Polymer Bulletin 37, 385–392 (1996)

Polymer Bulletin

Wear behaviour of discontinuous aramid fibre reinforced ultra-high molecular weight polyethylene

J. M. Hofsté, H. H. G. Smit, A. J. Pennings

Department of Polymer Chemistry, University of Groningen, Nijenborgh 4,
9747 AG Groningen, The Netherlands

Received: 29 April 1996/Accepted: 19 May 1996

Abstract

The wear of Ultra-High Molecular Weight Polyethylene has generated new concern regarding the long-term clinical performance of total joint replacements. To extend the lifetime of artificial joints, it is necessary to decrease the wear rate of UHMWPE. One possible solution is the incorporation of aramid fibres. Wear rates were determined with a pin-on-roll apparatus with a nominal contact stress of 3.0 MPa at a sliding velocity of 0.24 m/s. The volumetric wear rate decreases with the incorporation of the fibres. A minimum in wear rate is observed at 5 volume percent fibres.

Introduction

On account of its high wear resistance, Ultra-High Molecular Weight Polyethylene (UHMWPE) is highly suitable for use as a construction material in orthopaedics, for the manufacture of hip and knee prostheses (1, 2). The current clinical practice of using UHMWPE as hip-prostheses in younger patients, with an expected lifetime of more than 20 years, has led to renewed concern about the wear and durability of UHMWPE (3). The major problem related to the long-term clinical performance of these implants is adverse tissue reactions caused by the generation of UHMWPE debris. The particles of UHMWPE debris generated at the articulating surfaces are transported to the hard and soft tissue surrounding the joint, and cause chronic inflammatory reactions and bone resorption. These reactions are dependent on the size and morphology of the wear particles as well as the number of particles and volume of debris generated.

To extend the lifetime of artificial joints, it is necessary to decrease the wear rate, which in turn reduces the number and volume of debris generated. Addition of fibres to polymers is known to improve not only their mechanical properties, but also their tribological properties. According to Friedrich, fibre reinforcements are most effective in the range of lower speeds, higher contact pressure and smooth counterparts, conditions agreeable with hip prostheses (4). It seems that the choice of the fibre is very crucial for the final result. In case of glass and carbon fibres the nature of the typical wear debris consisted of broken and pulverised fibres. It is possible that these hard splinter components act as third-body abrasives, leading to enhanced roughening of the steel counterpart, which may in turn cause an increase in composite wear by the preferred abrasive mechanism (5). In aramid composites, the ruptured pieces are fine fibrils which are non-abrasive. Thus the abrasive effect of broken fibres on the composite as well as on the counterface is almost absent in the case of an aramid composite, resulting in a lower wear rate (4).

Beside its excellent wear properties, aramid is a good candidate for use in orthopaedics, because Wan et al. and Wening et al. have shown that aramid fibres show no cytotoxic or mutagenic activity *in vitro* (6,7).

An understanding of, both, the mechanical properties and the tribological behaviour of the composites is necessary for their application. The previous paper already discussed the mechanical properties of the composites (8). The present work deals with the sliding wear characteristics of UHMWPE and aramid reinforced UHMWPE.

Experimental

Sample preparation

The sizing of the PPTA, Twaron®, fibres with lengths of 6 mm, supplied by Akzo Nobel, was removed by Soxhlet extraction with dichloromethane. The fibres were vacuum-dried prior to all experiments. The UHMWPE (Hifax 1900 from Hercules), with an average molecular weight of $4 \bullet 10^6$ kg/kmol, was used as received.

In order to get a fairly homogeneous composite, mixing was accomplished by swirling the necessary amount of UHMWPE powder and chopped fibres with compressed dry nitrogen (8). The composites were obtained by compression moulding of the UHMWPE powder/PPTA fibres mixtures at 225 °C for 3 hours at a pressure of about 50 atmospheres. The composites were slowly cooled to room temperature, under pressure. The same procedure was used to prepare the UHMWPE samples. Pins with a length of 20 mm and surfaces of 16 mm^2 (4 mm × 4 mm) were machined out of the moulded samples.

