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Observations of residual sub-surface shear strain in the ultrahigh molecular weight polyethylene acetabular cups of hip prostheses

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Analysis of bearing surfaces of explanted cups can help to determine the wear mechanisms that are responsible for generation of wear debris. In this study a microscope polariscope was used to detect residual subsurface shear strains, deformation and subsurface cracks in explanted Charnley acetabular cups. The wear surfaces were compared to an acetabular cup from a hip joint simulator test. The six explanted cups that were studied had all failed after long periods of implantation, with penetrations ranging from 2.1 to 3.8 mm. The explanted and simulator cups both had a smooth, high-wear region. High residual subsurface shear strains were found in the high-wear region of most cups, with certain cups possessing subsurface cracks running parallel with the surface 5–10 μm deep, close to the areas of high residual subsurface shear strain. This was caused by plastic deformation and subsurface fatigue of the polymer surface.

1. Introduction

The wear of the ultrahigh molecular weight polyethylene (UHMWPE) component remains a major cause for concern in long-term joint replacement. More than half a million diseased or damaged joints are replaced annually in the world, and the number of patients at risk from prostheses failure is continually increasing. A typical joint consists of a smooth hard metal or ceramic counterface which articulates on a softer UHMWPE component. The hard metal counterface should have a very smooth surface, as it has been shown that the wear rate of the UHMWPE is dependent on the surface roughness (R_a) of the hard metal component [1]. Over the past 20 years there have been a considerable number of studies of the wear of UHMWPE, and these have shown large variations in the wear factors under different conditions [2]. The volume of work already carried out stands as a testament to the importance of UHMWPE as a bearing material, and it is conceivable that UHMWPE will remain a major material in total replacement joints for the foreseeable future. UHMWPE has good wear resistance, and the actual wearing out, or the wearing through, of the acetabular component is not generally a problem in hip prostheses. However, wear of the UHMWPE cup creates two problems. First, as the head of the femoral component bores into the cup its angular movements are restricted, which results in impingement of the neck of the stem on the cup rim, shock loading, and socket loosening in a proportion of patients over time [3]. Secondly, the generation of wear particles of UHMWPE, which can penetrate the bone–implant interface, can lead to adverse tissue and cellular reaction. This in turn can mediate bone resorption and the formation of a thick fibrous capsule around the prosthesis. A connection has been established between such tissue reactions and the loosening of prosthetic components, culminating in the need for a revision operation [4, 5]. The extent and type of cellular reaction that is experienced relates to the number and morphology of the wear particles [6]. Transportation and elimination of very small particles is carried out by the lymphatic system. Overload will occur if the number or the size of the particles reaches a critical level, above which the particles are not transported away and accumulate around the joint to produce chronic inflammatory and foreign-body response, leading to bone resorption. An understanding of the mechanisms of generation of wear particles is essential if it is to be attempted to control and reduce the number of particles generated in artificial joints, and hence improve their long-term clinical performance.

In this work a microscope polariscope was used to study subsurface shear strains in the explanted Charnley cups. These cups were then compared with an acetabular cup taken from hip joint simulator test. The six explanted cups that were studied were taken from hip prostheses that had failed after long periods of implantation, and had all displayed large penetration

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rates of the femoral head into the acetabular cup (ranging from 2.1 to 3.8 mm). All were removed at revision operations, with the need for revision being loosening of either the cup or stem, apart from one cup for which the stem had fractured. In addition to the explanted cups, one worn cup from *in vitro* testing in the Leeds hip joint simulator and an unworn Charnley cup (used as a control) were also studied. In our recent studies [7, 8] we observed residual (plastic) subsurface shear strains in UHMWPE pins sliding on smooth stainless steel counterfaces in unidirectional wear tests. These plastic shear strains developed during long periods of sliding under peaks or ridges on the polymer surface (typical amplitude of the ridges was approximately 10 μm), until they reached a magnitude at which surface failure occurred, material was removed and a large incremental change in the wear rate of the polymer occurred. This macroscopic wear of the asperities and ridges of the polymer surface is due to high localized contact stresses and the surface friction force. This macroscopic wear mechanism should be contrasted with conventional wear mechanisms, where the microscopic asperities of the metal counterface (typical amplitude < 0.01 μm) remove material from the polymer surface by adhesion/fatigue and abrasion processes [9, 10]. In this study the explanted acetabular cups, and cups taken from hip joint simulator tests, were analysed in the same way as the wear pins [7, 8] for evidence of residual subsurface shear strain and macroscopic polymer asperity wear mechanisms.

