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Material Performance

Effect of counterpart material and water lubrication on the sliding wear performance of crosslinked and non-crosslinked ultra high molecular weight polyethylene

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Abstract

This paper deals with the effects of counterpart material and aqueous environment on the wear of ultra high molecular weight polyethylene (UHMWPE). Specimens of radiation crosslinked and non-crosslinked UHMWPE were exposed to unidirectional sliding against austenitic stainless steel, a hardened 100Cr6 steel coated with a diamond like carbon layer (DLC), a CoCrMo alloy and against alumina. The tests were performed in normal atmosphere and in distilled water. The results revealed that the UHMWPE(C) (cut from the core of the non-crosslinked UHMWPE block) has a better wear resistance than UHMWPE(S) (cut from the surface of the non-crosslinked UHMWPE block), UHMWPE-X (crosslinked UHMWPE) has a higher wear resistance than UHMWPE(C). One exception is dry sliding against Al_2O_3 where UHMWPE(C) is superior to UHMWPE-X. Under wet conditions, the lowest wear rate was achieved with UHMWPE-X sliding against CoCrMo.

The results show that the wear of the material strongly depends on the type of counterpart material. The effect of water lubrication varies from pairing to pairing.
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Keywords: UHMWPE; Crosslinked UHMWPE; Counterpart; Wear rate

1. Introduction

Ultra high molecular weight polyethylene (UHMWPE) has several beneficial properties, e.g., high wear resistance, low friction, chemical stability and bio-compatibility [1]. It is considered as an engineering thermoplastic and is widely used in low stress sliding applications against metallic surfaces such as bushings, slide bars, and seals. UHMWPE is also used for acetabular cups in total hip replacements and in knee joints because of its proven excellent wear resistance and bio-compatibility [2].

In the past, a lot of research focussed on the factors that affect the wear of UHMWPE. Several wear reducing surface treatments and structural modifications have been developed and investigated. Crosslinking of UHMWPE by ionizing radiation has been shown to improve the wear resistance significantly [3,4]. Makoto Ohta investigated the wear rate of UHMWPE that was crystallised under molecular orientation. Their results showed that the wear properties were improved [5].

But the fact that wear is a system property and not a material property is of practical importance in engineering. This means that not only the bearing material itself but a number of different factors have to be considered when resolving a wear problem or developing a design that will have adequate wear life [6]. So, it is obvious that the counterpart material and the environ-

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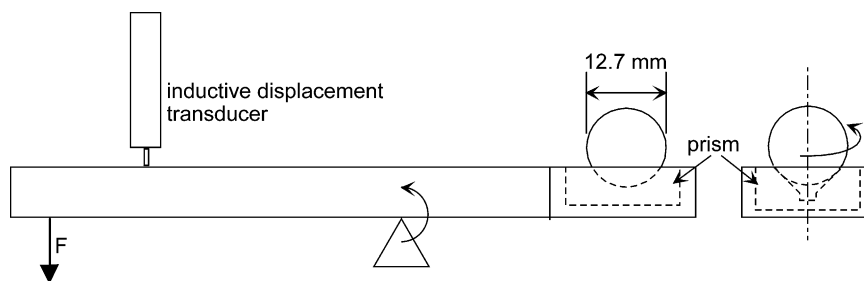*E-mail address:* jacobs@fh-luebeck.de (O. Jacobs).

Fig. 1.   Schematic of the "Tribodata" test rig.

ment will have significant effects on the wear property of the tribological system.

In this paper, the tribological properties of UHMWPE sliding against different counterpart materials under dry and wet conditions were investigated with a ball-on-prism apparatus. For comparison, three kinds of UHMWPE specimens were used in this work.

2. Experimental details

2.1. Test rig

A detailed description of the test rig and the testing procedure is given in [7,8]. This paper summarizes only the basic features.

The tests were performed according to ISO 7148-2/ section 5.2 with a ball-on-prism test system "Tribodata" from Dr. Tillwich GmbH, Horb, Germany. A metallic prism with an opening angle of 90° containing the specimens was pressed against a ball (Figs. 1 and 2). The load was applied by dead weights via a lever.

