MILITARY TECHNICAL COLLEGE

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THE INFLUENCE OF STAINLESS STEEL SURFACE ROUGHNESS UPON THE FRICTION AND WEAR OF POLYETHYLENE UNDER DRY AND LUBRICATED CONDITIONS

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ABSTRACT

Investigations of the friction and wear of Ultra-high Molecular Weight Polyethylene (UHMWPE) in reciprocating sliding against a range of stainless steel counterfaces of various initial surface roughness, are described in this paper. The tests were carried out either with the wear specimen under dry conditions of contact or lubricated by distilled water. A single sliding speed of 0.097 m/s and two constant loade of 5N and 10N were used.

The results have shown that there is an optimum scale of surface roughness which yields minimum dry wear rate and coefficient of friction for UHMWPE sliding on EN 58J stainless steel. The tests conducted under water lubricated conditions showed an appreciable reduction in the coefficients of friction and wear rates compared with the values obtained under bry conditions. A mechanism is proposed for the increased wear rate and coefficient of friction on smoother surfaces.

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INTRODUCTION

Polymeric materials have found wide tribological applications in recent years. Polymeric bearings, for example, are generally self-contained, self-lubricating and usually accommodating to the detailed geometrical form of the harder, sliding components which they support. There are probably more polymeric bearings produced than any other type and their characteristics attract much attention.

In the tribological field, Polytetrafluoroethylene (PTFE) has proved to be remarkable and by far the most significant fluorocarbon used. Similar to UHMWPE, PTFE has a coefficient of friction lower than graphite and indeed lower than any other solid and that is due to the smooth molecular structure of this material [1] .

In this paper, attention will be focused upon the tribological characteristics of UHMWPE; one of the less widely used polymeric bearing materials. The reason for this choice is that UHMWPE is now extensively used in total joint replacements for the human body.

Over the past decade, extensive studies have been concerned with UHMWPE in association with medical grade stainless steel as they were favoured internationally for total replacement load bearing joints in the human body. It was reported that thin transfer films of UHMWPE highly orientated in the direction of sliding, established themselves on the stainless steel counterface under dry sliding conditions [2-5]. These transfer films of polymer play an important role in dictating the coefficient of friction, the wear rate and the generated surface roughness of the sliding components. The latter has a significant effect upon the wear rate of the polymeric component [6-7]. However, the development of such transfer films of polymer can be inhibited by the presence of liquid.

In the present work, the coefficients of friction and the wear rates of UHMWPE sliding against stainless steel counterfaces, with initial surface roughness in the range 0.008 μm - 0.22 μm (Ra), under both dry and wet sliding conditions, were described.

EXPERIMENTAL

THE RECIPROCATING FRICTION AND WEAR TESTING MACHINE

The general layout of the pin-on-flat reciprocating configuration used in this work is shown in Figure 1. The mechanical power was taken from a variable speed motor to a gear-box where the drive was changed by an off-set crank to allow a reciprocating motion to the carriage supporting the stainless steel counterface which was located in a plexiglas bath. The bath was filled with liquid if required. The polyethylene pin was located in a pin-holder fixed in a vertical position by a pin-holder arm. This arm was supported by an air-bearing to enable precise evaluation of friction and wear. The friction force was measured by a force transducer which restrained the pin-holder arm. The output signal of the transducer was amplified and displayed on an X-Y pen recorder. The pin was loaded directly by dead weights.

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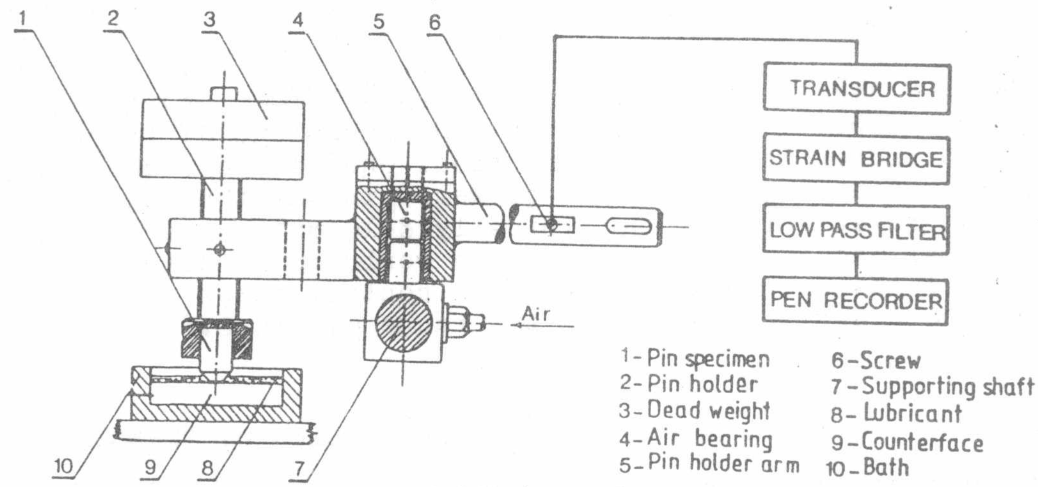


