JOURNAL OF MATERIALS SCIENCE: MATERIALS IN MEDICINE **10** (1999) 83–90

Diamond-like carbon coatings for orthopaedic applications: an evaluation of tribological performance

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A detailed investigation of the tribological behaviour of vacuum arc diamond-like carbon coated Ti–6Al–4V against a medical grade ultra-high molecular weight polyethylene is conducted in this work in order to investigate the potential use of diamond-like carbon coatings for orthopaedic appplications. Lubricated and non-lubricated wear experiments are performed using a standard pin-on-disc wear tester. The coefficient of friction is monitored continuously during testing and wear rate calculations are performed using surface profilometry measurements of worn disc surfaces. Sliding wear tests show the existence of two distinct friction and wear regimes distinguished by physically different mechanisms. In the first stages of wear, adhesion and abrasion are the dominant mechanisms of wear while fatigue processes are activated later in the tests. The effects of diamond-like carbon coating structure, surface roughness and lubrication on tribological behaviour are presented. Optimal process–structure–property design for vacuum arc plasma deposition is utilized in order to obtain strong adhesion to the titanium alloy substrate. Diamond-like carbon coatings significantly improve the friction and wear performance of the orthopaedic bearing pair and show exceptional promise for biomedical applications. © *1999 Kluwer Academic Publishers*

1. Introduction

In arthroplasty, the function of the artificial joint is to restore smooth articulation between the bones of the joint. In total joint replacements, the orthopaedic bearing components are typically manufactured from highly polished alloys that articulate against a medical grade ultra-high molecular weight polyethylene (UHMWPE) insert. The choice of UHMWPE polymer to replace damaged cartilage in the articulating joint stems from its high toughness, its low friction coefficient and superior creep resistance. The choice of titanium is derived from its low modulus for better load transfer to surrounding healthy bone [1], high specific strength and superior fatigue resistance. As an orthopaedic alloy, however, the titanium alloys are limited by their sensitivity to contact wear and fretting corrosion [2]. Orthopaedic surfaces are susceptible to oxidative wear caused by repetitive disruption of passive oxide films and the subsequent reoxidation of the exposed metal surface. As a consequence, hard metal oxides accelerate the abrasive wear of the bearing surface roughening and result in metal ion release into the local joint environment that can illicit further biological reactions. While ion implantation has been utilized to improve the wear behaviour and fretting resistance of titanium alloy components, a coating appears necessary for eliminating the potential problem of metal ion release. In this regard, diamond-like carbon (DLC) coatings are not only chemically inert and biocompatible in these applications but can serve as useful wear coatings [3–5].

Recent studies [4, 5] demonstrate that DLC coatings can provide viable solutions to the problems of wear and degradation in total joint replacements. DLC coating technology enables the conformal coating of complex shapes. In this respect, DLC coatings are superior to ceramic components [6] that are limited by their inherent brittleness and manufacturability. Additionally, DLC coatings can be processed with precise dimensional tolerances and surface finishes necessary for orthopaedic applications.

DLC coatings are not without limitations and structural properties can vary widely depending on the deposition techniques employed. One of the greatest challenges of DLC technology is adhesion and internal stresses. Vacuum arc plasma deposition can eliminate this problem through deep intermixing of the substrate and film via pulsed high voltage substrate bias [7–9]. The pulsed bias technique provides flexibility in controlling the incident ion energy so that film properties can be tailored. Further, multilayer coating structures of discretely deposited "soft" layer (at high negative bias voltages) and "hard" layer (at low negative bias voltages) are a promising approach to adjust the internal residual stresses and to improve the coating adhesion strength to the underlying substrate.

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DLC produced by the vacuum arc plasma technique is also known as amorphous diamond. These non-crystalline coatings are hydrogen free, highly sp^3-bonded (up to 85%, [9]) and closely mimic the characteristics of natural diamond. These amorphous coatings have a very high hardness (60 GPa), high mass density ($3.0\,g\,cm^{-3}$, [8, 9]), low surface roughness and good film adhesion necessary for orthopaedic applications.

The purpose of this study is to investigate the tribological behaviour of DLC (deposited by vacuum arc plasma deposition) coated Ti–6Al–4V against UHMWPE in order to evaluate the potential of such coatings for total joint replacements. The details of the structural characterization and mechanical properties using transmission electron microscopy, Raman spectroscopy and nanoindentation are reported elsewhere [9]. In this work, short-term and long-term pin-on-disc sliding tests are conducted in order to assess the tribological properties and to evaluate the structural integrity of the coating. Two environments are considered in this study: a non-lubricated condition representing the extreme case of adhesive wear and a distilled water lubricated condition serving as a reference for future tests in biological fluids. For comparison, non-coated Ti–6Al–4V alloys sliding against UHMWPE are evaluated. Coefficients of friction are recorded *in situ* during the sliding tests and the wear surface evolution is examined progressively using optical microscopy and scanning electron microscopy (SEM). Wear rate calculations are performed using surface profilometry measurements of worn disc surfaces and weight loss methods. The tribological behaviour of UHMWPE, Ti–6Al–4V and the DLC coatings are studied using friction and wear data. Wear debris formation and wear surface evolution are studied in order to optimize the DLC coatings for orthopaedic applications.

