# Wear of ultra-high molecular weight polyethylene against damaged and undamaged stainless steel and diamond-like carbon-coated counterfaces

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The wear of ultra-high molecular weight polyethylene (UHMWPE) in artificial joints and the resulting wear debris-induced osteolysis remains a major clinical concern in the orthopaedic sector. Third-body damage of metallic femoral heads is often cited as a cause of accelerated polyethylene wear, and the use of ceramic femoral heads in the hip is gaining increasing favour. In the knee prostheses and for smaller diameter femoral heads, the application of hard surface coatings, such as diamond-like carbon, is receiving considerable attention. However, to date, there has been little or no investigation of the tribology of these coatings in simulated biological environments. In this study, diamond-like carbon (DLC) has been compared to stainless steel in its undamaged form and following simulated third-body damage. The wear of UHMWPE was found to be similar when sliding against undamaged DLC and stainless steel counterfaces. DLC was found to be much more damage resistant than DLC. Under test conditions that simulate third-body damage to the femoral head, the wear of UHMWPE was seven times lower against DLC than against stainless steel ($P < 0.05$). The study shows DLC has considerable potential as a femoral bearing surface in artificial joints.

## 1. Introduction

The wear of ultra-high molecular weight polyethylene (UHMWPE) and wear debris-induced osteolysis remain a major focus of research in orthopaedic implants. In the last 2 y, much attention has been paid to different types of polyethylenes and the degradation produced by different sterilization methods. Much less attention has been focused on the properties of the femoral counterface which is one of the most important variables in the tribological design of artificial joints. It was shown very clearly by Isaac *et al.* [1] over 10 years ago that bone cement particles damage metallic femoral heads and this was cited as a cause of increased polyethylene wear [1]. The effect of roughened femoral heads on the wear of UHMWPE was also clearly described by Weightman and Light in laboratory studies [2]. Subsequently, it was shown that both bone [3], metallic [4] and hydroxyapatite [5] particles can all damage metallic femoral surfaces and be possible causes of increased UHMWPE wear. It has also been shown that bone cement with zirconia radio-opaque additives produces more damage than bone cement with barium sulphate radio-opaque additives in laboratory tests [3, 6], and that alumina ceramic femoral heads are much more resistant to third-body damage than stainless steel femoral heads [7]. It has also recently been demonstrated that a single 1–2 μm deep scratch to a metal surface, typical of third-body damage, can cause a 30- to 70-fold increase in polymer wear rate [8]. These factors all contribute to the widely held view that alumina ceramic heads are the femoral material of choice in the hip. However, there are concerns about its brittleness and it is not readily available in head sizes less than 28 mm, which is a distinct disadvantage, as a reduction in head size from 32 mm to 22 mm can cause a two-fold reduction in wear.

The principle of using a very hard, smooth, damage-resistant counterface is now widely accepted [9], and alternative materials that can be used on smaller diameter femoral heads and on knee prostheses are now being sought. Diamond-like carbon coating (DLC) is one potential material [10]. In assessing femoral counterface materials, it is necessary to study the wear of UHMWPE against the material, study the damage resistance of the material and, in addition, assess the wear of UHMWPE against the damaged material. In this study the tribological properties of DLC have

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been compared to stainless steel in a series of tests aimed at predicting the wear of polyethylene on the undamaged surfaces, assessing the damage resistance of the two surfaces to PMMA bone cement and a diamond stylus, and finally, determining the wear of polyethylene against damaged counterfaces.

## 2. Materials and methods

### 2.1. Materials

Ultra-high molecular weight polyethylene (UHMWPE) GUR412 compression-moulded sheet, was used in a non-irradiated form. Palacos bone cement, which contains a zirconia radio-opaque additive, was used for the damage tests. Stainless steel (316L) counterfaces were used to represent the femoral head. The 316L stainless steel counterfaces were lapped to give a mean surface roughness of 0.01 μm (range 0.005–0.015 μm) measured on a Talysurf 6 contacting profilometer with a cut-off of 0.08 mm and phase-corrected PCR filter.

The stainless steel counterfaces were either studied untreated or coated with diamond-like carbon (DLC). The DLC coating was deposited by r.f. plasma-assisted glow discharge (CVD). The coating is described fully elsewhere [10] and was approximately 1 μm thick. DLC surface treatments have the potential to modify the surface topography of the femoral heads. In the case of this particular coating, there was little change in the average surface roughness after the surface treatment with all average surface roughness values falling within the specified range value for the initial surface finish. However, closer examination of the DLC talysurf traces in Fig. 1, showed some localized pores in the surface up to 1 μm deep and also some local isolated peaks up to 0.5 μm high. These features which were not seen on the lapped stainless surface were attributed to the surface coating.

