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Wear of surface engineered metal-on-metal hip prostheses

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The wear of existing metal-on-metal (MOM) hip prostheses (1 mm^3/million cycles) is much lower than the more widely used polyethylene-on-metal bearings (30–100 mm^3/million cycles). However, there remain some potential concerns about the toxicity of metal wear particles and elevated metal ion levels, both locally and systemically in the human body. The aim of this study was to investigate the wear, wear debris and ion release of fully coated surface engineered MOM bearings for hip prostheses. Using a physiological anatomical hip joint simulator, five different bearing systems involving three thick (8–12 μm) coatings, TiN, CrN and CrCN, and one thin (2 μm) coating diamond like carbon (DLC) were evaluated and compared to a clinically used MOM cobalt chrome alloy bearing couple. The overall wear rates of the surface engineered prostheses were at least 18-fold lower than the traditional MOM prostheses after 2 million cycles and 36-fold lower after 5 million cycles. Consequently, the volume of wear debris and the ion levels in the lubricants were substantially lower. These parameters were also much lower than in half coated (femoral heads only) systems that have been reported previously. The extremely low volume of wear debris and concentration of metal ions released by these surface engineered systems, especially with CrN and CrCN coatings, have considerable potential for the clinical application of this technology.

Introduction

Failure of hip prostheses due to polyethylene wear debris-induced osteolysis in young and active patients has led to considerable clinical interest in alternative metal-on-metal (MOM) bearings for hip prostheses. These MOM bearing couples have been shown to have much lower wear rates than polyethylene bearings in *in vitro* simulator tests [1, 2] with wear rates for MOM prostheses approaching 1 mm^3 per million cycles, which are close to those found in recent clinical studies [3]. While these low wear volumes and the nature of the metallic debris produced may have the potential to overcome the problems of inflammation and osteolysis inherent with polyethylene bearings [4], metallic wear debris from cobalt chrome bearings is extremely small, typically less than 30 nm [5]. These small particles have also been reported in periprosthetic tissue [6] and provide a large surface area and surface energy for ion release.

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TABLE I Material combinations tested in hip joint simulator tests

Heads	Number	Inserts	Number
LC CoCrMo	3	HC CoCrMo	3
TiN coated LC CoCrMo	3	TiN coated HC CoCrMo	3
CrN coated LC CoCrMo	3	CrN coated HC CoCrMo	3
CrCN coated LC CoCrMo	3	CrCN coated HC CoCrMo	3
CrN coated LC CoCrMo	3	TiN coated HC CoCrMo	3
CrN coated LC CoCrMo	3	DLC coated HC CoCrMo	3

Clinical research has demonstrated that patients with long term (> 20 years) MOM total hip replacements have substantially higher cobalt and chromium ion concentrations in their serum and urine than controls [7]. There have been isolated cases of cytotoxic effects from metal debris and tissue necrosis *in vivo*, particularly when metal wear was high [8]. Recent *in vitro* cell studies with nanometer-sized metallic wear debris have shown cytotoxicity at high-particle concentrations [9]. In addition, there have been reports suggesting that the release of metal ions from metallic implants may cause type IV delayed-type hypersensitivity reactions in some patients, which could be linked to an increased risk of implant failure [10]. There is, therefore, considerable interest in further reducing the wear, wear debris and ion release of MOM bearings for hip prostheses.

Surface engineering of the metallic bearing surface offers an alternative approach to reduce metallic wear debris in MOM bearing couples for hip prostheses. In the first part of this study, half coated prostheses (coated femoral heads against high carbon ($> 0.2\%$) CoCrMo alloy acetabular inserts) were investigated for their potential to reduce wear, wear debris and metallic ion release [11]. Whilst substantial improvements were achieved with these half coated prostheses, there is the potential to further reduce the wear on the uncoated metal inserts, by applying surface engineered coatings to both femoral heads and acetabular inserts. The aim of this study was to investigate the wear of fully coated surface engineered prostheses in short-term hip joint simulator tests and with a selection of surface treatment in long-term simulator studies.