2. Materials and methods

The history of the six explanted cups that were used in the study is given in Table I. The simulator worn cup was run for 5×10^6 cycles with a peak load of 2.9 kN, corresponding to an equivalent implantation time of 4 years. The total penetration was 0.58 mm (corresponding to a linear penetration rate of 0.145 mm year^{-1}), and the femoral head roughness was 0.027 μm. In addition to these, a new unworn cup was studied as a control. The UHMWPE cups were all carefully mounted and clamped in the microtome vice in such a way as not to induce any residual shear strains. Once mounted, 30 μm-thick slices of UHMWPE were cut from the cups, in a direction perpendicular to the wear surface. These 30 μm slices were then mounted on microscope slides and viewed under a microscope that was configured as a polariscope. This allowed the residual shear strains in the slices to be studied due to the birefringent nature of UHMWPE.

Birefringence (or double refraction) is a phenomenon that is observed in many transparent non-crystalline materials. Birefringent materials are normally optically isotropic; however, when they are deformed they become optically anisotropic. The result of the anisotropy created by loading is to produce three principal refractive indices which coincide with the three principal axes of stress or strain. When plane-polarized light enters a deformed plate, it can be resolved into two components coincident with the two principal stress directions. These two components of light propagate through the material with different velocities, resulting in a phase difference when they emerge from the material. The two components are then resolved by the analyser along its axes of polarization, resulting in the formation of two sets of extinction lines. These are isoclinics and isochromatics; the former are related to the orientation of the principal axes of stress or strain, and the latter are lines of constant principal strain difference. If the plane-polarized light is replaced by circularly polarized light, as in the polariscope, the extinction lines are a function of the strain difference only, i.e. isochromatic fringes. If the material is taken beyond the elastic range into the plastic region, then the resultant birefringence is a function of the permanent deformations or residual strains, and as such is still evident when the load is removed. When white light is used, the extinction lines appear as coloured fringes. The colour of the fringes indicates the amount of the residual shear strain (black indicates no deformation), the colours then change as listed in increasing magnitude of residual shear strain: grey, yellow, orange, red, purple, blue and green.

Observations of the residual shear strains in the UHMWPE cups posed two problems; first the cups were clearly opaque, and secondly the strain fields in the UHMWPE were clearly three dimensional. These difficulties were overcome by cutting the cups into 30 μm-thick sections. This enabled the circularly polarized light of the polariscope to pass through UHMPWE and allowed the assumption to be made

TABLE I Details of the explanted cups studied

Cup no.	Age (years)	Sex	Weight (kg)	Period of implantation (years)	Reason for revision operation	Total penetration (mm)	Linear penetration rate (mm year^{-1})	Surface roughness, (R_a), of the femoral head (μm)
1	68.5	M	84.0	11.7	Loose stem and cup	2.1	0.18	0.019
2	63.2	M	74.4	12.3	Fractured stem	3.8	0.31	0.040
3	65.2	M	79.4	10.0	Loose stem and cup	3.6	0.36	0.030
4	30.5	M	76.2	5.7	Loose stem and cup	2.28	0.4	0.062
5	51.0	F	54.4	6.4	Loose stem and cup	2.16	0.34	NM[a]
6	33.9	M	65.5	12.4	Loose stem and cup	3.33	0.26	0.024

[a] NM, not measured.