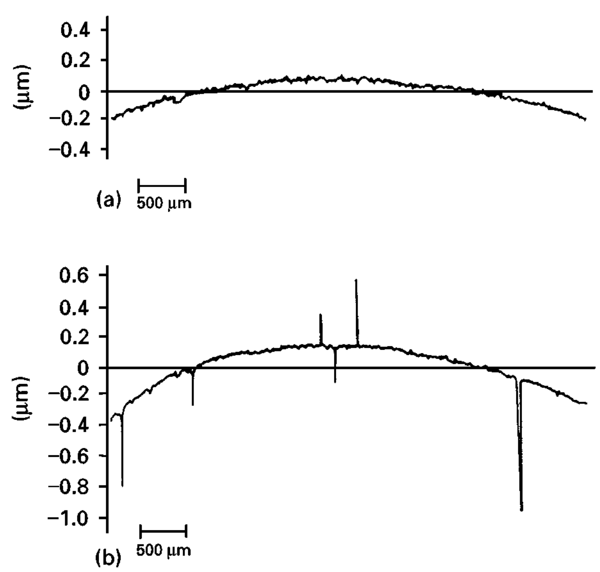


*Figure 1* (a) Surface profile of the undamaged metal surface, and (b) the DLC coated surfaces, which show both pores in the surface and isolated peaks.

### 2.2. Methods

The tribological studies were carried in three parts. In the first part of the study, the wear of UHMWPE was compared on the stainless steel and DLC surfaces in their undamaged form. In the second part of the study, the resistance of stainless steel and DLC to third-body damage was assessed. In the final part, the wear of UHMWPE was determined against scratched or damaged stainless steel and DLC surfaces.

The standard Leeds pin-on-plate wear-testing procedure was used for the wear tests in the first part of the study [11]. The six-station pin-on-plate reciprocator was used with a stroke length of 40 mm, a load of 160 N per pin with a contact face diameter of 3 mm. The test was run for 240 km over a 4 wk period with wear measurements being made every 60 km. Bovine serum was used as a lubricant and this was changed every week (every 110 h). Three wear stations were run with DLC counterfaces and three with stainless steel counterfaces. The wear volumes were determined gravimetrically every week, and control pins were also weighed to compensate for changes in moisture uptake. The wear volume was plotted as a function of sliding distance, the slope of the line being the wear rate. The incremental wear factors, $K$, were determined for each measurement interval from the equation

$$K = \frac{V}{PX} \text{mm}^3\,\text{N}^{-1}\,\text{m}^{-1} \qquad (1)$$

where $V$ is the wear volume (mm$^3$), $X$ the sliding distance and $P$ the load. The mean wear factor and standard error were calculated for the two materials, and statistical analysis and comparisons performed by Students $t$-test.

In the second part of the study, the damage resistance of the counterfaces was assessed by sliding PMMA bone cement pins with radiopaque additives over the counterfaces. Bone cement pins with a contact diameter of 3 mm and load of 160 N were slid over the counterfaces with a stroke length of 40 mm for a period of 21 h. This produced a total sliding distance of approximately 15 km. Bovine serum was used as a lubricant. At the end of the test the damage to the counterface was determined by measuring the roughness of the wear track using the Talysurf 6 contacting profilometer. Three plates of each material, stainless steel and DLC, were tested in the six-station reciprocating-wear tester. The roughness of each plate was measured at three places across the wear track at the end of the test.

In order to investigate the wear of UHMWPE against damaged counterfaces in the third part of the study, three new counterfaces of each material were deliberately scratched with a 2 μm radius diamond stylus with an applied load of 0.4 N. Each plate was scratched ten times perpendicular to the sliding directions at a spacing of 5 mm. After scratching, the scratch profile, and damage were measured with the Talysurf. A standard wear test using six polyethylene pins was then carried out over six periods of 24 h. At the end of each 24 h period, the wear volume was determined and the test restarted. A load of 160 N was applied to each pin with a stroke length of 40 mm as specified previously [11].