The normal load acting onto each specimen surface was $F_N = 21.2$ N. The counterpart balls had a diameter

Fig. 2.   Prism with fixed polymeric specimens and ball.

of $d = 12.7$ mm. The balls rotated uniformly with a frequency of $f = 1$ s^{-1} around their vertical axis resulting in a sliding speed of $v = 28.2$ mm/s in the sliding contact. The wear test conditions are summarised in Table 1.

For the tests under wet conditions, the prisms were filled with distilled water. To compensate for the loss of water by evaporation, water was steadily refilled drop by drop via a manually controlled drip. This ensured that the contact area was always covered by distilled water.

In order to separate creep effects from wear effects, a static loading phase of 60 h duration preceded the wear test. Under this static load, the balls penetrated into the specimen surface due to creep and plastic deformation of the polymer. The contact area increased steadily and the contact pressure decreased until it fell short of the yield limit [7]. Only then was the motor switched on and the wear could be measured without a significant contribution caused by creep.

The data acquisition was performed via inductive displacement transducers (Fig. 1). The signals of the displacement transducers were read every 10 min and stored on a PC system. The resulting penetration depth vs. time curves were converted into wear volume (ΔV) vs. sliding distance (Δs) curves. After some time, when the wear process entered a steady state, these wear volume curves became linear (see Section 3.1) with slope $\Delta V / \Delta s$. Dividing this slope by the normal load,

Table 1
Wear test conditions

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

F_N, gives the specific wear rate, k_s:

$$k_S = \frac{\Delta V}{F_N \cdot \Delta s}$$

The specific wear rate is a kind of characteristic material property for given loading conditions.

Each test was conducted three times. The specific wear rate values presented in the following diagrams are average values from these three tests.

2.2. Sample materials

Two different types of UHMWPE were used in the test: non-crosslinked UHMWPE (UHMWPE(S), UHMWPE(C)) and crosslinked UHMWPE (UHMWPE-X).

The non-crosslinked UHMWPE was GUR 1020 by Poly-HI-Sodider Dt, GmbH, Germany. The powder was compression moulded to a block of 50 mm thickness. The UHMWPE(S) specimens were taken directly from the surface of the block. The UHMWPE(C) specimens were cut from the core of the block. No significant difference in the mechanical properties could be found. The properties of the material are shown in Table 2.

The UHMWPE-X block was compression moulded of GUR 1050 powder by Centerpluse ortheopedics Ltd, Germany.

The test specimens were cut from the sample block with a high speed diamond saw. The dimensions were 10 mm × 10 mm × 2 mm. The surface was neither ground nor polished to avoid transfer of abrasive particles to the polymer surface. These specimens were glued onto the specimen holders of the wear testing apparatus. For this purpose, each specimen surface was cleaned with alcohol and the rear side was treated with a special polyolefin primer before being inserted into the prisms. Finally, the surfaces of the balls and specimens were cleaned with alcohol prior to the test.

2.3. Counterpart materials

Four different materials were used as counterparts materials:

- *W-DLC coated 100Cr6 steel (W-DLC)*. 100Cr6 is a frequently used bearing steel but not corrosion

resistant. To protect the 100Cr6 balls against corrosion, they were electrolytically plated with Ni and additionally coated with a tungsten doped diamond like carbon (W-DLC) coating. These counterpart materials led to extremely low wear rates of some PEEK compounds, especially in water [9].
- *Cold worked X5CrNi18-10 steel (CrNi)*. This material is the most frequently used counterpart of polymers in an aqueous environment.
- *Al_2O_3 sintered ceramic (Al_2O_3)*. Alumina is extremely hard and chemically inert. It can be used when austenitic stainless steels are not sufficiently corrosion resistant. Alumina is frequently used in combination with UHMWPE in artificial hip joints.
- *CoCrMo alloy (CoCrMo)*. This cobalt based alloy is corrosion resistant and bio-compatible. It is the standard material for artificial hip joints.

The properties of the counterpart materials are shown in Table 3.

3. Results and discussion

3.1. Running-in behaviour

Three types of wear curve were observed in this work; Table 4 assigns the tested material (UHMWPE(C), UHMWPE-X) combinations to the respective wear curve type.

