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Mechanical and tribological properties of short discontinuous UHMWPE fiber reinforced UHMWPE

J. M. Hofsté, B. van Voorn, A. J. Pennings*

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

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Abstract

The tribological properties of Ultra-High Molecular Weight Polyethylene have 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 UHMWPE fibers. Mixing of the two components was accomplished by swirling the UHMWPE powder and chopped UHMWPE fibers with compressed nitrogen. During this mixture procedure opposite surface charges will be generated on the UHMWPE powder and UHMWPE fiber. The electrostatic attraction could be responsible for the coherence of the two components, leading a composite with fairly uniformly distributed and randomly oriented fibers was obtained. With this method a fiber volume fraction up to 60 volume percent could be achieved. In this composite the matrix and fibers are of the same chemical nature. The inherent chemical compatibility of the composite components is likely to promote good bonding at the interface, through which a composite with excellent mechanical properties is made. The ultimate stress and modulus of the 60 volume percent composite show an improvement of 160 and 600 percent, respectively, in comparison with the neat UHMWPE. The wear rates were determined with a pin-on-roll apparatus with a nominal contact stress of 3 MPa at a sliding velocity of 0.24 m/s. The volumetric wear rate decreases with the incorporation of the UHMWPE fibers.

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 (1-6). The current clinical

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* Corresponding author

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). 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 fibers to polymers is known to improve not only their mechanical properties, but also their tribological properties (7-12).

The properties of a composite are generally a function of fiber content, fiber aspect ratio, fiber orientation, void content, fiber-matrix adhesion, fiber and matrix properties, and processing methods (13-17). For a good reinforcement the fiber-matrix interface is very significant. At the interface loads are transferred from the matrix to the fiber. This load transfer depends, among others, on the degree of fiber matrix adhesion. In the UHMWPE reinforced UHMWPE composite the matrix and fibers are of the same chemical nature. The inherent chemical compatibility of the composite components is likely to promote good bonding at the interface, through which a composite with excellent properties can be made (18-21).

The possibility to fabricate a composite in which both the matrix and the fibers are made of the same polymer, e.g. UHMWPE, lies in the fact that the different morphologies of the matrix and the fibers causes a difference of melting temperature. The melting temperature of the UHMWPE matrix is 142 °C, while the UHMWPE fiber has a melting temperature of 148 °C.

This paper deals with the preparation of the short UHMWPE fiber reinforced UHMWPE composite and the influence of the volume fraction fibers on the mechanical and the tribological properties.

Experimental

Sample preparation

The UHMWPE, Dyneema, fibers, supplied by DSM, have a tensile strength of 2.8 GPa, modulus of 87 GPa and an elongation of 3.5 %. The fibers were chopped into length of 6 mm. The UHMWPE (Hifax 1900 from Hercules), with $M_w = 4 \cdot 10^6$ kg/kmol and $M_n = 2 \cdot 10^5$ 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 fibers with compressed dry nitrogen (22). The composites were obtained by compression moulding of the UHMWPE powder/UHMWPE fibers mixtures at 144.5 °C for 3 hours at a pressure of about 60 MPa. The composites were slowly cooled to room temperature, under pressure. The same procedure was used to prepare the UHMWPE samples but was compression moulded at a temperature of 225 °C.

Mixing of the components

A proper dispersion of the fiber is necessary to achieve uniform composite properties. For instance, a cluster of short fibers, instead of uniform dispersed fibers, will only weaken the composite due to the fact that fibers on the inside of the cluster are not contributing to the properties. These clusters may even act as actual failure sites (13). In spite of high its high ductility the UHMWPE fibers could be chopped into a length of 6 mm. Blending was accomplished by swirling the UHMWPE powder and chopped fibers with compressed dry nitrogen to achieve a homogenous mixture. During this mixture procedure opposite surface charges will be generated on the UHMWPE powder and UHMWPE fiber. This charging mechanism is called tribocharging (23,24). It is a process in which two bodies are contacted and separated again with the result that each body becomes electrically charged. In spite of the same material used for the powder and fibers, the UHMWPE powder becomes positively and the UHMWPE fibers negatively charged. This may be caused by the different morphology of the two components.

The electrostatic attraction could be responsible for the coherence of the two components, leading to a uniform dispersion of the fibers, which is necessary to achieve uniform composite properties. With this method, a discontinuous short UHMWPE fiber reinforced UHMWPE composite is achieved. The maximum fiber volume fraction which can be incorporated in UHMWPE is 60 volume percent.

A great advantage of this method is that the fibers are not damaged during the processing method. In general incorporation of fibers into a thermoplastic matrix is achieved by blending the chopped fibers with the plastic in an extruder (13). The process involves large shear fields which results in fiber breakage due to tensile and bending stresses. Subsequent processing such as injection moulding leads to further break-down. All these problems are not observed in the dry mixing method.