Sliding wear tests

Dry sliding experiments were carried out using a steel roll, 25 cm in diameter. A schematic sketch of the apparatus is given in Figure 1. The counterface used was stainless steel with a surface roughness R_a of 0.1 μm and hardness of 180 HRB. Wear tests were carried out at a normal load of 48 N, producing a nominal contact stress of 3.0 MPa at a sliding velocity of 0.24 m s^{-1}. All experiments were carried out thrice. The steel roll was cooled by compressed air, through which influence of the interfacial temperature, caused by friction, on the wear behaviour was ruled out.

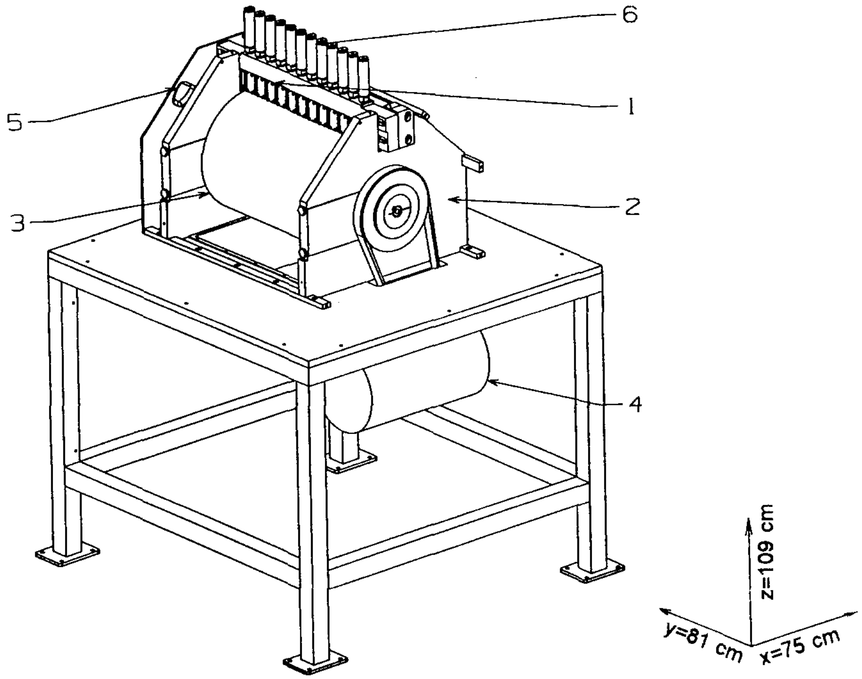

Figure 1 *A schematic presentation of the wear apparatus with (1) pin holders, (2) housing, (3) wear roll, (4) motor, (5) tachometer, and (6) pneumatic pressure inlet. The control unit has been left out.*

The pins were removed, cleaned and weighed, at daily intervals. The mass loss was obtained by weighing the test specimens on an analytical balance before and after every test run. The specific wear rate $\hat{W}_p$ was calculated from the expression (4)

$$\hat{W}_p = \frac{\Delta m}{\rho L A p} = \frac{W_v}{p} \qquad (1)$$

where Δm is the mass loss, ρ is the density of the material, L is the sliding distance, A is the contact area, p is the contact pressure, and W_v is the dimensionless wear rate. $\hat{W}_p$ has the dimension of $(\text{stress})^{-1}$, but it is more meaningful to the use units $mm^3\ N^{-1}\ m^{-1}$ whose physical significance is more readily apparent. The reciprocal of the specific wear rate is considered to be the wear resistance of the material.

Microscopic examination of the worn surfaces of the specimens was carried out by scanning electron microscopy (SEM).

Results and discussion

Figure 2 shows the variation of volume loss as a function of sliding distance for the UHMWPE and aramid fibre reinforced UHMWPE composites samples, with a nominal contact stress of 3.0 MPa at a sliding velocity of 0.24 m s^{-1}. The pure UHMWPE shows the highest volume loss. The volume loss reduces with the incorporation of 5 volume percent aramid fibres, but increases slightly for the composite with 10 percent.