- Wear curve type 1 (Fig. 3a e.g. dry sliding of UHMWPE(C) against W-DLC): No significant running-in phase can be identified but the wear rate is constant from the beginning.

Table 2
Properties of the UHMWPE versions

Material	Density (kg/m^3)	Young's modulus (MPa)	Tensile strength (MPa)	Yield stress (MPa)	Strain at failure (%)
UHMWPE	935	720	45	23	390
UHMWPE-X	932	869	29	20	323

Table 3
Properties of the counterpart materials

Material	Roughness R_z (µm)	Hardness (HV)
W-DLC	0.22	1500
X5CrNi18-10	0.31	375
Al_2O_3	0.46	1625
CoCrMo	0.37	474

Table 4
Attribution of the combinations tested to the different wear curve types

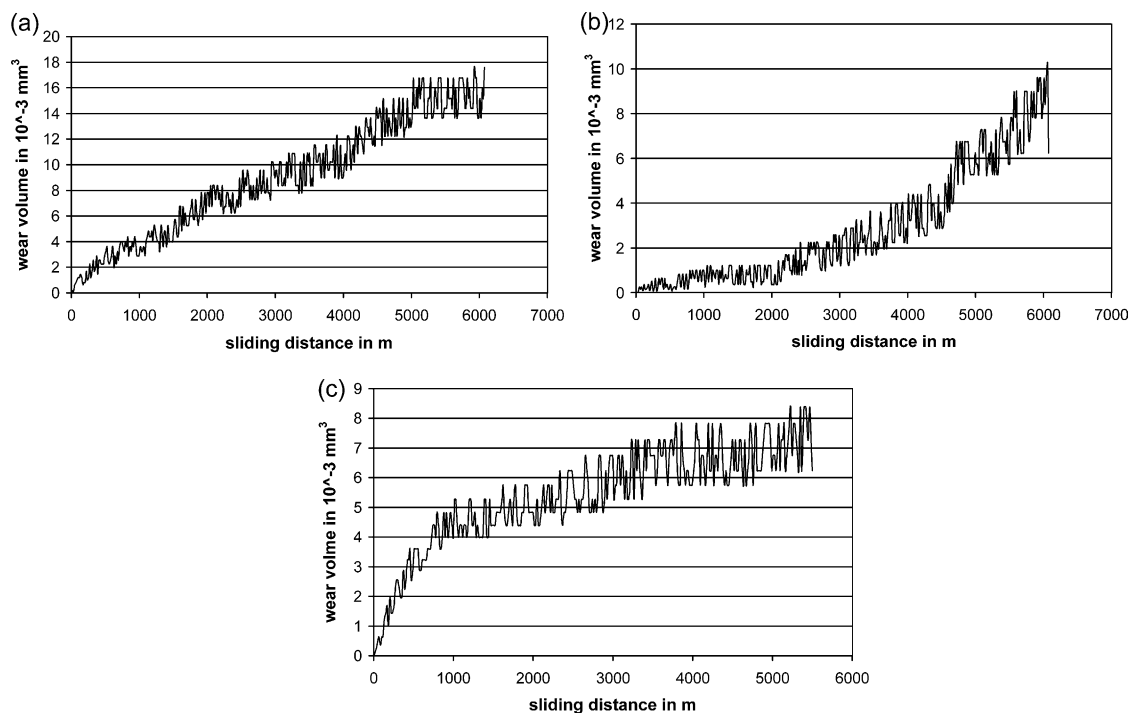|	UHMWPE(C)		UHMWPE-X	
	Dry	Wet	Dry	Wet
CrNi	1	1	1	1
Al_2O_3	1	2	1	1
DLC	1	1	3	3
CoCrMo	1	1	3	1

Fig. 3. The types of wear curves: (a) type 1, dry sliding of UHMWPE(C) against W-DLC; (b) type 2, sliding of UHMWPE(C) against Al_2O_3 in water; c) type 3, sliding of UHMWPE-X against W-DLC in water.