2. Experimental procedure

2.1. Materials

Medical grade UHMWPE was supplied by the Department of Biomaterials and Biomechanics at the Hospital for Special Surgery in New York. All polymeric material in this study was Hostalen GUR 4150 (Hoechst Celanese, Houston, TX), in extruded rod form. The polymer was machined into hemispherically ended pins for conformal sliding contact. The polymer pins had the following geometry: diameter, $\phi = 6.35$ mm, radius of curvature, $R = 3.175$ mm, and pin length, $l = 12.7$ mm. The polymer pins for short-term tests were polished using an Al_2O_3 water slurry of 0.3 μm and then 0.05 μm powder-size in order to remove machining marks. After polishing, the pins were ultrasonically cleaned in order to remove any attached Al_2O_3 particulate or debris. This was followed by a final wash with distilled water. After cleaning, the pins used for dry tests were naturally dried for two weeks in the ambient laboratory atmosphere while the pins for wet tests were soaked in distilled water for two weeks prior to wear testing.

Commercially available Ti–6Al–4V (annealed) from Robin Materials (Mountain View, CA) was used as the substrate for DLC coatings. The Ti–6Al–4V alloy was machined into discs with a diameter, $\phi = 25.4$ mm and thickness, $t = 6.35$ mm. The discs were ground flat with SiC and alumina in order to obtain a mirror finish surface roughness, (Ra approximately 0.05–0.06 μm) comparable to orthopaedic surface roughness. Substrates were ultrasonically cleaned in acetone and methanol to remove debris or contaminants. DLC coatings were subsequently deposited onto the titanium alloy discs using a vacuum arc plasma technique developed at the Lawrence Berkeley National Laboratory [9]. A 30 min predeposition sputtering in argon plasma was conducted to remove the oxidative passivation layer on the Ti–6Al–4V disc surface.

The deposition of the DLC coatings includes a two-step process that is described in detail elsewhere [8–10]. The first step is to produce a highly adherent but relatively “soft” (hardness of the order of 15–25 GPa) thin layer (approximately 25–30 nm in thickness) on the titanium alloy substrate using a high pulsed bias of -2.0 kV. In the second step, a low pulsed bias of -0.2 kV is used to produce the “hard” surface layer. The total coating thickness is of the order of 100 nm. In addition, two multilayered (three or five layers, 100–150 nm thick) DLC coatings are prepared with sequentially deposited “soft” and “hard” layers in order to study the effects of the DLC structure on the tribological properties. Unless otherwise specified, the DLC coating refers to the standard two-layer process.

2.2. Methods

A standard unidirectional pin-on-disc test configuration was used for the wear studies. The frequency was fixed at 1 cycle s^{-1} corresponding to a sliding velocity of 44 mm s^{-1}. The short-term tests were sustained for 500 m of sliding while long-term tests were sustained for 44 km of sliding (1.0 million cycles) unless premature failure occurred. The long-term tests were interrupted intermittently (at 100 000, 250 000, 500 000 and 750 000 cycles) for optical examination. A 9.79 N dead weight was applied to the system resulting in an initial maximum contact stress of 30.0 MPa (calculated from Hertzian contact theory). The nominal contact stress dropped quickly to 12.5–15.4 MPa after short-term sliding and slowly decreased as the pin deformed to a steady state value of 6–7 MPa.

The dynamic friction forces were measured *in situ* using strain gauges. The amplified strain gauge outputs were sampled at 40 Hz. The coefficient of friction (COF) was determined by averaging the 40 measurements acquired during each cycle. The progressive wear loss of UHMWPE pins was determined from dimensional changes of the pin-end scar diameter. This technique provided polymer wear volume and eliminated the complexity of lubricant absorption and wear debris attachment.

The wear rate, K, of the UHMWPE pins was calculated as $K = V/PL$, where V was the volume loss calculated from pin-end geometry change, L was the sliding distance, and P was the applied dead weight.

For each short-term sliding test, three experiments were conducted to obtain an average value of COF and wear rate. In order to elucidate the friction and wear surface evolution of the pins and discs, optical microscopy of the surfaces was performed at the completion of the short-term tests or at each intermittent stop during the long-term tests. A Jeol 35F SEM with back-scattering detectors was used for detailed surface fractography at the completion of each wear test. The polymer pin surfaces were sputter-coated with a 20 nm layer of Au–Pd for SEM characterization.

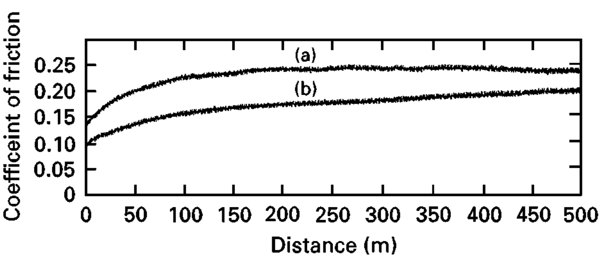

Figure 1 Short-term dynamic coefficient of friction of UHMWPE pins sliding against the non-coated (a) and DLC coated (b) Ti–6Al–4V discs under unlubricated test conditions.