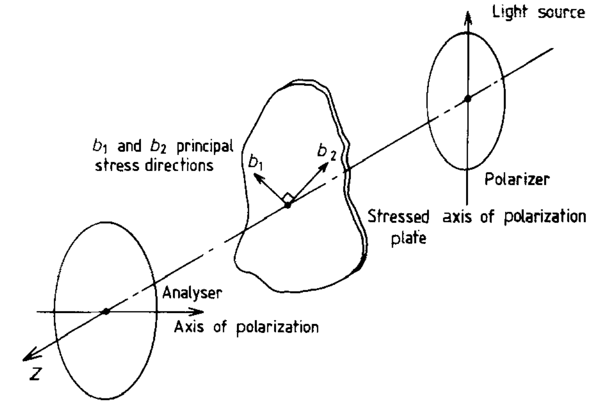

Figure 1 A specimen cut in the XY-plane, indicating the maximum and minimum stresses in the plane (b_1' and b_2') which are not necessarily the principal stresses.

that the slices were sufficiently thin in relation to the specimen size to ensure that the stresses and strains did not change in either magnitude or direction throughout the thickness of the slice. When the slice shown in Fig. 1 was viewed in a direction normal to the XY plane, i.e. along the Z-axis, the isochromatic fringes were a function of the stresses in the XY-plane only and were not affected by the strains in the Z-direction. The slice shown in Fig. 1 is a general one and is not necessarily coincident with any of the principal axes. In sliding wear tests in which there was only unidirectional motion, the strain fields were a function of the orientation of the slice. The strains present in a slice taken along the direction of sliding will be a function of the combined applied normal force due to loading and the shear forces tangential to the surface induced by friction. However, in a plane perpendicular to sliding, the shear strain pattern is a function of the applied normal load alone. In an acetabular cup the direction of the sliding and dominant tangential shear forces are variable, and are not limited solely to one direction. The strain field in a slice of the cup (x, y) cut normal to the surface (xz plane), will be a function of the combined loading and tangential surface friction force in the x-direction. In this study sections were cut with random orientation from the cup for various positions on the articulating surface.

3. Results

The explanted cups displayed two distinct regions, which have been recorded in previous studies [11, 12]. These were a high-wear region and a low-wear region. The high-wear region had a smooth surface in comparison with the low wear region. The high-wear regions of the cups were the articulating surfaces during normal walking activity. In contrast to this smooth, highly polished worn region were the low-wear areas which were much rougher, these being associated with less-frequent activity and articulation. The original machining marks, surface pits and polymethylmethacrylate (PMMA) bone cement particles were evident in the low-wear region. The transition between these two areas was often marked by a ridge [11]. The cup from the *in vitro* simulator test displayed two distinct regions: a region of wear corresponding to part of the cup upon which unchanging repeated articulation took place, and a region of zero wear in which there had been no contact or articulation between the femoral head and socket.

3.1. The high-wear region

The sections of UHMWPE taken from two of the explanted cups did not show any residual subsurface shear strain in the microscope polariscope. The explanted cup 1 had been implanted for 11.7 years and displayed the lowest penetration of the selected explanted cups. It also possessed the smoothest femoral head with a roughness of only 0.019 μm R_a. In this cup there were no signs of any birefringence present at the time of sectioning. In addition, cup 4, which had a high linear penetration of 0.4 mm year^{-1}, with a femoral head roughness of 0.062 μm R_a was also free of any subsurface shear strain. Fig. 2 shows the birefringent micrograph of the residual strains in this cup (no. 4), where there was a complete absence of any residual shear strain (the dark wavy lines across this section are tidal marks from the microscope slide glue). The surface of the control cup was different from the surfaces of cups 1 and 4, in that small amounts of residual strain associated with the machining process were evident.