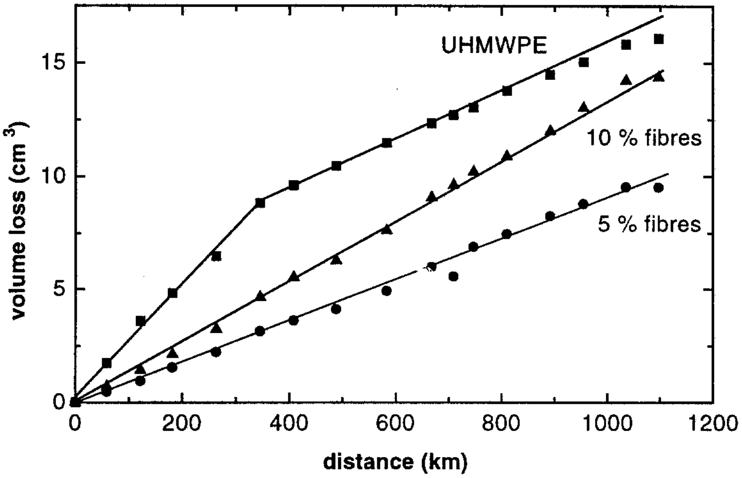

Figure 2 *Volume loss as a function of sliding distance for ■ UHMWPE, ▲ UHMWPE reinforced with 10 volume percent aramid fibres, and ● UHMWPE reinforced with 5 volume percent aramid fibres.*

The wear behaviour of a material depends critically upon its mechanical properties. Especially the ultimate tensile strength, σ_u, and breaking elongation, ϵ_u, seem to be the most important material properties that influence the wear behaviour. The Ratner-Lancaster experimental correlation, $\Delta V \propto (\sigma_u \epsilon_u)^{-1}$, describes this relationship (9). Since ($\sigma_u \epsilon_u$) represents the strain energy at break in a tensile test, the Ratner-Lancaster correlation implies that the toughness of the polymer is the most important property that governs the volumetric wear rate ΔV. The mechanical properties and thus ($\sigma_u \epsilon_u$) of a composite are influenced by the volume fraction of fibres. Figure 3 shows the stress-strain curve of UHMWPE reinforced with 5 and 10 volume % aramid fibres. The differences in failure behaviour is obvious. The pure UHMWPE shows a yield point, plastic deformation, and breaks at an elongation of 275 %. With the incorporation of the fibres, the plastic deformation is inhibited and the composites break at a lower elongation, with a lower ultimate tensile strength. In general, the ultimate tensile strength increases if there is adhesion between the matrix and the fibre (10). The lower ultimate strength of the composites may be caused by the low adhesion between the aramid fibres and UHMWPE matrix. The composite with 10 volume percent aramid fibres breaks at a lower elongation (160 %) than the composite with 5 volume percent aramid fibres (220 %). It is obvious that the factor (σ_u ϵ_u) decreases with the volume fraction of fibres, which may have a negative influence on the volumetric wear rate. Thus, basically, there are two opposite effects which determine the final wear behaviour of the aramid reinforced UHMWPE composites. The incorporation of fibres may have (i) a positive effect on the wear behaviour because of the probability of stress transfer and the increase in hardness (4), and (ii) a negative effect because of the decrease of (σ_u ϵ_u). Because of these two opposite effects, a minimum in wear rate can be observed at a certain volume fraction fibre. In our case this minimum is observed at a volume fraction of 5 percent.

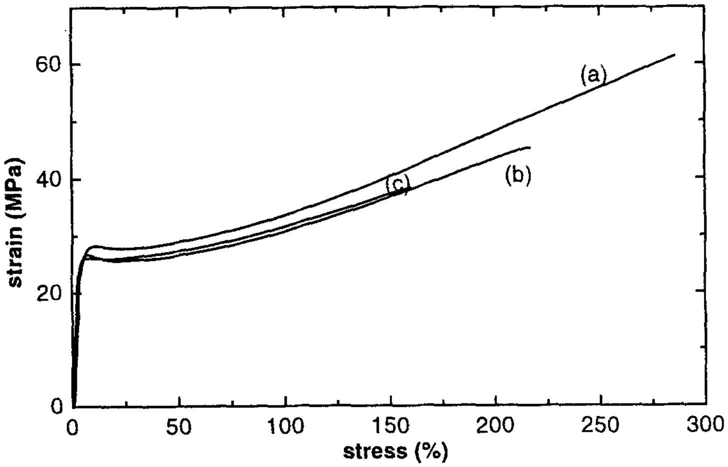

Figure 3 *Stress-strain curve for a) UHMWPE, b) UHMWPE reinforced with 5 volume percent aramid fibres, and c) UHMWPE reinforced with 10 volume percent aramid fibres.*

