The effect of sliding velocity on the friction and wear of UHMWPE for use in total artificial joints

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Abstract

The effect of two different sliding velocities on the friction and wear of ultrahigh molecular weight polyethylene (UHMWPE) has been investigated in a tri-pin-on-disc apparatus using bovine serum as the lubricant. UHMWPE pins were slid at velocities of 35 and 240 mm s^{-1} on stainless steel counterfaces with the surface roughness R_a being varied in the range 0.014–0.078 μm. The coefficient of friction was found to be in the range 0.07–0.2 and was not dependent on the sliding velocity. The highest friction values were found with a counterface roughness R_a of 0.042 μm. Sliding velocity had little effect on the wear factor. For smooth counterfaces with a surface roughness of less than 0.05 μm, all the wear factors were less than 1.3×10^{-8} mm^3/Nm and there was no significant difference in the wear factors produced for the two different sliding velocities. An increase in the counterface roughness to between 0.07 to 0.08 μm increased the wear factor by over twenty times to a value greater than 3×10^{-7} mm^3 N^{-1} m^{-1}. For these rougher counterfaces a statistically significantly higher wear factor was found for the lower sliding velocity. The results show clearly that variation in the sliding velocity has only a small effect on the wear of UHMWPE compared with the changes found when the counterface topography was altered. The results indicate that it is reasonable to accelerate tri-pin-on-disc wear tests by increasing the sliding velocity within the range specified, but it is essential to control the topography of the counterface.

1. Introduction

There is currently considerable interest in the wear of UHMWPE in total artificial joints [1,2]. Although the joints do not generally wear out [3], UHMWPE wear particles generated at the articulating surfaces can enter the tissues surrounding the prosthesis [4] and cause adverse cellular reactions [5] which lead to bone resorption loosening and the need for a revision operation [6–8]. At present there is considerable research effort aimed at producing material combinations and tribological conditions that can reduce the volume of UHMWPE wear in the body. Laboratory wear tests such as polymer pin-on-plate [9] are used extensively to evaluate material combinations prior to manufacture of prostheses for testing in full joint simulators [10]. A review of recent literature shows that there is considerable variation in the wear factors produced for UHMWPE in different studies. In some studies wear factors as low as 10^{-8} mm^3 N^{-1} m^{-1} have been produced [11,12] while in others, wear factors higher than 10^{-7} mm^3 N^{-1} m^{-1} were predicted [13,14]. Tribological conditions of these tests can vary and different sliding velocity, lubricating fluid, and counterface topography have been used by different groups. It has been shown recently [15] that the counterface can be modified by polymer transfer in water-lubricated tests and this produced variation in wear rate throughout the test. In general, increased counterface roughness produced an increased wear factor for the polymer. However, it has been recognised that this polymer transfer is unlikely to happen in the body and it has been demonstrated that with bovine serum (a protein containing lubricant) little or no polymer transfer occurred onto the counterface, the counterfaces remained smooth and generally the wear rates remained constant throughout the test [15]. It was concluded that a protein-containing lubricant, such as bovine serum, was a more appropriate lubricating medium for laboratory wear studies of UHMWPE for artificial joints. Nevertheless, there appear to be considerable differences in the wear rates of UHMWPE in laboratory tests with bovine serum as a lubricant when test protocols with different sliding velocities have been used [11–14]. The purpose of this study was to investigate the effect of different sliding velocities on the friction and wear of UHMWPE when sliding on smooth stainless steel counterfaces for a range of surface topographies in the presence of bovine serum as a lubricant.

