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Wear of artificial hip joint material

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Abstract

A non-conforming apparatus was devised to study the wear properties of hip replacement materials (stainless steel femoral head and mainly ultra-high molecular weight polyethylene, UHMWPE). The analysis was by wear depth and various types of microscope examination of the worn surfaces. The importance of proper femoral head surface conditions is emphasized. The dry worn debris matched that retrieved from revision surgery indicating the in vivo wear was without fluid lubrication. A qualitative model is presented to explain the observed wear and wear rate profiles. The long-term wear was within a narrow range that matched in vivo results. Tests on polyetherether ketone (PEEK) polymer indicated that it had superior wear properties to UHMWPE.

Keywords: Hip joint material; UHMWPE; PEEK

1. Introduction

The total hip replacement (THR) operation is outstanding successful but there are associate problems. Of the many 1000 operations preformed annually in the UK there is a revision rate of about 10% after 10 years which appears to be increasing [1]. Not only do revision operations cost more, the outcomes are less successful than with the primary operation [2].

Various THR designs are recommended under particular circumstances [3] but the best option with longest track record is still considered to be the Charnley prosthesis where ultra-high molecular weight polyethylene (UHMWPE) articulates against a stainless steel femoral head [4]. Placing aside dislocation and problems associated with the actual THR operation, long-term failure appears to be dominated by osteolysis, i.e. destruction of the surrounding bone due to an immune reaction to debris mainly arising from the wear of the prosthesis [5]. Originally engineers suggested failure occurred because of insufficiencies in either the bone cement used to fix the prosthesis or the methodology of the surgeon [6–9]. Obviously third body wear, etc. can have an effect on joint failure but the overall problem has proven to be more complex. In addition there has been an order of magnitude difference between the wear rates obtained in hip simulators and that observed in vivo [10,11]. There also is disagreement as to whether the THR joint is lubricated in vivo [12–15]. These issues need to be addressed.

In order to achieve an increase in lifetime for the THR joint there is a need to examine the wear characteristics of the prosthesis materials with a view to reducing the observed failure rate.

2. Experimental

This work was performed in the Department of Orthopaedic Surgery, Queen's University Belfast by an interdisciplinary team of Medical Personnel, Scientists and Engineers as recommended by Learmouth [16] as being essential for positive advancement in the whole area. Considered opinion was that some of the reported anomalous behaviour may be due to the complexities of the systems used. Indeed varied preliminary results were only overcome here by positive input for all three disciplines and led to the development of a simple apparatus to study the relative wear of the hip replacement components. The design of the apparatus also allowed

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for subsequent modification to more closely simulate in vivo conditions.

The apparatus is shown in Fig. 1 and consisted of a vertical sealed stainless steel test chamber that contained a stainless steel femoral head (d = 22.25 mm DePuy Elite) held on the end of a vertical rotating shaft and resting down on a polymer disc (t = 6 mm, d = 40 mm) secured on the inner floor of the chamber.

A cantilever arm imparted normal body weight down through the rotating vertical shaft via a thrust race and vibration-free bearings. An electric motor imparted rotation to the shaft. The main structure was made of a rigid steel box section and was earthed. Vibration, particularly from passing traffic was eliminated by a damping base plate. Temperature controlled water was circulated through the outer skin of the test chamber to hold it to normal body temperature. Inserted thermocouples monitored the test chamber temperature. Penetration of the femoral head into the polymer disc was followed by means of a kinematically mounted cathetometer. The worn surfaces were examined under a SCM, scanning electron microscope (Joel Winsem JSM 6400) and an atomic force microscope (AFM) (Dimension 3000).

The femoral heads used conformed to ISO-5832-9 while the UHMWPE met BS7253 Part 4 (1990). The test discs were surface finished to BS7251, Part 4 (1990) resulting in surface marks 25 μm in width.

The test chamber and femoral head were soaked in a 2% weight aqueous Neutracon solution (non-ionic detergent) for 2 h and then rinsed with distilled water. Together with the discs they were further cleaned in methanol in an ultrasonic bath for 1 h, rinsed with distilled water and dried with optical grade tissue following standard microscope dust-free conditions. Loading of the test chamber was conducted using filtered oxygen-free nitrogen and ultra-pure air dusters following microscope procedures to ensure dust-free conditions prevailed. The chamber was sealed, brought to temperature, weight loaded and the creep penetration followed. A control disc was set aside under similar conditions. Once equilibrium creep penetration was achieved (<4 h) rotation at 90 rpm was commenced and run for approximately 2×10^6 rotations, with the penetration being recorded at regular intervals. Finally the motor was stopped, loading and the test chamber removed. The hip replacement materials were taken out of the test chamber for weighing and microscopic examination.

