Wear, 40 (1976) 255 - 264

THE WEAR OF ULTRAHIGH MOLECULAR WEIGHT POLYETHYLENE AND A PRELIMINARY STUDY OF ITS RELATION TO THE *IN VIVO* BEHAVIOUR OF REPLACEMENT HIP JOINTS

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(Received April 22, 1976)

Summary

The mechanisms of wear in plastics are reviewed. Some wear tests on ultrahigh molecular weight polyethylene are described and the relevance of the results to *in vivo* situations is discussed.

Introduction

Many modern artificial joints involve plastics. Usually the plastic remains stationary and a metal surface moves against it. An important factor governing the lifetime of such a joint is the rate at which the plastic wears away: the metal should not deteriorate or wear, but the plastic is gradually worn away as the metal surface continually moves against it. Ultrahigh molecular weight polyethylene (U-PE) is the most widely used of the plastics for bearing applications in prostheses. Its particular advantages for this purpose have been outlined by Atkinson [1] and a paper by Dowson *et al.* [2] describes the wear of U-PE in laboratory tests using tri-pin-on-disc machines. This paper discusses the processes involved when U-PE wears in different types of wear machine and considers the relevance of these results to *in vivo* situations.

Summary of wear mechanisms

Lancaster [3] has reviewed the three wear mechanisms involved when plastics are used in bearing applications. They are: abrasive wear, caused by

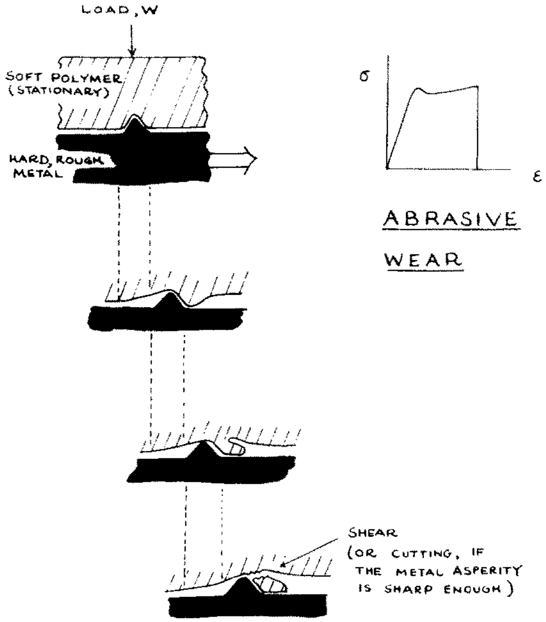

Fig. 1. Abrasive wear.

hard asperities on the counterface or by hard particles between the surfaces; fatigue wear, involving the detachment of material as a result of cyclic stress variations on a localised scale; and adhesive wear, when there is transfer of material from one surface to the other due to the forces of adhesion between them. These processes are illustrated in Figs. 1 - 3.

Abrasive wear

When the metal surface is fairly rough, hard irregularities in the surface penetrate the softer plastic and remove material by shear or cutting. From the stress–strain curve shown for a typical thermoplastic such as U-PE it can be seen that the total deformation of the plastic before fracture will be made up of an initial elastic component plus a plastic component. Ratner [4] suggested that the most important parameter controlling abrasive wear is the energy required to detach lumps of polymer. This is given by the area under the stress–strain curve which is approximately equal to the product of the breaking strength S and the elongation to break e. Thus the wear rate should be proportional to $1/Se$ and for a low wear rate under abrasive conditions, when the counterface is rough, the product Se should be as large as possible.

Fatigue wear

For fatigue wear to predominate, a polymer is required which can be deformed to a considerable extent and still recover completely when the deforming force is removed, *i.e.* an elastomer is required. The metal

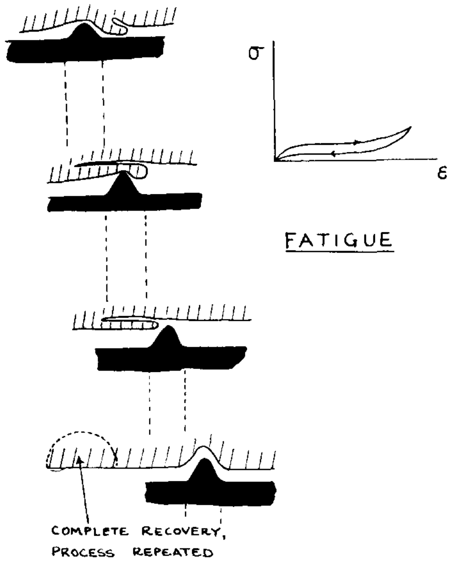

Fig. 2. Fatigue wear.

