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Macroscopic and microscopic wear mechanisms in ultra-high molecular weight polyethylene

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Abstract

Studies of the wear of ultra-high molecular weight polyethylene sliding on relatively smooth metallic and ceramic counterfaces under a wide range of tribological conditions in pin-on-disc and pin-on-plate tests, hip joint simulators and components taken from patients, have demonstrated evidence for two separate types of wear processes. Microscopic wear processes were associated with the very small asperities or the smooth counterfaces (less than 0.2 μm). Macroscopic polymer asperity wear processes were associated with stress concentrations under the much larger peaks in the polymer surface (amplitude less than 10 μm). For constant load tests with rougher counterfaces, microscopic asperity wear dominated. However for smooth counterfaces ($R_a < 0.02$ μm) under constant load, the contribution of microscopic asperity wear was small, and incremental increases in wear rates were caused by removal of macroscopic polymer asperities due to high subsurface strains and failure. In artificial joints under dynamic loading, the macroscopic polymer asperity wear processes were accelerated by subsurface cracking and fracture producing high wear factors on smooth counterfaces.

1. Introduction

The majority of total artificial joints currently implanted in patients consist of a highly polished metal or ceramic component which articulates on ultra-high molecular weight polyethylene (UHMPWE) material. Although this combination of materials has been used extensively over the last 30 years [1], and over half a million implants of this type are used every year, the current clinical practice of using these prostheses in increasing numbers of younger patients, with an expected lifetime in excess of 20 years, has generated renewed concern about the wear and durability of UHMPWE. Although there are still relatively few cases of prostheses actually wearing out [2, 3], the major concern relating to the long-term clinical performance of these implants is adverse tissue reactions caused by the generation of UHMWPE debris [1]. The particles of UHMPWE debris generated at the articulating surfaces are transported to the hard and soft tissue surrounding the joint [4, 5] and cause a chronic inflammatory reaction [6] and bone resorption [7]. A recent clinical study has correlated the amount of bone resorption around the neck of hip prostheses with the volumetric wear of the UHMWPE acetabular cup [8]. This type of bone resorption around the neck of the femoral component is a major cause of loosening of the implant, pain to the patient and the need for a revision operation. Laboratory cell culture studies have shown that UHMWPE particles activate macrophages (inflammatory cells) and that these activated macrophages stimulate osteoclasts to cause local bone resorption around the implant [9]. These tissue and cellular reactions to wear debris which cause bone resorption are dependent on the size and morphology of the wear particles as well as the number of particles and volume of debris generated. If as bio-tribologists, we hope to be able to extend the lifetime of artificial joints, it is necessary to understand and control the different wear processes that determine the volume and morphology of UHMWPE debris generated under a variety of tribological conditions that occur in artificial joints.

The roughness of the counterface is certainly an important factor in increasing the wear rate of UHMWPE [10] and it has been shown clearly that a single defect in the counterface can also cause a dramatic increase in the wear [11]. The importance of counterface roughness was demonstrated in a series of explanted hips, removed from patients because of failure and loosening, where high wear rates were caused by damage to the stainless steel femoral heads [12]. The damage has subsequently been attributed to third body wear by bone cement particles [13]. However there were a number of prostheses in this series of explants [12] where the surface roughness of the femoral head remained low ($R_a < 0.03$ μm) and yet they showed high penetration and wear rates (penetration of 0.7 to 3.2 mm during a life time of 10 to 14 years, which cor-

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responded to wear factors of 1.1×10^{-6} to 5.8×10^{-6} mm^3 Nm^{-1}. These results suggest that other factors and wear processes may be causing high wear rates in artificial hips with smooth femoral heads. The nature of the different wear processes is particularly important as they may modify the morphology of the wear particles as well as increase the volume and number of particles produced.

Recently, a laboratory study was undertaken to investigate the removal of UHMWPE from the surface of wear pins, when sliding with a constant velocity under a constant load on a smooth metal counterface on a tri-pin-on-disc-machine. These studies [14, 15] showed that:

(a) The wear rate was not constant.

(b) The UHMWPE pin surface did not remain flat.

(c) Incremental changes in the wear rate were associated with removal of material from peaks or ridges (amplitude up to 10 μm) on the polymer surface.

(d) Thin section microscopic polariscopy showed high residual shear strains under these peaks in the polymer surface prior to the loss of material. The strains were higher in the plane parallel to the direction of sliding.