3. Results and discussion

The unworn femoral head surface was examined and it was found that certain were of inferior quality. Fig. 2 shows a micrograph of one such head where, despite conforming to the required standard, the surface was criss-crossed with prominent polishing lines and possessed embedded carbide grains and holes. Fig. 3 highlights one of the holes which were formed either by the physical removal of protruding carbide grains or by outgassing during manufacture. Such surface imperfections will give increased polymer wear and provide some explanation for the wide variation in reported

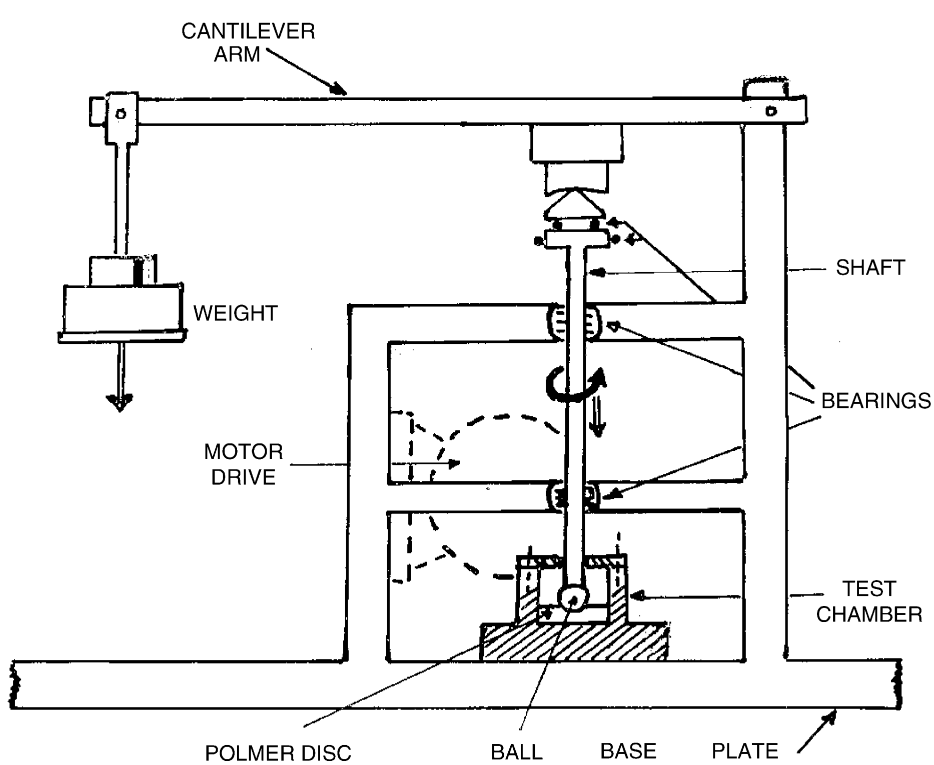

Fig. 1. Hip prosthesis test rig. The weight was 15 kg at 0.64 m from the fulcrum. The thrust race was 0.137 m from the fulcrum.

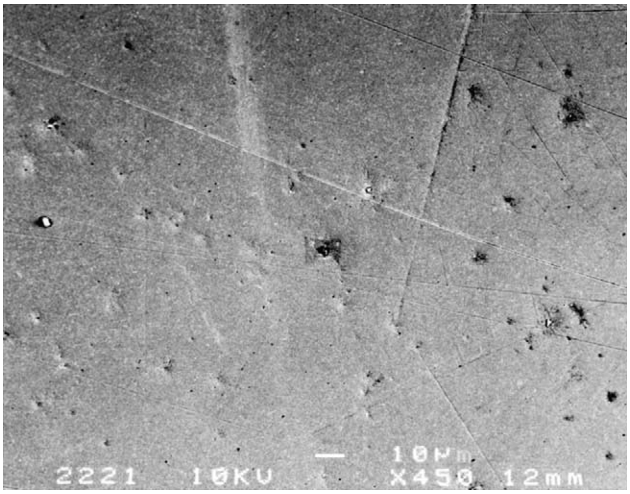

Fig. 2. Micrograph of an unworn femoral head of inferior quality, showing polishing lines carbide grains and holes formed by grain removal and outgassing.

wear rates. All femoral heads used in this work were free from such gross imperfections.

Static loading of the components showed that the UHMWPE suffered creep penetration to an ultimate depth that depended directly on temperature. While the femoral head surface remained pristine, the disc still retained the surface polishing marks at the base of the indent. Creep, therefore was in the bulk of the polymer forcing displaced polymer to form a circular buildup lip around the head, polymer, air interface. Only increased frictional wear and heating arising with rotation of the head will result in the polymer in the indent softening and being displaced to support the applied weight.