- Wear curve type 2 (Fig. 3b e.g. sliding of UHMW-PE(C) against Al_2O_3 in water): There are two linear states. At the beginning, the wear proceeded moderately, but after about 2000 m of sliding distance, a sharp kink occurred in the wear curve. After this transition, the wear rate increased tremendously. Fig. 4 shows the wear rates of UHMWPE(C) sliding against Al_2O_3 in water before and after the wear transition, the wear rate after the kink is much higher than that before the kink.

- Wear curve type 3 (Fig. 3c, sliding of UHMWPE-X against W-DLC in water): The initial wear rate was relatively high. After about 1000 m sliding distance, the wear process entered a steady state and the slope of the curve became smaller than at the beginning.

Most experiments revealed type 1 wear curves under dry as well as wet conditions. This indicates that the whole wear process is controlled by one main mechanism. Fig. 5a and b shows lots of grooves caused by a
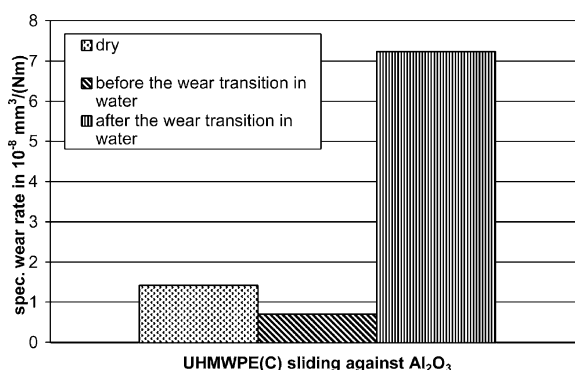

Fig. 4. Specific wear rates of the UHMWPE(C) sliding against Al_2O_3 in water (before and after the wear transition) and dry sliding of UHMWPE(C) against Al_2O_3.
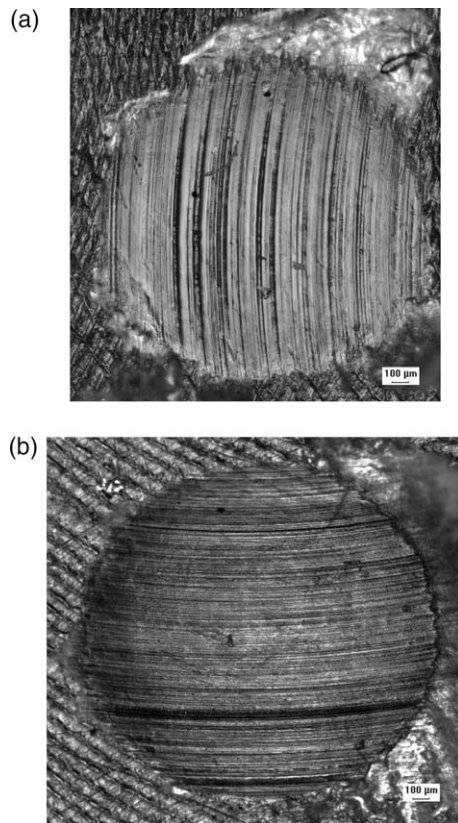
Fig. 5. Light micrographs of the wear marks. (a) UHMW-PE(C) after dry sliding against CrNi; (b) UHMWPE(C) after dry sliding against W-DLC.

ploughing process on the wear marks of UHMWPE(C) after dry sliding against CrNi and W-DLC. This ploughing mechanism was predominant in most cases, even though the depth and width of the grooves and the size of the wear marks differed from counterpart to counterpart. Possible reasons may be the different

counterpart surface topographies leading to a different size of the wear debris particles, which act as a third body abrasive.

Wear curve type 2 suggests that mild wear mechanisms dominated at the beginning but after about 1000 m these mechanisms were masked by other competitive mechanisms and this change led to the increase of the wear rate.

Wear curve type 3 was observed in a few (Table 4) tests of UHMWPE-X. Some papers [6] explain this type of wear curve by the development of a lubricating transfer film on the counterpart surface during the running-in phase. Once this transfer film is formed, it should reduce the wear during steady state. We could not find such a closed transfer film on the counterpart balls with SEM. Moreover, non-crosslinked UHMWPE with its linear molecules should have a better capability to form a transfer film but it produced purely linear wear curves.