3. Results

3.1. Friction and wear studies

A significant reduction in the COF is observed when DLC coatings are applied to the Ti–6Al–4V substrates. Fig. 1 is a plot of the COF as a function of sliding distance for the (a) uncoated titanium alloy and (b) the standard two-layer DLC coating for unlubricated short-term (500 m) conditions. The COF for the unlubricated sliding of UHMWPE against Ti–6Al–4V demonstrates a transient period in the initial 200 m of sliding prior to reaching a steady state value of COF on the order of 0.23. In comparison, the COF for the dry sliding of UHMWPE against DLC coated Ti–6Al–4V is initially lower ($COF_{init} = 0.1$) and remains lower in the quasi-steady state condition ($COF_{ss} = 0.20$). The improvement of frictional performance by means of using DLC coatings is also prevalent for the distilled water lubricated conditions. For the wet sliding conditions, a quasi-steady state COF value of 0.18 and 0.08 is measured for the non-coated and DLC coated conditions, respectively. These findings are summarized in Table I.

Initial surface roughness plays a crucial role in the frictional mechanisms of the bearing pair. Fig. 2 illustrates the effect of the polymer surface roughness effect on the frictional behaviour when sliding against the DLC coated disc in the lubricated condition. The polished polymer pin (Ra = 0.05 μm) sliding against the smooth coating results in a higher friction coefficient ($COF_{ss} = 0.07$) than that for the as-machined (Ra = 0.10 μm, $COF_{ss} = 0.04$) polymer pin. This behaviour is attributed to the larger initial contact area and concomitant adhesive transfer for the smooth sliding pair surfaces. Further, the surface roughness directly effects the build-up of any boundary lubrication film between the sliding pair.

The structure of the DLC coating affects the sliding friction coefficient significantly. Fig. 3 compares three different DLC structures: (a) a two-layer structure with "hard" outer layer, (b) a five-layer structure with a "soft" outer layer, and (c) a three-layer structure with a "soft" outer layer. The two-layer DLC coating with the "hard" outer layer shows a very long stable decrease to a low steady state level, $COF_{ss} = 0.04$ (Table I). The three-layer DLC coatings with the "soft" outer layer result in an initial jump in COF followed by quick decrease in friction levels. The drop-off in dynamic friction coefficient indicates the point at which the outer layer is worn off the underlying substrate. A similar, but less dramatic effect, is seen in the five-layer coating. Additionally, the nominal COF level for the five-layer DLC coating decreases to approximately 40% of the friction value for the three-layer coating. Although friction coefficients are greater than the two-layer structure, the five-layer DLC structure results in the least amount of coating damage and the lowest UHMWPE wear rate for long-term sliding tests.

The wear rates of the polymer for the various bearing systems are affected strongly by the DLC structure, surface roughness and test environment. Tables I and II summarize the findings of this study for both

TABLE I UHMWPE polymer pins: Wear rates and coefficients of friction at 500 m sliding distance[a]

Ti–6Al–4V disc	Ra (μm)	Lubricant	Pin wear rate ($\times 10^{-6}$ mm^3 Nm^{-1})	COF
Polished				
No DLC coating	0.055	Dry	2.04	0.236 ± 0.001
	0.08	Dry	2.41	0.170 ± 0.001
	0.075	Distilled water	Failure	0.165 ± 0.005
	0.09	Distilled water	Failure	0.130 ± 0.002
Two-layer DLC	0.06	Dry	1.02	0.162 ± 0.001
Two-layer DLC	0.03	Distilled water	1.51	0.067 ± 0.007
As machined				
No DLC coating	0.10	Distilled water	N/A	0.113 ± 0.003
Two-layer DLC	0.07	Dry	1.76	0.198 ± 0.001
	0.09	Distilled water	N/A	0.040 ± 0.004
Three layer DLC "soft" outer layer	0.06	Distilled water	N/A	0.245 ± 0.005
Five-layer DLC thin "soft" outer layer	0.06	Distilled water	N/A	0.112 ± 0.003

[a] All the pins are hemispherically-ended (ϕ = 6.35 mm) under a dead weight of 9.79 N. Unless specified otherwise, the two-layer DLC coating has a thickness of 100 nm with a hard outer layer.

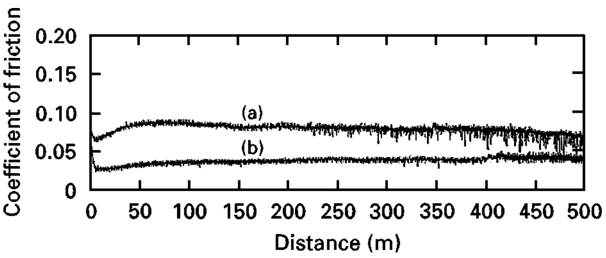

Figure 2 The effect of surface roughness on the long-term dynamic coefficient of friction of polished (a) and as-machined (b) UHMWPE pins sliding against DLC coated Ti–6Al– 4V discs under water lubricated test conditions.