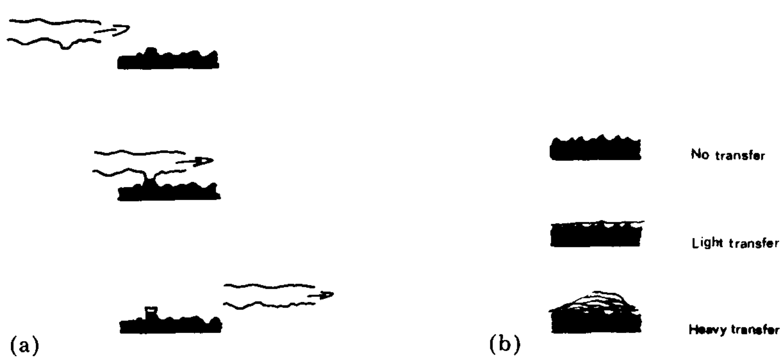

Fig. 3. Adhesive wear: (a) simple adhesive wear; (b) transfer film formation.

asperities must be more rounded so that they do not cut the polymer, which eventually slips over the tops of the asperities. Thus smoother metal surfaces are required to produce the situation shown in Fig. 2 which, if it is repeated many millions of times, could lead to a fatigue crack and subsequent removal of material. If the counterface is fairly smooth, most thermoplastics will undergo some fatigue wear because localised deformation will not always exceed the elastic limit. There is evidence from the work of Ratner and Lu're [5] and of Brodskii and Reznikovskii [6] that fatigue wear will depend upon the ease with which chemical bonds in the polymer can be broken. Any process which makes this rupture easier, such as oxidative degradation, will result in increased fatigue wear.

Adhesive wear

Adhesive wear often results in the formation of a transfer film of plastic on the metal counterface. This may increase or decrease the wear rate as indicated in Fig. 3. The amount of adhesive wear will depend on a number of factors including the load, the environment, the sliding speed and the nature of the plastic.

Thus the general picture emerges of wear as a complex process involving abrasive, adhesive and fatigue components. The relative importance of each component will change as wear continues and modifications take place to the rubbing surfaces. Abrasive wear will be the most important initially, but adhesive and fatigue components will play an increasingly important role, particularly when the counterfaces are relatively smooth.

Wear tests

Three wear machines were used in these tests, two tri-pin-on-disc machines and a nine-head linear reciprocating machine.

In the tri-pin-on-disc machines the polymer pins are loaded against a rotating steel disc contained in a cylindrical bath. The pins are located in a pin holder such that they continuously slide over the same track on the disc. The holder is kept stationary by means of three cantilevers bolted to the machine frame.

It is possible to vary the speed of rotation of the disc and the force applied to the pins. The disc may also be made to oscillate rather than rotate. Tests have been carried out using various forces, under dry conditions or with distilled water in the bath. The velocity used was generally 240 mm s^{-1}.

The nine-head linear reciprocating machine operates at the slower speed of 18 mm s^{-1}. Each of the nine heads is loaded independently, and on each a force is applied to a polymer pin resting on a reciprocating steel plate.

The polymer pins were all turned from a single block of ultrahigh molecular weight medium density polyethylene*. The pins were cylindrical, with one end machined to a truncated cone of 120° included angle, presenting a wear face of 8 - 10 mm^2. This geometry was chosen on the grounds that the relatively small wear surface area would cause the initial machined surface of each pin to be removed rapidly, subsequent wear being representative of the bulk material rather than influenced by the initial surface topography. The conical form provided a large back-up of material which helped to minimise distortion under load.

The steel counterfaces were of surgical grade stainless steel, EN 58J, polished to produce a surface with a centre-line average value R_a of better than 0.025 μm, with a random texture.

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*RCH 1000 Surgical Grade Polyethylene, a Hoechst material obtained in the U.K. from High Density Plastics Ltd., Todmorden, Lancashire.