Another conclusion made from figure 2 is that the wear is proportional to the sliding distance, but in the case of pure UHMWPE, the wear rate reduces after a few hundred kilometres. The wear of UHMWPE is characterised by abrasive and adhesive wear (11). Adhesive wear manifests itself as the polymer begins to adhere to the metal counterface. A polymer film is built up on the counterface as adhesive wear continues to occur. It might be possible that in the case of pure UHMWPE, this transfer film is formed after a few hundred kilometres, and the UHMWPE slides against itself, through which the wear rate decreases. With the incorporation of fibres it may be possible that this transfer film formation is reduced and no wear reduction is observed.

The slope of the volume - sliding distance graph is actually the wear rate. The specific wear rate can be calculated by dividing the wear rate by the contact pressure (equation (1)). The wear rate of UHMWPE decreases from 5.3×10^{-10}

$mm^3\ N^{-1}\ m^{-1}$ to $2.2 \times 10^{-10}\ mm^3\ N^{-1}\ m^{-1}$ after the transfer film formation on the roll. Still, the composite with 5 volume percent fibres shows the lowest specific wear rate of $1.8 \times 10^{-10}\ mm^3\ N^{-1}\ m^{-1}$. The composite with 10 volume percent fibres shows a specific wear rate of $2.7 \times 10^{-10}\ mm^3\ N^{-1}\ m^{-1}$. So a minimum is observed at 5 volume percent fibres. Friedrich observed the same behaviour: the glass- and carbon fibre reinforced PA 66.6 composites show a minimum at about 15 volume percent fibres (4).