FIG.(1) DIAGRAMMATIC LAYOUT OF THE MACHINE

MEASUREMENTS AND TEST PROCEDURE

Before each test, the bath, the polymer pins and the metal counter-face were throughly cleaned, the latter ultrasonically. The friction measurements were taken every 15 minutes and the coefficient of friction was calculated from the traditional formula:

$$\mu = F/W$$

where F is the friction force measured by the load transducer and W is the normal load on the polymeric pin. The wear pin was removed periodically, typically after about 15 km of sliding, carefully cleaned with a tissue soaked with alcohol, left overnight at 20 °C and a relative humidity of 40 % and then weighed a number of times on an accurate balance. A knowledge of the mean loss of weight and the density of the polymer enabled the volume of material removed by wear to be ascertained.

Graphs were plotted of volume lost due to wear (V) in mm^3 against sliding distance (L) in m. The slope of the line of the graph, divided by the normal load (W) on the pin, is the wear rate:

$$\text{Wear rate} = V/(W.L) \qquad mm^3/(N.m)$$

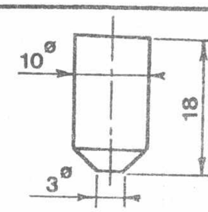
All tests were carried out at room temperature where the ambient temperature ranged from 15 °C to 20 °C and the humidity from 40% to 50%. Surface profilometry was carried out using a Rank Taylor Hobson Talysurf (5-120).

MATERIALS AND SPECIMEN PREPARATION

A) THE POLYMER

The UHMWPE used in the experiments was RCH 1000, surgical grade polyethylene. Table 1 shows the form and dimensions of the pin and some relevant properties of this material. One of the reasons for selecting a truncated conical form of wear pin was that the wear face would be relatively small, typically 8-10 mm^2, so that any influence of initial machining upon wear rate would be restricted to the early stages of the wear experiments. The contact faces of the pins were turned to a surface finish in the range 0.3 to 0.6 μm Ra.

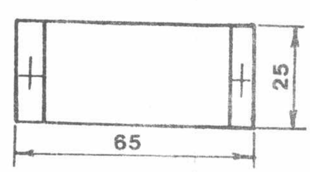
Table 1. Physical and mechanical properties of UHMWPE (RCH 1000)

PROPERTY	VALUE	PIN DIMENSIONS
Molecular weight Density (kg/m) Vickers hardness Bulk shear stress (MPa) Yield stress (MPa)	3.5×10^6 940 5.3 24 28.4	

B) THE STAINLESS STEEL

The counterfaces were made from austenitic surgical grade stainless steel, type EN 58J. This is an acid and heat resistant steel. Table 2 shows some important properties of this steel and the form and dimensions of the counterface. The counterface surfaces were all initially prepared by random grinding to a similar roughness and then lapped to the required Ra value.

Table 2. Physical and mechanical properties of surgical grade stainless steel (EN 58J)

PROPERTY	VALUE	PLATE DIMENSIONS
Specific gravity Modulus of elasticity Tensile strength Poisson's ratio Vickers Hardness	7.96 210 GPa 540 MPa 0.283 160	

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EXPERIMENTAL RESULTS

FRICTION AND WEAR FOR UHMWPE ON STAINLESS STEEL IN DRY SLIDING CONDITIONS

The wear rates of UHMWPE are plotted against the initial counterface surface roughnesses in Figure 2. As can be seen, there is a good indication of a minimum wear rate of about 0.1×10^{-7} mm^3/N.m at a counterface roughness of about 0.08 μm Ra. For smooth surfaces (Ra < 0.08 μm) the wear rates decreased with increasing roughness before coming to the optimum wear rate. On the other hand, with rough surfaces beyond the optimum roughness (Ra ≳ 0.1 μm) the wear rates increased steadily with an increase in the initial surface roughness.