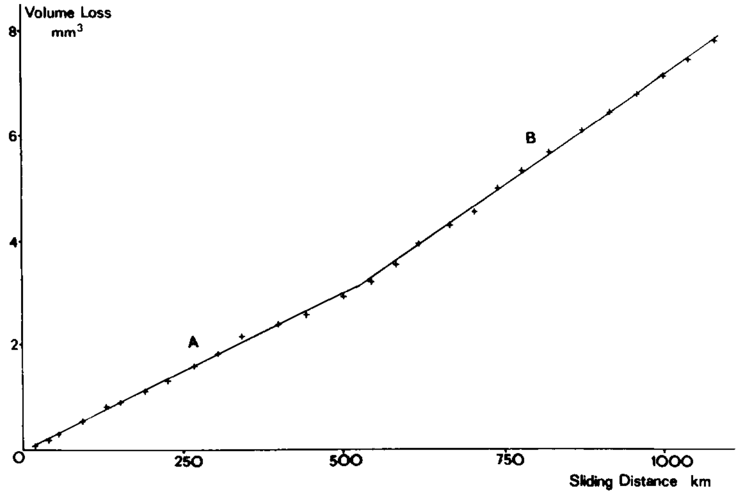

Fig. 4. Typical wear graph for ultrahigh molecular weight polyethylene sliding against surgical grade stainless steel (EN 58J) under dry conditions.

In all cases wear was measured by stopping the machines periodically and weighing the pins on an accurate and sensitive balance. The loss in weight (generally of the order of micrograms) was attributed to wear and could be converted to volume loss knowing the polymer density. Controls were used to allow for the change in weight due to the uptake of water by the polymer specimens.

Summary of results

The results are presented as graphs of volume loss against sliding distance. The form of the wear graph is similar in each case. Figure 4 shows a typical wear graph, in this case for a dry pin-on-disc test, under unidirectional motion, with a force of 25 N per pin (nominal stress 4 N mm^{-2}). The graph consists of two straight lines, designated section A wear and section B wear. The changeover occurs here after a sliding distance of 440 km. The wear rates (the slopes of the respective portions divided by the applied force) are 2.5×10^{-7} mm^3 N^{-1} m^{-1} and 3.4×10^{-7} mm^3 N^{-1} m^{-1} for this particular test. Wear rates have been found to be independent of applied force (in the range 25 - 145 N), given the same conditions otherwise. It should be emphasised that this form of wear graph, with an increase in the wear rate after a certain sliding distance, has been found with wet and dry conditions in unidirectional and reciprocating wear tests. The onset of section B wear occurs at lower sliding distances as the applied force is increased, *e.g.* after 97 km with a force of 145 N per pin. Some mean wear rates under different conditions are given in Table 1.

TABLE 1

Typical wear rates (dry)

Type of test	Section A wear rate ($mm^3\ N^{-1}\ m^{-1}$)	Section B wear rate ($mm^3\ N^{-1}\ m^{-1}$)	Onset of section B (km)
Pin-on-disc (25 - 145 N)	2.2×10^{-7}	3.6×10^{-7}	97 - 480
Nine-head reciprocator (45 N)	0.9×10^{-7}	2.0×10^{-7}	340
Six-head reciprocator (45 N)	0.8×10^{-7}	—	—
Journal bearing simulator (45 N)	1.1×10^{-7}	2.6×10^{-7}	75

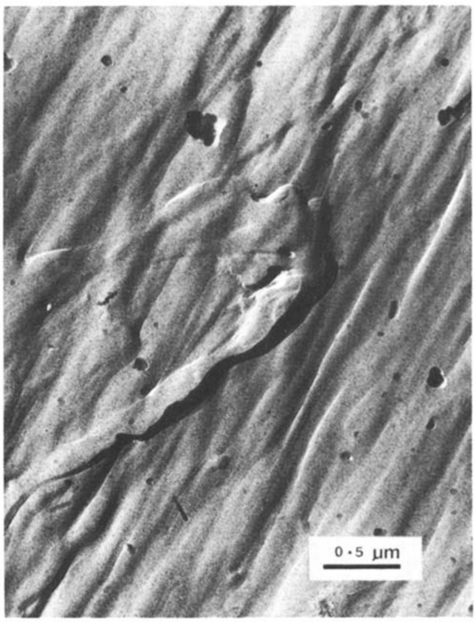

Fig. 5. Polyethylene wear-pin surface on completion of a test showing an adhesive wear particle about to be lost from the surface; sliding direction bottom left to top right. Transmission electron micrograph.