Fig. 4 shows a wide view of the worn femoral head with a considerable buildup of wear debris adhesion at the edge of the wear indent area. Fig. 5 is another wide view of the wear area on the femoral head. There is no sign of any abrasive wear of the metal surface but evidence of adhesive wear is

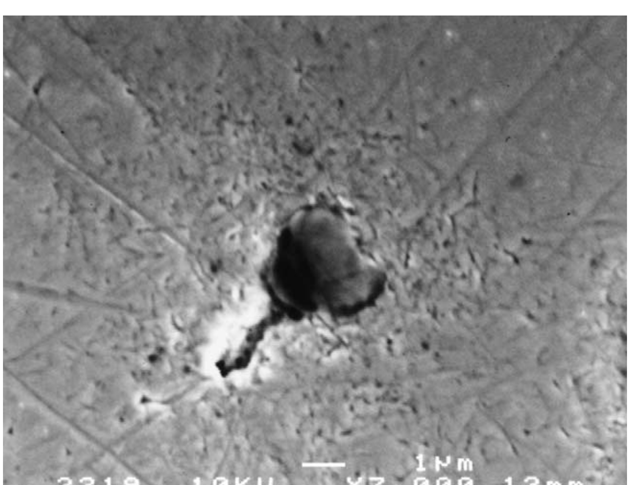

Fig. 3. A close-up on a grain removal hole in an unworn inferior quality femoral head.

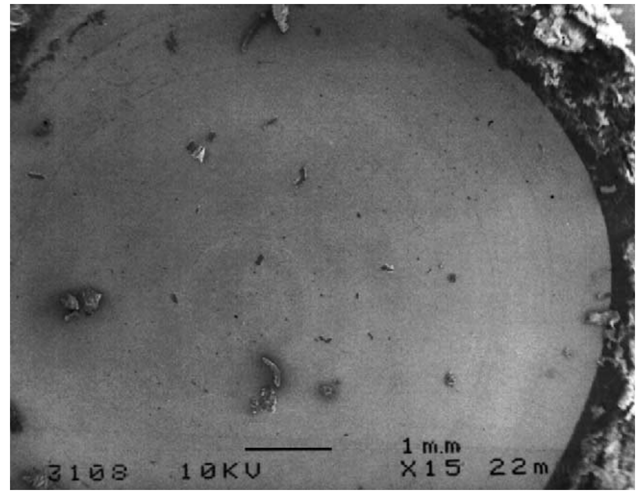

Fig. 4. Wide view of the femoral head wear area, with considerable debris at the edge of the wear region.

visible at B. The delaminated polymer wear strips at A attest to severe surface fatigue wear of the polymer having taken place. Such fatigue wear has been reported in revision prosthesis [17–19]. The morphology of the flaklet debris taken from periprosthetic tissue has been shown not to match that from simulator wear tests [19–21]. The micrograph in Fig. 6 of some of the typical adhered flaklet debris from this work by contrast exhibit a similar morphological form to that found in vivo. Such a match suggests that the methodology used in this work paralleled that in vivo. Further, it shows that wear in a prosthesis is largely without lubrication.

The outer edge of the wear area of the femoral head given in Fig. 7 has substantial amounts of surface fatigue fragments at A, and evidence of transfer film buildup at B. Closer examination of the transfer film region indicated that it was comprised of adhered fatigue flaklets and many micron and submicron scale polymer fibrils, e.g. Fig. 8. Some of the fibrils are being generated off the surface of the flaklet as illustrated

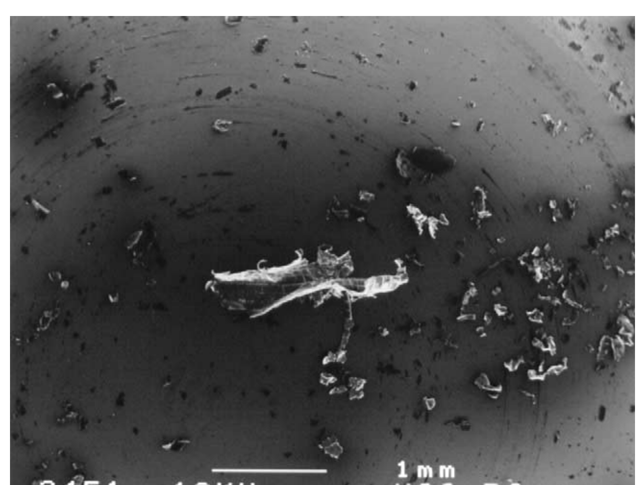

Fig. 5. Wide view of adhesive and fatigue wear on the femoral head.