The remaining explanted cups all showed signs of residual subsurface shear strain and birefringence in the high-wear region. Cup 2 had the highest penetration of 3.8 mm combined with one of the longest implantation times of 12.3 years. A micrograph of the highly worn region is shown in Fig. 3. The white band that extended 30 μm below the articulating surface of the cup defines the region of residual shear strain. The dark area below this, further from the articulating surface of the cup, is an area of zero strain difference (optically isotropic) where the circularly polarized light had passed through without being modified. The thin, narrow white lines passing across the section were due to deformations in the material caused by imperfections in the blade of the microtome knife. Occasional yellow areas existed within the white region and indicated a greater amount of shear strain and deformation. Also evident in this highly strained region lying just below the surface (approximately 7 μm) was a crack that appeared to reach the surface of the cup towards the left-hand side of the micrograph. Cup 3 had a total penetration of 3.6 mm over an implantation time of 10 years (0.36 mm year^{-1}). Pits were apparent in the highly polished high-wear region of this cup, which were of the order of 140 μm across and 30 μm deep. Fig. 4 is a micrograph taken from cup 3, showing two areas of high residual shear strain and a subsurface crack that extended between the two. The depth of the crack varied between 5 and 10 μm below the surface, and occasionally it penetrated to the surface. Cup 5 had a total penetration of 2.16 mm over quite a short period of implantation (0.34 mm year^{-1}). The observations here were very similar to those for the last cup with a strained region

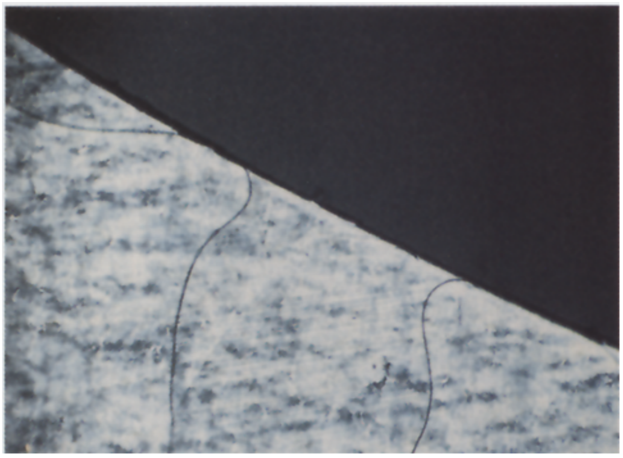

Figure 2 Micrograph of a 30 μm section cut perpendicular to the surface of the high-wear area of cup 4, showing a complete absence of any shear strain.

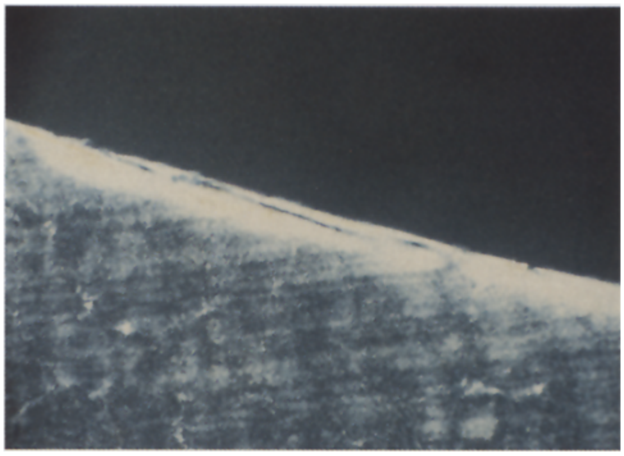

Figure 3 Micrograph of a 30 μm section cut perpendicular to the wear surface in the high-wear region of cup 2. The white band of residual strain is approximately 30 μm deep. The dark area below this is an area of zero stress. Immediately below the surface (approximately 7 μm) there is a crack which reaches the surface at one point. The yellow areas indicate a larger degree of residual shear strain.

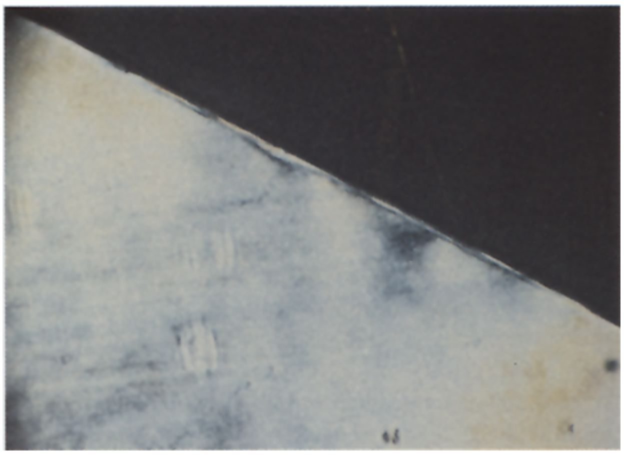

Figure 4 Micrograph of a 30 μm section perpendicular to the wear surface in the high-wear region of cup 3, showing two areas of high residual shear strain (the yellow areas) with a subsurface crack 5–10 μm below the surface, extending between the two.