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TABLE 1. Test conditions

Test configurations	Number of tests	Sliding velocity (mm s^{-1})	Initial counterface roughness R_a (μm)	Sliding distance (km)	Number of wear measurements (N)
A	2	240	0.014	710	45
B	2	35	0.018	62	24
C	1	240	0.048	311	9
D	1	35	0.042	45	9
E	1	240	0.078	311	9
F	1	35	0.072	45	9

2. *Materials and methods*

Eight tri-pin-on-disc wear tests were carried out with six different sets of test conditions (A to F). The test conditions are specified in Table 1. In three test conditions (A, C, E), a high sliding velocity of 240 mm s^{-1} was used, while in the other three test conditions (B, D, F) a low sliding velocity of 35 mm s^{-1} which is closer to physiological conditions (0–30 mm s^{-1}) was used. The first two test conditions (A, B) were run on very smooth counterfaces with an initial R_a of between 0.01 and 0.02 μm. The second two test configurations (C, D) were run on slightly rougher counterfaces with an initial R_a of between 0.04 and 0.05 μm. The final two tests (E, F) were run on the roughest counterfaces with an R_a of 0.07 to 0.08 μm. All tests were run with bovine serum as a lubricant in order to inhibit the formation of polymer transfer film on the counterface and to try and maintain a constant counterface roughness and a constant wear rate throughout the tests. All tests were run with a constant load of 80 N per pin which gave a nominal contact stress of approximately 12 MPa. The test duration was between 35 and 710 km, depending on the sliding velocities, with the higher sliding distances being achieved with the higher velocities. A sliding distance of 20 km corresponded to approximately one year's lifetime of an artificial hip joint. All tests were run to ensure a minimum of nine wear measurements to enable statistical analysis of the results and comparison of the six test conditions.

The tri-pin-on-disc wear testing apparatus has been described previously in the literature [9,11]. It consisted of a unidirectional rotating stainless steel disc or counterface onto which a carrier was loaded containing three polymer wear pins [11]. The polymer pins were loaded with a constant load throughout the test. The disc and the pins were contained within a lubricating bath which contained bovine serum. The bath also contained a fourth polymer pin which did not come into contact with the sliding surface and was used as a control for measurements of moisture absorption from the lubricant. The wear tests were run continuously for 5 days (between 15 and 110 km sliding distance) and then the wear pins were removed, cleaned and weighed on a microbalance to determine the wear volume of the polymer. Any weight change in the control pin due to moisture absorption was compensated for in the calculation of the wear volume in the wear pins. This procedure, which has been described in detail previously [9,11], was repeated every week and hence the wear volume was determined as a function of sliding distance throughout the test. In addition, the roughness of the stainless steel counterface was monitored throughout the study to enable any changes in the test conditions to be detected.

Friction was measured using a strain gauge attached to an arm which prevented the rotation of the pin-carrier. Friction was measured in each of the tests to determine the effect of sliding velocity and counterface roughness on the friction coefficient. In addition, the temperature of the polymer pins was monitored for the different sliding conditions. Small thermocouples were inserted in the polymer wear pins approximately 0.5 mm away from the wear surface. The temperature of the pin was determined for each of the test conditions given in Table 1.

The wear test results were analysed by calculating the mean and standard error of the wear factor K for each of the test conditions. The wear factor K was defined as [9,11]

$$K = \frac{V}{PX}$$

where P is the load in newtons, X is the sliding distance in metres and V is the wear volume in cubic millimetres. The means and standard errors were compared statistically using a one way analysis of variance.

3. Results

Examples of the results of wear volume plotted against sliding distance are shown for two of the tests (B and E) which are at the extremes of the range of the test conditions. The wear volume is plotted against sliding distance for test condition B, which was a smooth counterface and low sliding velocity, and is shown in