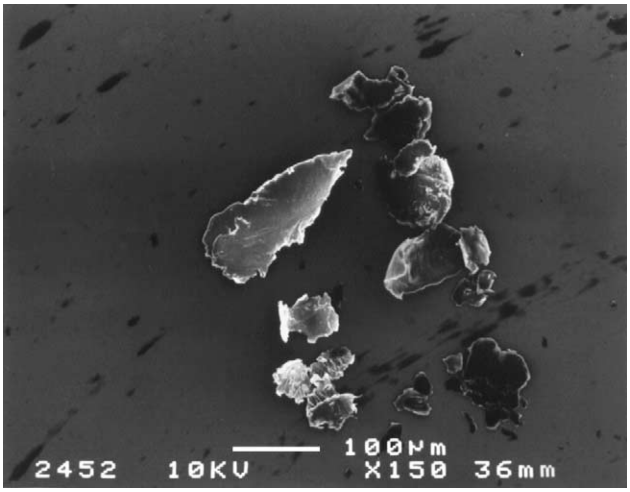

Fig. 6. Test debris on the femoral head similar to that observed in vivo.

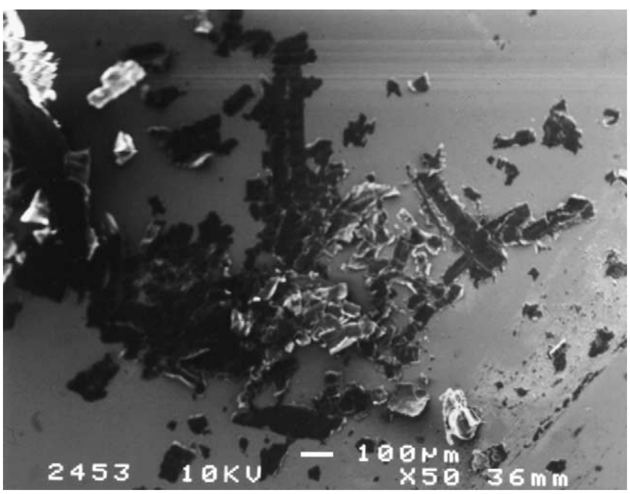

Fig. 7. Delaminated polymer strips and adhesive wear on the outer edge of the femoral head wear area.

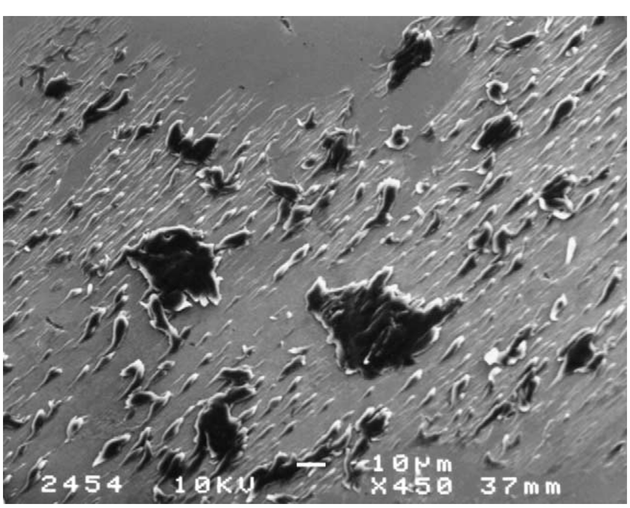

Fig. 8. Closeup on adhesive wear of flaklets adhered to the femoral head. Smeared polymer fibrils are visible.

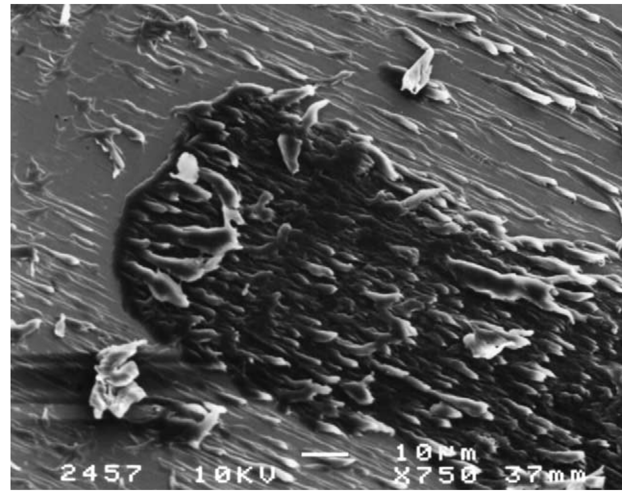

Fig. 9. Magnification of the fibril formation observed on an adhered polymer flaklet.

