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Tribological behavior of artificial hip joint under the effects of magnetic field in dry and lubricated sliding

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Abstract. In recent years, there is an increasing utilization and demand to use magnetic fields in bioengineering application due to its beneficial effects. Although in the last decade more attention has been given by tribologists to the electromagnetic processes taking place between sliding surfaces, which influence the tribological behaviors, but no attention has been concern with the sliding surfaces of the artificial implant joints. Therefore, the present work aims to elucidate the tribological behavior of an artificial joint implant under the effect of magnetic fields.

Experimental investigation was carried out on a specially designed and constructed hip simulator on which the variations in the coefficients of friction and wear rates of the sliding surfaces were evaluated under the influence of a medium strength magnetic field suitable to apply in the human body. A realistic Ti-alloy implanted stem was used with an inserted head made from surgical grade stainless steel. This head was allowed to rub against UHMWPE sockets. The utilized type of prosthesis was "The JRI Modular Muller Standard-Total Hip Design". The performed experimental tests were conducted under both dry and lubricated sliding conditions using physiological saline solution. The designed simulator allows the coefficients of friction and the wear rates to be evaluated under realistic physiological loading and motion cycles encountered during normal walking of the human body. Comparative results are presented between the artificial joint performance in the presence and absence of the applied magnetic field.

The experimental results have indicated that the presence of a medium strength magnetic field of 270 Gauss strength between rubbing surfaces resulted in high beneficial reductions in friction and wear rate of UHMWPE sliding on stainless steel either under dry or saline lubricating conditions. Therefore recommendation was forward to subject artificial implants made of stainless steel/UHMWPE combination of material to such medium strength magnetic field in animal clinical trials aiming to prolong the implant life.

Scanning investigation of rubbing surfaces has revealed that the transfer of polymer to the counterface plays a dominant role in dictating the frictional and wear behaviors under dry sliding condition. Smooth molecular profile of the polymer-transferred leads to progressive reductions in friction and wear while the lumpy polymer transfer, formed at the beginning of sliding, increases both friction coefficient and wear. Two action mechanisms dominate the sliding process; adhesive and abrasive mechanisms. The presence of saline lubricant retards the formation of the beneficial polymer transfer thus leading to faster abrasion of the polymeric counterface which explains the relatively rapid and progressive increases in friction and wear.

1. Introduction

In normal engineering field, tribologists have recognized and used the principles of magnetism for separating the rubbing surfaces and consequently reducing friction and wear. This was accomplished

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either by the utilization of a load-carrying force, generated by the flow of a conducting fluid, within a magnetic field, thus forming a magnetohydrodynamic (MHD) lubrication [1] or in case of no lubricant, by the repulsion associated with the magnetic field [2]. Wear of metals, in particular, has received great attention from many investigators. Kumagai [3] has found that under the effect of magnetic field, a conducting fluid is capable to generate a pressure exceeding the ordinary hydrodynamic pressure, thus wear was reduced for the ferromagnetic material surfaces. Wear tests were performed under a very weak magnetic field intensity of 100 A/m. For the dry sliding, for nickel against carbon steel materials, Kumagai et al. [4] found that the transition from mild wear to severe wear was retarded with increasing magnetic flux density. Meanwhile, Hiratsuka et al. [5] tested metals under a strong magnetic field of 3.5×10^5 A/m and found a considerable decrease in wear owing to the magnetic field. A model of adhesive wear in the presence of magnetic field was proposed by Muju et al. [6], who concluded that the wear rate of materials, having low magnetic permeability, was reduced on application of a DC external magnetic field [7]. Hiratsuka [8] also reported a reduction in wear of metals under boundary lubrication when applying a magnetic field. It was also reported that the presence of magnetic field between sliding surfaces of brass/steel and steel/steel resulted in a large reduction in wear rates in particular at light load [9].

The use of joint simulators provides a mean of testing materials in prosthesis form under conditions, which are close to the intended use. There are different levels of sophistication depending on the nature of the forces, motions and environment. Most of the simulators in operation are for hip prostheses with a smaller number for testing knee prostheses [10–12].

The effect of magnetization has been used in many biomedical applications. However, no attention has been paid to the influence of magnetic field upon the performance of artificial joints. Externally applied pulsed electromagnetic generator of 27.12-MHz frequency [13] has treated only rheumatism and arthritis sufferers with pain and inflammation. This resulted in a remarkable reduction of inflammation and swelling with pain relief and improved mobility. At present, much work deals with the effects of magnetic fields generated by cordless telephones and telephone transceiver upon the human head [14–16]. However, no explanation was given to the reasons for such magnetic sources and effects. Presumably, this was due to the complexity of the phenomena-taking place in the joint. The magnetization will alter the lubricant, affects the joint tissues and the state of surface energy for sliding surfaces. Furthermore, it can lead to variations in the mechanical, physical, chemical and electric properties of the sliding surfaces, either for natural or artificial joints. The magnetic field may be generated or applied to human body. Therefore, the present work aims to investigate the effects of magnetic field upon the artificial joint performance in terms of friction and wear.