Fig. 1. This graph shows the wear of six polymer pins (two tri-pin-on-disc heads), sliding for 4 weeks with a sliding distance of 15.5 km per week. Under these conditions with a smooth counterface the weekly wear volumes of the pins were small and hence the measurements were affected by variations in moisture uptake between the pins. Although the average moisture uptake was compensated for by the weight change of the control pins, the fluctuations in a single pin from week to week were thought to be due to fluctuations in moisture content of the polymer pins. In addition, one pin demonstrated an abnormally low wear volume throughout the test, and this was attributed to additional uptake of moisture in this pin, which produced a weight gain or negative wear volume at the beginning of the test. Larger numbers of wear measurements were made for test conditions A and B in order to try and reduce the variability found in the mean wear factor caused by variations in moisture uptake. In contrast, the wear volumes found in test E with the roughest counterface were much greater, and much less variation was found was in the graphs of wear factor plotted against sliding distance (Fig. 2). In this test which was carried out at the higher sliding velocity (240 mm s^{-1}), with over 100 km sliding distance each week, wear volumes of approximately 2 mm^3 were measured and fluctuations in the weight due to moisture update were negligible.

For each of the six test conditions A–F, an average wear factor K was calculated from the weekly wear volume measurement on each pin and a mean and standard error calculated for the total number of mea-

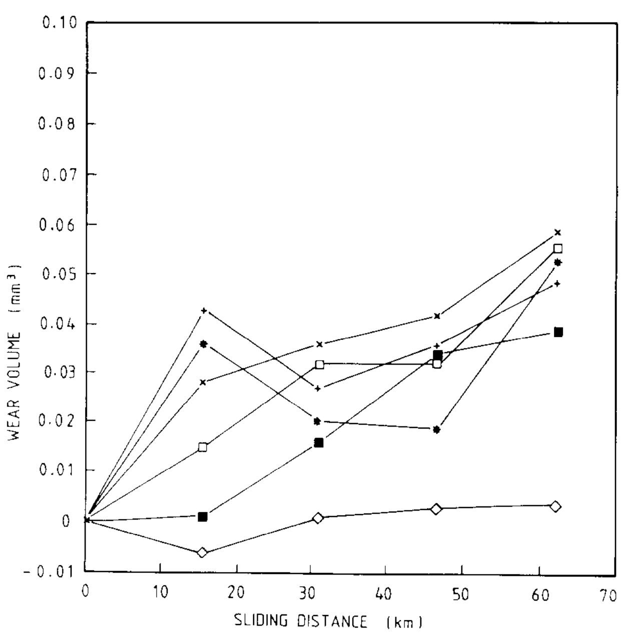

Fig. 1. A graph of wear volume plotted against sliding distance for test B with a smooth counterface and low sliding velocity (35 mm s^{-1}).

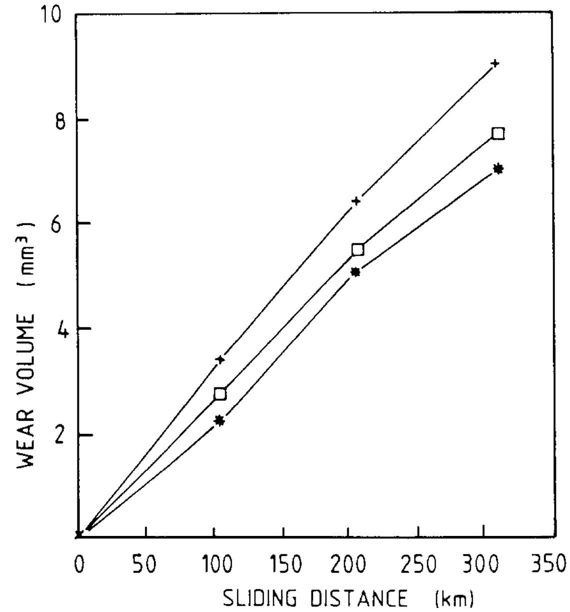

Fig. 2. A graph of wear volume versus sliding distance for test E with a rough counterface and high sliding velocity (240 mm s^{-1}).