in Fig. 9 indicating their formation by adhesive wearing due to the passage over the polymer disc counterface. Thus the flaklet is adhered to the surface of the head and is progressively being worn down with the uni-directional orientation of the adhered polymer fibrils indicating the movement. Clear areas between the adhered fibrils show a faint granular nanostructure of grain size 0.2–1 μm. Granular submicron debris recovered from periprosthetic tissue falls within this range [22–24]. Also the nanostructure between the fibril indicates that a thin film of polymer is adhered to the surface of the femoral head. Fig. 10 confirms this and has a clear view of the covering film when it has suffered a brittle fracture due to crystalline formation and fatigue. The film also has polymeric adhesions blended into its structure at A with transfer film in evidence at B. At C there are features suggestive of the criss-crossing polishing lines existent on the underlying stainless steel. Fig. 11 focuses on the rim wear area of the femoral head. Fibrils and their associated transfer film are in

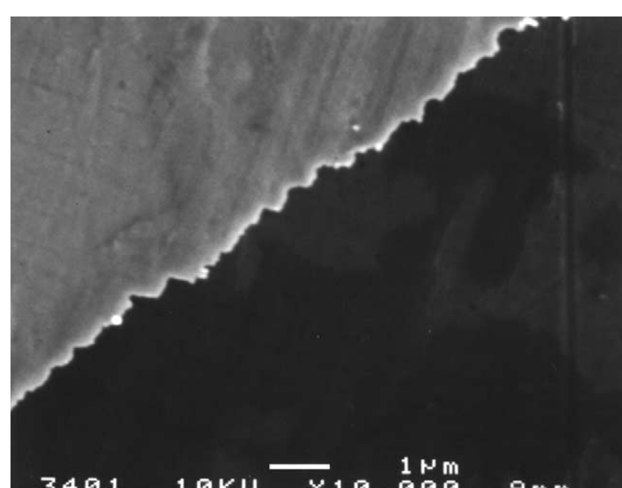

Fig. 10. Brittle fracture crack edge of the polymer film on the surface of the femoral head.

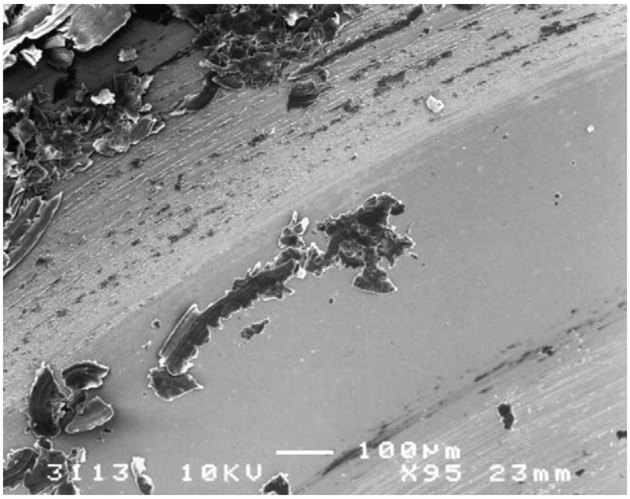

Fig. 11. Adhesive wear and delaminated debris at the edge of the femoral head wear area.

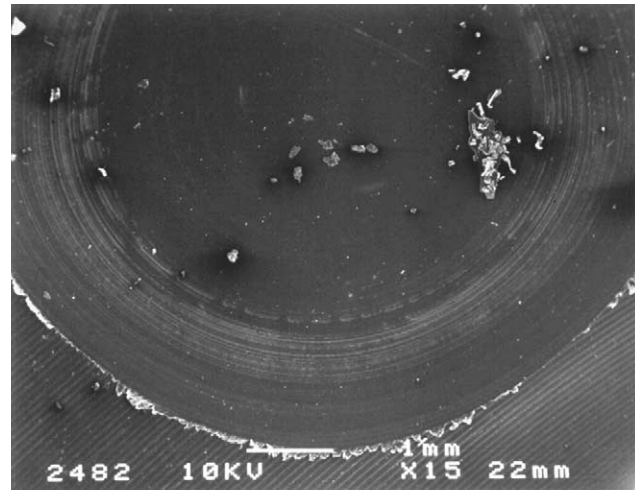

Fig. 13. A closeup on the outer region of the polymer disc wear area showing fatigue flaklets, adhesive wear fibrils and debris buildup on the edge of the wear area.

evidence at A and correspond to the fibril formation area on the disc. The delaminated strip B still retains the polishing marks indicating its origin from the original surface region of the disc.