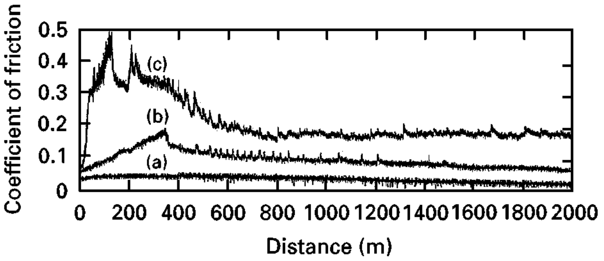

Figure 3 The effect of coating structure on the long-term dynamic coefficient of friction for a two-layer DLC with hard outer layer (a) five-layer DLC with thin, soft outer layer (b) and three-layer DLC with soft outer layer sliding (c) against UHMWPE pins in water lubricated test conditions.

short-term (500 m) and long-term (22 km) sliding, respectively. Fig. 4 shows the wear rates, K, of the as-machined UHMWPE pin as a function of sliding distance for both the non-coated and the DLC coated titanium alloy disc counter bearing in water lubricated conditions. It is clear that the use of DLC coatings significantly reduces the polymer sliding wear rates while protecting the underlying titanium alloy substrates from failure. For the non-coated Ti–6Al–4V discs, the surface oxidation mechanisms are exacerbated in the presence of the aqueous media and result in increased levels of abrasion and severe scoring of both bearing materials via oxide debris.

Fig. 5 shows the effect of DLC structure on the wear rates of the polymer pins under lubricated conditions (summarized in Tables I and II). The different coating structures result in substantially distinct wear rates early in the tests. The three-layer DLC coating with the “soft” outer layer demonstrates the highest wear rate. As sliding continues to about 12 km, the wear rate decreases quickly and approaches that obtained with the “hard” outer layer DLC coating. This change in wear rate is linked to the wear-through or spallation of the soft outer layer. In contrast, the five-layer DLC coating with the thin “soft” outer layer provides the lowest wear rates for the first 22 km of sliding. The improved wear performance for the five-layer

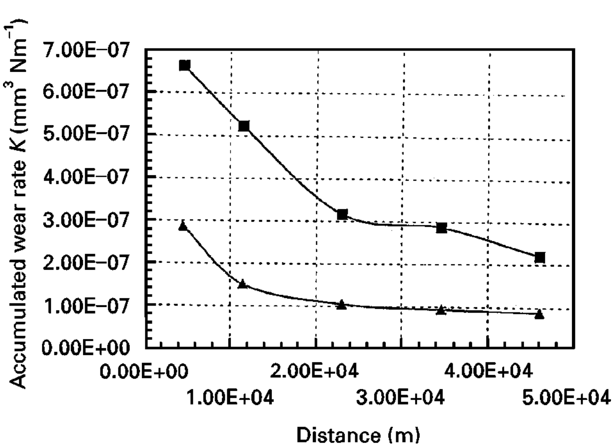

Figure 4 Accumulated wear rates of UHMWPE pins sliding against (■) non-coated and (▲) DLC coated Ti–6Al–4V discs under lubricated test conditions.

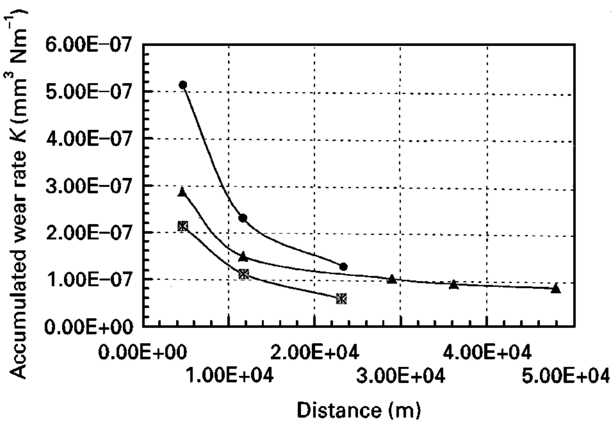

Figure 5 Accumulated wear rates of UHMWPE pins sliding against (▲) two-layer DLC coating, (●) three-layer DLC coating and (*) five-layer DLC coated Ti–6Al–4V discs under lubricated test conditions.

TABLE II UHMWPE as-machined: wear-rates and coefficients of friction at 0.5×10^6 cycles of sliding (22 km)[a]

Ti–6Al–4V disc	Ra (μm)	Lubricant	Pin wear rate ($\times 10^{-7}$ mm^3 Nm^{-1})	Coating damage	COF
As machined					
No coating	0.10	Distilled water	2.20 ± 0.22	Ti–6Al– 4V failure	0.072 ± 0.002
Two-layer DLC	0.06	Dry	1.33 ± 0.13	No	0.217 ± 0.002
	0.09	Distilled water	1.13 ± 0.11	Severe	0.038 ± 0.005
Three-layer DLC “soft” outer layer	0.06	Distilled water	1.30 ± 0.13	Local	0.017 ± 0.002
Five-layer DLC “soft” outer layer	0.06	Distilled water	0.62 ± 0.06	Local/mild	0.017 ± 0.005

[a] All the pins are hemispherically-ended ($\phi = 6.35$ mm) under a dead weight of 9.79 N. Unless specified otherwise, the 2-layer DLC coating has thickness of 100 nm with a hard outer layer.

structure is most likely the result of the lubrication provided by "soft" carbon debris and reduced internal stresses of the structure [9]. Once the tests proceed for more than 20 km of sliding, and outer layers are worn, the wear rates for the different DLC structures gradually approach average values near $1 \times 10^{-7}\,\mathrm{mm^3\,Nm^{-1}}$.