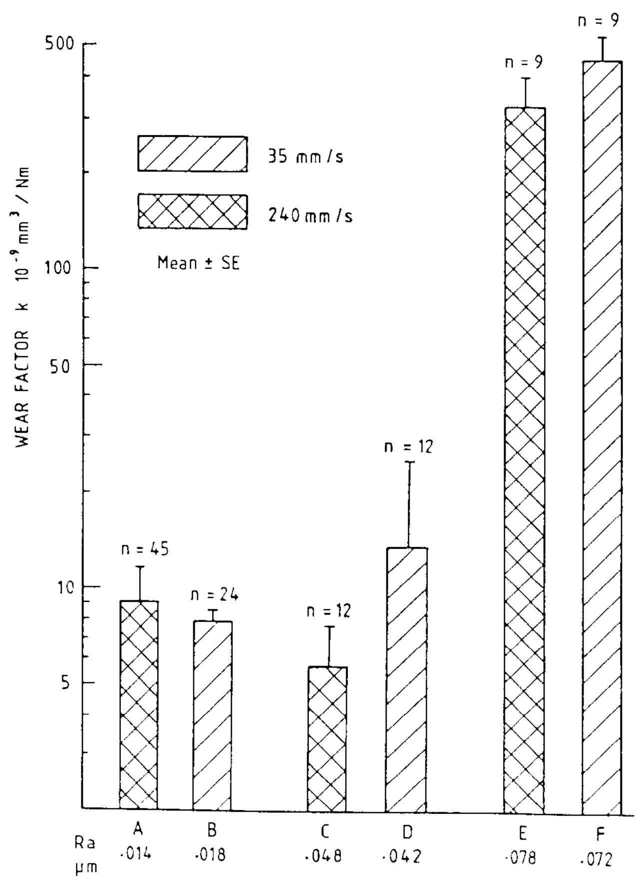

Fig. 3. A histogram of the average wear factors for the six test conditions showing the different sliding velocities and counterface roughness. Error bars show +1 standard error on the mean.

TABLE 2. Average wear factor

Test configurations	Counterface roughness R_a (μm)	Sliding velocity (mm s^{-1})	Average wear factor K ($\times 10^{-9}$ mm^3 N^{-1} m^{-1})	Standard error ($\times 10^{-9}$ mm^3 N^{-1} m^{-1})
A	0.014	240	9.0	±0.6
B	0.018	35	7.9	±2.1
C	0.048	240	5.7	±0.6
D	0.042	35	13.2	±8
E	0.078	240	317	±17
F	0.072	35	457	±27

surements made in each test condition. This method of analysis assumed no systematic change in wear factor throughout the tests. Figures 1 and 2 show that there was little systematic change in the wear through the test and this was consistent with the results of the other tests. In addition, measurements of the counterface roughness R_a showed little change throughout the test, and this was consistent with previous work [15] which showed a constant volumetric wear rate throughout the test when bovine serum was used as a lubricant.

The average wear factors for each of the test conditions are presented in the histogram in Fig. 3. This graph shows clearly that the dominant parameter affecting the wear factor in the test conditions was the counterface roughness, with the roughest counterface in tests E and F producing a twenty-fold increase in the wear factor compared with the other four test conditions. The sliding velocity has a much smaller effect on the wear factor. Hence it was necessary to compare the effect of the different sliding velocities for each of the surface roughnesses, (i.e. A and B, C and D, E and F).

Table 2 gives details of the mean and standard errors of the wear factors for each of the test conditions. For the smoothest counterfaces (A and B), the wear factors were very similar and the sliding velocity had little effect on the wear factor. It must be noted, however, that for the same wear factor a higher sliding velocity always produced a greater sliding distance and hence a greater wear volume. For test conditions C and D with a surface roughness R_a of between 0.04 and 0.05 μm, the wear factors were low and similar to those found in tests A and B. However, test D carried out at the lower sliding velocity did give a slightly higher wear factor but the difference was not statistically significant. In contrast, tests E and F on the rough counterfaces did give much higher wear factors (greater than 3×10^{-7} mm^3 N^{-1} m^{-1}) and in this case the lower sliding velocity gave a 50% greater wear factor than for the higher sliding velocity. The difference in these wear factors was statistically significant ($p<0.05$, Student's t test).