Fig. 12 is a wide view of the polymer disc indented wear area. There is evidence of polymer debris in the relatively smooth central area at A and buildup at the outer edge of the wear area. These features attest to severe fatigue wearing having taken place. The unworn disc surface beyond the worn indent exhibits machine polishing marks. The prominent striated transfer film at B on the approaches to the edge of the wear area of the indent slope exhibits polymer fibrils that correspond to the region B of Fig. 7. These fibrils are generated off the surface of material adhered to the corresponding counterface surface on the femoral head.

An enlargement of wear outer region in Fig. 13 shows the striated polymer fibrils to be fatigued (area A). Large flaklets similar to those retrieved in hip revision surgery [19] are present at B. The buildup of worn polymer debris at the edge of the disc worn area will continue to register in the final weighing of the disc even though its origins will have been from the worn indent polymer volume. Thus a sizable amount of wear material will still register in the final disc weighing, resulting in a bias and wide variation in the weight determination of the wear rate. In this work the typical variation in weight loss was in the order of ±50%. Indeed in some cases registered weight loss was close to zero.

A close-up on the beginning of the outer wear tracks is given in Fig. 14 highlighting both the deposition and smoothing of transfer film at A and the drawing out of fine fibrils on the indent outer slope at B. Fig. 15 emphasizes the pronounced edge wear lines with intense fibril production in this region.

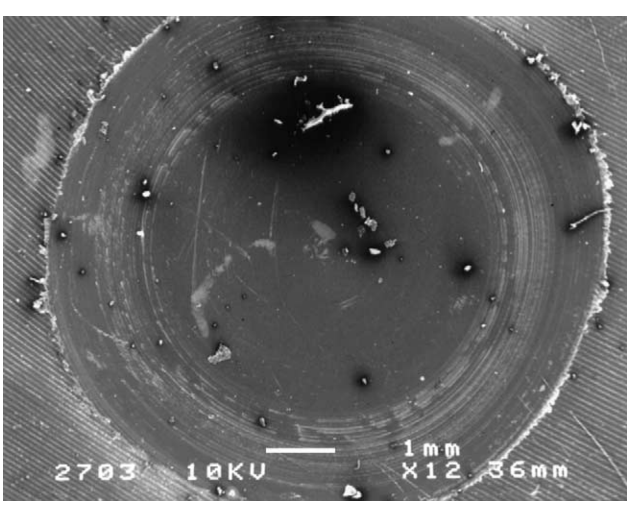

Fig. 12. Wide view of the polymer disc wear area with flaklet debris and adhesive wear fibrils on the outer wear slope.

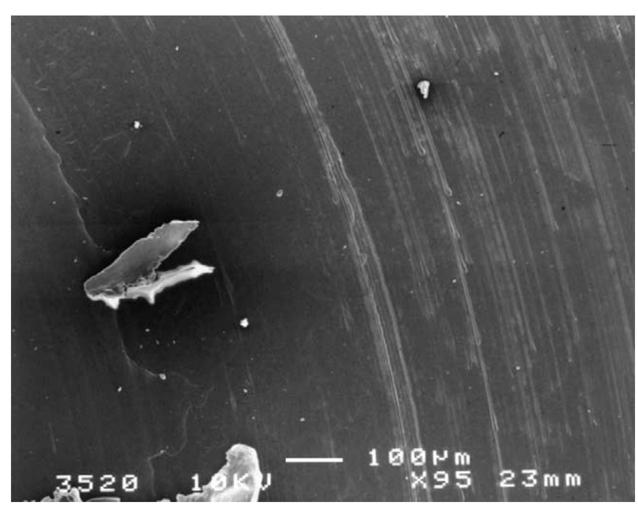

Fig. 14. A closeup on the beginning of the outer wear tracks with the edge of a transfer film and fibril formation evident.

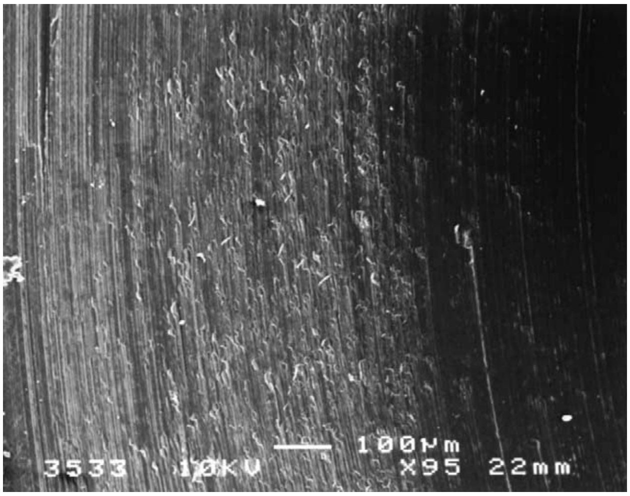

Fig. 15. Pronounced edge wear lives with intense fibril production at the lower edge of the wear area.