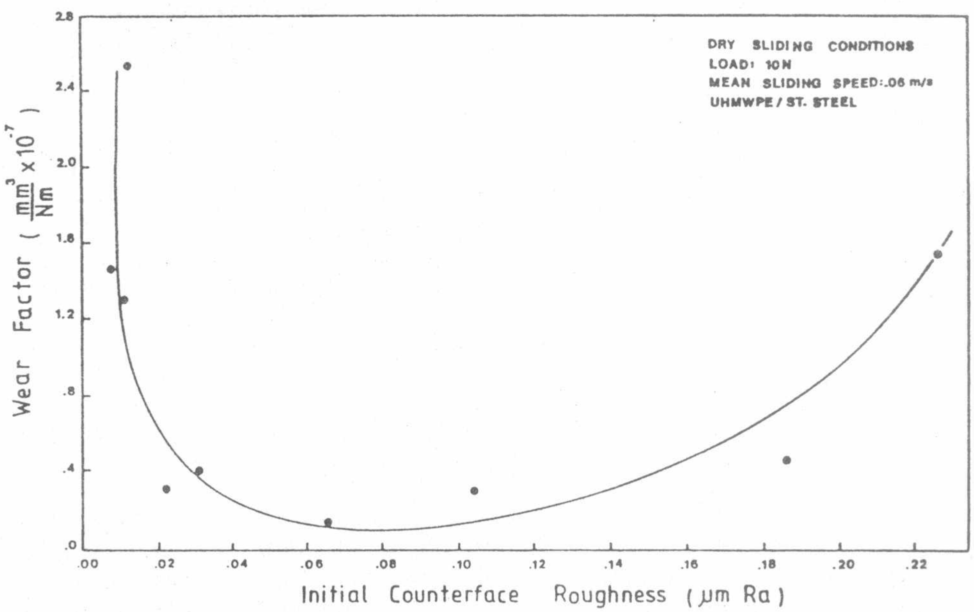

FIG. (2) THE EFFECT OF THE INITIAL COUNTERFACE ROUGHNESS ON THE WEAR FACTOR IN DRY SLIDING CONDITIONS

The average coefficients of friction for the dry tests were also plotted against the initial counterface roughness in Figure 3. The graph illustrates that higher coefficients of friction were recorded for both the smooth and rough counterfaces compared with the medium roughness (Ra=0.08-0.12 μm) counterfaces. Although there is indication that the coefficients of friction were not greatly affected by the variations in counterface surface roughness as the wear rates, but still there is feature for a minimum coefficient of friction of 0.085 at a surface roughness of about 0.06 μm Ra.