Figure 4 shows a histogram of the coefficient of friction for each of the test conditions. The sliding velocity appeared to have little effect on the coefficient of friction. Furthermore, the surface roughness had only a limited effect on the coefficient of friction, with the highest friction occurring in tests C and D with the counterface roughness between 0.04 and 0.05 μm. Most importantly there was no correlation between the wear factor K and the coefficient of friction, as shown in Fig. 5, where the mean wear factor is plotted against the coefficient of friction for all six test conditions. Temperature measurements showed extremely low temperature rises 0.5 mm from the polymer surface with the maximum temperature rise of 3 °C above the temperature of the lubrication bath being recorded in the case of the roughest counterface at the highest sliding velocity.

The wear factors measured in this study under different conditions were dominated by the topography of the counterface. Figure 6 shows the wear factor plotted against the counterface roughness on a log–log

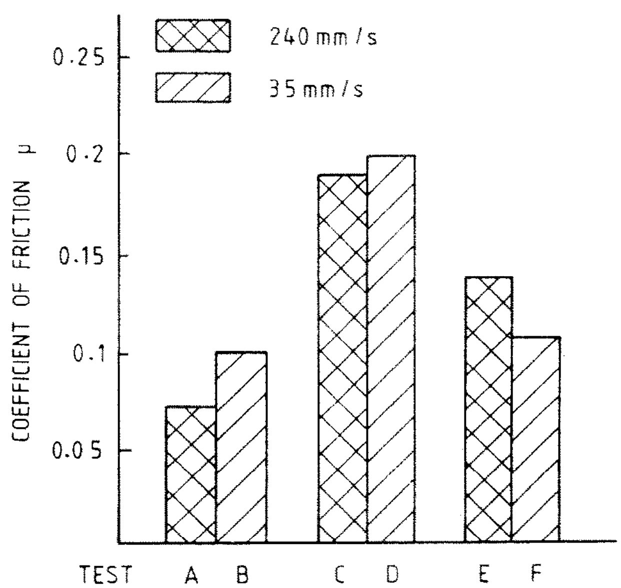

Fig. 4. The histogram of the mean coefficients of friction for the six test conditions indicating the different sliding velocities.

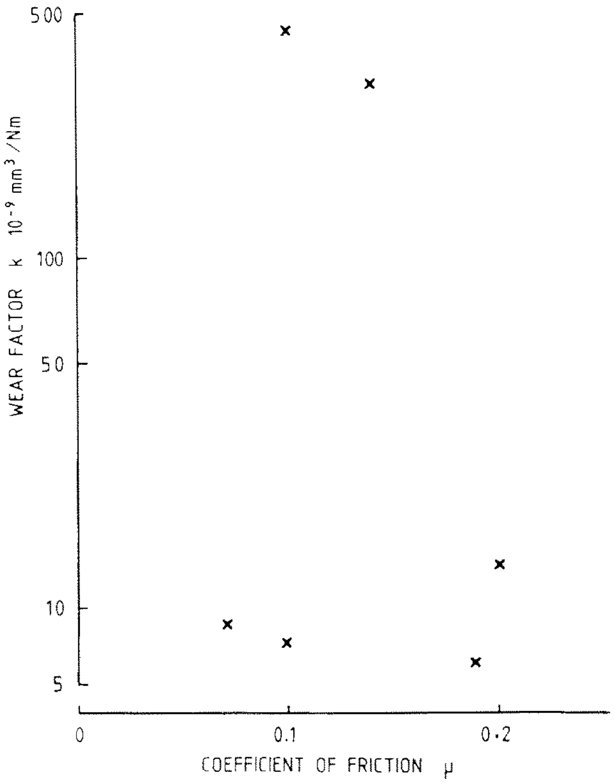

Fig. 5. A graph of the wear factor plotted against the coefficient of friction for the six test conditions.