2. Simulator design

A dynamic hip simulator has been designed and constructed to allow *in-vitro* investigation of the friction and wear, taking place at the articulating surfaces of the artificial hip, under the effects of magnetic fields. The simulator duplicates the human walking cycle dynamic conditions. The controlled inputs, for the simulator, are the time-histories of parameters of dynamic activities, which are the cyclic motion, and the flexion/extension moments of the joint. A belt drive and a cam system apply the specific load and displacement inputs, while allowing unconstrained relative motion between the articulating components. Figure 1 illustrates the actual load on the hip joint while performing the walking cycle while Fig. 2 demonstrates the motion angle of the normal hip. Two strain gauges cemented to a leaf-spring cantilever pick up friction torque exerted on the acetabular cup. The hip simulator is shown in Fig. 3.

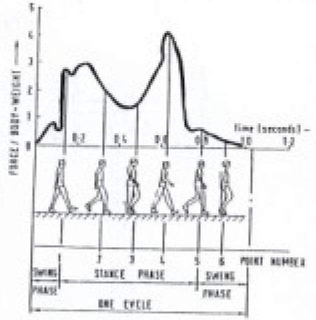

Fig. 1. The actual load on the hip joint while performing walking cycle.

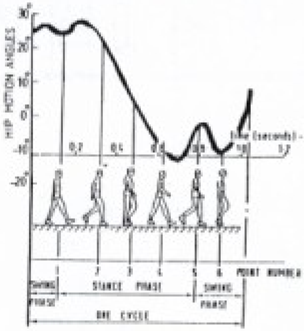

Fig. 2. Motion angle variations of normal hip joint.

3. Tested joint materials

An artificial hip design "The JRI Modular Muller THR Design" which is frequently used at present was purchased from Joint Replacement Instrumentation Ltd. (JRI) in UK.

(1) Modular Muller Standard Design made of Titanium (Ti-6Al-4V) standard Curved Stem with Long Neck with 12/14 taper spigot for head fixation and replacement (Code No. 09.12.24-CE 0473/ISO 5832/III).

(2) Stainless Steel (Surgical Grade 316 L) femoral head of 28 mm diameter for Long Stem Neck and 12/14 taper hole (Code No. 93.28.30-CE 0473/ISO 5832).

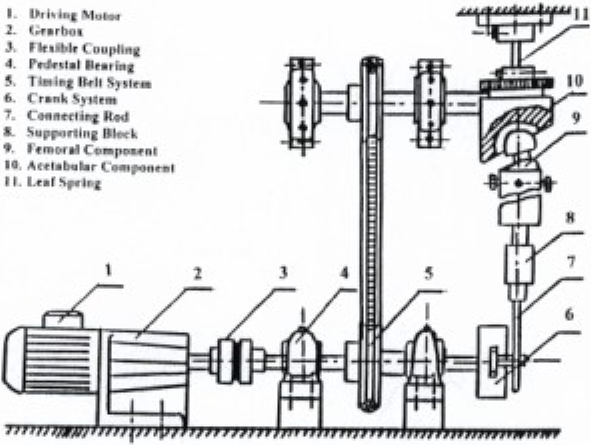

Fig. 3. Schematic layout of the designed hip simulator.

Table 1

Physical and mechanical properties of surgical grade ultra high molecular weight polyethylene UHMWPE (RCH 1000)

Property	Value
Molecular weight	3.5×10^6–4.0×10^6
Specific gravity	0.940
Vickers hardness at 20°C	5.3 ± 0.3
Rockwell hardness	55
Flexural modulus	0.68 – 0.89
Bulk shear strength	24 MPa
Tensile strength at:	
• Strain rate = 3.28×10^{-3} s^{-1}	28.4 MPa
• Strain rate = 3.28×10^{-2} s^{-1}	30.6 MPa
Thermal conductivity	0.42 W m^{-1} K^{-1}
Thermal diffusivity	2.42×10^{-7} m^2 s^{-1}
Water absorption in 24 h	<0.1 %

(3) Ultra-High Molecular Weight Polyethylene (UHMWPE) Cemented Acetabular cup of 50 mm outer diameter and 28 mm inner diameter (Code No. 09.28.01-CE 0473/ISO 5834/II).