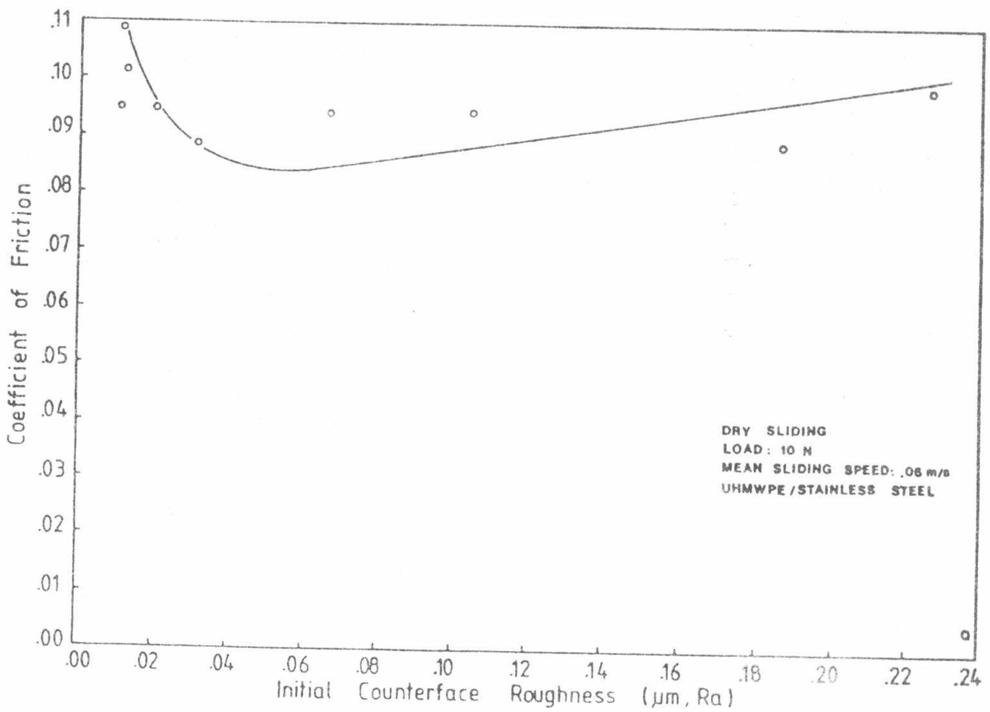

FIG. (3) THE EFFECT OF THE INITIAL COUNTERFACE ROUGHNESS ON THE COEFFICIENT OF FRICTION

TRANSFER FILM THICKNESS OF UHMWPE ON STAINLESS STEEL

Measurements of the maximum transfer film thickness of the polymer adhering to the stainless steel counterface at the completion of the dry tests were carried out using the talysurf. The variation of transfer film thickness as a function of the initial counterface surface roughness is shown in Figure 4. It is clear that the smooth surfaces retained much thicker transfer films than the rough ones. Maximum transfer film thicknesses in the range 0.15-0.45 µm were measured on smooth surfaces ($Ra < 0.08$ µm) while for rougher surfaces the maximum transfer film thicknesses were almost constant at about 0.05 µm. On very smooth surfaces, the thickness of the transfer film was substantial and it decreased significantly with an increase in roughness, up to the optimum roughness, where the minimum friction and wear were obtained. It is important to note that the measurements obtained gave rough estimates of the actual transfer film thickness, as some features were probably lost when the Talysurf needle travelled across the relatively soft film of polymer.

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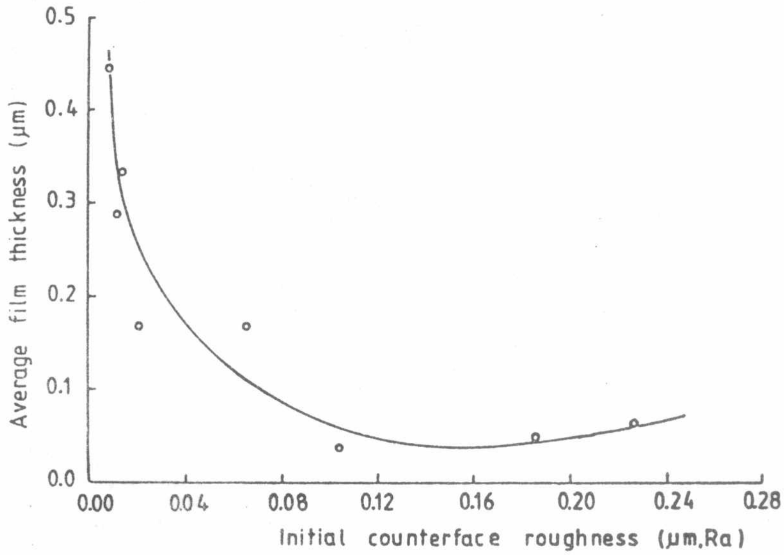

FIG. (4) AVERAGE POLYETHYLENE TRANSFER FILM THICKNESS AS A FUNCTION OF THE INITIAL COUNTERFACE ROUGHNESS IN DRY SLIDING

FRICTION AND WEAR FOR UHMWPE ON STAINLESS STEEL IN DISTILLED WATER LUBRICATED CONDITIONS

The results of this set of experiments indicated that both the wear rates and the coefficients of friction increased with increasing initial surface roughness of the counterfaces without evidence of minimum values similar to those reported in the dry tests, Figures 5 and 6. In general, wet tests exhibited slightly higher wear rates than those obtained in dry sliding for roughnesses greater than about 0.05 μm Ra. For surface roughnesses lower than 0.05 μm Ra, the wear rates were much lower in wet than in dry sliding conditions.

