ELSEVIER

Wear 244 (2000) 20–28

WEAR

www.elsevier.com/locate/wear

Sliding wear performance of HD-PE reinforced by continuous UHMWPE fibres

O. Jacobs [a,*], N. Mentz [a], A. Poeppel [b], K. Schulte [b]

[a] *Department of Mechanical Engineering, Fachhochschule Lübeck-University of Applied Science, Stephensonstr. 3, 23562 Lübeck, Germany*
[b] *Polymer and Composites Section, Technical University Hamburg-Harburg, Denickestr. 15, 21073 Hamburg, Germany*

Received 9 March 1999; received in revised form 29 March 2000; accepted 10 May 2000

Abstract

This paper deals with the wear and creep resistance of a new composite material consisting of high density polyethylene (HD-PE) reinforced by continuous ultra high molecular weight polyethylene (UHMWPE) fibres.

Unidirectional PE/PE laminates with fibre contents between 0%and 50% by volume were produced via hot pressing of HD-PE powder impregnated UHMWPE fibres. Flat specimens were tested in a ball-on-prism tribometer with polished steel balls. The penetration of the steel balls into the composite specimen was measured continuously. Creep deformation and material removal by wear were separated.

The results were compared with the neat UHMWPE (good wear resistance but poor creep resistance and mechanical properties) and HD-PE (better creep resistance but poor wear resistance). The composites were found to combine the good wear resistance of UHMWPE with a superior creep resistance and mechanical properties. Further work is needed to improve the homogeneity of the composites in order to reduce the scatter of the wear results.

Keywords: Sliding wear performance; High density polyethylene; Ultra high molecular weight polyethylene

1. Introduction

Polyethylene with extremely long polymers chains [ultra high molecular weight polyethylene (UHMWPE)] is widely used in bearing applications [1,2]. The advantages of this material are high wear resistance, low friction and chemical inertness. Biological compatibility and high resistance to the biological environment complete this property profile which recommends UHMWPE for the application in endoprosthesis bearing as, e.g., artificial hips and knees [3]. Numerous research papers are dedicated to the tribological properties of UHMWPE and its use in technical and medical bearing applications [4–6].

However, UHMWPE has some important disadvantages: it strongly creeps under load [7] and its Young's modulus and yield strength are lower than for usual high density polyethylene (HD-PE). This restricts the load bearing capacity of UHMWPE bearings, and causes progressive fitting inaccuracy due to creep.

HD-PE reinforced by UHMWPE fibres should combine good mechanical properties with the outstanding friction and wear characteristics of UHMWPE. Several groups developed and tested such a composite materials. Stern et al. [8] used chopped fibres as reinforcement, whereas von Lacroix [9] produced composites with continuous fibres and studied their mechanical properties and microstructure. The strength and modulus of these materials as measured in fibre direction exceed by far the values of the neat polymers (Table 1).

The present paper focuses on the wear and creep resistance under wear loading of these new composite materials. The effect of the UHMWPE fibre volume content on the wear of a HD-PE matrix was experimentally determined and compared with neat UHMWPE and HD-PE.

2. Experimental method

2.1. Sample preparation

2.1.1. Raw materials

The sample material consisted of HD-PE reinforced by continuous UHMWPE-Fibres. As a reference material specimens of neat HD-PE were manufactured and tested. For comparison some specimens were made of UHMWPE which is the state of the art material for endoprosthesis applications.

* Corresponding author

0043-1648/00/$ – see front matter
PII: S0043-1648(00)00419-1

Table 1
Characteristic properties of the materials investigated [9,10]

Material	Density (kg/m^3)	Tensile strength (MPa)	Young's modulus (MPa)
UHMWPE (bulk)	935	20	708
UHMWPE (fibres)	970	3000	95 000
HD-PE	956	28	1400
Composite (50% UHMWPE fibres)	960	850	28 000

The HD-PE used was the Abifor 1300/20 powder provided by Billeter Kunststoffpulver, Germany. The UHMWPE used was also delivered as a powder, type GUR 1120 [2] from Ticona. The molecular weight was determined by measuring the viscosity of a solution of the polymer. The average molecular weight was found to be $M_\eta = 4 \times 10^6$ g/mol.

The UHMWPE fibres used were provided by DSM (Dyneema SK65). The average diameter of the fibres was to about 30 μm. The fibres were available as rovings of 176 tex consisting of roughly 800 filaments.

2.1.2. Sample production

2.1.2.1. UHMWPE specimens. The powder was measured out to give plates of a pre-defined thickness of about 2 mm. Then the material was filled into a hot press and pre-compacted at a pressure of 25 MPa acting over a period of 15 min without any heating. In the next step, the press was heated up to a temperature of 200°C. At this temperature a pressure of 1 MPa was applied over a period of 15–20 min. During the subsequent cooling phase, the pressure was increased stepwise to avoid the formation of pores and surface warping due to shrinkage.

2.1.2.2. HD-PE specimens. In general, the procedure was the same as for UHMWPE. The processing parameters were: 15 min cold pressing at 12 MPa, final compaction at 130°C under a pressure of 2.5 MPa acting over a period of 15 min.

2.1.2.3. Composite specimens (laminates). The laminate production is described in detail in Ref. [9]. The process can roughly be divided into three steps.