All above items were sterilized and well backed before utilization in the experimental tests on the simulator. Table 1 demonstrates the physical and mechanical properties of UHMWPE.

4. Test procedure

In the present work it was essential to use test arrangements, which provide known, reproducible and generally steady conditions of load, speed, environment and contact conditions. Thus, the performance of natural hip joint in terms of the joint movement, range of motion, velocity, frequency, number of walking cycles for the hip joint and the hip load, was studied and duplicated, as possible, in the present designed simulator performance. These were as follows:

- *Joint Movement*: Hip joint has three degrees of freedom, i.e., move about three mutually perpendicular axes. However, in the present study only flexion and extension movements for the ball and socket hip joint were examined on the simulator. For the natural hip joint the angles of movement varies between plus and minus 20°. These angles were adjusted in the simulator.
- *Range of Motion*: The American Academy of Orthopaedic Surgeons (AAOS) has adopted the terminology in which the neutral position of any joint is zero degree. The zero position of the hip joint is one in which the thigh is aligned with the trunk in all planes. This was determined in the simulator and the flexion/ extension angles were measured from this position.
- *Velocity, Frequency and Number of Cycles*: In the present work, normal walking cycle was taken in consideration. The speed varies during walking from zero at the turning points to a maximum of about 75 mm/s. In the simulator, a crank mechanism was designed to give exact motion to that described. Normal subjects walked about 90 steps/min. Subject with an implanted hip joint or beyond age 60 walks at a slower velocity with smaller steps and the frequency is about 80 steps/min.
- *Hip Joint Load*: The values quoted for forces in the hip joint in normal walking vary according to the walking phase. The load varies from almost zero to three times body weight. The largest peaks of load occur over a time span of about 0.2 s, while the light loaded regions take place over about 0.4 s. In the simulator, a cam system was designed to give the exact load variations with time of cycle and the peak load was taken 15 kg.

The wear of artificial components joint is the most important factor in long-term durability. Semlitsch and Willert [17] in a study lasted 30 years have shown that polyethylene cups and stainless steel balls are favorable for older patients with a moderate range of activity. Polyethylene wear of 100–300 μm/year is to be expected. In the present study the polyethylene rate of wear was evaluated by weigh measurements at interval of tests. The recorded weight measurement value is the average of five balance readings.

The wear rate of the UHMWPE liner is calculated from the equation:

$$\text{Wear Rate} = V/(W \cdot L),$$

where: V = the cumulative polymeric volume loss in mm^3, W = the peak applied load in N, L = the cumulative sliding distance in m.

Before each interval of test, the rubbing surfaces were thoroughly cleaned to remove all traces of grease and other forms of contamination. The metal counterface was cleaned ultrasonically to remove any traces of loose wear particles.

The friction between rubbing surfaces was measured throughout the wear test at random interval of time and the average of six readings represents the value quoted in the present work. The friction torque measurement was achieved by recording the deflection of reaction cantilevers by means of cemented strain gauges. The signals from the strain gauges were amplified and converted to an X–Y pen recorder through a strain meter unit. The reproducibility of the friction and wear test values was evaluated and was typically found to be within approximately 20%, which was considered acceptable.

The most effective magnet design is one using concentric circles of alternating polarities. This allows for the maximal penetration to, and action on, the investigated sliding surfaces. The concentric-circle magnet, used in the present work, has more magnetic field lines to spare.

5. Test results and discussion

5.1. Frictions and wear of UHMWPE against stainless steel under dry conditions

In the present work, the wear rate values in the range 0–10 km of sliding were not plotted and were considered as running-in period values. The wear rate of UHMWPE sliding against surgical grade stainless steel under dry sliding conditions is illustrated in Fig. 4. The results indicate that the wear rate was initially high (2.145×10^{-7} $mm^3/N\,m$) and then decrease with increasing sliding distance to reach a minimum wear rate of 1.29×10^{-7} $mm^3/N\,m$ at a sliding distance of 41.47 km. The wear rate values start to increase slightly after that minimum value with further increase in sliding up to the end of test. The reason for such behavior is that for the dry sliding of UHMWPE against stainless steel the high wear rates are due to highly adhered polymer "lumps" on the smooth steel counterface. Very small wear particles of polymer become detached and accumulate between the asperities or within the valleys of the machining marks on the steel counterface forming these lumps. Thus, abrasive effects dominate the wear process for the steel rougher surface. With the progression of sliding, these lumps smear down forming a thin film of highly oriented with the long molecular chain in the direction of sliding. This is responsible for the decrease in surface roughnesss and consequently the wear rate values up to the minimum wear. Beyond the optimum wear rate, the transfer become a mixed mode of polymer transfer which is closer to that found on rougher surfaces but it retain similarity to that resulted at the optimum, which lead to slight increase in wear rate values [18,19].