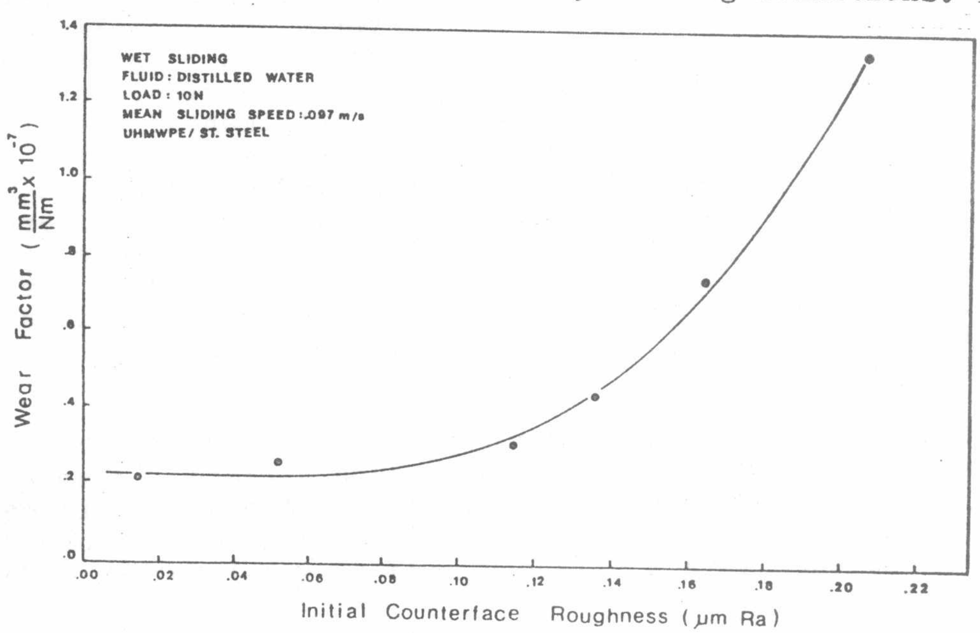

FIG. (5) EFFECT OF THE INITIAL COUNTERFACE ON THE WEAR RATE OF UHMWPE ON STAINLESS STEEL

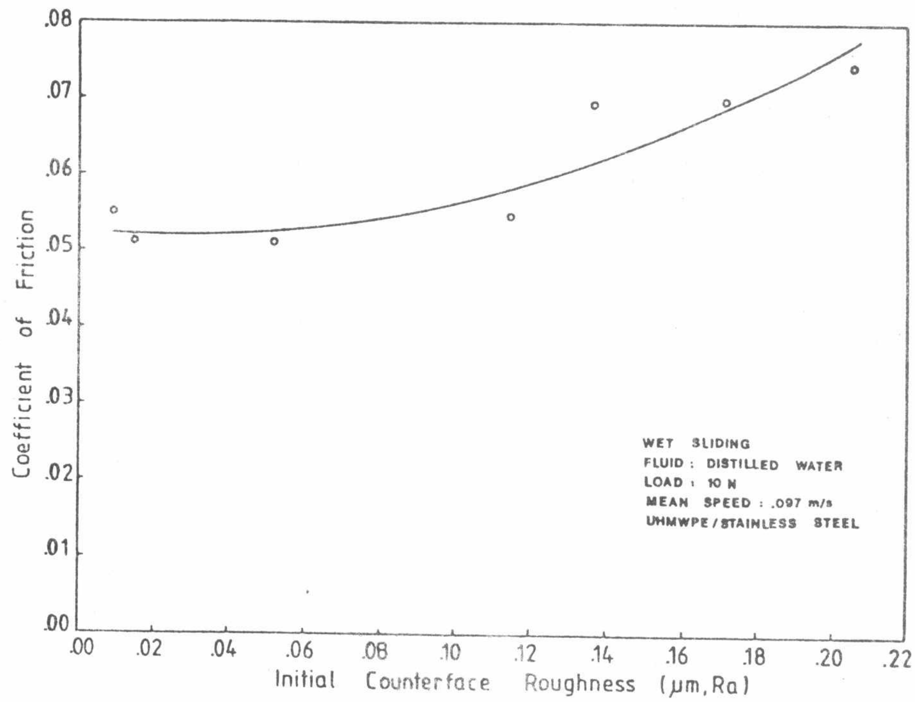

FIG. (6) EFFECT OF THE INITIAL COUNTERFACE ROUGHNESS UPON THE COEFFICIENT OF FRICTION

DISCUSSION OF RESULTS

FRICTION AND WEAR IN DRY SLIDING CONDITIONS

During the dry tests of UHMWPE against stainless steel, the smooth counterfaces exhibited a gradual deposition of polymeric transfer film which appeared to adhere to the counterface. On these smooth surfaces (Ra < 0.08 μm), an adhesive mechanism was effective and accounted for the observed high wear rates. Talysurf measurements showed that the transfer was heavier on very smooth surfaces and gradually decreased with increasing roughness. On rough surfaces above the optimum range, little transfer was detected. The existence of such transfer on smooth surfaces had a detrimental effect upon the friction and wear. Talysurf measurements had also indicated that the surface roughness of steel increased from 0.008 to 0.054 μm Ra due to build up of transfer films on the very smooth surfaces. Therefore, the high wear rates obtained on initially smooth surfaces were caused by an increase in roughness, real area of contact and temperature at the interface. Furthermore, the change in the mode of contact from polymer-metal to polymer-polymer transfer can significantly contributed to the high wear rates observed.

At the optimum roughness condition, it is proposed that both adhesion and abrasion processes were small. On rough surfaces, wear rates were dictated by the abrasion mechanism which resulted in an increase in wear rates with increasing roughness. In addition, the collection of wear debris at the contact site can have an accelerating effect on the wear process.

The study has revealed that the variation of the coefficient of friction with surface roughness followed the form of the corresponding relationship for the wear rates. The decrease in the transfer film thickness with increasing roughness on smooth surfaces accounted for the decrease in the coefficient of friction. The experimental findings imply that, on rough surfaces above the optimum roughness, a proportional relationship exists between the friction and the roughness.

FRICTION AND WEAR IN WET SLIDING CONDITIONS

The wet tests revealed that both the wear rates and the coefficients of friction increased with an increase in roughness. On very smooth surfaces, the lower wear rates in wet than in dry tests were due to the inhibition of a heavy detrimental transfer film in distilled water. On rough surfaces beyond 0.05 μm Ra, the effectiveness of abrasion, the plasticisation of the polymer surface by the action of water and the deterioration in its mechanical properties played the main role in easing the wear process in wet than in dry sliding.