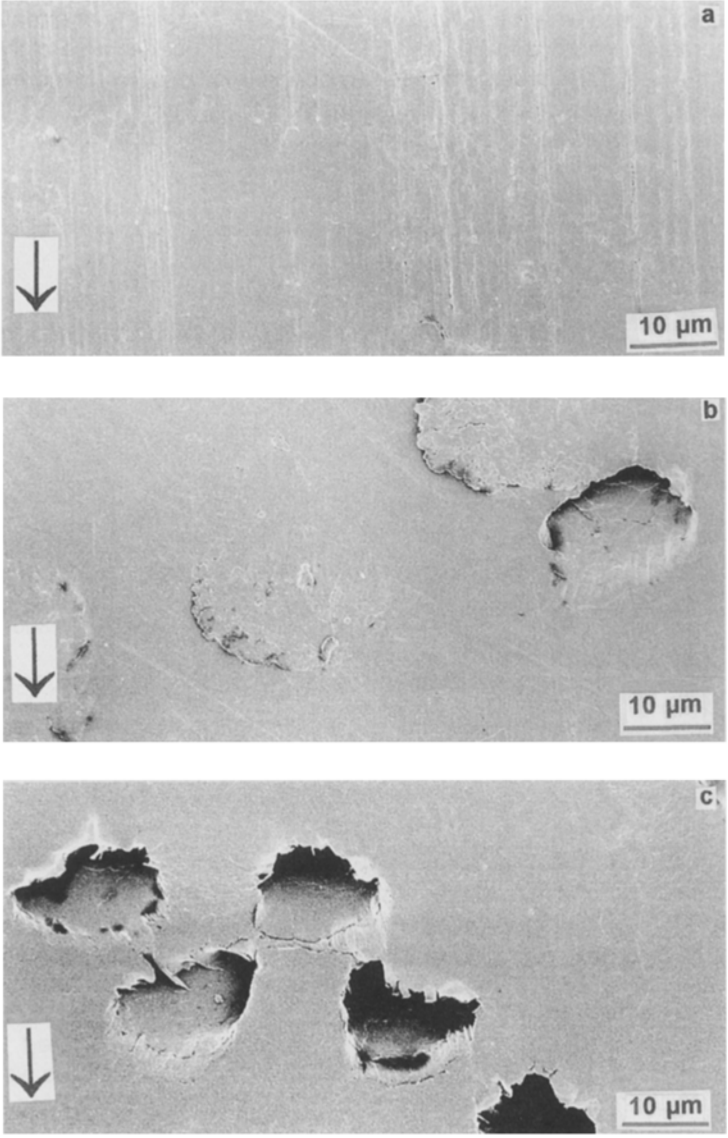

Figure 4 *SEM micrographs of the worn surfaces of a) UHMWPE, b) UHMWPE with 5 volume percent aramid fibres, and c) UHMWPE with 10 volume percent aramid fibres.The arrows show the sliding direction.*

Figure 4 shows the scanning electron micrographs of the worn surfaces of pure UHMWPE and UHMWPE with 5 and 10 volume percent aramid fibres. A few observations can be made. The UHMWPE surface shows longitudinal scratches caused by the asperties of the counterface. This behaviour is not observed in the case of the composites. These worn surfaces are smoother, but also show defects which have the same dimensions as the cross section of the aramid fibres, i.e., 12 μm. The disparate thermal expansion properties of the fibres and matrix lead to an inevitable build up of residual stresses during fabrication. Therefore it may be possible that higher stress concentration is observed in UHMWPE at the fibre ends, through which these UHMWPE parts are more easily damaged during the sliding tests. More defects are observed at the surface at higher fibre volume fractions.

Conclusions

This study highlights the influence of the incorporation of aramid fibres on the wear rate of UHMWPE. The volumetric wear rate, which is influenced by the strain energy, decreases with the incorporation of the fibres. Because the wear behaviour of the composite is determined by two opposite effects, (i) a positive effect behaviour because of the probability of stress transfer and the increase in hardness and (ii) a negative effect because of the decrease of (σ_u ϵ_u), a minimum in wear rate is observed at 5 volume percent fibres.

The wear of pure UHMWPE is characterised, among others, by adhesive wear and the formation of a transfer film, through which the UHMWPE slides against itself, which in turn reduces the wear rate. With the incorporation of the aramid fibres it may be possible that this transfer film formation is limited. This may explain the difference in wear behaviour after a few hundred kilometres. The pure UHMWPE shows a reduction in specific wear rate, while the composites show a linear behaviour throughout the sliding test.

The worn surface of the composites shows defects, which have the same dimensions as the cross section of the fibres. The UHMWPE at the fibre ends are more easily damaged during the sliding tests, because of residual thermal stresses.

The volume loss decreases with the incorporation of the aramid fibres, inspite of the poor adhesion between the UHMWPE matrix and aramid fibres. If it is possible to create a better adhesion between the two components an even better wear resistance may be observed.

Acknowledgement

The authors wish to thank Akzo Nobel Central Research, especially Dr. J.W.G. Mahy, for their financial support, the technical team and A.B. Verweij for the pin-on-roll apparatus, and H. Nijland for the SEM micrographs.

References

1 de Boer J (1984) Ph.D. thesis, University of Groningen, Groningen, The Netherlands
2 Dumbleton J H (1981) Tribology of natural and artificial joints. Elsevier, North-Holland Amsterdam
3 Cooper J R, Dowson D, Fisher J (1993) Wear 162-164: 378
4 Friedrich K (1986) Friction and wear of polymer composites. Elsevier Amsterdam
5 Vishwanath B, Verma, A P, Kameswara Rao, C V S (1993) Wear 167:93
6 Wan H, Williams R L, Doherthy P J, Williams D F (1994) J. Mater. Sci. Mater.Med. 5: 441
7 Wening J V, Marquardt H, Katzer A, Jungbluth K H (1995) Biomater. 16: 337
8 Hofsté J M, Bergmans, K J R, de Boer J, Wevers R, Pennings A J (1996) Pol. Bul. 36: 213
9 Wang A, Sun D C, Stark C, Dumbleton J H (1995) Wear 181-183: 241
10 Akin-Öktem G, Tinçer T (1994) J. Appl. Polym.Sci. 54: 1103
11 Gunther J, Rose R M (1994) J Long-term Eff. Med. Impl. 157: 4