The coefficient of friction variations of HHMWPE against stainless steel versus sliding distance is shown in Fig. 5. The initial sliding period is characterized by relatively high coefficient of friction (μ = 0.295) and then the friction values decrease to a minimum of 0.2 at the same sliding distance of the optimum wear rate (40 km). Beyond the optimum the friction coefficients slightly increase to reach

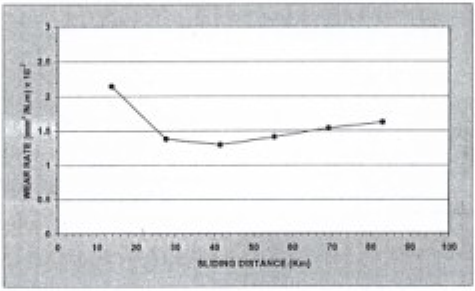

Fig. 4. Wear rate of UHMWPE/Stainless steel under dry sliding condition.

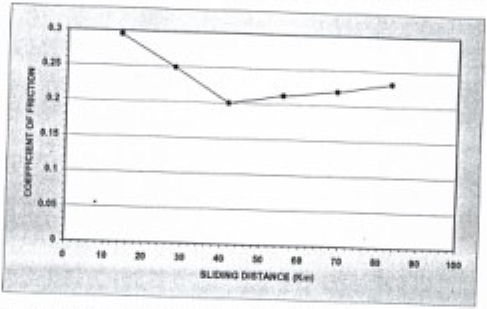

Fig. 5. Coefficient of friction of UHMWPE/Stainless steel under dry sliding condition.

0.23 at the termination of test. The obtained friction values are consistent with previous studies, which indicate that the dry coefficient of friction for UHMWPE against surgical grade stainless steel is in the range 0.1–0.3 depending on the test conditions. Briscoe [18] has shown that at low sliding velocities (ca 5 mm/s) at room temperature high-density polyethylene forms two types of transferred film when it is slid against a smooth clean counterface in air. He noted that at the onset of sliding the frictional force is quite high and a relatively thick, ca 0.1 μm, and reasonably highly drawn transferred layer is deposited. Once sliding has progresses the friction force decreases by 20% and a much thinner, ca 10 nm, but patchy transferred layer is produced. The film is highly drawn in the direction of sliding. The thick film transfer has been designated as "lumpy" while the thin film has been termed "smooth molecular profile" polymer.

5.2. Friction and wear of UHMWPE against stainless steel under lubricated conditions

Figure 6 illustrates the wear rate values versus the sliding distances for the UHMWPE socket against the stainless steel ball in the presence of saline solution. It can be seen that there is a general trend of linear increase in the wear rate with increasing sliding distance. It is believed that this behavior is related to the polymeric material inability to form appreciable polymeric transfer films on the steel counterface coupled with the ease with which material can be torn out from the polyethylene surface during sliding. The presence of lubricant also contributes to the retardation or inhabitation of polymer transfer formation. Furthermore, the porous nature of this polyethylene, caused by the transition from low to high density during crystallization, probably accounts for the ease of penetration and tearing of the material by metal asperities, leading to the relatively high rates of wear observed. Lloyd and Noel [19] have noted that for UHMWPE against steel in water the abrasion occurred more or less uniformly and the wear tracks occurred in isolated regions separated by wide relatively unworn areas. For the polymer surface a characteristic chevron-type pattern indicating stick-slip process occurring on a micro-scale was observed. In addition, it was found that extensive water absorption and swelling of the polymer occurred during testing, which clearly has an effect on the mechanical properties and the polymer ability to resist deformation and wear. These factors combined may explain the high wear rates observed. These observations consequently suggest that, qualitatively at least, the ability of a material to form and sustain transfer films on the metal counterface plays a very important role in determining wear rates. The present results

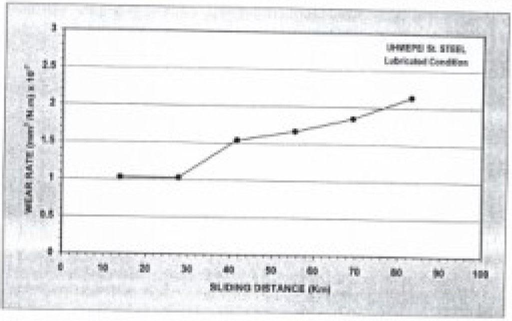

Fig. 6. Wear rate of UHMWPE/Stainless steel under lubricated sliding.