(1) Impregnation: endless fibre bundles were pulled with a pre-defined constant speed through a suspension of HD-PE powder in iso-propanol. Speed and powder concentration inside the suspension determined the amount of matrix powder picked up by the fibre bundles.

The fibre bundles were spooled upon a steel plate. Simultaneously, the plated was moved with a constant speed transverse to the fibre direction so that the bundles were laid up exactly one beneath another, i.e. without gaps and overlap.

(2) Prepreg production: after drying, the impregnated fibre sheets together with the steel plates were put into a hot press and consolidated at a temperature of 130°C and a pressure of 5 MPa. The resulting pre-impregnated sheets (prepregs) were about 0.25 mm thick. Process temperature and time are a compromise: the temperature has to exceed a minimum value for getting sufficient matrix flow and impregnation — too high temperatures, on the other hand, would cause the loss of molecular orientation inside the UHMWPE fibres leading to a loss in mechanical performance.

Before proceeding with the specimen lamination, the fibre content of the prepregs was checked experimentally. For this purpose, the prepregs were weighed. Since the density of fibres and matrix are almost identical, the fibre content could be calculated by

$$\frac{V_F}{V_C} = \frac{M_F}{M_C} = \frac{m_F L_P W_P}{M_C w}$$

with $V_{C(F)}$=total (fibre) volume; $M_{C(F)}$=mass of the composite (and fibres, respectively); m_F=fibre bundle density (=176 g/mm); L_P=length of the prepreg; W_P=width of the prepreg; w=step width between laying up of neighbouring fibre bundles (=diameter of fibre bundles=1.5 mm).

Only those prepregs with correct fibre content (within a few percent scatter) were used for the subsequent production of laminates.

(3) Laminate production: from the prepregs, unidirectional (all fibres aligned in one direction) laminates were produced. Each laminate consisted of eight prepreg layers. This lay-up was placed in a die and compacted at a pressure of 0.7 MPa and a temperature of 140°C. In a next step, the die with the laminate inside was cooled down under pressure. At about 40°C, the die was opened and the laminate was taken out of the die.

The final thickness of the specimens amounted to about 2 mm.

2.1.2.4. Machining of specimens. From the sample plates (neat matrices and composites), small specimens of about 10×10 mm were cut by a high speed diamond saw. These specimens were glued onto the specimen holders of the wear testing apparatus. For this purpose, the specimen rear side was treated with a special polyolefin primer.

Parallel specimen orientation with the fibres aligned in sliding direction was distinguished from transverse specimen orientation (compare Fig. 1).

2.2. Material characteristics

The characteristic properties of the materials used are listed in Table 1. UHMWPE has a lower strength and Young's modulus than HD-PE due to lower crystallinity. However, the according values of the UHMWPE fibres are much higher due to the molecular orientation, which allows to exploit the high potentials of covalent bonds in fibre direction. For this reason, the composites have strength and stiffness values far beyond the values of the bulk matrix polymers. However, the properties of the composite cannot be estimated from the values of the fibres and the matrix by a rule-of-mixture. The heat applied during processing distorts the molecular orientation thus reducing the mechanical

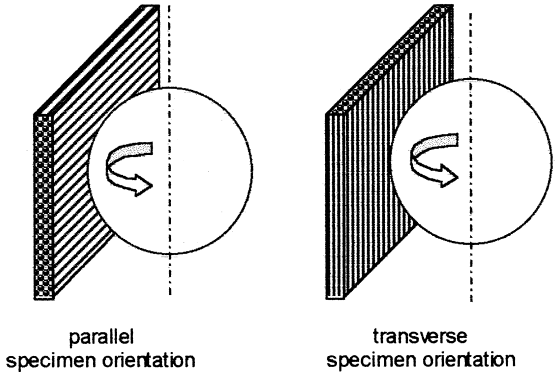

Fig. 1. Schematic of parallel and transverse fibre orientation relative to the sliding direction.

performance [9]. The composite properties are highly sensitive to the processing conditions (as will be seen later).

Fig. 2 shows an optical micrograph of a section cut through the composite. The specimen was cut perpendicular to the fibres and ground with an abrasive paper. Fibre rich regions (*F*) can be distinguished from matrix rich regions (*M*). Inside the fibre rich regions, single fibres can hardly be distinguished because the material was smeared and mixed up.

2.3. Testing procedures

For an initial screening, wear tests were performed in a simple standard wear testing apparatus under dry conditions. More realistic testing conditions were used in later investigations.

2.3.1. Experimental setup

The testing apparatus used was of the ball-on-prism type [11] from Dr. Tillwich, Horb, Germany, schematically shown in Fig. 3a. A metallic prism with an opening angle of 90° containing the specimens was pressed against a bearing steel ball (Fig. 3b). The load was applied by dead weights via a lever. In order to avoid high load fluctuations due to induced vibrations, the weights were attached to the lever via soft screw springs.

Six specimens can be tested simultaneously, all six bearing balls driven by one motor thus having exactly the same sliding speed. However, only four specimens were tested at the same time to prevent mutual disturbance due to bumping of the dead weights against one another.