3.2. Surface evolution

Non-lubricated sliding of the titanium alloy disc and UHMWPE pin results in serious levels of wear damage. After only 500 m of sliding, SEM (Fig. 6) reveals that (a) the surface of the titanium disc is covered with transferred polymer debris and (b) the polymer surface is covered with surface cracks near regions of substantial plastic deformation. At severe levels of deformation, the polymer surface extrudes or delaminates into thin sheets of polymer debris, as shown in Fig. 6c. Continuous sliding eventually leads to catastrophic failure when the titanium oxides debris initiates severe surface scoring on both counterparts. When DLC coatings are utilized in unlubricated environments, the level of polymer deformation is significantly reduced (Fig. 7).

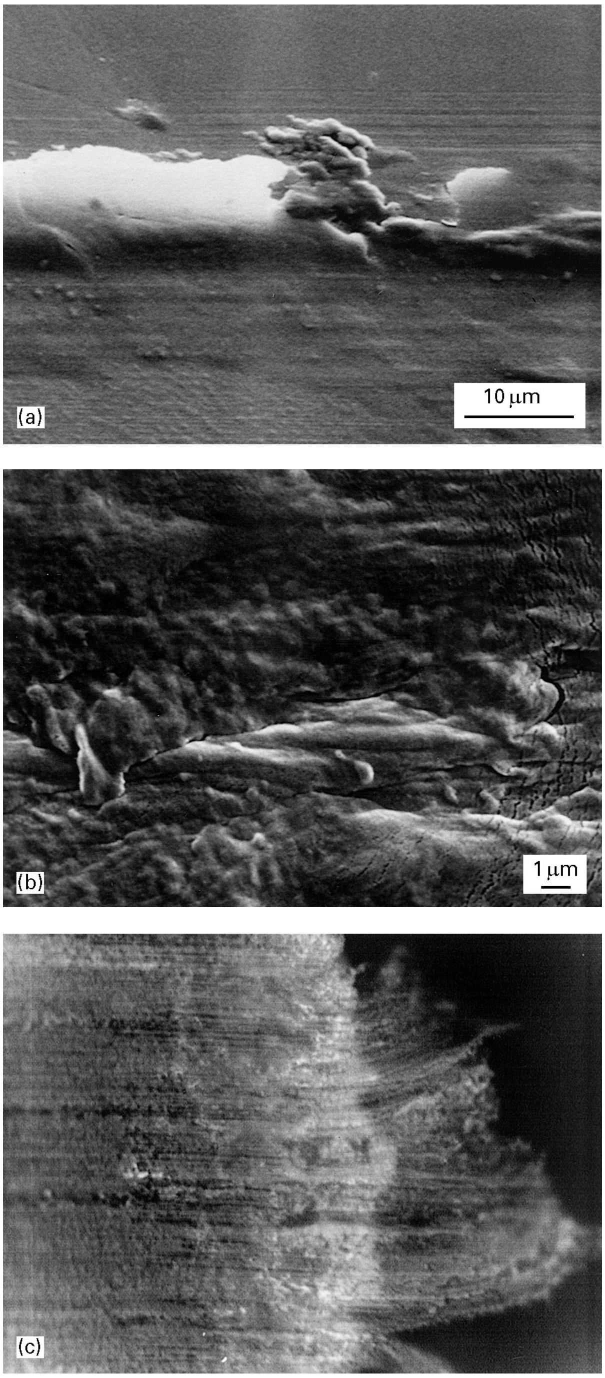

Figure 6 Scanning electron micrographs showing (a) lumpy polymer transfer to the uncoated Ti–6Al–4V disc after 500 m of dry sliding and (b) surface cracks in the UHMWPE which precede the (c) delamination of polymer flakes in the extrusion direction.

The introduction of distilled water for the non-coated titanium results in the occurrence of catastrophic failure due to severe oxidation and abrasion of the bearing surfaces. Fig. 8 shows the surfaces of the (a) polymer and (b) titanium alloy disc after only 500 m of sliding. Fig. 8a illustrates the plastic tearing along the deep abrasion grooves that eventually led to debris in the form of elongated fibrils. The Ti–6Al–4V disc surface is simultaneously scored by metal oxide particles as shown in Fig. 8b. It is believed that the distilled water increases the reactivity of the metal surface with the environmental media resulting in enhanced levels of metal surface oxidation and abrasion mechanisms.