3.2. Wear rates

3.2.1. Wear rates under dry conditions

UHMWPE(S), was tested in dry sliding against CrNi, W-DLC, Al_2O_3 and sliding against Al_2O_3 in the water. Fig. 6 shows the results. It can be seen that the wear rates of the UHMWPE(S) are generally higher than that of UHMWPE(C) for every testing condition.

Obviously, the wear properties of the material are strongly influenced by the processing conditions. The non-crosslinked UHMWPE used in the experiments was produced by compression moulding. After moulding, the material solidifies first at the surface where the polymer is in direct contact with the cooled die wall. The core retains the heat for a longer time because the polymer is a poor heat conductor. Hence, the crystallinity in the core is higher than that at the surface. Higher crystallinity means better anchoring of the single molecules and higher wear resistance, as it was in
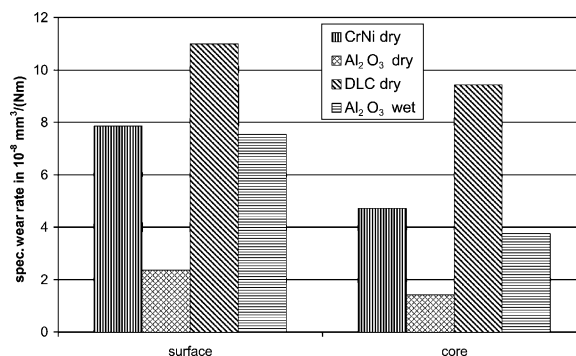

Fig. 6. Specific wear rates of UHMWPE(S) and UHMWPE(C) sliding against different counterpart materials under dry and wet conditions.
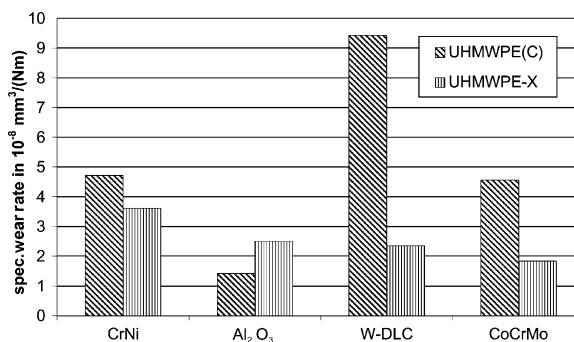
Fig. 7. Specific wear rates of UHMWPE(C) and UHMWPE-X under dry conditions.

fact found experimentally. According to this result, non-crosslinked UHMWPE bearings are better produced with material from the core if possible.

Fig. 7 shows that the specific wear rate of UHMWPE(C) and UHMWPE-X varies greatly with the type of counterpart material. Under dry conditions, the wear rate of UHMWPE(C) is highest against W-DLC and lowest against Al_2O_3. The wear rate of UHMWPE-X, too, strongly depends on the counterpart material but the ranking order is different from UHMWPE(C). Under dry conditions, the wear rate of UHMWPE-X is highest against CrNi steel, and lowest against CoCrMo.

To some degree, the effect of the counterpart materials might be attributed to different roughness values. But Fig. 8 shows that the counterpart roughness, R_z, does not correlate with the polymer wear rate. The nature of the counterpart materials seems to be the main factor that affects the wear rate. Different counterpart materials can lead to different wear mechanisms. For UHMWPE(C), the wear processes was mostly controlled by the ploughing mechanism (Fig. 5a and b). In Fig. 9a, which shows the wear mark on UHMWPE(C) after dry sliding against CoCrMo, we can additionally see some cracks (marked in "c") perpendicular to the

sliding direction. This suggests that surface fatigue also affected the wear process. The wear process of the UHMWPE(C) against Al_2O_3 is more complex than the others. Fig. 9b shows the wear mark of UHMWPE(C) after dry sliding against Al_2O_3; we can see lots of grooves and cracks transverse to the sliding direction, which indicates that ploughing and fatigue mechanisms affected the wear process.