Dead weights of 10 N were applied. The distance between support of the lever and steel ball was three times shorter than the distance between dead weight and support so that

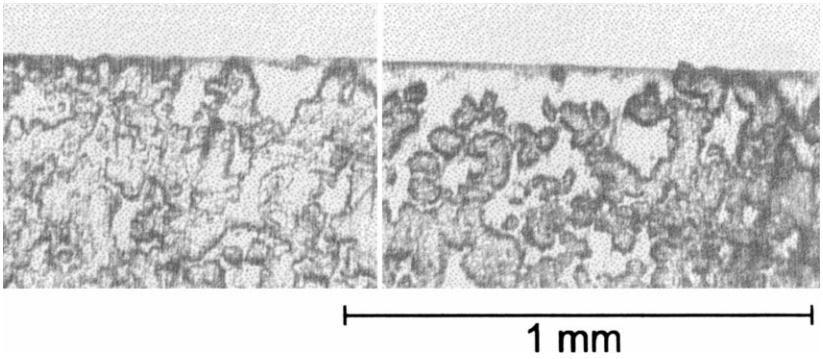

Fig. 2. Light micrograph of a section cut through a PE/PE composite with a fibre content of 30 vol%. The dark areas are fibre rich regions.

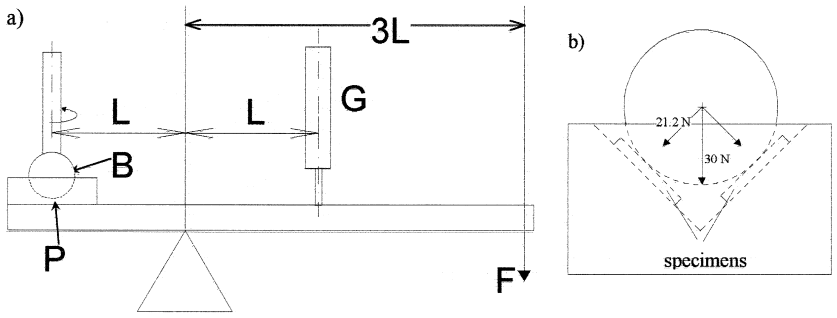

Fig. 3. Schematic of the wear testing apparatus used for the wear and creep tests (a). P=specimen holder (prism), B=steel ball rotating around the vertical axis, G=inductive strain gauge, F=dead weight (10 N), L=lever on specimen side. Lever on dead weight side is 3 L. (b) is a magnified front view of the specimen holder with inserted specimens loaded by the steel ball.

the load acting onto the prism was 3×10 N=30 N. This load was distributed over two specimens, each specimen surface forming an angle of 45° with the vertical axis. Therefore, a normal load component acting onto the specimen surface was $F_N=15\sqrt{2}=21.2$ N (see Fig. 3b).

The counterparts were bearing balls of hardened 100Cr6 steel with a diameter of $d=12.7$ mm. The steel balls rotated uniformly with a frequency of 1 Hz, giving a continuous sliding speed of $v=\pi d\cdot\cos 45^\circ\cdot f=28.2$ mm/s.

The data acquisition was performed via inductive strain gauges (see Fig. 3a). The signals of the strain gauges were read every 30 min and stored by a PC system.

2.3.2. Creep tests

In technical bearing applications creep as well as wear could cause fitting problems after a longer period of loading. In order to separate these two effects as far as possible, special creep tests were performed.

Before starting with the wear tests, the specimens were statically loaded in the wear test rig for a duration of about 60 h. Under this static load, the balls penetrated into the specimen surface producing plastic deformation and creep of the specimen surfaces.

The loading conditions were the same as described above for the wear tests.

2.3.3. Wear tests

During the creep deformation process, the contact area increased continuously and the contact pressure decreased asymptotically to a value below which creep almost disappeared (see Section 3.1). When this situation was reached, the motor of the wear testing apparatus was switched on without unloading the specimens in the meantime to assure that the wear process starts at the same position where creep has already diminished. This procedure was chosen in order to get plain wear data without superposition by creep deformation. Creep acceleration due to frictional heat was negligible because of the low sliding speed. The results presented in Section 3.2 will justify this assumption.

However, it should be recognised that at the beginning of the wear tests, the contact area is larger and contact pressure was smaller than if the apparatus were started immediately after inserting the specimens. This would be different in real bearing applications.

Table 2 summarises the wear test conditions.

Table 2
Wear test conditions

Contact geometry	ball-on-flat
Angle between axis of rotation and specimen surface	45°
Ball diameter	12.7 mm
Counterpart	hardened steel 100 Cr6
Sliding speed	28.2 mm/s
Normal load	21.2 N
Duration of creep tests	60 h
Duration of wear tests	60 h

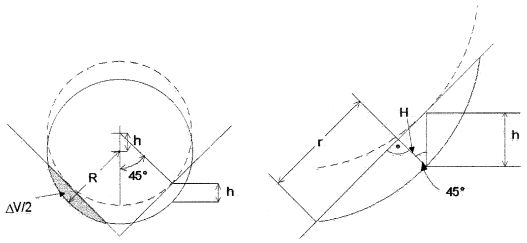

Fig. 4. Relation between vertical motion, h, of the lever and penetration of the steel ball into the specimen surface, H.