Materials and methods

Materials

Twenty eight millimetre diameter hip prostheses were used in this study. The femoral heads were manufactured from medical grade low carbon (LC; $< 0.07\%$) wrought CoCrMo alloy (ASTM F1537-94), and the inserts were manufactured from medical grade high carbon (HC; $> 0.2\%$) wrought CoCrMo alloy (ASTM F1537-94). Titanium nitride (TiN), chromium nitride (CrN) and chromium carbonitride (CrCN) coatings were applied by arc evaporative physical vapour deposition (AEPVD) and the diamond-like carbon (DLC) coating by plasma assisted chemical vapour deposition (PACVD). The thicknesses of the TiN, CrN and CrCN coatings were between 8 and 12 µm, whereas the thickness of the DLC coating was 2 µm. All coatings were deposited by IonBond Ltd. The wear of these coated components was compared to clinically used MOM hip joint prostheses. The sizes of the heads were carefully controlled to provide a constant radial clearance of 30 µm between the final articulating components after coating. Heads and inserts were polished after coating to a surface finish R_a, with the exception of the DLC coated heads which had an unpolished R_a of < 0.02 µm before the wear tests. The coating process caused droplets of coating several micrometres high to be deposited on the surface of the femoral heads. Post coating polishing removed or levelled off any asperities formed by micro metal droplets leaving small pits on the surface of the femoral heads and acetabular inserts. Five different combinations of components were developed with three pairs of samples tested for each combination as shown in Table I.

Simulator tests

The wear tests were conducted at 1 Hz using the Leeds Mark II physiological hip joint simulator [1, 2]. The wear rates and debris produced in this hip simulator are compared to the wear rates and debris found in a second simulator and from *in vivo* tissue samples in references [2, 5]. This particular simulator and test condition was chosen because it produced the more clinically relevant wear rates of the order of 1 mm^3/million cycles [2]. The inserts were placed in the superior position to the heads and inclined in the anatomical position at 45° to the vertical axis (Fig. 1). A single axis twin peak Paul type loading curve [12] was applied through the vertical axis of the simulator (Fig. 2). Two directions of motion were

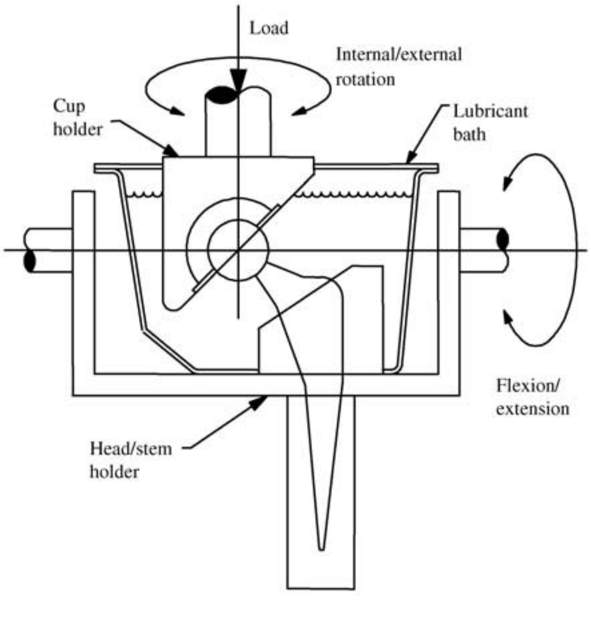

Figure 1 Schematic of a single test cell from the Leeds Mk II hip joint simulator [1].

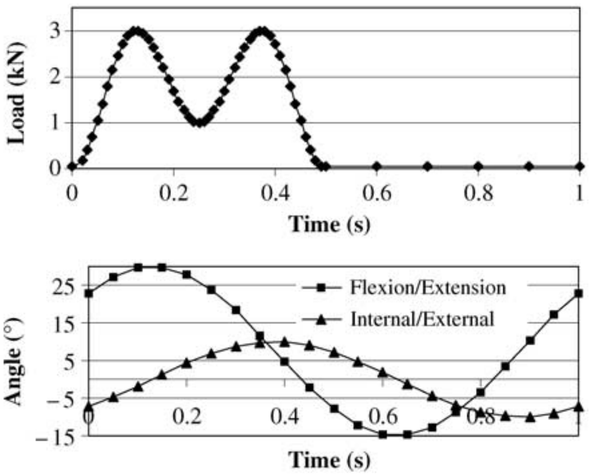

Figure 2 Load and movement cycle of the Leeds Mk II hip joint simulator [1].