It is believed that section A wear is predominantly an adhesive wear process. In section B wear the adhesive mechanism continues but is augmented by a surface fatigue mechanism, thus causing the wear rate to rise. The evidence for this comes from microscope examinations of the worn polymer surfaces, backed up by the fitting of wear data to fatigue equations.

A powerful tool in the study of fine surface detail is transmission electron microscopy of replicas of the surface. Figure 5 is a micrograph of a two-stage carbon replica, shadowed with gold–palladium, of the worn surface

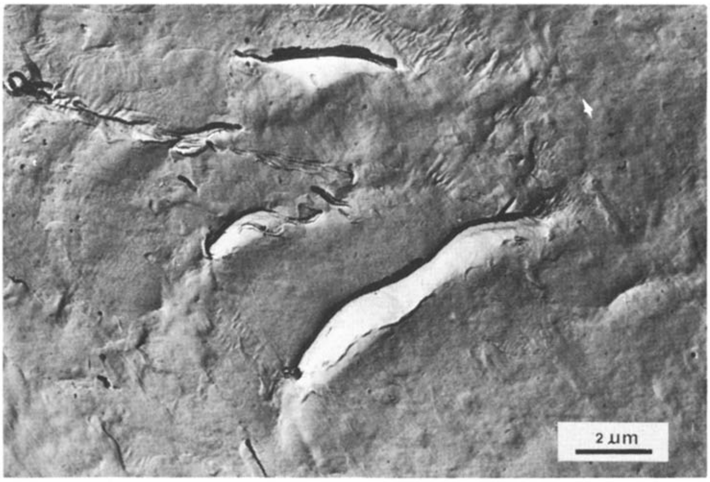

Fig. 6. Polyethylene wear-pin surface on completion of a test. Cracks can be seen roughly perpendicular to the wear direction. Transmission electron micrograph.

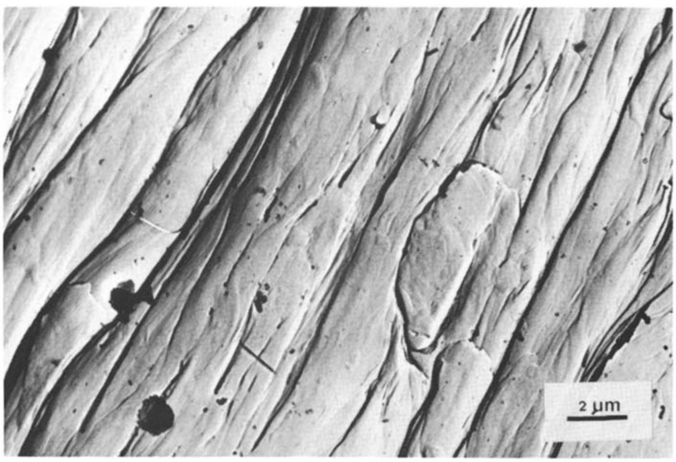

Fig. 7. Polyethylene wear-pin surface on completion of a test showing shallow pits (or fatigue "spalls") elongated in the sliding direction. Transmission electron micrograph.

of a polymer pin. Here adhesive wear has occurred. A small particle of polyethylene is being pulled in the wear direction. It is still held to the surface at each end, but these links are necking down and the particle is about to break away and be lost.

Figure 6 also shows a polyethylene wear surface, but here cracks can be seen perpendicular to the sliding direction. These are attributable to surface fatigue. On occasions, subsurface cracks form and cause a particle to "flake off" the surface. Figure 7 shows a number of hollows, or spalls, where flakes have been detached.