The coefficients of friction in wet sliding, on the other hand, also exhibited a gradual increase with the increase in the initial counterface roughnesses. This increase in friction was quite remarkable on rough surfaces and this is attributed to the increase in ploughing effect with increasing roughness with the addition of the increase in the real area of polymeric surface with the continuous wearing out of the truncated surface. In general, the coefficients of friction in the wet tests were lower than those in dry sliding due to the limit of transfer film formation in the presence of water. The presence of liquids on the steel surfaces can also alter their surface energy and sets up intermolecular forces which have a profound effect upon the friction and wear.

CONCLUSIONS

1. The results have confirmed the existence of an optimum surface roughness at which the wear rate, the coefficient of friction, for UHMWPE on stainless steel under dry sliding conditions, were minimum.

2. Below the optimum counterface roughness value the adhesion and the high transfer film thickness played a dominant role in increasing the coefficient of friction and the wear rate of UHMWPE in dry sliding, while above the optimum roughness the abrasive effect of the rough asperities, which steadily increased as the counterface roughness increased, controlled both the friction and wear behaviour.

3. The transfer film thickness and topography, which largely depend upon the initial counterface roughness value, may cause an increase or a decrease in the coefficient of friction and the wear rate by deteriorating or ameliorating the counterface roughness respectively. Reductions in the effective roughness by transfer film formation are thus likely to be a relevant mechanism for friction and wear reduction.

4. In wet conditions for UHMWPE sliding on stainless steel in the presence of distilled water, both the coefficients of friction and the wear rates increased with increasing initial counterface surface roughness. It is proposed that the presence of water restricts the transfer film formation and diminishes the adhesive action, therefore it facilitates a steady increase in the abrasive wear with an increase in surface roughness.

5. The effect of distilled water on the friction and wear of UHMWPE on stainless steel is very marked. It produces an appreciable reduction in the coefficients of friction and wear rates compared with the values obtained under dry sliding conditions.

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