applied, flexion–extension and internal–external rotation. The motions were 90° out of phase, such that an open elliptical wear track was generated between the components and a multidirectional friction force vector was applied to every point on the head and cup during the cycle. Tests were carried out in 25% (v/v) bovine serum supplemented with 0.1% (w/v) sodium azide [1]. The solution was changed at least every 330 000 cycles. The lubricating fluids were collected and stored at $-20\,^{\circ}\mathrm{C}$ for analysis of wear debris and determination of metallic ion concentration. Tests were carried out on all bearing combinations to 2 million cycles and on the CrN on CrN, CrCN on CrCN bearing combinations and the MOM controls to 5 million cycles. Interruptions were made at 0.5, 1, 2, 3, 4 and 5 million cycles for gravimetric determination of wear and surface analysis. Prior to the gravimetric measurement of wear, components were washed in detergent water, thoroughly rinsed in water, cleaned ultrasonically in isopropyl alcohol for 20 min and then left in an atmosphere controlled room for 24 h to dry and thermally stabilize. Wear was determined gravimetrically using an electronic balance (Mettler AT201, Mettler Instruments AG, Zurich, Switzerland) to an accuracy of 10^{-5} g. The mass of each component was taken from the mean of at least three measurements which were in the range of $\pm 0.03\,\mu\mathrm{g}$. Weight loss was converted into volume loss using specific densities of 8.33 for CoCrMo, 6.0 for CrN and CrCN, 5.4 for TiN, and 2.5 for DLC to compare the wear between different materials. The average volume loss and wear rate was determined from the mean of the values from three components for each type of coating. The data were then analysed by one way ANOVA and individual differences between means determined by the paired Tukey test.

Surface analysis

Analysis of surface roughness was performed using a Form Talysurf-120L surface profilometer (Taylor-Hobson, UK) with a 0.8 mm cut-off. The worn areas of the components were analysed at the end of the test by optical microscopy (Leitz, Laborlux 12 with JVC KY-F55B color video camera attached) at × 100 and × 200 magnifications, and scanning electron microscopy (SEM; JEOL JSM-6400, Japan) under conditions of secondary electron imaging at 5–15 kV.

Wear debris analysis

Wear debris was characterised from the serum collected during hip simulator testing at 0.33, 1 and 2 million cycles by transmission electron microscopy (TEM) as previously described by Tipper *et al*. [13] and Firkins *et al*. [5]. Approximately 125 ml of serum lubricant was centrifuged at 2000 g for 10 min. The pelleted debris was fixed using 2.5% (v/v) glutaraldehyde in 0.1 M phosphate buffer at pH 7.4 for 2–4 h, then washed with phosphate buffered saline (PBS), and post fixed with 1% (w/v) osmium tetraoxide in 0.1 M phosphate buffer. Samples were washed again, before being dehydrated through a series of graded ethanols. Samples were then polymerised using araldite resin for 20–24 h at 70 °C and sectioned (100 nm) using an LKB ultramicrotome fitted with a diamond knife. The samples were transferred onto copper grids for staining with lead nitrate and sodium citrate and were then double stained with uranyl acetate (15% v/v). Samples were washed with PBS and transferred to a Jeol 1200 EX transmission electron microscope. Images were taken at × 15 000–50 000. Energy dispersive X-ray analysis (EDX) was used to identify the composition of the wear particles. Negatives were scanned (Minolta Dimage Scan Multi) to obtain digital images. Using digital image analysis (Image Pro Plus, Media Cybernetic, USA), length measurements were recorded for at least 100 particles per material combination at each test period.

Ion concentration measurement

A Varian SpectrAA-10/20 atomic absorption spectrometer (AAS, Varian Inc., Surrey, UK), fitted with a Mark VI burner, was used to perform element determination for the serum lubricants collected during simulator testing. The three major elements in surgical grade CoCrMo alloy, cobalt, chromium and molybdenum were analyzed. In addition, the titanium concentration was measured in the lubricants from the TiN coated couples. Prior to the measurements, the AAS was calibrated by aspirating into the flame, solutions containing known concentrations of the elements to be determined. Absorption of each solution was measured, and a graph of measured absorption against the concentration of the solutions was plotted. Standard solutions were prepared by diluting $1000\,\mu\mathrm{g\,ml}^{-1}$ stock solution (BDH Laboratory Supplies, England) with distilled water, which covered the optimum absorbance range of each element (0–15 ppm for Co and Cr, 0–100 ppm for Mo and 0–300 ppm for Ti). All lubricants used for these measurements were collected after the first 0.33 million cycles of the wear test and stored at $-20\,^{\circ}\mathrm{C}$. Prior to measurement, the samples were defrosted and clarified by centrifugation (Centra-3, IEC, UK) at 2000 g for 1 h to remove the wear debris, and the clear supernatant was used for analysis. Each sample was measured three times and the mean value determined. The parameters for the measurements are presented in Table II.