## 3. Results

The volumetric wear rates of UHMWPE against the undamaged counterfaces are shown in Fig. 2. Two of the DLC plates produced lower wear rates than the stainless steel plates while the third plate had a greater wear rate. Analysis of the surface of the third plate did not reveal that it was rougher than the other plates, a usual cause of increased wear. However, it has to be recognized that a single defect or scratch on the surface can elevate the wear substantially and this is not always detected with two-dimensional profilometry. The mean and standard error incremental wear factors for both sets of counterfaces each treated as a group of data, showed little or no difference in the wear (Fig. 3). Statistical analysis using the Students $t$-test showed that the small difference in the means was not significant. The values for the average wear factor were similar to data recorded previously for smooth stainless steel, cobalt chrome alloy and alumina and zirconia ceramic counterfaces under similar conditions. Hence in its undamaged form, the DLC coating was considered not to affect the wear of UHMWPE markedly.

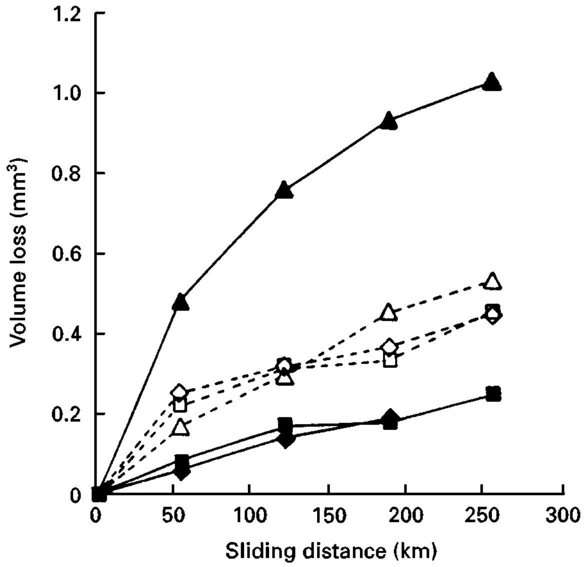


*Figure 2* Graph of volumetric wear of UHMWPE plotted against sliding distance for the undamaged counterfaces. Stainless steel: (□) 1, (◇) 2, (△) 3. DLC: (■) 1, (◆) 2, (▲) 3.

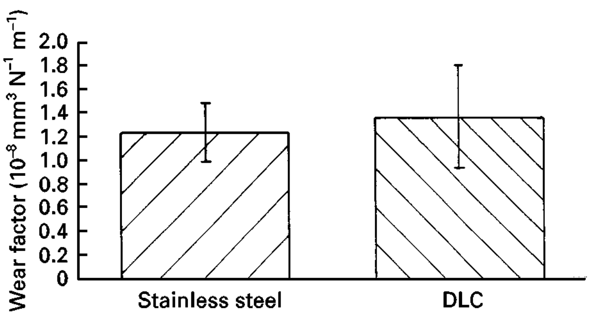


*Figure 3* Histogram of the mean wear factor $\pm$ SE for the undamaged stainless steel and DLC carbon counterfaces.

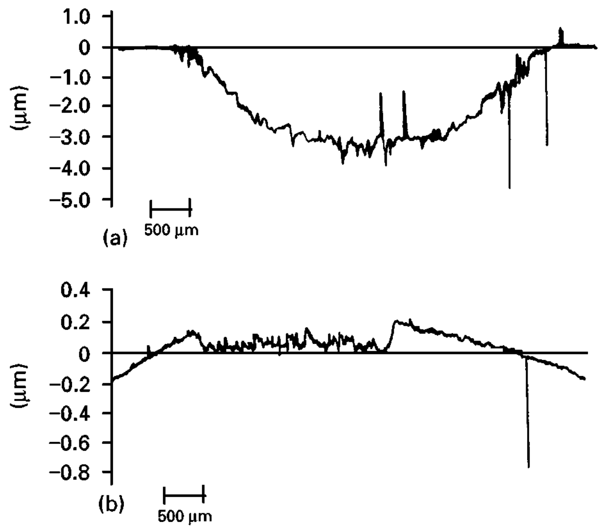


*Figure 4* Typical traces for the wear and damage to (a) the stainless steel counterface and (b) the DLC counterface, after the PMMA damage test.

The damage caused by the PMMA damage test was much lower on the coated carbon counterfaces compared to the uncoated stainless steel counterface. Fig. 4 shows that the depth of wear track on one typical DLC surface was less than 1 µm, and did not extend through the carbon coating compared to 8 µm on the stainless steel counterface. The surface roughness of the DLC coating was 0.15 µm compared to 2.2 µm for the stainless steel surface. Under these very severe conditions of damage with the PMMA pin sliding repeatedly on the counterfaces, the improved resistance to damage of the DLC coating was clearly shown. However, it should be noted that this type of severe damage was not representative of the damage found in metallic femoral heads.