2.3.4. Data processing

The signal received from the strain gauges gave the displacement of the lever in vertical direction, h. From these data, the penetration depth of the ball into the specimen surface, H, was calculated according to (see Fig. 4):

$$H = h\sin 45^\circ = \frac{1}{\sqrt{2}}h.$$

In the case of creep, the penetration depth H_{60} reached after 60 h static loading was taken as a measure for the creep susceptibility of the material.

During the wear tests, H vs. time curves were plotted. Fig. 5 shows an example of such a curve. This type of wear curves of polymers is described in literature by several authors [12,13]. Initially, the wear proceeds rapidly (running-in-phase). During the first 6 h, the slope of the h–t-curve continuously decreases until it reaches a roughly constant value (steady state). The slope of this linear part of the curve is the wear rate $w_{h/t}$ [12] and was taken as a quantitative measure for the wear susceptibility of the material.

3. Experimental results

3.1. Creep tests

Fig. 6 shows the results of the creep test on PE/PE with about 20% fibre content. The data recorded are the penetration of the ball into the specimen surface. Initially, the

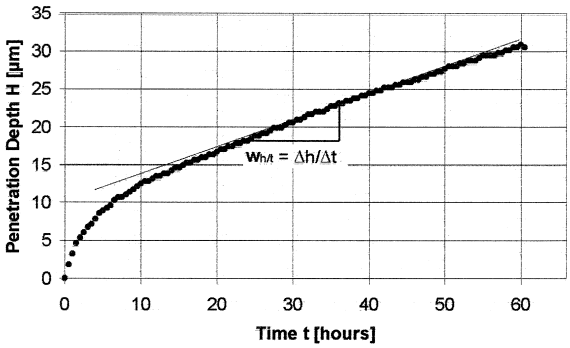

Fig. 5. Typical wear curve of a PE/PE composite with 30 vol% fibre content. The wear rate $w_{t/h}$ is the slope of the steady state part of the curve. Test conditions see text.

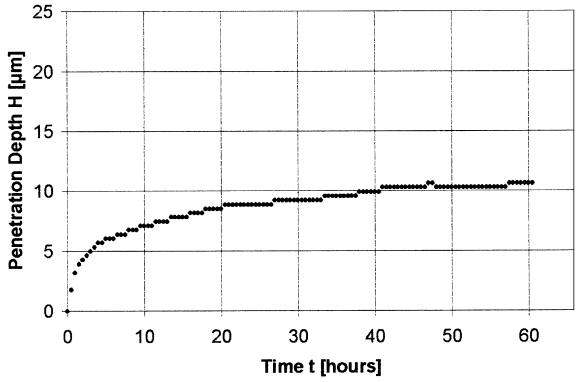

Fig. 6. Typical creep curve of a PE/PE composite with 21.4% fibre volume content.

material creeps very fast but then the creep decelerates continuously while the contact area increases causing a reduction of the contact pressure. After about 42 h, the contact pressure reaches a value at which the penetration motion almost diminishes.

Fig. 7 shows the creep test results of the neat UHMWPE. The general shape of the curve is identical to the PE/PE results but quantitatively there is a significant difference. It is obvious that this material creeps much faster than the fibre reinforced PE-HD. The deformation after 60 h amounts to about 30 μm which is about twice the value as in the case of PE/PE.

The results of all creep tests are summarised in Fig. 8. The creep resistance of HD-PE increases continuously with increasing fibre volume content. The difference between V_F=30% and 50% is marginal in comparison to the scatter bands. As expected, the UHMWPE creeps much more than the other materials.

One set of data at V_F=30% (assigned by a (1) in Fig. 8) strongly deviates from the other test results. These very first creep tests were performed with a sample material manufactured by a third person who was only briefly introduced to the manufacturing process. Nominally, the sample was produced in the same way as the other samples and the measured fibre volume content in fact was correct. Nevertheless, the creep data of this material scatter extremely with some

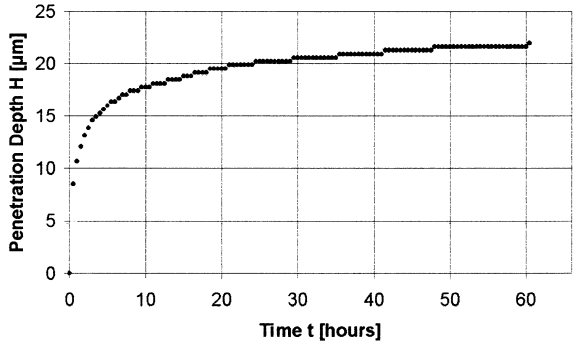

Fig. 7. Typical creep curve of a neat UHMWPE specimen.

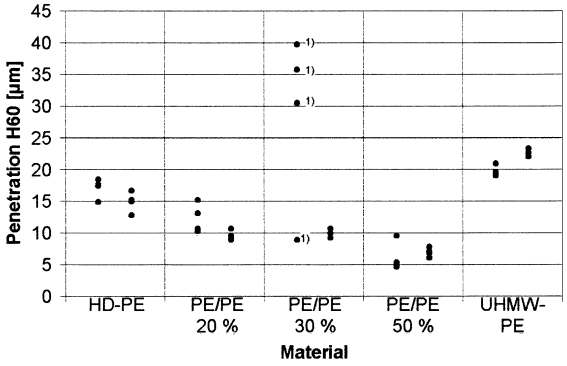

Fig. 8. Comparison of the creep behaviour (penetration depth after 60 h) of the different materials investigated. Two test runs per material with four specimens each time were performed. The first set of data at V_F=30% (1) was produced with a sample manufactured by a third person.

results even above the neat HD-PE matrix. This depicts the strong sensitivity of the material properties to processing conditions.