Tensile test

Tensile tests were performed on dumb-bell shaped specimens (dumb-bell shape: ASTM D1708-93, thickness 1 mm) at room temperature using an Instron (4301) tensile tester, equipped with a 5 kN load-cell, at a cross-head speed of 20 mm/min. The gauge length was 25 mm. The reported tensile data are the mean values of at least eight tests. Although the ASTM D1708-93 standard does not permit the determination of moduli, we have used the obtained values primary for the sake of comparison. The moduli presented in this paper are therefore only relative values.

Sliding wear test

Pins with a length of 20 mm and surfaces of 16 mm^2 (4 mm × 4 mm) were machined out of the moulded samples. Because of the mixing procedure and compression moulding step, the composites have a 2-dimensional discontinuous fiber orientation in the xy-plane. The pins were machined out in such a way that the z-plane is the contact surface, through which a part of the fibers are normal to the contact surface.

Dry sliding experiments were carried out using a steel roll, 25 cm in diameter. A schematic sketch of the apparatus is given in our previous article (11). 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.

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.

Results and discussion

Mechanical properties

Figure 1 shows the stress-strain curves of the UHMWPE fiber reinforced UHMWPE with an increasing amount of fiber. The difference in failure behaviour is obvious. The pure UHMWPE shows a yield point, plastic deformation, and breaks at an elongation of 220 %. With the incorporation of the fibers, the plastic deformation is largely inhibited and the composites show no yielding at all, and break at a lower elongation. The stress at break increases from 50 MPa of the neat UHMWPE to 130 MPa of the composite with 60 volume percent UHMWPE fibers. An improvement of 160 percent. In general the ultimate tensile strength increases if there is adhesion between the matrix and the fiber. The enormous stress improvement confirms the good bonding between the fiber and the matrix. The modulus increases from 0.8 GPa for the neat UHMWPE to 5.8 GPa, which is an improvement of more than 600 percent. Figure 2 shows the increase in stress and modulus with volume fraction fiber.

Tribological properties

Figure 3 shows the volume loss as a function of sliding distance for the neat UHMWPE and 10 and 30 volume percent UHMWPE fiber reinforced UHMWPE composites, with a nominal contact stress of 3 MPa at a sliding velocity of 0.24 m/s. The neat UHMWPE shows the highest volume loss. A modest decrease is observed for the composite with 10 volume percent fibers. The composite with 30 volume percent UHMPWE fibers shows the lowest volume loss during sliding against a smooth counterpart.

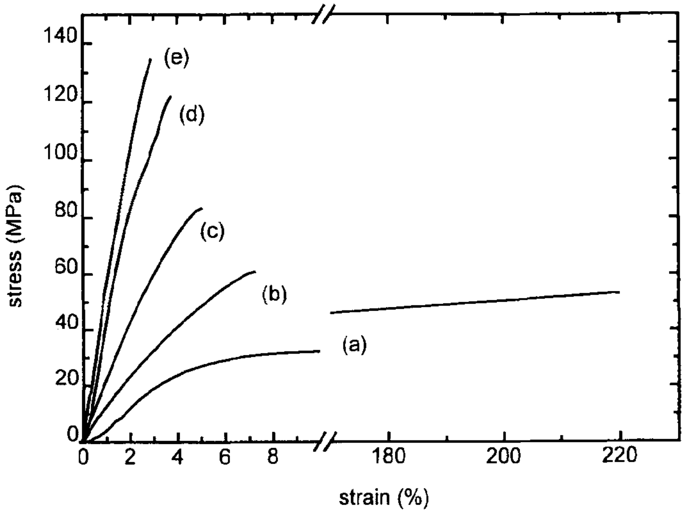

Figure 1 *Stress-strain curves for a) neat UHMWPE, b) 10 volume percent UHMWPE/UHMWPE composite, c) 30 volume percent UHMWPE/UHMWPE composite, d) 50 volume percent UHMWPE/UHMWPE composite, and e) 60 volume percent UHMWPE/UHMWPE composite.*

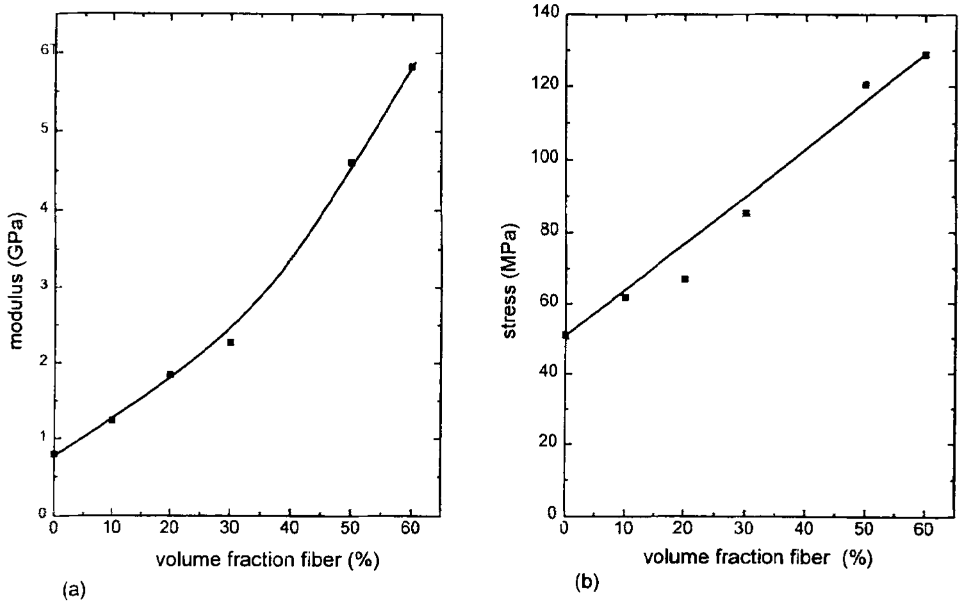

Figure 2 *Increase of a) modulus and b) stress with volume fraction UHMWPE fiber.*