TABLE II The parameters of atomic absorption spectroscopy measurement for each element

Parameters	Elements			
	Co	Cr	Mo	Ti
Instrument mode	Absorbance	Absorbance	Absorbance	Absorbance
Calibration mode	Concentration	Concentration	Concentration	Concentration
Conc. range (PPM)	0.05–15	0.06–15	0.2–100	1–300
Lamp current (mA)	7	7	7	20
Wavelength (nm)	240.7	357.9	313.5	364.3
Slit width (nm)	0.2	0.2	0.5	0.1
Delay time (s)	3	3	3	3
Measurement time (s)	3	3	3	3
Replicates	3	3	3	3
Air flow (l/min)	12	12	—	—
N_2O flow (l/min)	—	—	9.5	9.5
Acetylene flow (l/min)	1.5	1.5	5.5	5.5

Microhardness

Vickers microhardness was measured on the TiN, CrN, CrCN coatings, HC and LC CoCrMo alloys using a microhardness tester (Type M, Shimadzu Corporation, Kyoto, Japan). One hundred gram loading was applied on the three coatings, and 1000 g on the HC and LC CoCrMo alloys for 15 s. The microhardness values were determined from the mean of five indents taken on each surface.

Results

Wear rates

The mean wear results after 2 million cycles for the five surface engineered prostheses together with the MOM reference prostheses are presented in Figs. 3–6. The coated heads and the coated inserts demonstrated much lower wear than the traditional MOM prostheses. For the CoCrMo heads (Fig. 3), obvious high bedding-in wear rate was observed in the first million cycles, and the wear rate decreased during the steady wear period between 1 and 2 million cycles. The coated heads, however, had no bedding-in period and the wear rates remained constantly low in the whole two million cycles. By the end of the wear test, the wear of all coated heads was at least 23-fold lower than the traditional CoCrMo heads. The inserts had similar wear results to the heads. All the coated inserts showed very low steady state wear rates throughout the two million cycles, while the metal inserts showed a high initial bedding-in wear rate during the first million cycles, followed by a lower steady state wear rate between one and two million cycles (Fig. 4). The wear of the coated inserts was at least 6-fold lower than the traditional CoCrMo inserts. The wear rates (+95% confidence limits) for the first million cycles (bedding-in), the second million cycles (steady state) and over two million cycles (overall) are shown in Fig. 5. The overall wear rates of the surface engineered bearings were significantly lower (one-way ANOVA and paired Tukey test, $P < 0.01$) than the MOM prostheses. There was no statistically significant difference between the wear rates of the coated prostheses. For the MOM couples, more than 75% of wear occurred on the low carbon (LC) CoCrMo heads. This trend, however, was less evident for the surface engineered couples, especially for the dissimilar couples where no differences in wear rate for heads and inserts was found.

After 5 million cycles, the fully coated CrN on CrN and CrCN on CrCN combinations showed a 36-fold reduction in wear rate compared to the MOM control (Fig. 6). No significant damage was found to the CrN and CrCN coatings in these longer term tests.

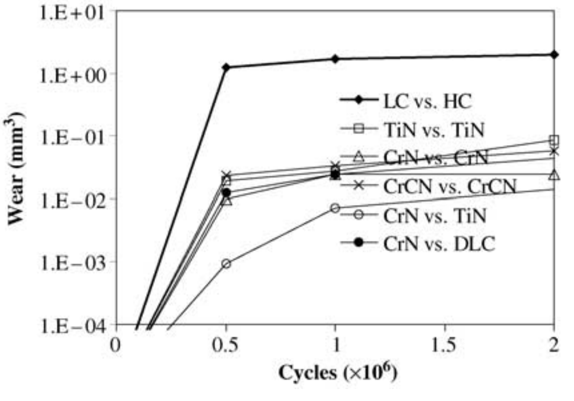

Figure 3 Mean wear of the femoral heads of the surface engineered prostheses and uncoated MOM prostheses in the first 2 million cycles. LC—low carbon CoCrMo, HC—high carbon CoCrMo.