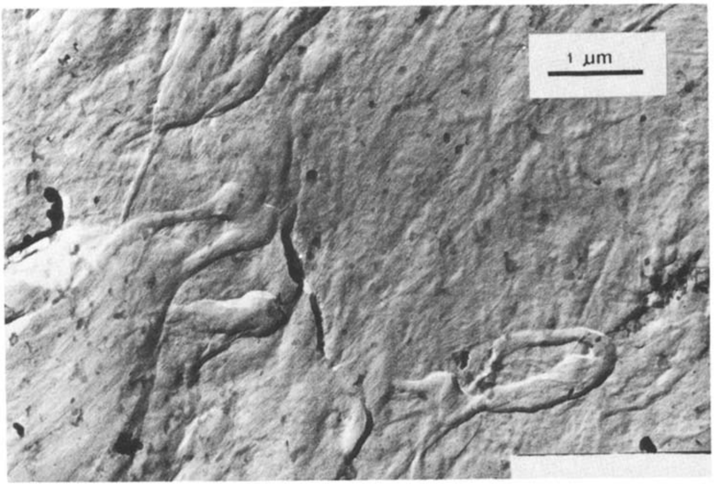

Fig. 8. The evidence for adhesive wear in a polyethylene acetabular cup. Transmission electron micrograph.

Wear of actual hip prostheses

Six hip prostheses of the type having a polyethylene acetabular cup have been obtained with between one and five years of service in the body. A careful examination of the worn surfaces of the polyethylene cups has shown that the wear mechanism has been predominantly adhesive in each case. Wear begins at the high spots on the surface and then spreads over all the bearing surface. Figure 8 shows typical evidence of adhesive damage in an acetabular cup that had been in service for one year.

Calculations suggest that fatigue could become important in prostheses after five to ten years service. The oldest prosthesis examined, with five years in service, did not show any signs of fatigue wear. However, it is believed that fatigue will become important and that, in consequence, the wear rate will increase after a time in service probably of the order of ten years.

Summary and conclusions

The nature and extent of wear in a plastic depends on many factors: the environmental conditions, the type of loading, the counterface roughness and the manner in which the two surfaces move against each other. Thus it will never be possible to simulate outside the body the precise working conditions of a joint *in vivo*. The question of the usefulness of wear tests such as are described here must then be asked. It is considered that such testing is not only justifiable, but essential, for the following reasons.

(1) The same wear mechanisms occur in the tests as in the body. Examination of six prostheses which had been in service showed clear evidence of adhesive wear. It was not possible to obtain a prosthesis which had been in service long enough, according to calculations, to show fatigue wear. However, Walker and Erkman [7] have presented micrographs of polyethylene hip sockets which, they claim, show fatigue cracking. Unfortunately the time in service is not stated.

Thus if a material can be produced which wears less in the laboratory tests, it should also wear less in the body. The indications are that different polymerisation and forming techniques might be useful in this respect.

(2) The different types of wear test, with quite different conditions, give wear coefficients of the same order of magnitude providing the same wear mechanisms prevail. This is encouraging because a prosthesis *in vivo* will be subject to many different types of motion. From a microscope examination of the worn acetabular cups, by measuring the extent to which the original machining marks had been removed after different lengths of time in service, it was possible to estimate the wear rate of the polyethylene *in vivo*. The wear rate found was similar to that measured in the laboratory using a reciprocating wear machine and similar conditions of stress, sliding velocity and counterface roughness. It is considered, however, that any estimate of prosthesis life must be treated with the greatest caution; body weight and the number of steps taken each day will vary considerably between patients.

Charnley [8] has measured the in-service wear of acetabular cups radiographically, after eight to ten years *in vivo*, and found large variations in the amounts of wear. Also, the wear *in vivo* was usually much greater than that in laboratory tests. However, the observations on acetabular cups removed from patients show that an appreciable amount of plastic deformation, or creep, has occurred. Thus the penetration of the femoral head, which is determined radiographically by the decrease in distance between the femoral head and the marker wire, is likely to be high and to vary, because it will include the plastic deformation of the acetabular cup in addition to the wear.

(3) Examination of the prostheses which had been in service indicated a small amount of oxidation of the polyethylene. The acetabular cups had changed colour slightly and the infrared spectra showed a significant increase in the number of carbonyl groups in the polymer. Furthermore, the number of carbonyl groups increased as the time in service increased. The presence of carbonyl groups implies some chain oxidation and chain scission. In this respect it is interesting to note that oxidative degradation in polymers has been associated with fatigue wear [5, 6]. Thus the evidence of oxidation could imply that the fatigue wear component is about to play an important role.

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