(e) The characteristics of the counterface changed during the test because of the formation of a thin transfer film.

In addition thin section microscopic polariscopy was used to examine the residual subsurface deformation in acetabular cups taken from simulators and high residual subsurface shear strains were also detected in these cups.

However, some aspects of these experimental studies appeared contradictory. As wear rate increased in the pin-on-disc tests, as a result of the transfer film roughening the counterface, the subsurface shear strains were not evident. In contrast acetabular cups which had high wear factors (of the order of 10^{-6} mm^3 Nm^{-1}) did show residual subsurface strains. It is possible that the different tribological conditions found in the joint simulator, such as time-dependent loading, variable velocity, and a range of contact stresses may influence the contribution made by the different wear processes to the overall wear of UHMWPE. It was clear, however, from these initial studies that the topography of both the counterface and the polymer surface were extremely important factors in controlling the wear process. In particular it is important to note the marked difference in the scale of the asperities on the two surfaces. The metal counterface had an R_a of 0.01 to 0.02 μm, while the polymer surfaces showed peaks with an amplitude up to 10 μm.

In order to investigate the effect of different tribological conditions on the wear processes a further series of laboratory tests was carried out on tri-pin-on-disc machines, with different loads and various initial counterface roughnesses, and on pin-on-plate machines with reciprocating motion, with variable velocity and constant load. The results of these studies were compared to wear rates and surface and subsurface analysis of acetabular cups taken from hip joint simulators [16], and cups explanted from patients and previous pin-on-disc studies [14, 15].

2. Materials and methods

The specification of the ten wear tests carried out is given in Table 1. Two tri-pin-on-disc tests [14] were run on smooth counterfaces at a standard load of 80 N per pin (test 1) and at a low level of load of 20 N per pin (test 2), which gave a nominal stress of 3 MPa. Two tri-pin-on-disc tests (3 and 4) were run with rougher counterfaces, (surface roughness R_a of 0.033 and 0.052 μm respectively). All four pin-on-disc tests were run with a sliding velocity of 240 mm s^{-1}. Six pin-on-plate reciprocating tests (5–10) were run on initially smooth counterfaces ($R_a=0.02$ μm) at nominal loads of 80 N per pin [10]. All these tests had an average sliding speed of 190 mm s^{-1}. Wear of the UHMWPE pins was measured by weekly weight loss, after sliding distances of between 50 and 100 km. After each period of sliding, the counterface roughness and topography of the polymer pin were measured using the Talsurf 5 (Rank Taylor Hobson). At the end of each test the residual subsurface strains in the polymer pins were analysed using thin section microscopic polariscopy [14, 15]. All the tests were run in deionised water. The details of the test protocols have been published previously [10, 14, 15]. In addition six Charnley UHMWPE acetabular cups, which had been explanted from patients after use of between 5.7 and 12.3 years were studied (cups 11 to 16). The average wear factors for these cups were calculated from the depth of penetration of the femoral head into the acetabular cup, assuming an average of 1.5 million walking cycles per patient per year [12]. The surface roughness of each femoral head was measured and thin section microscopic polariscopy was used to detect residual subsurface strains in the polymer cups. One additional cup, taken from a hip joint simulator test [16] after 4.4 million cycles, the equivalent of three years implantation time, was also studied in a similar manner.

3. Results

The wear volume is plotted against sliding distance for test 1 (smooth counterface and standard contact

TABLE 1. Test conditions of the tri-pin-on-disc and pin-on-plate tests

Test number	Test machine	Initial counterface roughness (μm)	Nominal control stress (MPa)	Sliding distance (km)
1	Tri-pin-on-disc	0.02	12	200
2	Tri-pin-on-disc	0.015	3	900
3	Tri-pin-on-disc	0.033	12	1500
4	Tri-pin-on-disc	0.052	12	900
5–10	Pin-on-plate	<0.02	12	350

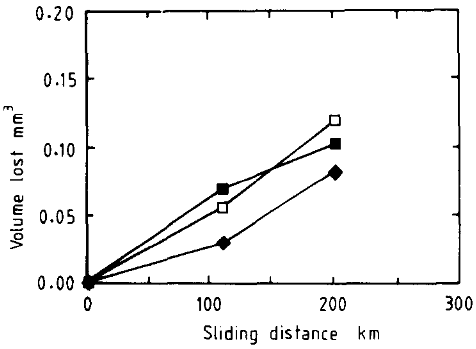


Fig. 1. The wear volume plotted against sliding distance for test 1 (pin-on-disc with a smooth counterface and normal contact stress (12 MPa).