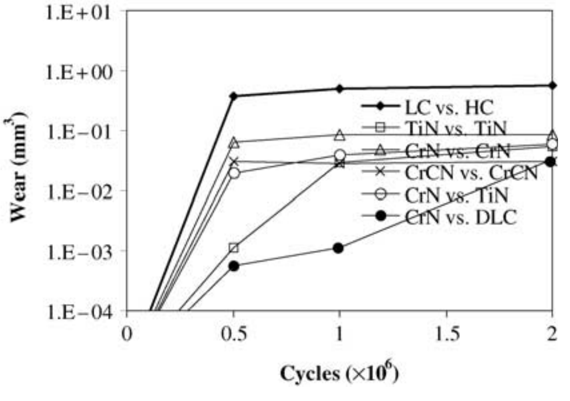

Figure 4 Mean wear of the inserts of the surface engineered prostheses and uncoated MOM prostheses in the first 2 million cycles. LC—low carbon CoCrMo, HC—high carbon CoCrMo.

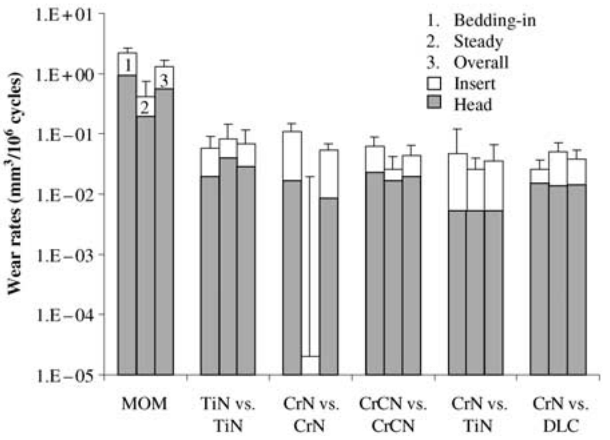

Figure 5 The wear rates after 2 million cycles of the surface engineered prostheses and uncoated MOM prostheses over the three different stages of the wear test.

Wear surfaces

The unworn coated surfaces are shown in Fig. 7(a)–(e). The TiN, CrN and CrCN surfaces all showed small pits on the surface coating. These pits did not penetrate through the coating, but resulted from the removal of micro-metal droplets from the surface during final polishing. In some cases comet tails were seen around the pits as a result of the polishing (Fig. 7(e)). The thin DLC coating formed by PACVD contained no such droplets. The TiN surface coating after 2 million cycles simulator testing is shown in Fig. 8(a) and (b). Some localised damage to the coating was seen on the TiN heads (Fig. 8(b)). Little damage was found on the CrN *vs.* CrN heads and inserts after two million cycles (Fig. 9(a) and (b)). Isolated failure was found on the CrN coated head (Fig. 9(c)). Similar patterns and appearances were found on the CrCN couples (Fig. 10(a) and (b)). Additionally there was some evidence of slight wear grooves on the CrCN coated heads (Fig. 10(a)). There was evidence of comet tail-like pits on the surface both after initial polishing (Fig. 7(c)) and after the wear testing (Figs. 9(b), 10(c) and 11(b)). When the CrN coated heads were articulated against the TiN coated inserts, generally the surface remained undamaged. However, one incidence of localized damaged was observed (Fig. 11(a)). No localized damage was observed on the CrN coated heads articulating against DLC coated inserts (Fig. 12(a)), however, fracture and cracking was seen along wear scratches on the DLC coating (Fig. 12(b)).

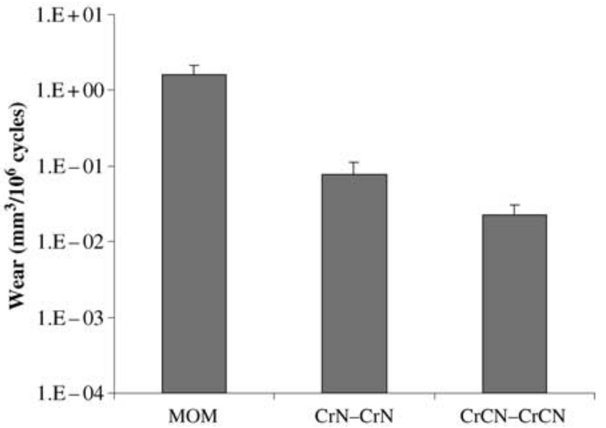

Figure 6 The wear rates after 5 million cycles of the CrN, CrCN surface engineered prostheses and uncoated MOM prostheses.