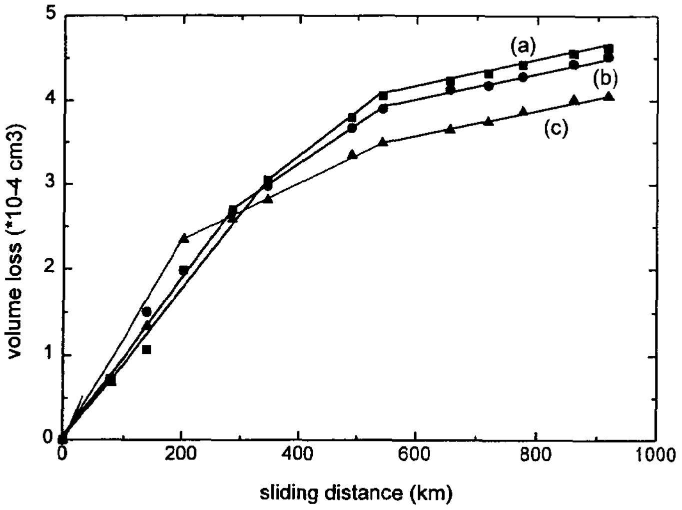

Figure 3 *Volume loss as a function of sliding distance for a) neat UHMWPE, b) UHMWPE incorporated with 10 volume percent UHMWPE fibers, c) UHMWPE incorporated with 30 volume percent UHMWPE fibers*

This wear improvement caused by the existence of the UHMWPE fibers may be explained by the load-supporting action of fibers proposed by Lancaster (25-27). Consider the fiber with a length l and radius r, oriented parallel to the loading direction and contacting the counterface at the end (Figure 4). If the modulus of the matrix is lower than the modulus of the fiber (the UHMWPE matrix has a modulus of 0.8 GPa, while the UHMWPE fibers has a modulus of 87 GPa), a tangential stress τ and a corresponding compressive loading of the fibers is produced because of the difference in the axial strains between the fiber and matrix. In this way the contact load is transferred from the matrix to the fiber. The contact stress σ_f of the fiber can be expressed as follows:

$$\sigma_f = 2\tau(l/r) + p \qquad (1)$$

with p the nominal pressure. This preferential load support of the normal load by the fiber shields the matrix, causing the contact pressure of the matrix with the counterface σ_m to be less than the nominal pressure p.

Because the composites have a 2-dimensional fiber orientation in the xy-plane and the z-plane is the contact surface, only a part of the fibers are normal to the contact surface, through which the fibers are not fully utilized. The higher the percentage fibers normal to the contact surface, the more load can be transferred to the fibers.

At higher volume fraction more stress can be transferred from the matrix to the fibers, through which a higher wear improvement is observed.

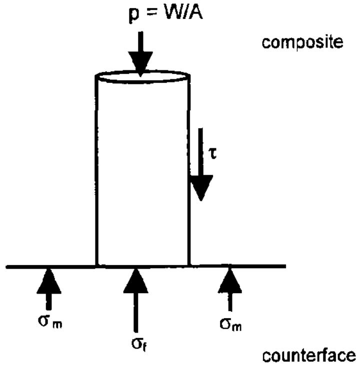

Figure 4 *Preferential load support of fiber-filled polymer with* τ *the interfacial shear stress,* σ_f *fiber contact pressure and* σ_m *matrix contact pressure.*

conclusions

This study highlights the influence of the incorporation of UHMWPE fibers on the mechanical and tribological properties of UHMWPE. During the dry mixing method each component becomes electrically charged, through which a composite with a fairly homogeneous mixture can be made. With this mixing method a fiber volume fraction up to 60 percent can be achieved.

The inherent chemical compatibility of the composite components undoubtedly promotes good bonding at the interface, through which a composite with excellent mechanical properties is made. The ultimate stress and modulus of the 60 volume percent composite show an improvement of 160 and 600 percent, respectively, in comparison with the neat UHMWPE.

The 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 UHMWPE fibers. This wear improvement caused by the existence of the UHMWPE fibers may be explained by the load-supporting action of fibers. Stress can be transferred from the UHMWPE matrix to the UHMWPE fibers. This preferential load support of the normal load by the fiber shields the matrix, causing the contact pressure of the matrix with the counterface σ_m to be less than the nominal pressure p.

At higher volume fraction more stress can be transferred from the matrix to the fibers, through which a higher wear improvement is observed.

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