stress, 12 MPa) in Fig. 1. The wear factors during this test were low (between 3.5×10^{-9} and 7.8×10^{-9} mm^3 Nm^{-1}). The surfaces of the polymer pins did not undergo any discrete changes in topography, and when the test was stopped after 200 km, a relatively short distance, thin section microscopic polariscopy cut in the direction of sliding, showed high residual subsurface shear strain under the polymer wear surface (Fig. 2). A band of material up to 40 μm below the surface was highly strained and the maximum value of the shear strain occurred approximately ten micrometres below the surface, under a peak in the polymer surface. Previous tests have shown that the largest shear strains develop prior to removal of a large portion of the wear surface [15]. A reduced stress level (3 MPa) was used in test 2, in order to limit the amount of subsurface plastic deformation caused by normal loading. The wear volume is plotted against sliding distance for this test in Fig. 3. The average wear factor during the first 400 km was low, (7×10^{-9} mm^3 Nm^{-1}). However during the period of sliding between 377 km and 506 km, a large wear step occurred as a significant portion of the polymer wear surface was removed from the highly stressed peaks on the pin surface. This was considered to occur as a result of the development of high residual subsurface shear strains (as shown in Fig. 2) and final rupture of the material at removal. After the loss of this highly strained material, the wear rate reverted to a low level for the remainder of the test. During both these tests

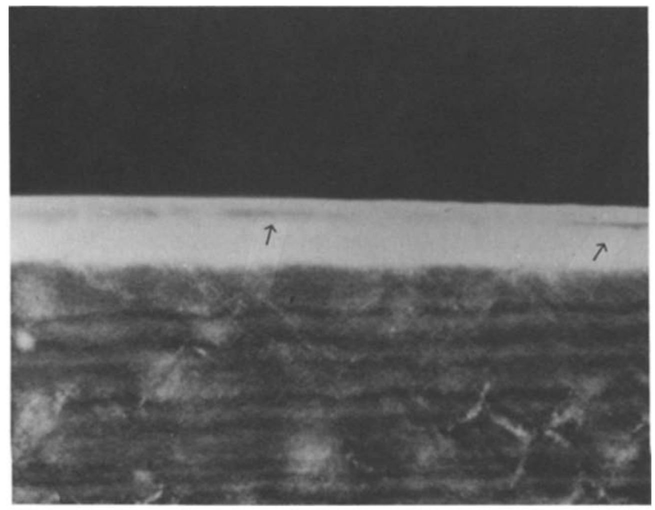


Fig. 2. A thin section polariscopic micrograph cut perpendicular to the surface of the wear pin in the direction of sliding at the end of test 1, showing a (white) band of residual shear strain below the surface and a shear strain concentration (5 to 10 μm below the surface) as a darker band marked by the arrows.

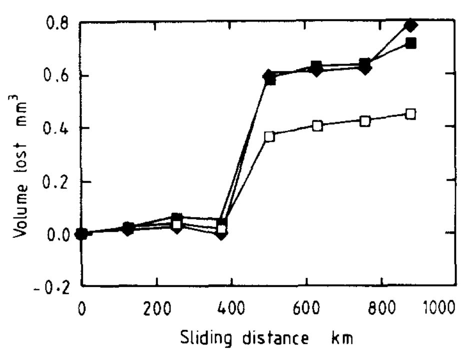


Fig. 3. The wear volume plotted against sliding distance for test 2 with a low stress level (3 MPa) and a smooth counterface.

the counterfaces remained reasonably smooth with only a thin polymer transfer film.