Surface roughness

The changes in surface roughness of the components throughout the tests are shown in Fig. 13. As the test progressed, the surface roughness decreased or remained unchanged for both coated heads and inserts from all surface engineered combinations (Fig. 13(a) and (b)). The high value for the TiN coated insert after 0.5 million cycles in Fig. 13(b) was due to the abnormal measurement of a local surface defect of one of the three inserts, which was demonstrated by the analysis on the measurement profile.

Wear debris

The wear debris produced by the MOM couples was generally less than 30 nm, as shown in Fig. 14(a). A very small number of particles between 50–200 nm were seen in lubricants from the bedding-in stage of the wear test. Wear debris produced by the TiN on TiN and CrN on CrN couples was similar in size. In both articulations, a small number of shards (particles greater than 100 nm in length) were seen during bedding-in. A shard ($\sim$ 500 nm) from the CrN on CrN couple is shown in Fig. 14(b). Following bedding-in, the wear debris was generally less than 30 nm in length. The CrCN on CrCN (Fig. 14(c)) and CrN on TiN couples (Fig. 14(d)) showed wear particles that were generally less than 30 nm throughout the test. The CrN on DLC combination gave debris of a similar size, with some particles up to 50 nm in length seen in the bedding-in stage of the test.

Metallic ion concentration

For all three major elements Co, Cr and Mo in the CoCrMo alloy, the metallic ion concentrations from all surface engineered prostheses were at least 20-fold lower than with the traditional MOM prostheses (Fig. 15). For the combinations involving TiN coating, the titanium ion concentrations were below the detection limit (1 ppm) of this element by AAS.

Microhardness

The TiN and CrN coatings had an equivalent hardness of 25 GPa, while the CrCN coating had a slightly lower value of 20 GPa. The hardnesses of the HC and LC CoCrMo alloys were 4.5 and 4.2 GPa, respectively. These results were consistent with previous measurements [14–16].

Discussion

The approach used in this study was to compare the surface engineered bearings with a clinical MOM bearing under a standard set of simulator conditions. Previous papers [2, 5, 12] have discussed the wear of MOM bearings in hip simulators and compared them to clinical or retrieval studies. While it is not the purpose of

