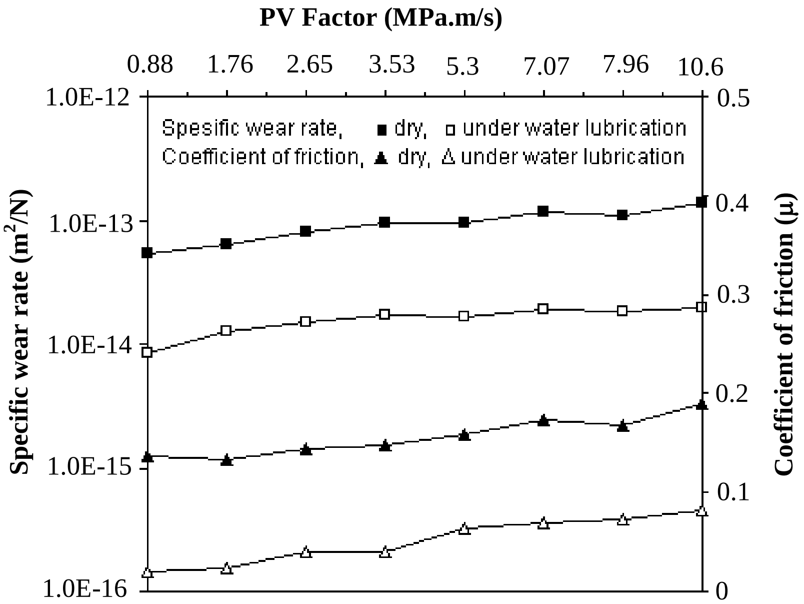
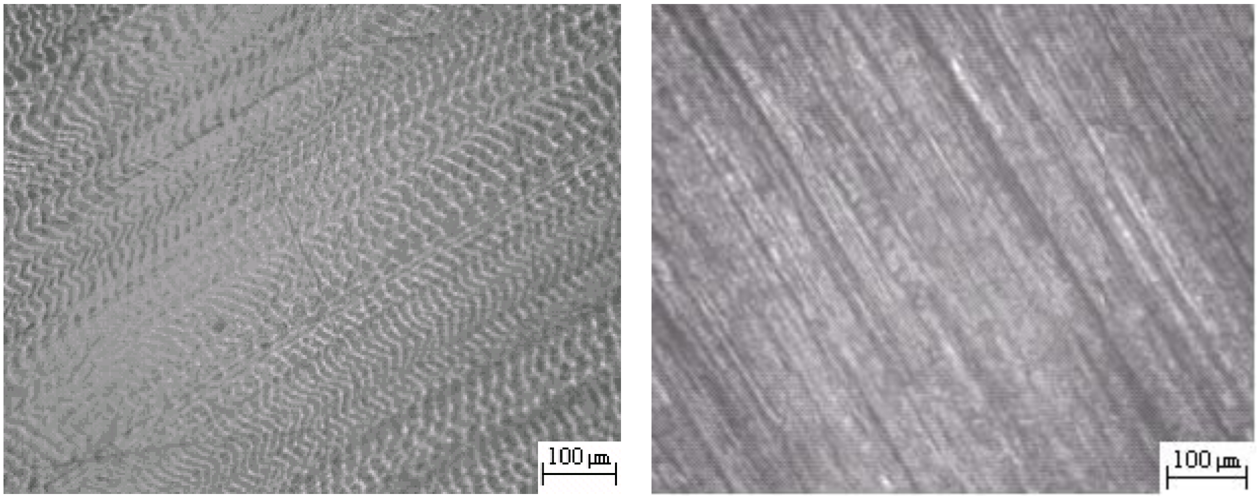


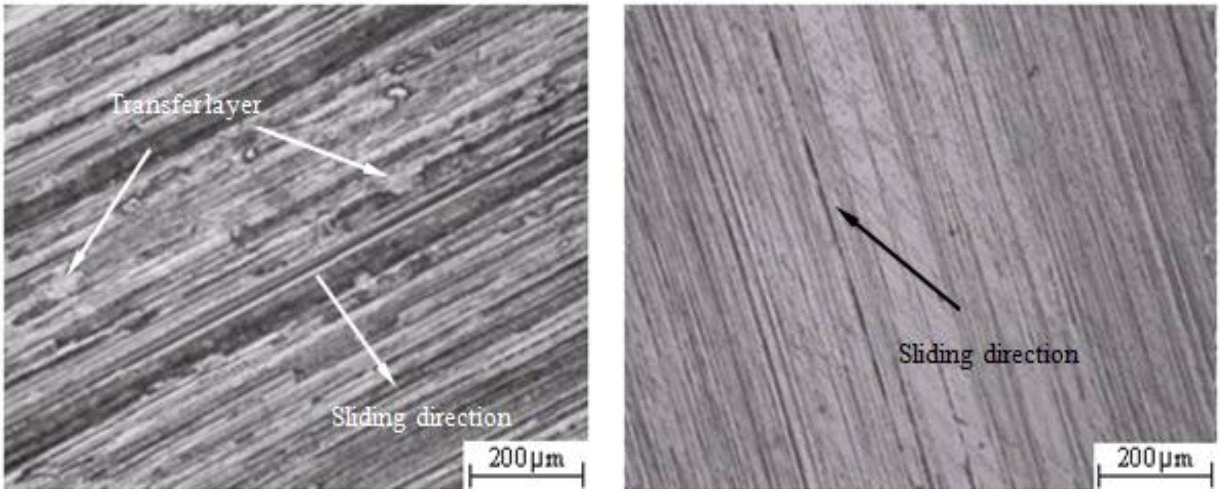
Figure 7. The relationship between specific wear rate-coefficient of friction and PV factor value of UHMWPE polymer under dry sliding condition and under water lubrication conditions.

GUR 1020 UHMWPE polymer pin against AISI 304L stainless steel disc at 150 N applied load and at 1.0 m/s sliding speed test for both dry and water lubricated conditions are given in Figure 8a and b respectively. In this figure the worm surface is wrinkled with wavy morphology and the wrinkling is denser with deep grooves for dry condition. This is due to the high temperature reaching the polymer surface. The high temperatures in the polymer surfaces result in softening the polymer surface and wrinkling present on the surface.



a b

Figure 8. The worn surfaces of UHMWPE pin polymers under: a, dry; b, water lubricated conditions; for 150 N and 1.0 m/sec sliding speed.



a b

Figure 9. The worn surfaces of 304L stainless steel disc: a, dry sliding conditions; b, water lubricated conditions (applied load: 100 N, sliding speed: 1.0 m/s).

Figure 9a and b shows the worn surface of counterface AISI 304L stainless steel disc. This figure shows the presence of some thin patches of UHMWPE polymer transfer film on the steel counter-face both at dry sliding and under water lubricated condition. However, this thin transfer film was less pronounced under water lubricated conditions because the polymer transfer layer was quickly rubbed away by the lubricant (Figure 9b). Generally, the presence of wrinkling on pin surface and the transfer film patches on the disc surface suggest the presence of abrasive and adhesive wear mechanisms.

Conclusions

1. The friction coefficients under lubricated condition for GUR 1020 medical grade UHMWPE polymer is lower than that of dry sliding condition.
2. The specific wear rates for GUR 1020 medical grade UHMWPE polymer under egg albumen lubricated condition is in the range of 0.5×10^{-14} m^2/N, while for dry sliding condition, the value is in the order of 8×10^{-14} m^2/N.
3. The specific wear rate for UHMWPE is significantly influenced by applied load, sliding speed values and

lubricant media.

4. Wear mechanism include abrasive and adhesive processes.

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