The wear rates on the two rougher counterfaces in tests 3 and 4 were much greater than on the smoother counterfaces. Figures 4 and 5 show that the wear volume graphs for these two tests can be considered in two sections; an initial high wear rate and a lower rate in the second part of the test. In test 3, with an initial

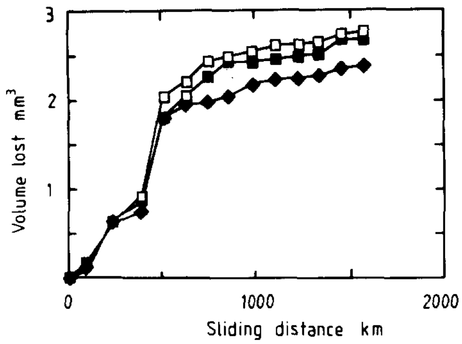


Fig. 4. The wear volume plotted against sliding distance for test 3 with a rougher counterface ($R_a = 0.033$ μm).

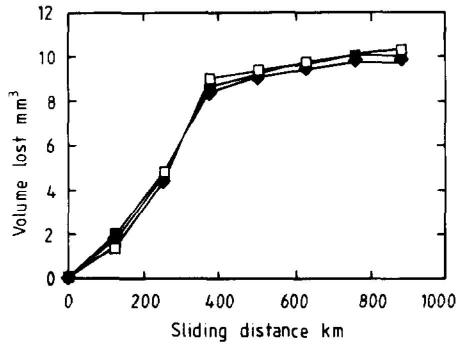
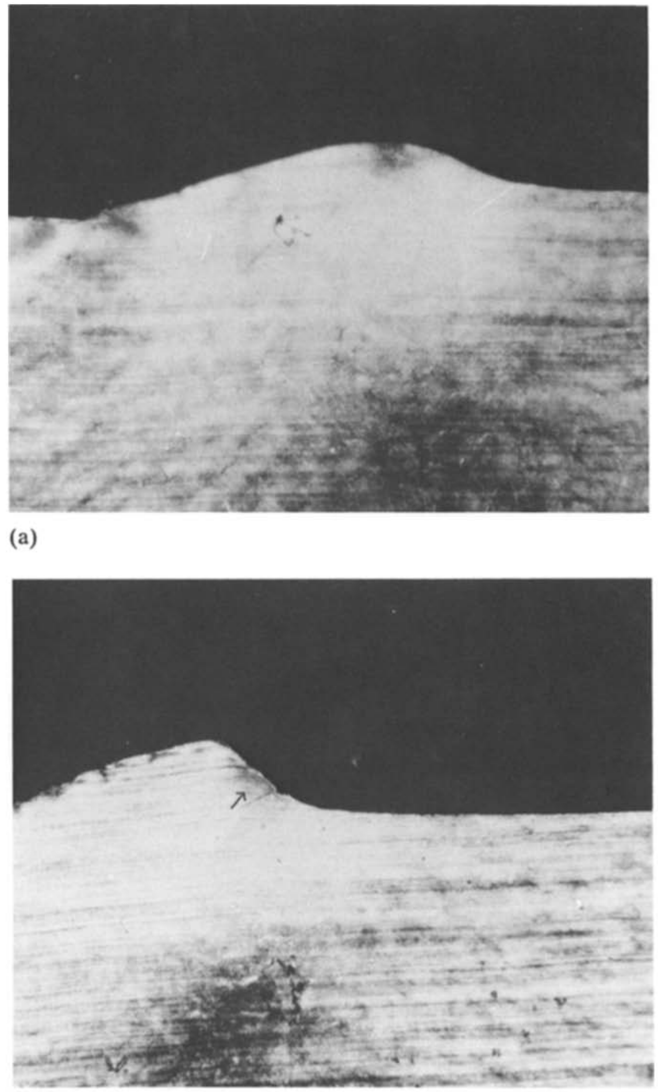


Fig. 5. The wear volume plotted against sliding distance for the roughest counterface ($R_a = 0.055$ μm).

TABLE 2. Change in wear factor with initial surface roughness for the pin-on-disc tests

Initial surface roughness of the counterface R_a (μm)	Average wear factor associated with microscopic asperity wear (10^{-8} mm^3 Nm^{-1})
0.02	0.6
0.015	0.7
0.033	5
0.052	28

surface roughness R_a of 0.033 μm, the average wear factor on the initial phase was 5×10^{-8} mm^3 Nm^{-1}, while in test 4 with an initial surface roughness of 0.055 μm the initial wear factor was 2.8×10^{-7} mm^3 Nm^{-1}. Unlike the previous tests on smooth counterfaces, there was less evidence of stepping in the wear graph (during the initial phase) in these tests and no marked changes in the surface topography of the polymer pins. It is likely that the microscopic asperities of the rougher counterfaces removed material from the polymer pin at a rapid rate, before plastic subsurface shear strains could be built up to cause subsurface failure. Table 2 shows the variation in wear factors associated with the asperities of the counterface, as a function of the initial surface roughness of the counterface. There was a 40-fold increase in wear rate with a three-fold increase in surface roughness. This was a greater increase in the wear rate with surface roughness than predicted in previous longer term studies with a pin-on-plate reciprocator [10].