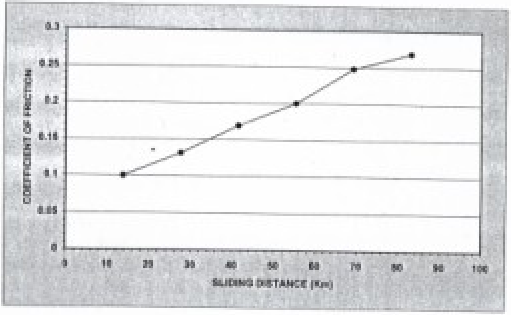

Fig. 7. Coefficient of friction of UHMWPE/Stainless steel under lubricated sliding.

indicate that the order of magnitude for the rates of wear, under the test conditions, was 10^{-7} mm^3/N m. The range of wear rates being 1.0×10^{-7} mm^3/N m to 2.13×10^{-7} mm^3/N m over the tested sliding distance (83 km) with an average wear rate value of 1.5×10^{-7} mm^3/N m which is similar to the average obtained for the dry test. However, by comparing the results obtained for the dry and lubricated tests, it can be seen that under dry conditions the wear rate values were much higher during the initial period of testing up to a sliding distance of 40 km. After this distance the dry wear exhibits lower values compared to lubricated tests.

The coefficient of friction of tested materials is plotted in Fig. 7 versus the sliding distance. The results indicate a continuous increase in the friction coefficients with increasing sliding distance. As the dominant wear process in the presence of saline solution is the abrasive wear process rather than the adhesive due to the absence of the beneficial transferred polymeric film, it is expected that both the wear and friction increase with increasing sliding distance. It is worth noting that the dry coefficient of friction values were comparable with those obtained under lubricated conditions for sliding distance over 70 km. Prior to this distance, the friction coefficients under lubricated conditions were much lower than those resulted in the dry test due to the absence of lumpy transfer and the cooling effect of the lubricant. The values obtained for the coefficient of friction of UHMWPE sliding on steel in the presence of saline solution were comparable with those obtained in the literature ($\mu = 0.1$–0.2) [20–22].

5.3. *Frictions and wear of UHMWPE against stainless steel under dry conditions in the presence of magnetic field*

The influence of the presence of magnetic field upon the wear rate of UHMWPE cup sliding against the stainless steel ball under dry sliding conditions is shown in Fig. 8. As can be seen there is a general trend of increasing wear rate with increasing sliding distance. This increase in wear was found to be almost linear starting at a wear rate value of 0.5×10^{-7} mm^3/N m at a sliding distance of 14 km (0.7 years of service) to reach a wear value of 1.37×10^{-7} mm^3/N m at the end of sliding test (83 km equivalent to 4.2 years of service). It is amazing to notice that the initial period of high wear rate, observed in similar test without the presence of magnetic field, was not present. Presumably, the presence of magnetic field inhibits the formation of lump transfer. The wear rate values started smoothly from relatively low value and increase gradually with increasing sliding distances. For each period of test, which occupies about 14 km of sliding, the wear rate increases at almost constant rate of about 0.2×10^{-7} mm^3/N m or less. By comparing the results obtained with those resulted in the dry sliding test without magnetic field effect it can be deduced that there is a considerable reduction in wear rate values in the presence of magnetic field. Such wear rate reduction reaches about 76% at the initial period of lump transfer and the percentage reduction in wear values during the steady state wear period started at 44% and decreased progressively with increasing sliding distance to reach 15.5% at the termination of sliding. These large reductions in wear rate values reflected the beneficial effect of the magnetic field under dry sliding conditions. The explanation for such reduction is not easy to interpret as a whole of complex phenomena takes place

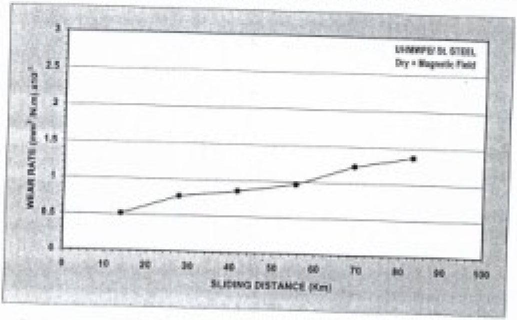

Fig. 8. Wear rate of UHMWPE/Stainless steel under dry sliding with magnetic field.