In order to produce controlled damage that was representative of the third-body scratches to metallic femoral heads, a diamond stylus with a 2 µm radius was used to scratch the metallic- and DLC-coated counterfaces. Fig. 6 shows the three-dimensional profile of a typical scratch on the stainless steel counterface. The depth of the scratch was typically 2 µm deep, with the heights of the lips of the scratches being variable in the range 0.5–1.5 µm with occasional peaks greater than this, Fig. 7 shows two typical two-dimensional profilometer traces of the stainless steel and DLC counterfaces. In both cases, the depth of the valleys was about 2 µm, with the diamond stylus penetrating the DLC coating. However, the main difference occurred in the heights of the lips of the scratches with the DLC coating preventing the high pile up at the edge of the scratch with heights typically about 0.1–0.3 µm. The wear rate of UHMWPE on the damaged DLC coated counterfaces was much lower than on the damaged stainless steel counterface. The mean and standard error wear factors are shown in Fig. 8. The wear factor for the damaged DLC was seven times greater than for the smooth counterface, while the wear factor for the damaged stainless steel

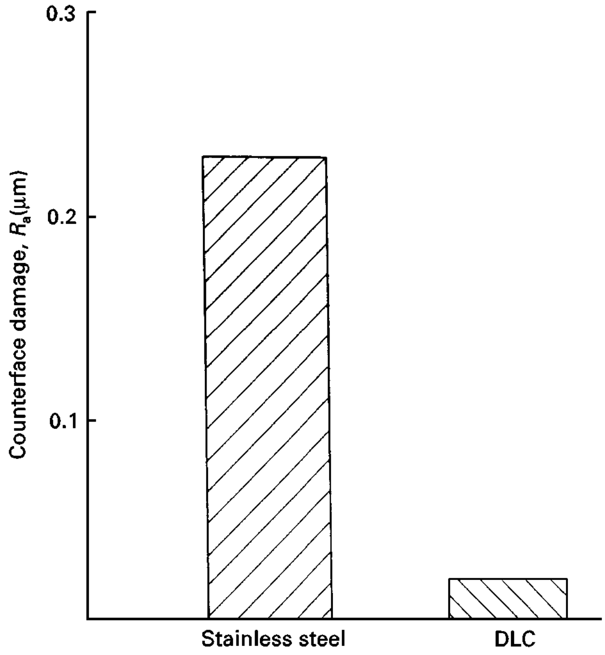


*Figure 5* The mean surface roughness of the counterfaces after the PMMA damage test.

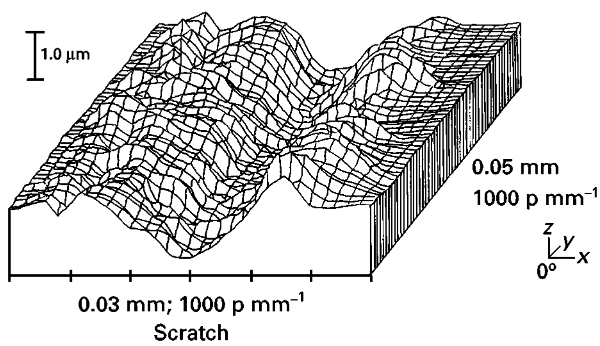


*Figure 6* Three-dimensional non-contacting laser profilometer trace of the scratch on the metallic surfaces.

was 50 times greater than the smooth counterface. The high wear rates on the scratched metal counterfaces was consistent with previous work [8].

## 4. Discussion

Metallic femoral heads have been shown to be damaged by third-body particles *in vivo* and laboratory experiments predict that these will increase the wear rate of UHMWPE acetabular cups. Laboratory tests also show little difference between the wear of UHMWPE when sliding on smooth metallic and ceramic counterfaces, yet clinical studies show lower wear rate with alumina ceramic heads compared to metallic heads. Laboratory tests have shown that alumina ceramic is more damage-resistant compared to metallic alloys, and therefore it is postulated that the reduced long-term wear rates with alumina ceramic are due to greater damage resistance and the ability to retain a smooth femoral counterface *in vivo*. However, this lower wear of UHMWPE with damaged ceramic counterfaces compared to damaged