(a)

(b)

Fig. 6. A thin section polariscopic micrograph cut perpendicular to the surface of the wear pin from test 3(a) and test 4(b) taken transversely across the pin showing the side runners at the left hand side of the micrographs. Substantial residual subsurface strains were seen under these peaks (white band), with a strain concentration on the inside face of the runner (darker fringes, arrow 6b).

The reduction in wear rate in the second part of tests 3 and 4 was coincident with a smoothing of the rough counterface by a UHMWPE transfer film and a change in the profile of the wear pin. Mid-way through both tests, large peaks or side runners were formed along the edges of the pin, in the direction of sliding. It was not clear if this was caused by preferential removal of material from the centre portion of the pin,

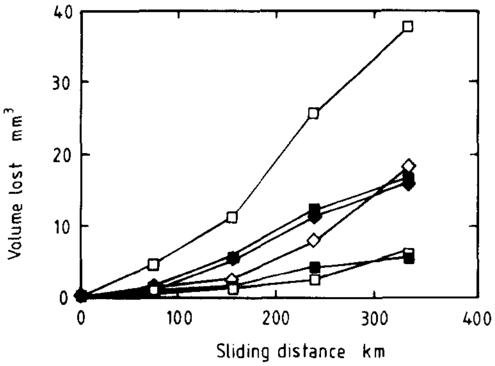


Fig. 7. The wear volume plotted against sliding distance for the six reciprocating pin-on-plate tests (5–10).

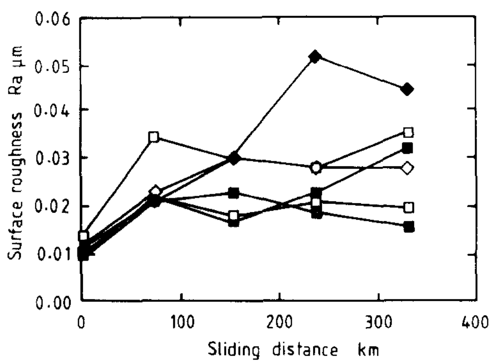


Fig. 8. The increase in surface roughness plotted against sliding distance for the six reciprocating pin-on-plate tests.

TABLE 3. The femoral head surface roughness and the wear factor for the acetabular cups

Cup	Final femoral head roughness (μm)	Wear factor (10^{-6} mm^3 Nm^{-1})
11	0.019	2.5
12	0.04	4.3
13	0.03	5.0
14	0.06	5.6
15	–	4.8
16	0.024	3.6
17	0.025	

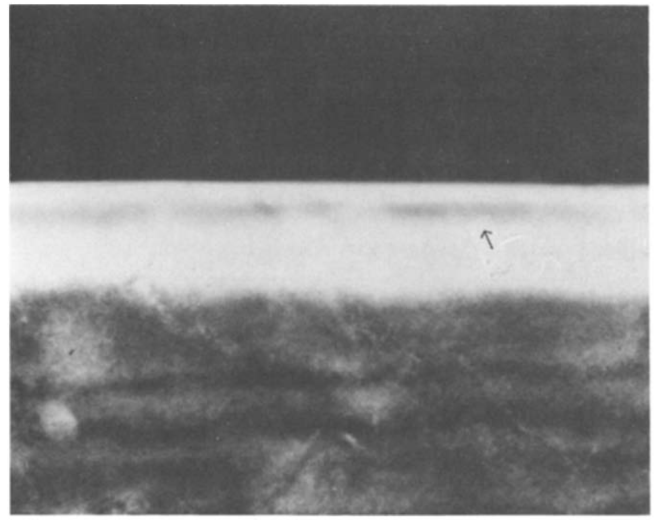


Fig. 9. A thin section polariscopic micrograph taken perpendicular to the wear surface of the cup after a simulator test, showing a thick (white) band of residual subsurface strain, with a strain concentration just below the surface.