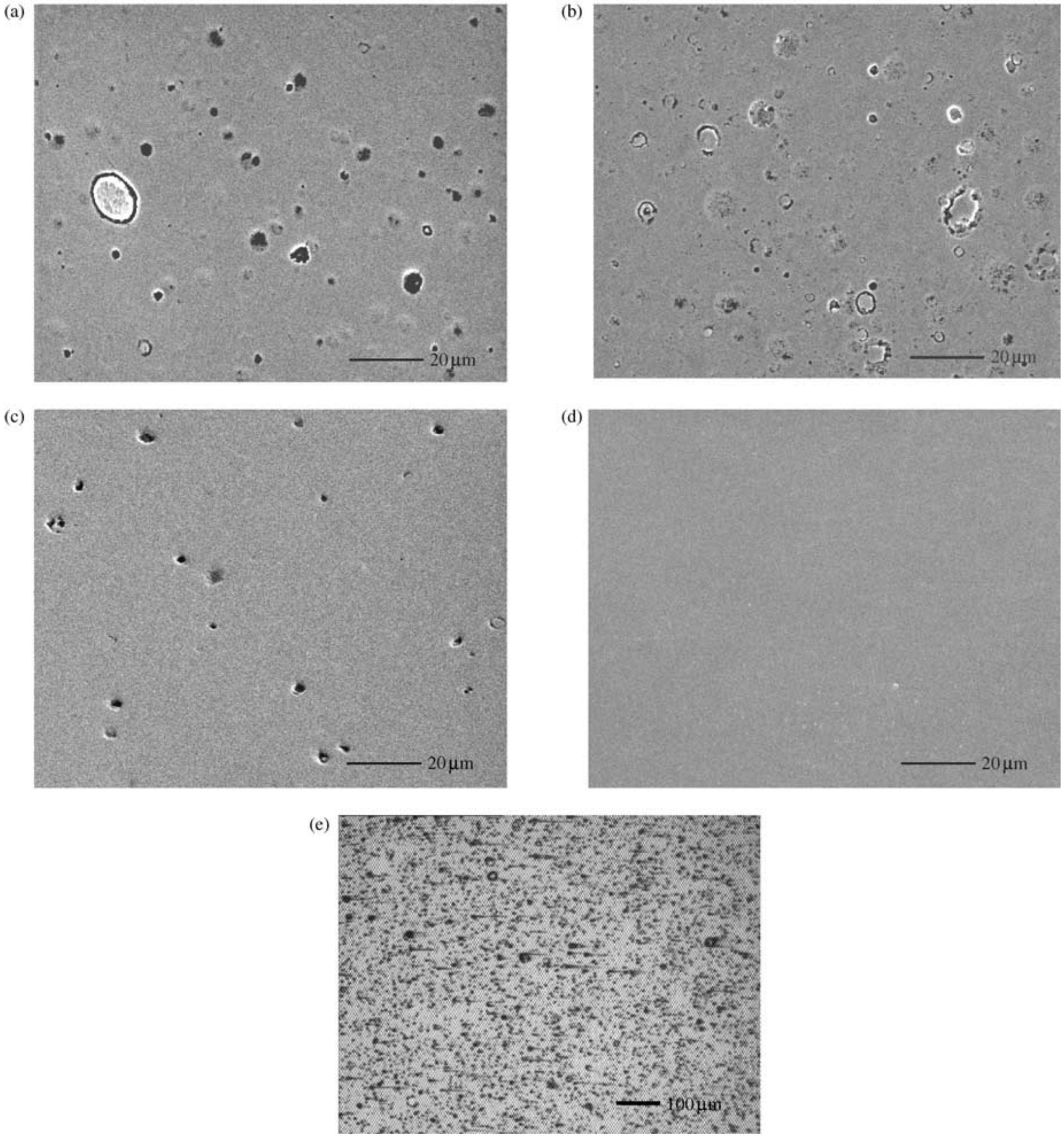

Figure 7 (a) Secondary SEM image of unworn surface of TiN coated femoral head, × 1000. (b) Secondary SEM image of unworn surface of CrN coated femoral head, × 1000. (c) Secondary SEM image of unworn surface of CrCN coated femoral head, × 1000. (d) Secondary SEM image of unworn surface of DLC coated insert, × 1000. (e) Light micrograph of the unworn area of a TiN coated insert, × 100.

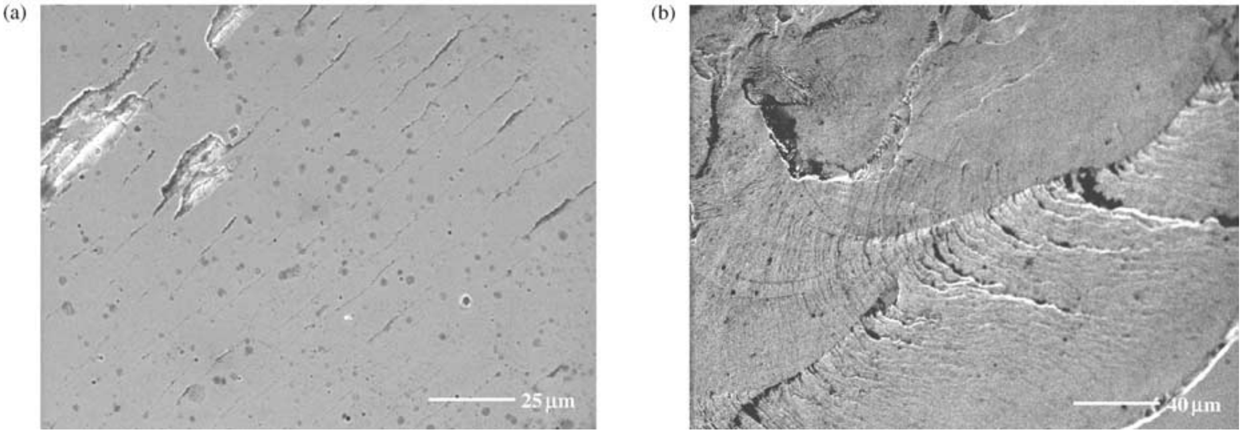

Figure 8 (a) TiN coated femoral head after 2 million cycles articulating against TiN coated insert, × 800. (b) Cohesive failure of TiN coated femoral head after 2 million cycles articulating against TiN coated insert, × 500.