The reason for the digressively increasing creep curves is twice.

(1) Creep of plastics always is a process, which decelerates in time. However, the general law for creep under uniaxial tensile loading is [14]

$$\varepsilon = \varepsilon_0 + at^n \Rightarrow \log \varepsilon \approx \log a + n \log t \quad \text{with } n < 1$$

If the above equation would be applicable, a log ε vs. log t plot should give a linear function. Fig. 9 shows such a plot of one of the creep experiments. The steadily decreasing slope shows that the decelration of the creep process is stronger than in the case of uniaxial loading.

(2) The main reason for this deviation between formula and experiment is the spherical contact geometry. While the ball penetrates into the specimen surface, the contact area continuously increases. The contact pressure and therefore the penetration speed decrease with time.

The stress field in the plastic material below the contact area is three-dimensional [7] and the contact zone is supported by the surrounding material. This causes some hindrance of the plastic flow.

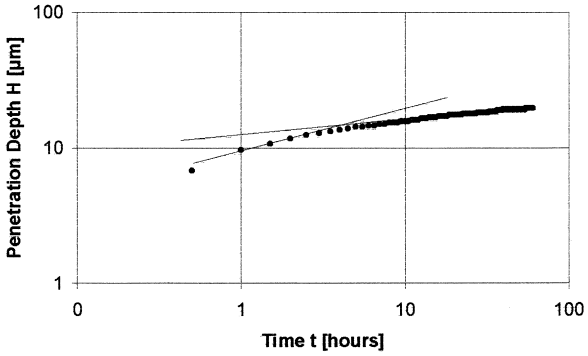

Fig. 9. Log–log presentation of a typical creep curve of UHMWPE. For the other materials similar curves were found.

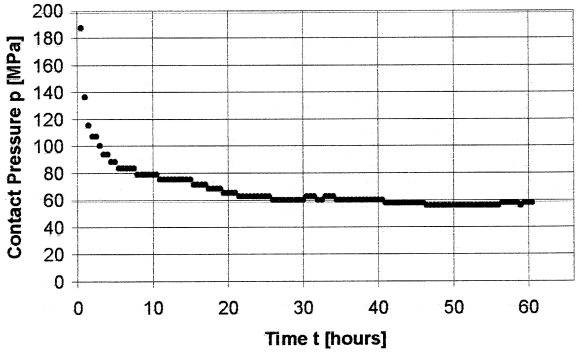

Fig. 10. Contact pressure vs. time curve for a PE/PE composite with 30.7 vol% fibre content. The curve asymptotically approaches a pressure of about 58 MPa.

The Hertz formula, although frequently used for the stress calculation in metal/polymer contact, is not suitable to derive the contact pressure and its effect on creep because it is based only on the elastic material reaction. In the first moment of contact between ball and specimen, the deformation is only elastic and the Hertz formula applies. Once the elastic stress in this phase exceeds the yield stress of the material a phase of plastic deformation and creep will follow. As a consequence, the contact area increases until the remaining stress falls below the yield limit. From this moment on, static equilibrium is reached and no further plastic deformation will be added.

The contact area at a time t, $A(t)$, can be derived from the penetration depth, $H(t)$, and the ball diameter, d: $A(t)=\pi dH(t)$ and the contact pressure at the time t is $p=F_N/A(t)$.

The contact pressure calculated in this way is plotted as a function of time in Fig. 10. During static loading, the contact pressure asymptotically approaches a value of about 58 MPa in the case of a PE/PE composite with $V_f=30.7\%$.

Below this pressure creep almost disappears. This value gives a rough idea of the maximum allowable pressure for the use of the material.

The same analysis was performed for HD-PE and the composite materials. The results are summarised in Fig. 11. These results again show the superior creep resistance of the

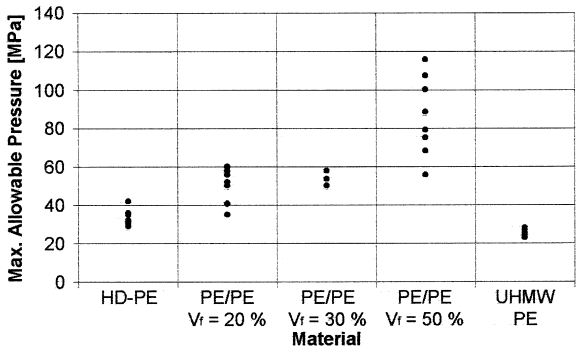

Fig. 11. Contact pressure value which is asymptotically approached after 60 h static loading and below which creep almost diminishes.