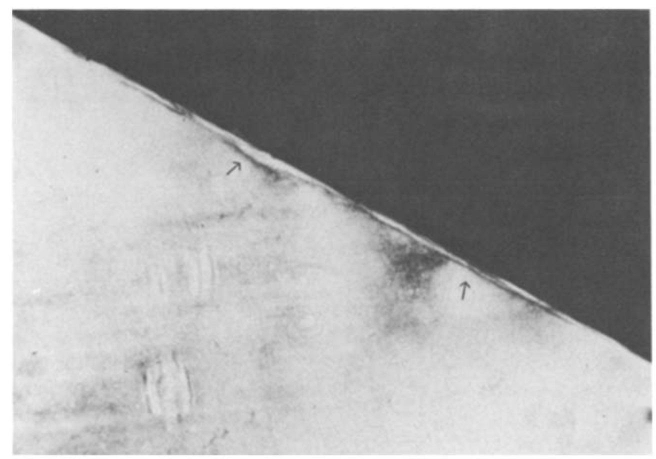


Fig. 10. A thin section polariscopic micrograph taken perpendicular to the wear surface of an explanted cup showing areas of high residual shear strain below the surface and extensive subsurface cracking.

or flow of the polymer to the outside of the contact. Unlike the peaks in tests 1 and 2 and previous studies [14, 15], these were not removed by subsurface failure and remained throughout the second portion of the test. The amplitude of these side runners was also very large (in excess of 100 μm in some cases). These pins showed substantial subsurface shear strain in the material under these peaks, when sectioned perpendicular to the wear surface and the direction of sliding and studied in the microscopic polariscope. Figures 6(a) and 6(b) show the polarised light micrograph of transverse sections through the pins at the end of tests 3 and 4, demonstrating both the surface profile and the residual strain. These types of side runners have been observed previously in wear tests.

The volumetric wear rate for the six reciprocating tests (5–10) are plotted against sliding distance in Fig. 7. The average wear factors were high in these tests (0.18×10^{-6} to 1.3×10^{-6} mm^3 Nm^{-1}) even though the initial counterfaces were smooth. However, there were quite significant increases in counterface roughness during the test, caused by an uneven polymer transfer film on the counterface. Figure 8 shows the variation in counterface roughness throughout the tests, and it can be seen from Figs. 7 and 8 that there is a correlation between the changes in counterface roughness and wear rate. It was considered that the asperities of the rougher counterface were primarily responsible for the wear in these tests, as with the rougher counterfaces in tests 3 and 4, and that subsurface strain did not have an opportunity to develop.

The calculated average wear factors of the acetabular cups and the surface roughnesses of the femoral heads are given in Table 3. Under dynamic physiological loading and movement, the wear factors were at least two orders of magnitude higher than in the pin-on-disc studies with smooth counterfaces. Though some of the femoral heads showed rougher counterfaces, the heads on the other prostheses remained reasonably smooth. The evidence from the laboratory wear pin tests would indicate that the asperities of smooth counterfaces would not generate such high wear rates. Most importantly though, five of the acetabular cups showed residual subsurface shear strains under the polymer wear surface (Fig. 9). In addition, subsurface cracking of the polymer was also seen in four of the cups in the areas of high residual strain (Fig. 10).

4. Discussion

A considerable spread of wear factors have been found for UHMWPE under a range of tribological conditions in this study. These range from 0.7×10^{-8} $mm^3\ Nm^{-1}$ in the pin-on-disc tests with smooth counterfaces to 5.6×10^{-6} $mm^3\ Nm^{-1}$ in acetabular cups. Previous studies have shown that the wear of UHMWPE was dependent on the initial roughness of the counterface [10]. This was also found in this study, but with a much greater increase in polymer wear with increased counterface roughness (Table 2) than previously reported [10]. This type of wear was associated with deformation (adhesion or abrasion) of a nominally flat polymer surface by repeated interactions with the microscopic asperities of the counterface. The results of the pin-on-plate and pin-on-disc tests also showed that the polymer transfer film modified the counterface and that it was necessary to monitor and control the counterface throughout the wear test to produce reliable data.