For the DLC coatings, the introduction of distilled water provides a small level of boundary-lubrication to the sliding counterfaces. After 500 m of sliding, the polymer surface shows undulated features that appear slightly roughened but with very few identifiable sliding scratches (Fig. 9a). No polymer tearing, delamination, or pitting sites are observed for the DLC coating systems in short-term sliding tests. For the long-term sliding tests, however, the polymer surfaces become progressively burnished, but damage is minimal in comparison with the non-coated cases. Fig. 9b shows the polymer surface after 1.0 million cycles (44 km) of sliding against a two-layer DLC coating. The micrograph depicts the onset of surface fibrillation of the polymer.

Fig. 10a–d shows the worn surfaces of three-layer, "soft" outer layer DLC coating after 22 km of sliding. In comparison with the standard two-layer coating

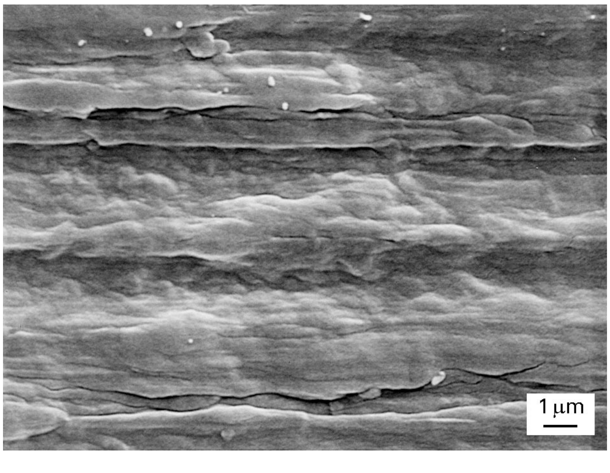

Figure 7 Scanning electron micrograph showing the undulated polymer surface after sliding 500 m of dry sliding against the DLC coated Ti–6Al–4V disc.

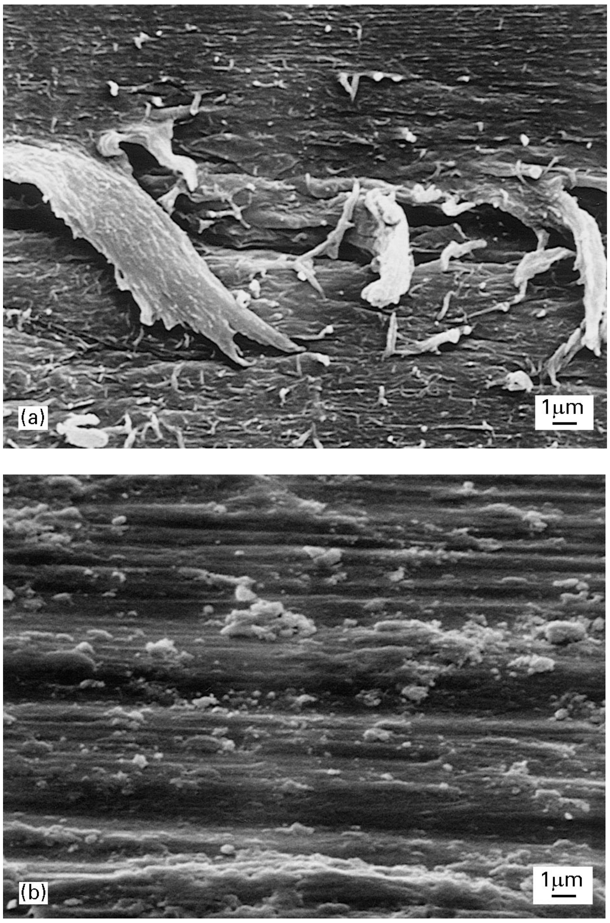

Figure 8 Scanning electron micrographs showing scratches (a) and torn fibrils in the UHMWPE, and the (b) corresponding scored Ti–6Al–4V disc after 500 m of water lubricated sliding.

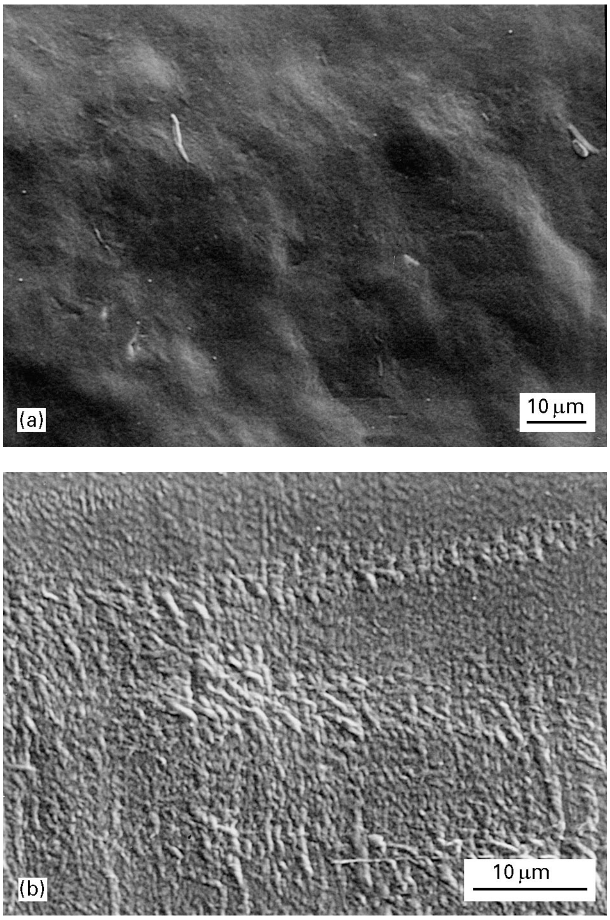

Figure 9 Scanning electron micrographs showing (a) slight undulations in the polymer after 500 m of sliding, and (b) fibrillation of the UHMWPE after 11 km of sliding in lubricated conditions.