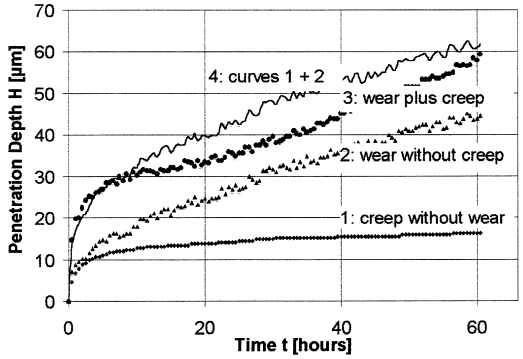

Fig. 12. Comparison of creep (curve 1), wear after a preceding creep phase of 60 h (curve 2) and wear without preceding creep phase (curve 3). Curve 4 is the sum of curves 1 plus 2. Material: neat UHMWPE.

composite materials, which can withstand higher loads than the neat matrices without significant creep.

3.2. Wear tests

While the steel ball slides over the specimen surface, the material experiences both: creep due to the normal load and wear due to frictional loading [7]. Fig. 12 shows for pure UHMWPE the difference between plain wear (curve 2: test started after 60 h static loading) and wear plus creep (curve 3: test started immediately after inserting the specimens). The curve 4 (sum of curves 1 and 2) shows that curve 3 can be well approached by adding wear and creep (curve 1). After about 6 h, the creep curve becomes flat and the slope of the wear curve is less affected by creep. To separate the material wear from plastic deformation and creep, the wear tests were started after the creep almost diminished. For this purpose all subsequent tests were started after a preceding creep phase of 60 h.

The wear curves (after a preceding creep phase of 60 h) of the composites exhibited a clearly pronounced running-in phase characterised by a high wear rate and followed by a steady-state phase with a lower and almost constant wear rate dh/dt. This running-in phase was less distinct or even missing in the wear curves of the neat matrices (Fig. 13).

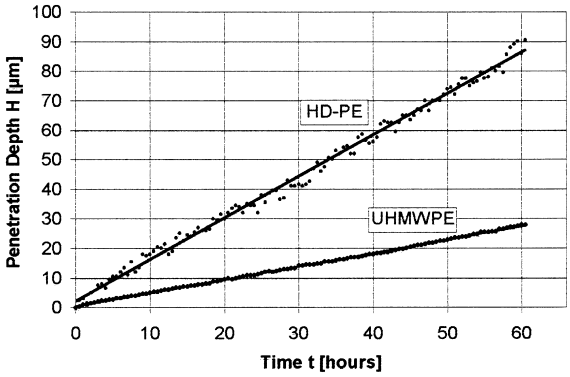

Fig. 13. Typical wear curve of the neat polymer matrices.

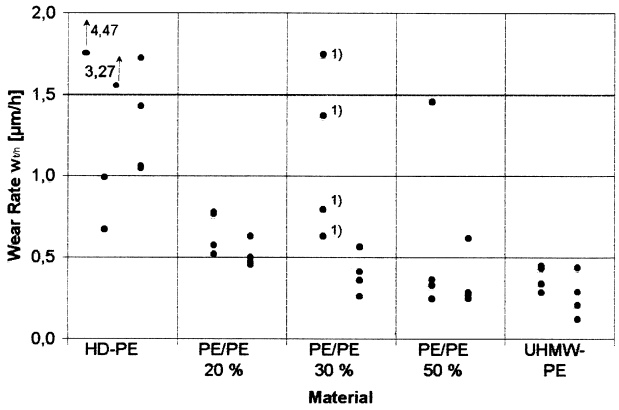

Fig. 14. Steady state wear rates of all materials tested. PE/PE means UHMWPE fibre reinforced HD-PE, the fibre content is quoted in vol%. The first set of data (1) for V_F=30% was measured with specimens produced by a third person who was only briefly introduced to the manufacturing procedure.

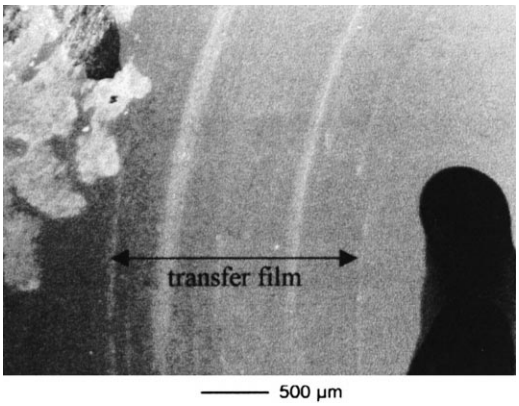

Fig. 16. SEM micrograph of the wear track on the steel ball showing a thin transfer film.

In a real tribological system, the running-in phase usually occurs only once per life. Therefore, and despite its high wear rate, this phase is less interesting than the steady-state phase. Additionally, during the period of steady state wear, creep becomes less significant. The steady-state wear rates of the different material tested are compared in Fig. 14.

In accordance with the creep tests, the wear of HD-PE can be significantly reduced by UHMWPE fibre reinforcement. In contrast to the creep tests, neat UHMWPE gives the best wear results but the composites with V_F>30% almost reach this high wear performance. The data display a greater variation than the creep results summarised in Fig. 8. Wear obviously is more sensitive to variations in the material homogeneity than creep. Nevertheless, the scatter of the fibre reinforced versions is smaller than for the pure HD-PE and is in the same order as for the neat UHMWPE.

Again, one of data for the material with V_F=30% (the same as in the creep tests) clearly does not fit into this figure. The reasons are discussed below.