Fig. 16 is an AFM scan of the smooth central indented wear area of the disc. The normal view shows surface plastic flow highlighted as lighter regions. The phase view indicates that much of the area is covered with a crystalline subsurface that developed in the polymer during prolonged rubbing contact. Any areas of delamination and the edges of plastic flow regions share a strong phase response indicating they are separate masses from the rest of the surface. The white centered scan lines show that there are some loose particles on the surface of the polymer. There are visible voids left in the surface where nanosized particles have been torn away. These particles form the basic fine polymer structure and are released as the final product of the wear process. Thus UHMWPE will by its very nature result in the production of fine particles that cause osteolysis [5]. Fig. 17 is a micrograph of the wear slope near the top edge of the wear indent. There is a lot of plastic flow present, the edges of which are clearly highlighted in the phase view. There is a little sign of the crystallinity observed in the central wear region and few voids. Some loose material is apparent as is some delamination at A. Details on the application of the AFM to worn UHMWPE are given elsewhere [25].

The stepped wear penetration profiles for four typical runs are presented in Fig. 18. There was an initial rapid indentation of the femoral head due to creep and fatigue wear. Some resulting debris became attached to the counter faces acting as a barrier to further penetration. The subse-

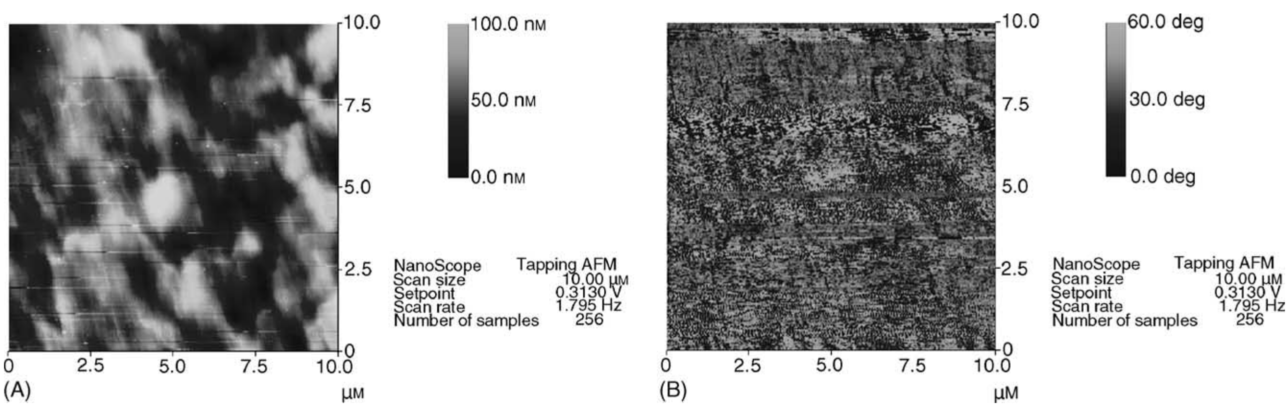

Fig. 16. (A) Topography near the centre of the polymer wear area showing graining plastic flow. (B) Phase view showing crystalline orientation void structure and fine granular overlay.