that has a "hard" outer layer, the three-layer DLC coating results in substantially more surface damage. Severe fibrillation and plastic deformation is evident in the polymer (Fig. 10a, b) while blistering and delamination occur in the outermost layer of the DLC coating (Fig. 10c, d). In comparison, the five-layer DLC coating with the thin "soft" outer layer provides the lowest polymer wear rate and the least amount of surface damage amongst all the systems in this study. This is associated with the lubrication provided by the wear of the outermost layer. It is believed that the "soft", graphitic layer provides a lubricating effect on the sliding pair and results in a decreased friction force, lower wear rate and little surface damage.

4. Discussion

In the early stages of sliding, polymer transfer due to adhesion results in high friction values and polymer wear loss rates. The polymer transfer occurs in the form of lumps and thin layers. The former mechanism generally leads to larger polymer wear loss rates and greater surface roughening while the latter transfer process is more adherent and protects the coating surface from further wear. The introduction of a DLC coating elicits a thin polymer transfer layer that results in lower dynamic friction coefficients and wear rates. Further, the addition of a DLC coating significantly alters the surface chemical and mechanical properties of the tribosystem. As a result, the severe oxidative wear of the Ti–6Al–4V is eliminated, and thus the tribological performance for both dry and lubricated conditions is substantially improved.

The structure of the DLC coating plays an important role in the tribological properties of the system. If internal stresses can be minimized and adhesion maintained, the films with thicker coatings can provide improved long-term wear resistance. A promising approach to solving this problem is the utilization of multilayer DLC coatings comprised of sequentially deposited "soft" and "hard" layers in order to minimize internal stresses and maximize substrate adhesion. The two-layer coatings with a "hard" outer layer are more effective in improving the sliding friction and wear performance as long as the integrity of the coating is maintained. An unfortunate consequence of the processing for the two-layer structure is high internal stresses that limit the maximum thickness of the coating [9]. In the case of the three-layer DLC coating with the soft outer layer, the strong surface interactions and high friction coefficients result in the high wear rates of the polymer. The five-layer DLC coating with the thin, soft outer layer results in very low rates of the UHMWPE. The primary structural success of this multilayer coating is the result of the reduced internal stress due to the layering [9–11] and the lubrication provided by the wear of the outer graphitic layer [12–13].