Moreover, Fig. 7 shows that the crosslinked UHMWPE-X has a higher wear resistance than UHMWPE(C) under dry conditions in most cases. One exception is the case when Al_2O_3 was used as the counterpart material. The transfer film produced by UHMWPE-X has a significantly different appearance than the transfer film of UHMWPE(C). The SEM micrograph in Fig. 10a shows the transfer film on alumina after dry sliding against UHMWPE(C). This transfer film consists of large lumps of re-compacted wear debris. The transfer film on alumina after dry sliding against UHMWPE-X, which is presented in Fig. 10b, consists of a closed oriented layer of UHMWPE-X.

3.2.2. Wear rate under wet conditions

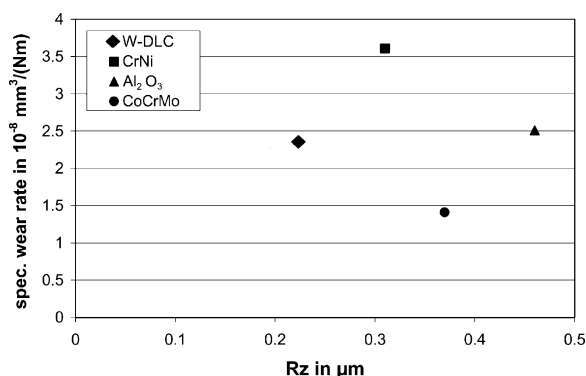Fig. 11 shows that the specific wear rates of UHMWPE(C) and UHMWPE-X in water varies

Fig. 8. Specific wear rates of all combinations after dry sliding against UHMWPE-X as a function of counterpart roughness, R_z.
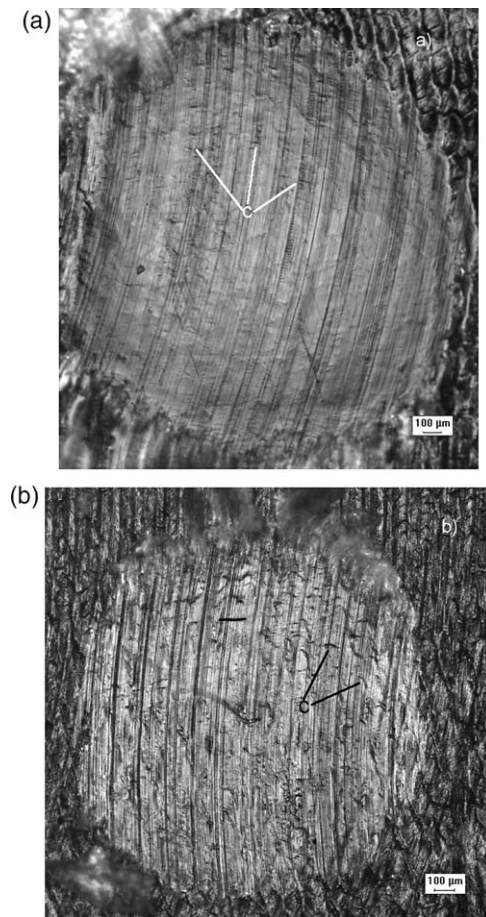
Fig. 9. Light micrographs of the wear marks of (a) UHMW-PE(C) after dry sliding against CoCrMo and (b) UHMW-PE(C) after dry sliding against Al$_2$O$_3$.

Fig. 10. SEM micrographs of the wear tracks on the counterpart. (a) Wear track on Al$_2$O$_3$ after dry sliding against UHMWPE(C); (b) wear track on Al$_2$O$_3$ after dry sliding against UHMWPE-X.

greatly with the type of counterpart material. The ranking order differs from dry sliding: in water, the wear rate of UHMWPE(C) sliding against W-DLC is highest and that of UHMWPE(C) sliding against the CrNi steel is lowest. UHMWPE-X gives a different ranking order in water: this time, W-DLC produces the highest wear rate whereas CoCrMo results in the lowest wear rate.

Generally, UHMWPE-X has a better wear resistance than UHMWPE(C) under wet conditions with the exception of the case where alumina was used as the counterpart material. Here, the difference between the UHMWPE types was marginal.