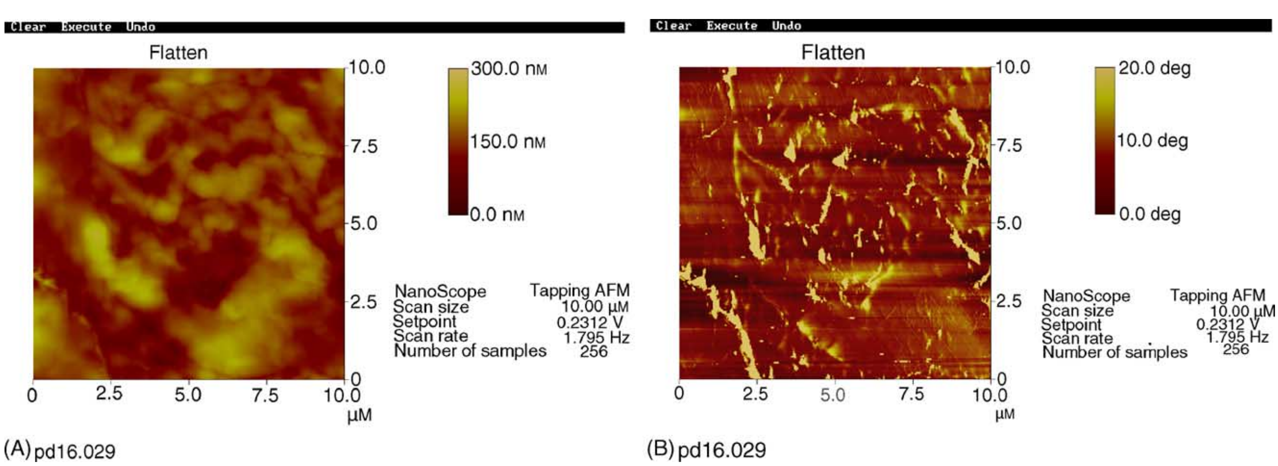

Fig. 17. (A) The top of the polymer wear slip with large plastic flow features and some delamination. (B) Phase view showing a high response from the delamination.

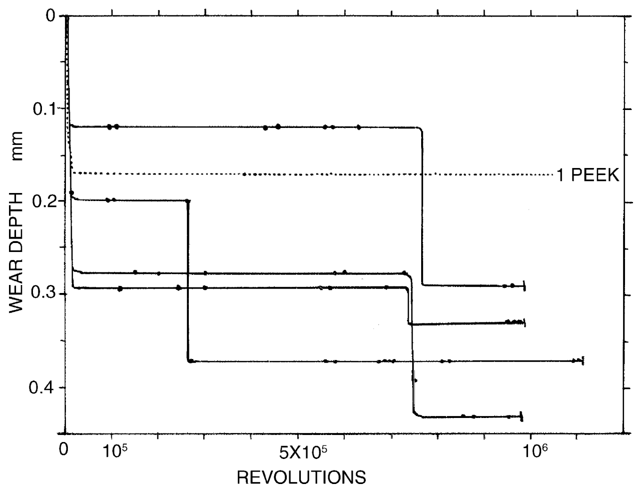

Fig. 18. Characteristic wear profiles for PEEK and UHMWPE under dust-free conditions.

quent plateau in the wear profile corresponds to the slow attrition of the entrapped interfacial debris. When all the polymer protruberances have been worn away, direct contact of the crown of the femoral head leads to thermal friction generated heating, crystallization and ultimately fatigue which causes polymer to be torn out from the central wear area. This results in a sudden penetration into the UHMWPE and a repeat of the debris interfacial attrition process. Early penetration depths recorded showed a wide variation but longer term the wear depth fell within a relatively narrow range. This suggested wear mechanism is different to other suggested models [26,27] and does provide some explanation as to the observed wide variation in wear rates.

The stepped wear penetration profiles minus the initial penetration for four identical experiments with UHMWPE and one with PEEK are presented in Fig. 18.

In Fig. 18 there is a wide variation in the initial UHMWPE penetration since the depth achieved depended on the capture of sufficient debris between the counterfaces to keep them apart. This process was variable as shown by the data. However as the wear proceeded the variability in the wear depth decreased. For PEEK the penetration remained constant at a value to support the weight through the fernoral head onto the polymer.

It should be noted that the wear rates in Fig. 18 were all for dust-free conditions. If dust was allowed into the system the wear rate recorded rose substantially.

Attempts were made to test other polymers. Polycarbonate discs were unsatisfactory, being worn through within hours. Polyetherether ketone (PEEK) proved to be a better polymer with ultimately a lower wear rate than UHMWPE and did not appear to generate fine polymer debris. PEEK has recently been accepted for in vivo use and holds out the possibility of improved performance for inbody implants.

4. Conclusions

The dry non-conforming wearing produced debris that closely paralleled that from periprosthetic tissue suggesting that hip replacements generally lack any fluid lubrication. Gross imperfections on the surface of the femoral head due to faulty manufacturing technique were in evidence with some cases, highlighting the need for careful inspection before use. It was important to follow standard procedures during testing in order to eliminate ingress of particles, etc.

The dry wear penetration process followed a multi-stepped pattern with an initial indentation due to creep and fatigue fracturing of the polymer. A plateau followed in which polymer debris attached to both counter faces acted as barrier to further penetration. The plateau in the wear corresponded to the slow attrition of entrapped debris which when completed led to a repeat in the process. The early penetration depth showed a wide variation which was reduced over the longer term.

In the plateau stage of the wear, the polymer disc possessed a central smoothly worn area of crystalline nature where fine debris was in evidence. Further out there was a circular bearing ridge where fibrils were being worn from accumulated debris. Around the edge of the polymer indent was a buildup of debris that invalidated weight loss wear measurements. The femoral head had an adhered polymer film and a scattering of attached debris. There was a circular adhesion of fibrils that corresponded to those on the disc slope. Crystallinity increased down the wear slope as did fine polymer debris generation. Fine polymer debris originated from the nature of the polymer.

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