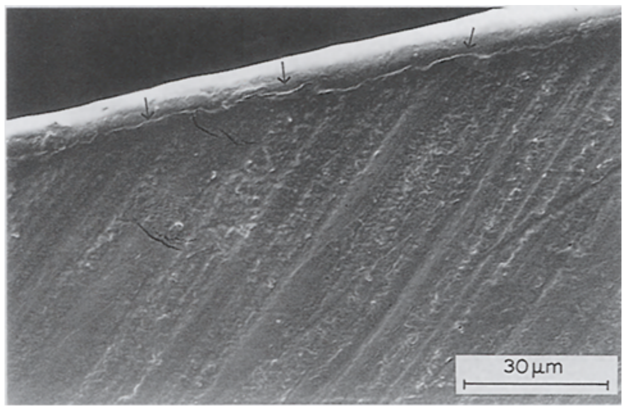

Figure 5 Scanning electron micrograph of a section of cup 6 cut perpendicular to the wear surface, showing a crack running parallel to the surface.

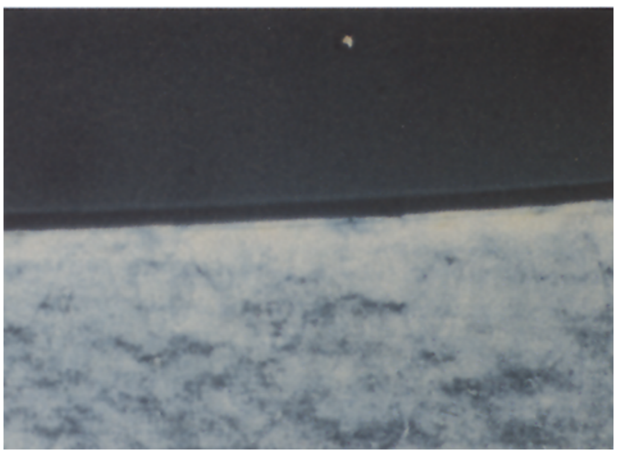

Figure 6 Micrograph of a 30 μm section of the simulator cup taken perpendicular to the wear surface in the high-wear region, showing a crack running parallel to the wear surface approximately 5 μm in depth through isolated regions of higher residual shear strain, indicated by the yellow areas.

30–40 μm deep which appeared as a white band below the surface through which there was evidence of subsurface cracking. The subsurface cracks were not continuous in length, but appeared intermittently under the surface in the high-wear region in areas of high residual strain. Cup 6 had been well worn and displayed a total penetration of 3.3 mm. This cup was representative of the high-wear regions of the cups where there had been deformation which appeared as white bands with periodic yellow patches, through which there was often a subsurface crack 5–10 μm below the surface. Fig. 5 is a scanning electron micrograph of a section of this cup perpendicular to the surface, which also showed a subsurface crack.

The worn simulator cup was similar in appearance to the explanted cups. It displayed similar regions of residual strain, although they tended to be white bands only, and clear evidence of a subsurface crack (Fig. 6).

3.2. The low-wear region

The low-wear regions in the explanted cups all displayed evidence of the original machining marks to a greater or lesser extent, combined with pitting and high deformation associated with embedded cement particles. The low-wear region of the cups the explanted cups showed little evidence of any residual shear strains, apart from the odd isolated highly deformed region which was thought to be associated with the embedding of a bone cement particle [13]. In contrast to this, the simulator cup only showed machining marks in the region of zero wear. This was due to the precisely controlled conditions of operation of the hip joint simulators, which only allow movement associated with a well-defined walking pattern [14].