One important result is that no significant differences could be found between parallel and transverse sliding direction. For both orientations, the running-in behaviour as well as the steady state wear rate were within the same scatter bands. For this reason, the data of parallel and transverse sliding tests have been mixed up in the above sections.

3.3. Micrography

To study the wear mechanisms, the specimens were sputtered with a thin gold layer and than examined in a SEM. The steel ball was inspected by the SEM without previous sputtering.

Fig. 15 gives an overview of the wear marks in UHMWPE and in PE/PE. On the back side of the wear mark, chips are formed. In the case of UHMWPE, these chips are very large. The composites, in contrast, form narrower worm-like chips. The entrance side of the wear mark exhibits a large amount of back-transferred and partly re-compacted chips in the case of the composite. This phenomenon is almost totally missing in the case of UHMWPE.

This comparison can be explained by the typical wear behaviour of UHMWPE. From the bulk material, oriented molecules are spooled-off forming a thin transfer film (Fig. 16) on the metallic counterpart. Excessive materiel

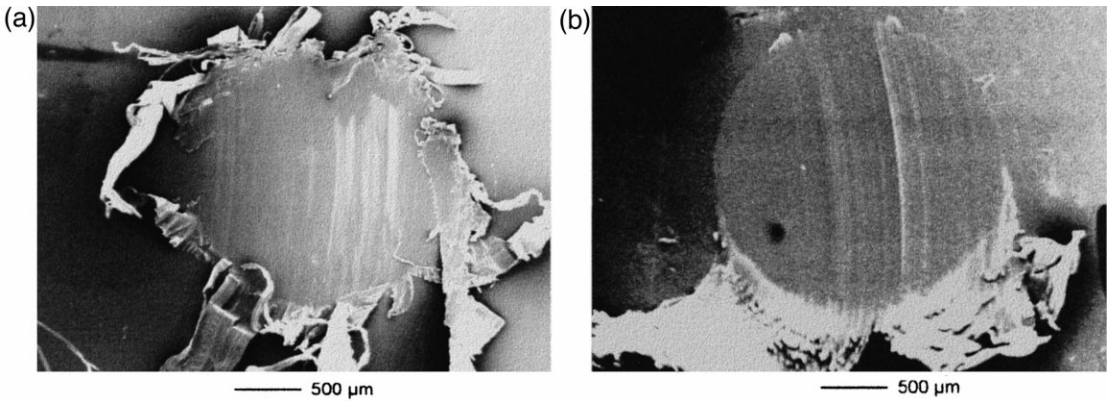

Fig. 15. Overview (SEM micrograph) of the wear mark in (a) UHMWPE and (b) in a PE/PE composite with a fibre volume fraction of 30%. Sliding direction from top (entrance side) to bottom.

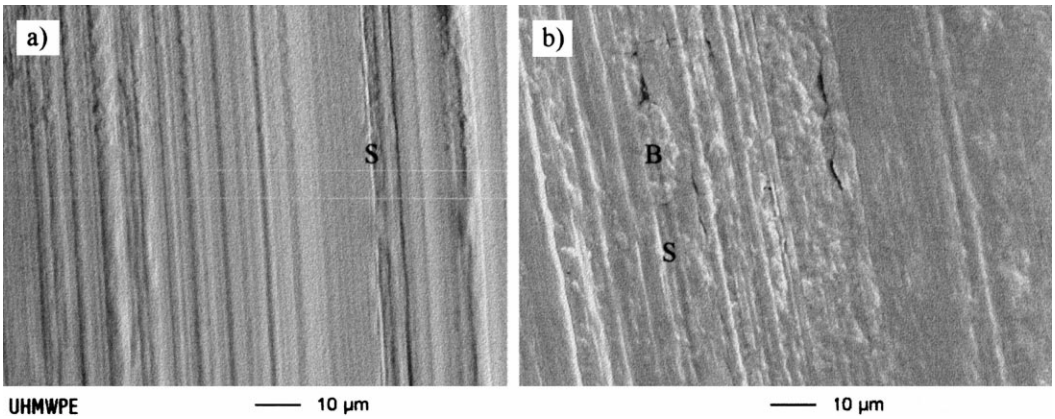

Fig. 17. SEM micrographs: detail of the worn surfaces of (a) bulk UHMWPE and (b) PE/PE with V_f=30%. Scratches (S) and back transferred chips (B) are visible. Sliding direction top–down. Fibre orientation in (b) is transverse to the sliding direction. Fibres are not visible.

forms large thin chips at the back side of the wear mark. The thin transfer film adheres strongly to the metallic counterpart, so that it cannot be stripped-off at the entrance side. In case of the composite, the transfer to the counterpart takes place less continuous due to the material inhomogenity and due to the presence of HD-PE. In a larger magnification (Fig. 17), UHMWPE shows a much smoother surface than the composite. In the composite surface, larger back-transferred chips (B in Fig. 17b) can be found. These larger chips are transported to the entrance side of the wear mark forming there the back-transferred chips.

Some small scratches can be seen in the micrographs which are more pronounced in the PE/PE composite due to the formation of larger and harder particles which can act abrasively.