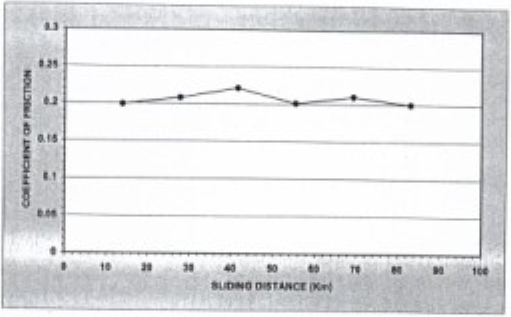

Fig. 9. Coefficient of friction of UHMWPE/Stainless steel under dry sliding with magnetic field.

between rubbing surfaces. Lee [23] has noted that both friction and wear involve solid-to-solid contacts governed by van der Waals and electrostatic interactions on the surface of a friction pair. For the dry sliding of a polymer on metal the adhesion component is affected by surface energetic of counterfaces. In addition, polymer deformation is an intrinsic property influencing adhesion and for polyethylene, the ratio of adhesion to deformation components of friction force is 0.032. Thus surface effect influences to la large extent both friction and wear of unlubricated glassy polymers. It is suggested that the presence of magnetic field has an effect in altering the surface energetic conditions by surface magnetic charging and probably causes the formation of a specific surface polymer structure by molecular orientation in the surface layer, similar to that obtained by polyner irradiation, responsible for the lowering in friction and wear values.

Figure 9 illustrates the variations in the coefficient of friction with sliding distance under the test conditions. The figure shows that throughout the tested sliding distance the coefficient of friction values display almost constant value of 0.2 ($\pm$0.01). This friction average value is equal to the minimum value obtained in dry test without the presence of magnetic field.

5.4. *Friction and wear of UHMWPE against stainless steel under lubricated conditions in the presence of magnetic field*

The results shown in Fig. 10 indicate that the polyethylene wear rate values obtained up to a sliding distance of 40 km were constant at a value of 0.513×10^{-7} mm^3/N m. After this period of constant wear, the wear slightly and progressively increases, over the remaining period of test, to reach a value of 0.77×10^{-7} mm^3/N m. Therefore, the increase in wear rates from the beginning of the steady state period to the end of test, which occupies 83 km, is not exceeding 0.26×10^{-7} mm^3/N m. This clearly emphasizes the amazing effect of the presence of magnetic field influencing the tribological behaviors of the rubbing surfaces either under dry or lubricated sliding. This influence is most pronounced in lubricated conditions as the results exhibits much lower wear rate values compared with those resulted under dry sliding. In the later case the wear rate values were almost doubled. It is suggested that another factor than the surface molecules orientation, was introduced and cooperated in the wear reduction. This factor is presumably

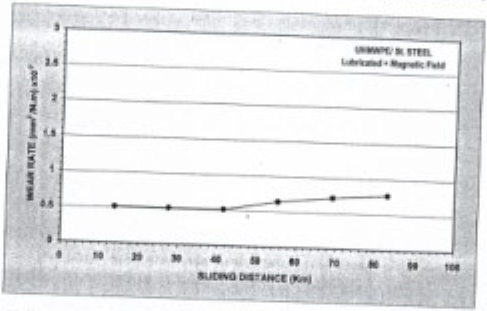

Fig. 10. Wear rate of UHMWPE/Stainless steel under lubricated sliding with magnetic field.

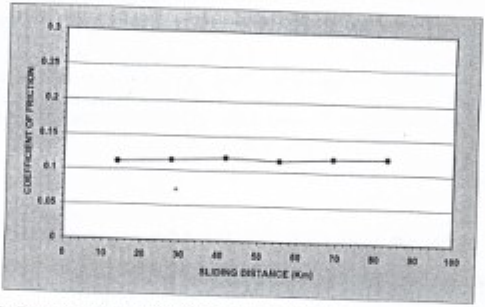

Fig. 11. Coefficient of friction of UHMWPE/Stainless steel under lubricated sliding with magnetic field.

the repulsive double-layer forces, which manifests itself in the presence of aqueous solutions. These double-layer forces are capable of repulsion the mating surfaces when they are relatively smooth and charged by constant magnetic field. Another factor is the Hall effect, which implies that when a magnet is placed over ionic solution as saline, which ionic charges, such as Na^+ and Cl^-, exist, some force will be exerted on the ions. The separation of ionic charges will produce an electromotive force, which can also contribute to the separation between mating surfaces thus resulting in lower friction and wear.

Figure 11 displays the results obtained for the coefficient of friction variations with sliding distance. As can be seen the test resulted in almost constant coefficients of friction of 0.11 throughout the examined sliding distance. This constant friction value reflects the benefit of magnetic field as in the similar lubricated test, without magnetic field, the friction coefficients increase progressively with sliding to reach a value of 0.27 at the end of test. The results obtained also show that the friction coefficients were half those obtained in the dry sliding test with the presence of magnetic field ($\mu = 0.21$ in average). Thus,

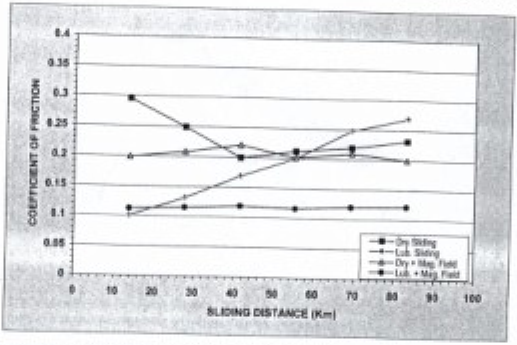

Fig. 13. Comparison for coefficients of friction of UHMWPE/Stainless steel under different test conditions.