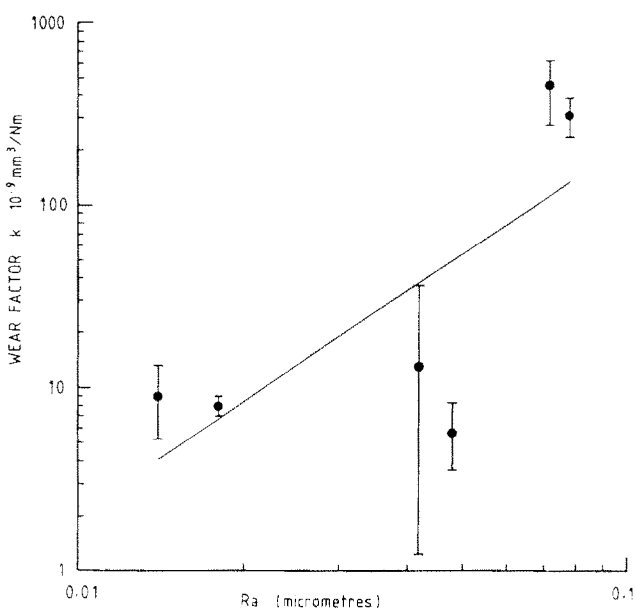

Fig. 6. A graph of the wear factor plotted against the counterface roughness on log–log scale.

graph which demonstrates the rapidly increasing wear factor with increasing counterface roughness. The best-line fit was described by the equation:

$$K = C(R_a)^B$$

where $C = 0.235 \times 10^{-4}$ and $B = 2.03$. The power function B produced a rapid rise in the wear factor once the surface roughness increased beyond 0.05 μm.

4. Discussion

The sliding velocity in an artificial hip joint can range from 0 to 60 mm s^{-1} during normal walking. Although some wear tests have been carried out at sliding velocities of 25 mm s^{-1}, many tests have been carried out at higher velocities up to 240 mm s^{-1} in order to accelerate the tests and to generate larger wear volumes of polymer. In lubricated sliding, an increased sliding velocity may increase the effectiveness of the elastohydrodynamic lubrication mechanisms and decrease friction and perhaps wear. In contrast, in dry sliding an increased sliding velocity may be expected to increase frictional heating, polymer softening and wear. Previous studies have demonstrated large differences in the wear factors. Cooper *et al.* [9,11] showed wear factors of approximately 10^{-8} mm^3 N^{-1} m^{-1} on smooth counterfaces with higher sliding velocities sliding in both water and serum, whilst Streicher *et al.* [13] showed consistently much greater wear factors of approximately 10^{-7} mm^3 N^{-1} m^{-1} for a range of counterface materials at much lower sliding velocities of 25 mm s^{-1}. However, the counterface roughnesses in ref. 13 were not clearly defined. In contrast, Weightman and Light [12] produced low wear factors with low sliding velocities on smooth counterfaces, although their tests were carried out with reciprocating motion. The results of this study showed quite clearly that relatively small changes in counterface roughness had a much greater effect on the wear factor for the polyethylene than large variations in the sliding velocity.