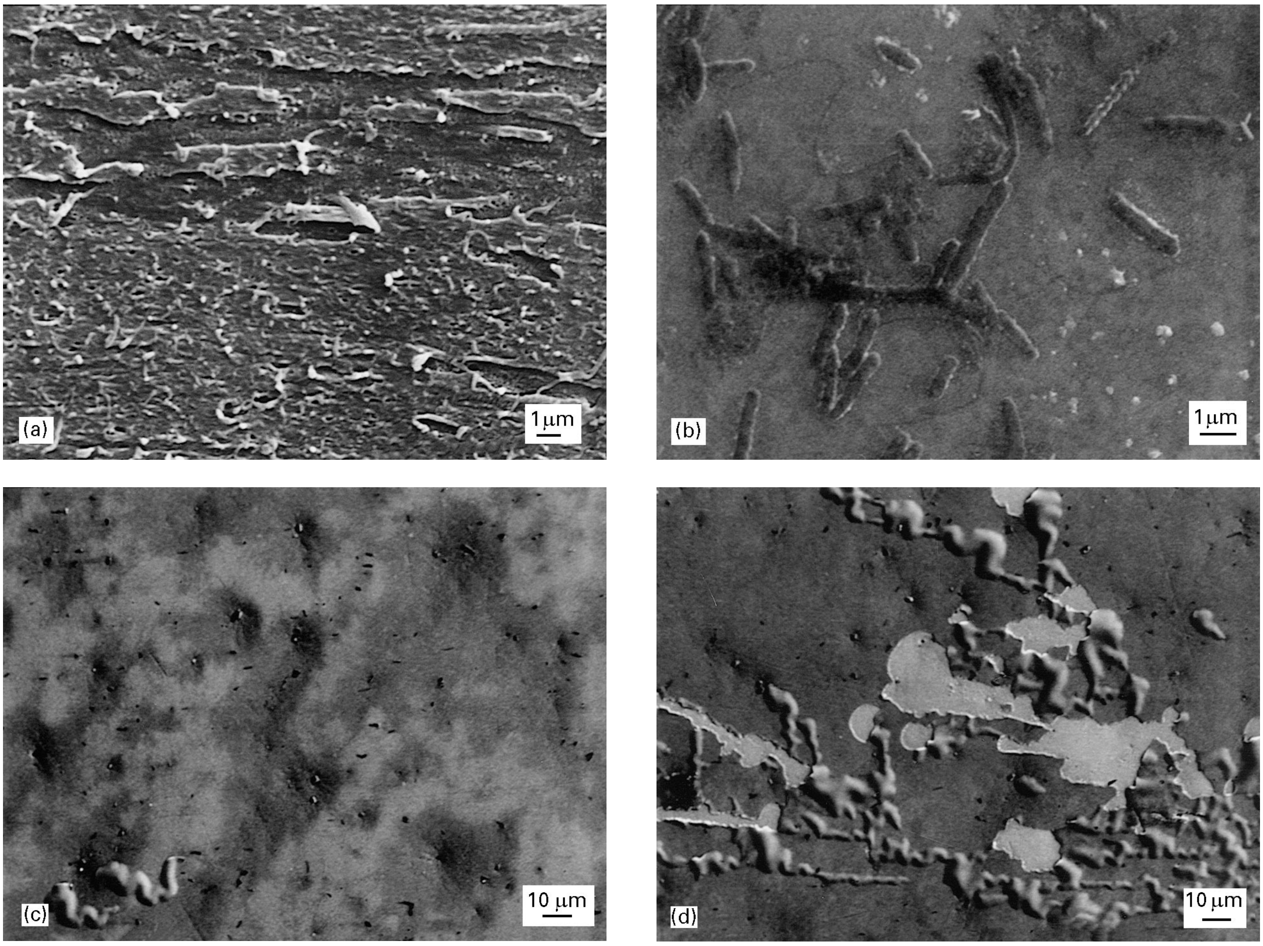

Figure 10 Scanning electron micrographs showing, (a) surface delamination of the polymer, (b) presence of fibril-form polymer debris, (c) the presence of (1) carbon microparticles and (2) polymer particle debris on the DLC coated disc, the onset of (d) delamination in the coating after 1 000 000 cycles of loading in a lubricated environment.

Surface layer failure is a concern for the DLC coated substrates. The initiation of the coating failure is most likely to occur while contact pressures are still high (> 16.0 MPa). Substrate surface roughness and topology (such as peak–valley height) are important factors in initiating coating failures. The underlying substrates with higher peak–valley magnitudes result in larger surface asperities and higher local stresses. The arising asperities experience higher deformation at contact points and result in earlier wear failures. The DLC coatings with the best wear performance are associated with substrates possessing small surface peak–valley magnitudes or those with a thickness great enough to suppress the underlying substrate surface asperity effects.

Lubrication makes a substantial difference in tribological performance. In dry sliding conditions, the DLC coatings perform well due to the transferred adhesive polymer films. On the other hand, the introduction of distilled water suppresses the polymer adhesive transfer due to the very low wettability of distilled water on both the UHMWPE and the DLC surfaces. Thus, the water environment does not provide sufficient lubrication to improve the wear performance for DLC coatings effectively. As mentioned previously, the use of an aqueous environment in the absence of a DLC severely degrades the tribology of the titanium alloy. Future improvements for the DLC coatings may be achieved if wear tests are performed with bio-fluids known to wet both surfaces [14].

Surface evolution characterized by microscopy reveals four basic types of wear debris generated by pin-on-disc sliding: flakes, lumps, fibrils (filaments) and round submicrometre particles. The flake-form debris is the dominant debris type in the long-term sliding conditions and is believed to be the result of extrusion processes or fatigue damage in the polymer. Polymer detachment is observed where frictional heating and shear stresses are elevated [15]. More evidence of this debris type is found in dry sliding cases where the frictional heat softens the polymer and facilitates the shear deformation and extrusion processes. The larger polymer lumps are formed in conjunction with adhesive polymer transfer. This type of debris is evident after long-term sliding and is usually present with polymer fibrils torn from the deep grooves (oriented in the siding direction). This suggests that lump and fibril debris types are linked with abrasive mechanisms associated with the plowing and tearing of the polymer. The last type of debris observed in this study is the small round particulate and is prominent in the non-coated systems suggesting that it is linked to abrasive mechanisms. This submicrometre debris is of critical concern to the orthopaedic community as its size-scale enables transfer through the lymph system and is known to elicit biological cell reactions in total joint replacements [16].

5. Conclusions

DLC coatings on titanium result in considerable reduction of wear rates and submicrometre debris formation in orthopaedic grade UHMWPE. The coatings provide lower friction and successfully protect the Ti–6Al–4V substrate from severe oxidation and subsequent abrasive mechanisms. The use of multilayer DLC coatings has great potential to provide tailored properties that improve the coating longevity and optimize wear performance. The improved tribology in addition to biocompatibility and cost-effectiveness make DLC coatings a very promising technology for orthopaedic bearing surfaces.

Acknowledgements

This work is partially supported by NSF grant No. 442 444-22 178 to the University of California at Berkeley and the Vice Chancellor's Research Award for Doctoral Students. The authors would like to thank the Hospital for Special Surgery for providing the medical grade UHMWPE for this study. The authors are especially thankful to Dr Ian Brown for providing access to the DLC coating deposition facility at the Lawrence Berkeley National Laboratory.

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Received 18 August 1997
and accepted 26 January 1998