The appearance of the worn composite surfaces did not depend on the fibre orientation. Fibres and matrix could not be distinguished in the micrographs. This is in accordance with the identical wear rates for parallel and transverse direction. This effect can be explained as follows. The fibres themselves possess a higher wear resistance than the matrix and should protrude from the surface after some time. Due to their soft nature (the strong covalent bonds are in-plane) when loaded perpendicular to the fibre axis, the fibres are compressed, the worn material is smeared-off and mixed up with the chemically almost identical matrix material. Therefore, after some time, the wear behaviour of the composite is almost the same as for neat UHMWPE.

This explanation also is in agreement with the pronounced running-in phase observed for the composites, whereas it is missing for both neat matrix materials.

4. Conclusions

The investigated UHMWPE fibre reinforced PE-HD promises to be a good substitute for UHMWPE as a bearing material. It combines a wear resistance similar to UHMWPE with very good mechanical properties.

The composite properties can be summarised as follows.

1. Strength and modulus of the composite are more than one order of magnitude above bulk PE.
2. The composites creep much slower than UHMWPE and even less than HD-PE. This allows for longer service periods of bearings.
3. The composites can be loaded to a higher degree (about two times higher than HD-PE and three times higher than UHMWPE) without significant creep.
4. The wear resistance of the PE/PE composites was found to increase continuously with the fibre content. Composites with V_F>30% reached almost the wear performance of UHMWPE.

One problem which needs more attention is the scatter in the creep as well as in the wear results. In several test series, there are single specimens exhibiting strong wear. Especially one of the two test series at V_F=30% shows strong scatter with some single results far above all other material samples. The reason of this behaviour could not be identified within this study. Possible explanations are:

- too high temperature during hot pressing could have caused fibre damage due to some relaxation of molecular orientation within the fibres;
- too rapid cooling down after hot pressing may have led to low crystallinity of the matrix;
- the inhomogeneous fibre distribution shown in Fig. 2 is significant, fibre poor regions reach dimensions in the order of 1 mm, the wear resistance can be expected to depend extremely on the fibre content in the interface zone.

These questions will be further investigated in future. So far, it can be stated that the material performance is extremely dependent on the manufacturing parameters. Continuously good material quality would require improved manufacturing specifications.

Acknowledgements

The authors gratefully acknowledge the help they received from several sides. The investigation was financially supported by the Technologiestiftung (Technology Foundation) Schleswig-Holstein, Germany, and by the German Research Foundation (DFG). The materials were supplied by DSM, Netherlands, and by Billeter Kunststoffpulver AG, Germany. Mr. Endlich from the SEM laboratory at the Fachhochschule Lübeck, Mrs. S. Fricke from the polymers laboratory at the FH Lübeck, and Dr. Köller from the Materials Laboratory at the Medical University Lübeck supported this study with helpful discussions and practical support during the experiments.

References

[1] H. Uetz, J. Wiedemeyer, Tribologie der Polymere (1984) Hanser Verlag, München.
[2] N.N., Technische Kunststoffe-berechnen, gestalten, anwenden, A.1.4: Typen und Eigenschaften, Hostalen GUR, Hoechst, Frankfurt, 1993.
[3] Polyethylene in Orthopaedics, Book of Abstracts, The Institute of Materials, London, Oct. 23, 1997.
[4] D.J. Kilgus, J.R. Moreland, G.A.M. Finerman, T.T. Funahashi, J.S. Tipton, Catastrophic wear of tibial polyethylene inserts, Clin. Orthop. Relat. Res. 273 (1991) 223–231.
[5] G.B. Cornwall, C.M. Hansson, A.J. Bowe, J.T. Bryant, Surface degradation features and microstructural properties of ultra-high molecular weight polyethylene (UHMWPE), J. Mater. Sci.: Mater. Med. 8 (1997) 303–309.
[6] P.S.M. Barbour, D.C. Barton, J. Fisher, The influence of stress conditions on the wear of UHMWPE for total joint replacements, J. Mater. Sci.: Mater. Med. 8 (1997) 603–611.
[7] M.D. McDonald, R.D. Bloebaum, Distinguishing wear and creep in clinically retreived polyethylene inserts, J. Biomed. Res. 29 (1995) 1–7.
[8] T. Stern, A. Teishev, G. Marom, Composites of polyethylene reinforced with chopped polyethylene fibres: the effect of transcrystalline interphase, Compos. Sci. Technol. 57 (1997) 1009–1015.
[9] F. von Lacroix, Polyethylen/Polyethylen-Entwicklung eines sortenreinen Verbundwerkstoffs, PhD Thesis, Tech. Univ. Hamburg-Harburg, Hamburg, 1998.
[10] A. Poeppel, unpublished results, Tech. Univ. Hamburg-Harburg, Hamburg, 1998.
[11] ISO 7148-2, Plain Bearings — Testing of the Tribological Behaviour of Bearing Materials-Part 2: Testing of Polymer-Based Materials, German Inst. Standardization, 1996.
[12] DIN 50 320 (German Standard), Verschleiss, Begriffe, German Inst. Standardization, 1990.
[13] O. Jacobs, K. Friedrich, K. Schulte, Fretting wear of high performance composites, R. Divikar P.J. Blau (Eds.), Wear Testing of Advanced Materials, ASTM-STP vol. 1167 (1992) 81.
[14] G.W. Ehrenstein, Mit Kunststoffen Konstruieren (1995) Hanser Verlag, Munchen.