3.2.3. Comparison of the wear rates under dry and wet conditions

The water lubrication may affect the wear resistance of the polymers in different ways:
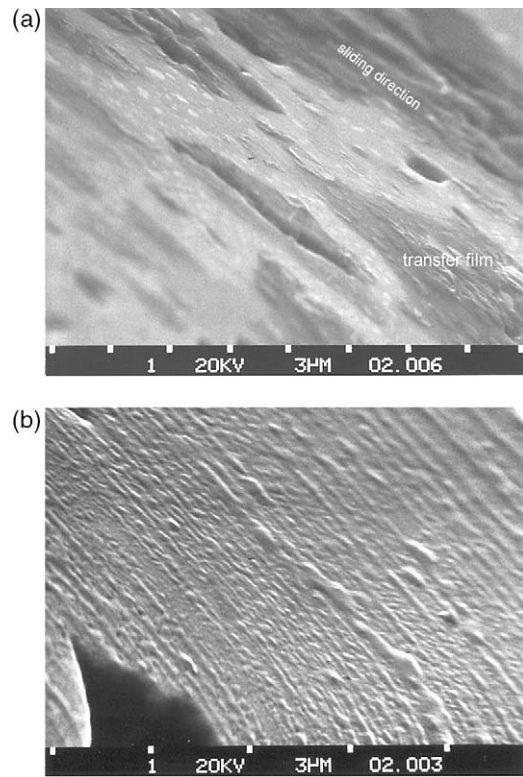
1. The water can have a lubricating effect leading to reduced shear stresses in the surface. Low shear stresses tend to lower the wear rate.
2. Water cools the polymer in the contact area and reduces the frictional heat. Allen et al. found that the temperature in the sliding contact may reach significant values without water, causing some softening of the polymer [2].
3. The water absorption of UHMWPE is smaller than 0.01%, but, nevertheless, it may reduce the shear strength of the UHMWPE slightly. Fig. 12 shows a wear mark on UHMWPE(C) after sliding against Al$_2$O$_3$ in water, there are some irregular pits on the wear mark, caused by the shrinkage of the UHMWPE during water desorption.
4. According to Fig. 13, UHMWPE(C) does not form a closed transfer film on the surface of the Al$_2$O$_3$ ball after sliding in water. The wear surface of UHMW-PE(C) after sliding against Al$_2$O$_3$ in water (Fig. 12) looks much smoother than that of UHMWPE(C) after dry sliding against Al$_2$O$_3$ (Fig. 9b). Water scavenges the surfaces of the ball and the UHMWPE and removes the wear debris from the surfaces. No
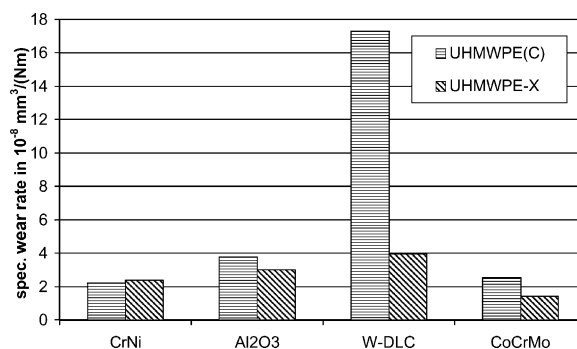
Fig. 11.   Specific wear rates of UHMWPE(C) and UHMWPE-X under wet condition.

protective layer of re-compacted wear debris can develop on the specimen surface and the virgin surface is continuously exposed.

If mechanisms (1) and (2) have a stronger influence on the wear process than (3) and (4), the wear rate will be smaller under wet than under dry conditions.

Water affects the different material combinations in different ways. Fig. 14 shows the ratio of the wear rates under wet conditions to the wear rate under dry conditions wear rate ratio $= k_S(\text{wet})/k_S(\text{dry})$. This diagram shows that water lubrication decreased the wear rates of both UHMWPE versions during sliding against CrNi steel and CoCrMo, so (1) and (2) must have been predominant. However, (3) and (4) obviously dominated the wear process of both UHMWPE versions during sliding against Al_2O_3 and W-DLC, where water lubrication increased the wear rate.

Additionally, the effects of a water lubrication change when the main wear mechanism changes during the wear process. In the case of UHMWPE(C) sliding in water against Al_2O_3, there are two linear domains.