3.3. The ridge region

All of the cups except cup 1 displayed clear evidence of a ridge between the high- and low-wear regions. The most obvious of these was found in cup 3, the cup which had one of the largest penetrations. Major deformation of the ridge region occurred, creating numerous interference fringes of a high order which were relatively deep compared with those in the high-wear areas.

4. Discussion

The generation of UHMWPE wear particles in artificial joints is a complex process, due to the highly variable tribological conditions that operate at a microscope level in the contact. Although there is a considerable amount of data available to predict the volume of UHMWPE wear particles [2] there is little understanding of the wear mechanisms and the types of particles that are produced under different tribological conditions. Our recent laboratory studies of the wear of UHMWPE on smooth counterfaces under a constant load with unidirectional sliding [7, 8] have shown that the development of localized residual subsurface shear strains (which have a higher magnitude and are closer to the surface in the direction of sliding where the friction force acts) causes subsurface failure and periodical increases in wear. We have termed this mechanism "macroscopic polymer asperity wear", as it is associated with the strain concentrations under the large asperities, ridges or peaks on the polymer surface (amplitude > 10 μm). For very smooth counterfaces this macroscopic asperity wear can dominate the wear caused by the microscopic asperities of the metal counterface. However, if the surface roughness of the metal counterface is increased, the microscopic asperity wear is increased and dominates, as the material is removed before plastic deformation is accumulated [9].

Both UHMWPE cups explanted from patients and the worn simulator cup in this study showed high residual subsurface shear strain, which is consistent with our laboratory observations of wear pins. However, two cups did not show this. Cup 4 had a roughened femoral head and high wear rate, and in this situation the wear caused by the microscopic asperities of the metal surface probably dominated, removing the polymer material before subsurface plastic strains were fully developed. Furthermore, in cup 1, which had a smooth femoral head, the residual strains were absent and it is possible that material had just been lost by the time-dependent deformation and wear process of the macroscopic polymer asperities, and that the residual shear strains had not had time to develop again [8].

In addition to the residual subsurface shear strain found in five of the cups, subsurface cracks were also found in the highly strained regions up to 10 μm below the surface. These subsurface cracks have not been seen previously in our unidirectional tests under constant loads on smooth surfaces. The difference may be explained by the different stress conditions acting on the macroscopic asperities or peaks of the polymer in the two situations. In the pin-on-disc tests a constant load and unidirectional friction force were applied, producing plastic deformation and failure. In the hip joint the loading was cyclic, and the direction of the friction force was variable, resulting in a high cyclic stress field in the macroscopic asperities or peaks of the polymer, and eventual crack formation and crack propagation. This fatigue process is likely to lead to delamination as described by Suh [15], and to an increased wear rate, as the crack propagation can accelerate the removal of material. It is likely that removal of material from one part of the contact produced increased stresses in adjacent areas (Fig. 4), and subsequent high plastic shear strains, fatigue and subsurface failure. High residual strains were also found under the ridge of the cups between the high and low regions, and around the cement particles in the low-wear area. In both cases this was caused by high localized contact stresses, but the relatively infrequent loading did not promote crack propagation.

This study provides further evidence that localized macroscopic wear mechanisms are extremely important in the wear of UHMWPE. Changes in the topography of the polymer surface produces peaks or waves up to 10 μm deep and localized stress concentration well above the nominal stress levels of the contact, which are relatively low in most hip prostheses. These result in plastic deformation and residual shear strains, which are increased in magnitude in the direction of sliding by the friction force. The loss of a wear particle as a discrete step relieves the stress in that area, but may produce high levels of stress in other areas of the contact. In the actual hip joint, where the asperities and peaks of the polymer surface are dynamically loaded and the direction of the friction force varies, subsurface crack propagation occurs, which accelerates the loss of material by the macroscopic polymer asperity wear process. This macroscopic polymer asperity wear process is likely to dominate unless the femoral head is significantly roughened, and the rate of wear caused by the abrasive microscopic asperity wear of the metal counterface is increased dramatically. The relative contribution of these two wear processes not only controls the volume and number of wear particles generated, but is also likely to have a marked effect on their size and morphology.

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