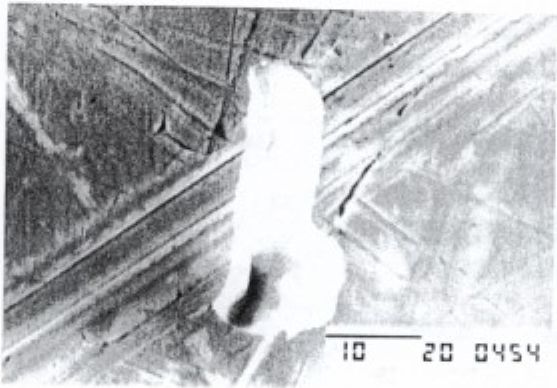

Fig. 14. View of patch buckled polymeric film, which has detached by abrasion and had rolled on the steel surface. The later exhibits abrasive wear grooves due to hard steel debris partially embedded in the softer polymer.

tial orientation with the direction of sliding. The surface traction rumples the layer and removes roughly elliptical patches of film. The underlying mechanisms have not been investigated but due to the layered and oriented nature of the film transverse cracking and delamination are likely elements. The observed back transfer of platelets of film was found and are consistent with this mechanism although the debris it can be concluded that the effect of magnetic field is more pronounced in reducing the coefficient of friction in lubricated sliding compared with the dry sliding. This is due to the repulsive double-layer forces, which tend to increase the gap between mating surfaces thus reducing both the friction and wear. In the human body, the presence of body fluids around the implanted joint is inevitable and this highlight the importance of the friction and wear results in the presence of magnetic field. The results reflect the amazing importance of using magnetic field to extend the life of the implant as both the friction and wear are minimum.

5.5. *Comparison of friction and wear of UHMWPE against stainless steel under different test conditions*

Figure 12 illustrates that the wear rate values in the presence of magnetic field, either dry or lubricated, were much lower than those resulted in the absence of magnetic field. Although the lubricated sliding results exhibit higher wear rate values for sliding distances exceeding 35 km, the contrary was found under the effect of magnetic field. In the later case, the lubricated wear display much lower values than in dry sliding. Over about 40 km (2.1 years of real service) all the wear rate traces display an increase in value with increasing sliding distance. The results clearly demonstrate the amazing beneficial effect of the presence of the investigated magnetic field in reducing the wear rates of UHMWPE/Stainless Steel combination.

Figure 13 also shows a comparison for the coefficient of friction versus sliding distance for the tests carried out on UHMWPE/Stainless Steel combination of materials. All the results obtained over a sliding distance of 40 km display coefficient of friction values in the range 0.20–0.27 except the results obtained in lubricated sliding conditions in the presence of magnetic field. The later case exhibits constant coefficient of friction value of 0.1, which is much less than other test results.

5.6. *Scanning electron micrograph of worn surfaces*

Scanning electron microscopy (SEM) of the stainless steel worn surface, at different intervals of tests, has revealed that transferred films of polymeric material take place on the steel counterface with substan-

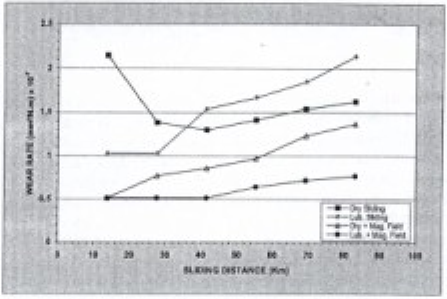

Fig. 12. Comparison for wear rates of UHMWPE/Stainless steel under different test conditions.