The wear rates before and after the kink are quite different (Fig. 4) which indicates that the main wear mechanisms had changed. The wear rate in water is even lower than that under dry conditions before the kink, so (1) and (2) must have been the predominant mechanisms. But after the kink, (3) and (4) must have masked (1) and (2) because the wear rate was now higher than that under dry conditions.

Obviously, water affects the wear rate of the different UHMWPE types in the same direction when the same counterpart materials are used. Water lubrication decreases the wear rates of UHMWPE(C) and UHMWPE-X against the metallic counterparts, i.e. CrNi steel and CoCrMo alloy. However, water increases the wear rates of UHMWPE(C) and UHMWPE-X against Al_2O_3 and W-DLC. This indicates that the main wear mechanisms are the same for the different UHMWPE types as long as the same counterpart materials are used. The effects of water lubrication—wear reducing effects as well as wear increasing effects—seem to be more pronounced for the non-crosslinked UHMWPE than for the UHMWPE-X.
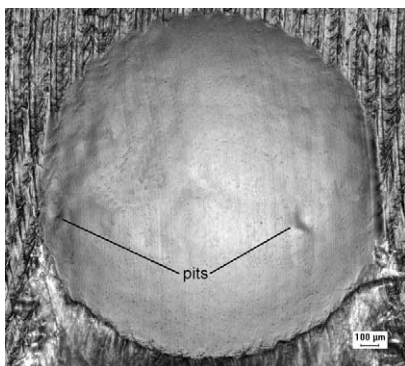

Fig. 12.   Light micrograph of the wear mark of UHMWPE(C) after sliding Al_2O_3 in water.
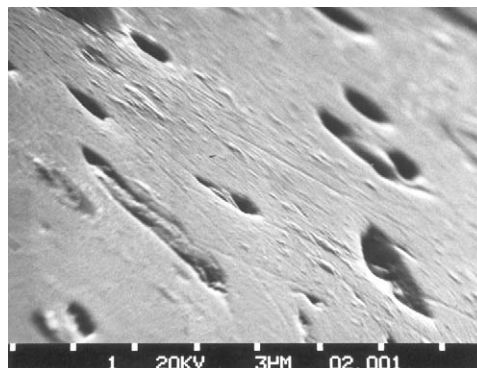

Fig. 13.   SEM micrograph of the wear track on Al_2O_3 after sliding against UHMWPE(C) in water.
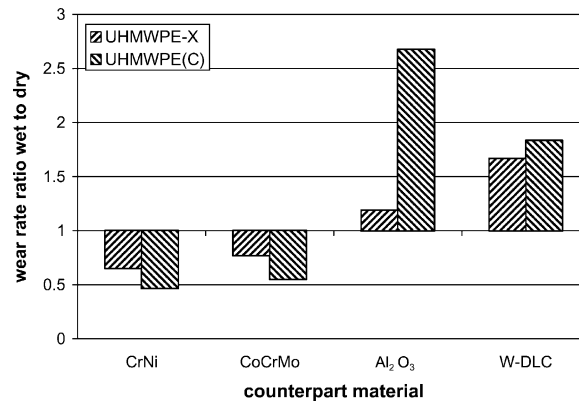
Fig. 14.   Ratio of wear rates under wet conditions to wear rates under dry conditions.

4.   Conclusion

1. The material from the core of the non-crosslinked UHMWPE block has a better wear resistance than that from the surface, non-crosslinked UHMWPE bearing surfaces are better produced of material from the core if possible.
2. The wear of the material depends strongly on the type of counterpart material and the testing conditions. Under dry conditions, UHMWPE(C) sliding against Al_2O_3 shows the best wear resistance. Under wet conditions, UHMWPE-X sliding against CoCrMo shows the best wear resistance.
3. UHMWPE-X has a better wear resistance than UHMWPE(C) in most cases. An exception is when Al_2O_3 used as counterpart material. In this case, UHMWPE(C) showed a better wear resistance than UHMWPE-X because of the different transfer film morphologies on the counterpart surface.
4. Water lubrication may increase or decrease the wear rate, depending on the material combination and the main wear mechanism. Wear reduction was observed against counterparts of CrNi steel and CoCrMo, enhanced wear was found for UHMWPE sliding against alumina and W-DLC.

Acknowledgements

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