For the tests on smoother counterfaces (tests A–D) the change in velocity did not cause a statistically significantly change in the wear factor. In these four tests the friction coefficients were greater than 0.07, indicating a mixed or boundary lubrication regime. It would appear that under these conditions the increased sliding velocity did not generate fluid film lubrication and hence did not markedly affect wear. For the tests with the roughest counterfaces (E, F), when the wear factors were extremely high, the higher sliding velocity produced a significantly lower wear factor. In these two tests, the coefficient of friction was higher in test E, when there was a lower wear factor. It is recognised that the protein in the bovine serum is denatured and adheres to sliding surfaces during these tests [15]. Changes in sliding velocity and small changes in temperature may alter the boundary lubrication mechanisms of the protein and hence have a small affect on both friction and wear. It was shown clearly in Fig. 5 that sliding velocity had little effect on friction, while surface roughness of the counterface did change the coefficient of friction, with the highest value for friction occurring for a counterface roughness of 0.04–0.05 μm. However, there was no correlation between the coefficient of friction and the wear factor for UHMWPE. The results of this study indicate that differences in wear factors of greater than one order of magnitude found in previous studies are much more likely to be attributed to the differences in counterface roughness and surface topography used, rather than to different sliding velocities used in the tests. These results also indicate that it is not unreasonable to use higher sliding velocities in comparative wear screening test on different counterfaces in order to accelerate the volumetric wear of the polymer.

The results of this study do emphasise the importance of the roughness of the counterface on the wear of the polymer pins. The changes in the wear factor for different counterface roughness found in this study with bovine serum were found to be very similar to those found in a previous study carried out with deionised water, where the change in the counterface roughness caused by polymer transfer was monitored throughout the test (Fig. 7). The variation in the wear factor shown in Fig. 6 for these pin-on-disc tests was very similar to the results published by Weightman and Light [12] for a reciprocating pin-on-plate test. Wear factors close to 10^{-8} mm^3 N^{-1} m^{-1} were found in both studies for counterface roughness values of less than 0.05 μm. However, higher values of K were found in this study when the R_a was greater than 0.07 μm, than were found in the study of Weightman and Light for similar R_a values. It has to be recognised that the surface topography can vary considerably for the same R_a value; in particular, as the counterface gets rougher the wavelength of the surface asperities is likely to have a marked effect on the wear of the polymer [16]. Lancaster [16] proposed that for smooth counterfaces adhesive/fatigue asperity wear processes would dominate. However, when the counterface gets rougher and the ratio of the height of the asperity to the asperity wavelength increases, abrasive wear and cutting action are likely to occur. The large increase in the wear factor with the rougher counterfaces in tests E and F would be consistent with abrasive action increasing the wear factor. Further studies with more detailed analysis of the counterface topography are required to substantiate this interpretation of the results.

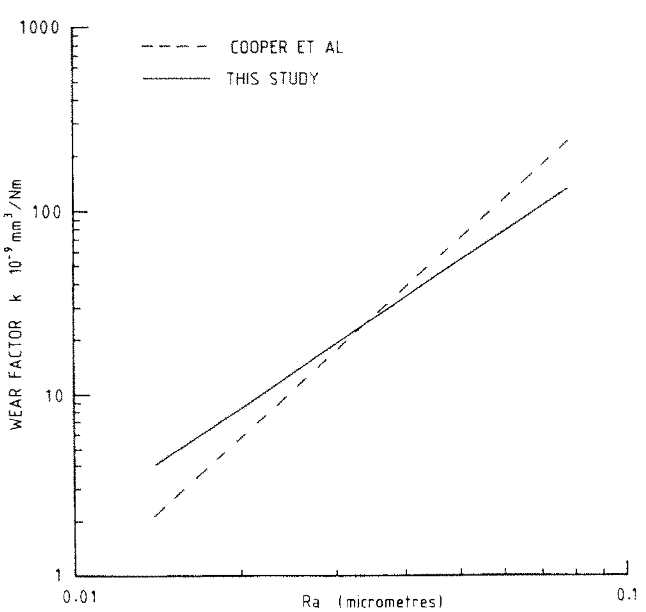

Fig. 7. A comparison of the variation in wear factor with counterface roughness found in this study with that found in a previous study [15] which was carried out in deionised water.

In conclusion, the results of this study have shown that the sliding velocity has only a small effect on the wear factor for polymer pins in a tri-pin-on-disc configuration for smooth counterfaces. The different counterface roughnesses used in this study have a much greater effect on the wear factor of the polymer pins.

Acknowledgments

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