This conventional view of polymer wear associated with the counterface roughness, which we describe as "microscopic asperity wear", is likely to dominate the wear processes for rougher counterfaces. However, it failed to explain the incremental changes in wear rates that occurred in test 2 and previous studies [14, 15] on smooth surfaces, the residual subsurface shear strains and changes on topography of the polymer surface. Most importantly it was unlikely that increased microscopic wear could account for the higher polymer wear rate (greater than 10^{-6} $mm^3\ Nm^{-1}$) in the acetabular cups which articulated on relatively smooth femoral heads.

The experimental evidence in this study and previous papers [14, 15], would indicate that the topography of the polymer surface was extremely important in producing these increases in wear of UHMWPE. The scale of the peaks and asperities of the polymer surface was typically 10 to 100 times greater than the asperity heights on the smooth counterfaces. These peaks were deformed when load was applied producing surface and subsurface stress concentrations as shown schematically in Fig. 11. We have described the removal of materials from these highly stressed polymer peaks as "macroscopic polymer asperity wear", in contrast with the wear caused by the much smaller scale microscopic asperities of the counterface. The analysis of the polymer pins in tests 1 and 2, and previous studies [14, 15] using thin section microscopic polariscopy showed high residual shear strains under the polymer peaks to a depth of 40 μm below the surface (Fig. 2). It is likely that this deformation gradually built up under continuous sliding until the plastic failure strain was reached and the polymer peak was removed. This offers an explanation for the large incremental changes in wear rate when sliding on smooth counterfaces. The much lower underlying wear rate found in other periods of these tests was considered to be produced by the microscopic asperities of the counterface. Residual subsurface strains were not found in the high wear rate tests on rough counterfaces. In these tests, where the wear caused by the counterface asperities was high, material was removed from the counterface before the subsurface plastic strains could develop. Hence macroscopic polymer asperity wear was small.

The polymer pins in tests 3 and 4 and the reciprocator tests (5–10) produced large peaks or side runners at the edge of the pin, in the second half of the tests. These were not like the polymer peaks seen on smooth counterfaces, as they were of a larger amplitude, the subsurface shear strains were much deeper and they were not periodically lost. The maximum shear strain in the plane transverse to sliding was on the inside slope of the peak, and could have been associated with

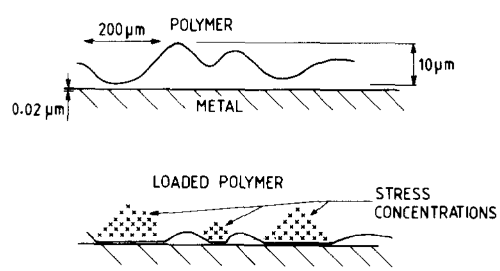


Fig. 11. A schematic diagram showing the relative scale of the surfaces and the proposed macroscopic polymer asperity wear mechanism.

flow of material from the peak into the flat central wear portion. An explanation of why these peaks on the edge of the contact were not removed may arise from analysis of the lubrication on the contact. The formation of these slide runners appeared to help stabilise the wear rate on the pin-on-disc tests. It was clear from these and previous wear tests that the topography of both counterfaces was extremely important in determining the contribution made by different wear processes.

These experimental studies under a constant load indicated that higher wear rates were more likely to be dominated by wear caused by the counterface asperities of a rougher surface, with little contribution from subsurface macroscopic polymer asperity wear processes. Hence it was a considerable surprise to find that many of the acetabular cups from hip joints had high wear factors in excess of 10^{-6} mm^3 Nm^{-1}, with relatively smooth counterfaces and also showed significant subsurface shear strain. In addition, under dynamic loading conditions found in artificial joints, subsurface cracking was also found in the highly strained region. Subsurface cracks had not been seen in wear pins under a constant load. Subsurface crack propagation may well have accelerated the failure and removal of material from the highly strained polymer peaks, hence greatly increasing the "macroscopic polymer asperity wear processes". This type of subsurface fatigue and wear, may well explain the occurrence of high wear rates in acetabular cups which articulated on smooth "undamaged" femoral heads under cyclic loading which are more than two orders of magnitude greater than wear factors under constant load on equivalent surfaces on pin-on-disc tests.

These macroscopic polymer asperity wear processes were not only important with respect to the increased volume of wear debris produced, but may also produce larger wear particles which can cause adverse tissue reactions in the body. Previous studies of wear debris from laboratory tests [15] and debris taken from joints in the body indicate the presence of large aspect ratio wear particles, which could be produced by macroscopic polymer asperity wear processes.

Acknowledgments

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