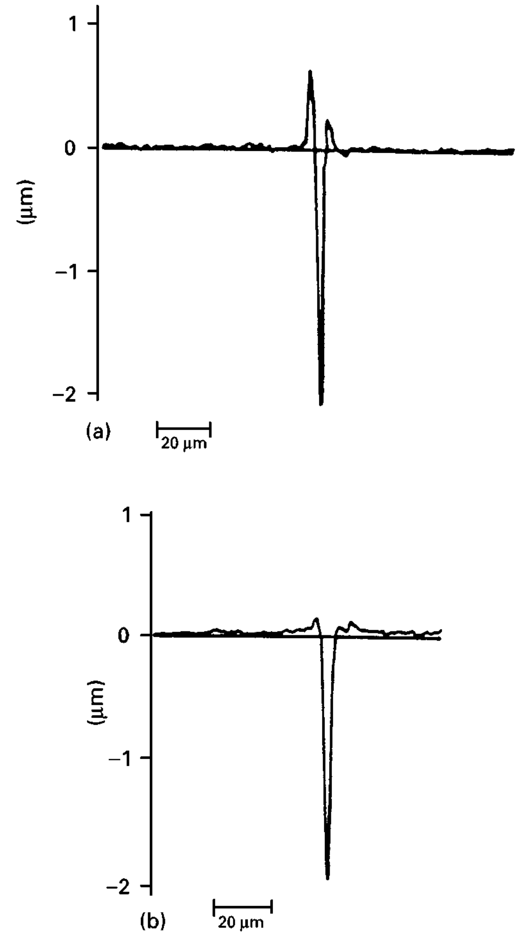


*Figure 7* Two-dimensional traces of the scratches to (a) the stainless steel and (b) the DLC counterface.

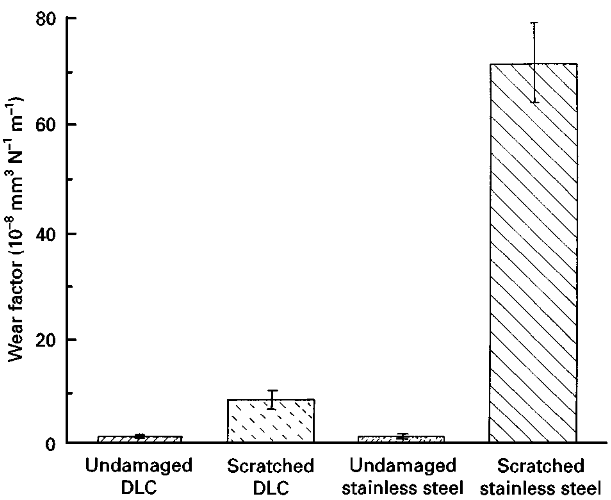


*Figure 8* The mean wear factor ± standard errors for the wear of polyethylene on the scratch counterfaces.

metal counterfaces has not actually been demonstrated *in vitro*.

It appears appropriate that, in the tribological evaluation of hard coatings for femoral heads, the wear of polyethylene is determined against undamaged and damaged counterfaces in comparative tests with metallic counterfaces. This approach was used in this study and although the DLC produced no difference in wear for the undamaged tests, it produced significantly lower wear rates than metals in the damage test.

Examination of explanted Charnley prostheses show many scratches with depths greater than 1 μm deep and peaks or lips to the scratches can be detected in the range 0.1–5 μm $R_p$. The artificial scratches produced on the stainless counterfaces are not untypical of this clinical damage. The DLC coating, on the other hand, prevented the high peaks or lips being formed, with much lower $R_p$ values than for the damaged stainless surfaces. This is a probable explanation for the lower wear rate on the damaged DLC compared to the damaged stainless steel. Previous studies of damage to alumina ceramic have also shown deep valleys to the scratches with little positive displacement in the height of the lips. This type of scratch is considered to be less harmful to the wear of UHMWPE.

Simple configuration wear tests and also this type of simple damage test, can well be criticized for not being representative of *in vivo* conditions, and it could be said that adding third-body particles to a hip-joint simulator is a more realistic test. It has been found that adding particles to solutions to simulate third-body wear produces highly variable results, due to variation in particle mechanics, entry into the contact and distribution in the test cell. The simple approach adopted in this study allowed much more control of the experimental variables, and produced less variation in the results. This has been shown to produce a highly significant difference between the materials.

This study shows that DLC has considerable potential benefits as a hard coating for femoral heads. There remain concerns about inconsistencies and variations in this type of coating and clearly further laboratory studies are required under more sophisticated conditions, including using third-body particles to evaluate the coating fully. However, these simple configuration first-stage tests are particularly encouraging.

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