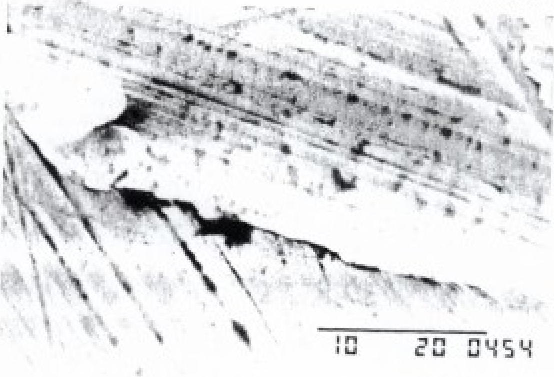

Fig. 17. SEM for the polymeric transfer after forming a smooth film on the steel counterface in the direction of sliding. A lump transfer is evident at the edge of the wear track.

will certainly be heavily worked in the contact after displacement from the surfaces. In filled systems of transferring polymer, evidence of micro-abrasion is evident and the debris is often observed to be in the form of rolls or scrolls. With highly conforming contact, as with ball and socket of the artificial hip, the polymeric wear debris do not escape easily from the contact. The wear debris of UHMWPE act as a lubricant and that resulted in reductions in both friction and wear of the polymeric surface. Microscopic examination has shown evidence that a few large metal asperities detached from the steel surface and became partially impeded in the softer polymer surface leading to abrasion of the steel counterface. Figures 14–17 illustrate the sequence of mechanisms taken place between the polymer and the steel counterface under dry sliding condition.

6. Conclusions

From the results obtained in the present research work the following conclusions can be drawn out:

(1) The designed simulator is certainly prove useful. The design is simple and reliable as the results of five consecutive cycles were compared and the discrepancies were found to be negligible with maximum differences of ±1 deg for the motion angle and ±1 N for the applied variable load. The simulator has been demonstrated to be capable of applying controlled and repeatable load-histories for in-vitro experimentation.

(2) The wear rate, of UHMWPE cup against surgical grade stainless steel femoral head, under dry sliding conditions, reveals two distinct regions. The initial region is related primarily to adhesion mechanism with a lumpy polymer transfer on the counterface resulting in relatively high friction and wear. The second is characterized by reduced friction and wear (45% less than the initial

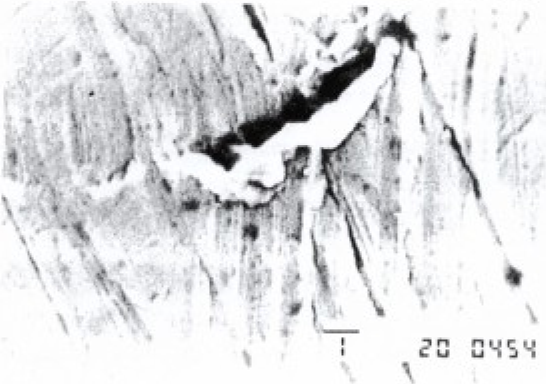

Fig. 15. SEM for the polymeric transfer at the initial period of sliding. The transferred patched film has been abraded and rolls of film are evident at a direction normal to sliding.

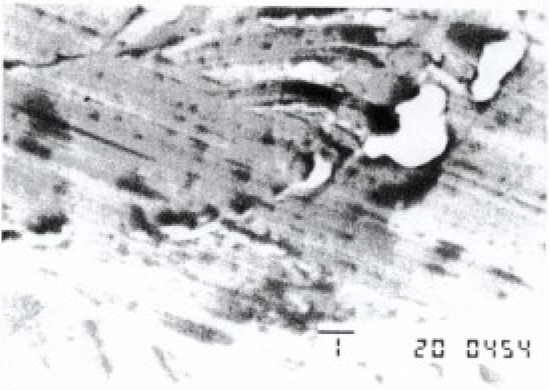

Fig. 16. SEM for the polymeric lumpy transfer at the initial period of sliding. Polymeric wear debris adhered to the steel counterface.

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period), as the polymer transfer forms an adhered oriented film of smooth molecular profile on the hard steel.

(3) The wear rate values, for the investigated materials on the simulator, were relatively lower than the values noted in the literature for the same materials tested on pin-on-disc machines under similar testing conditions. This was due to the difference in contacting surface configurations between the pin-on-disc and the ball-on-socket. In the later case, the Hertzian contact zone moves in a circular path over the cup surface and changes in size with the variations in applied load. On the other hand, the friction values were in agreement with friction values in the literature for the same materials.

(4) The presence of saline lubricant between rubbing UHMWPE and stainless steel resulted in higher wear rates compared with dry sliding due to lubricant absorption and swelling of polymer which deteriorate the polymer surface properties and its ability to resist deformation and wear. In addition, the friction coefficient is also affected by this polymer surface deterioration resulting in progressive increase in friction with sliding.

(5) The application of magnetic field of 270 Gauss strength, has amazing beneficial effects on both friction and wear, either under dry or lubricated sliding, as high reductions were encountered in friction and wear of UHMWPE sliding on stainless steel. These reductions were more pronounced under saline lubricated conditions and reached about 50% of those resulted in dry sliding.

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