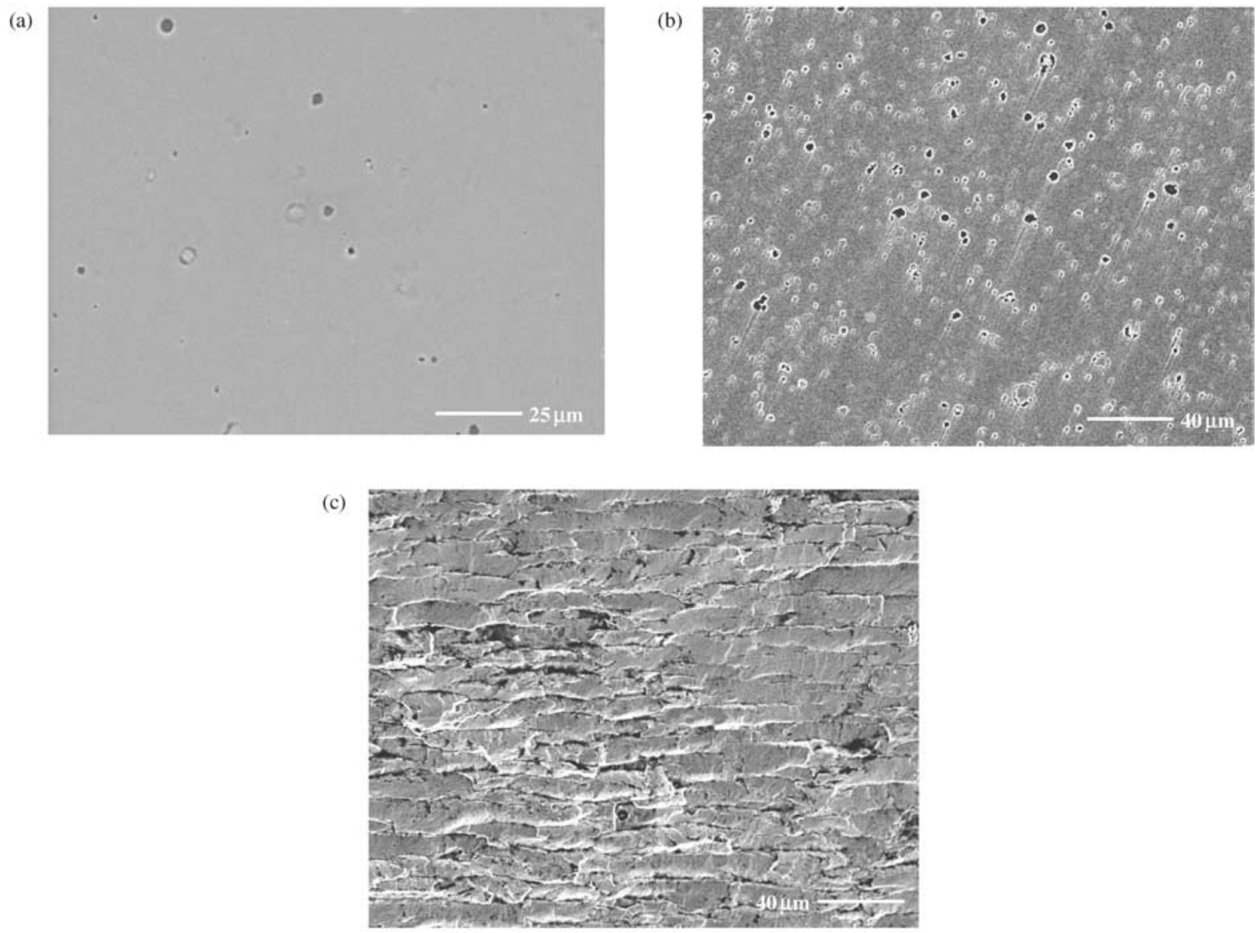

Figure 9 (a) Undamaged region of a CrN coated femoral head after 2 million cycles articulating against CrN coated insert, × 800. (b) CrN insert showing characteristic comet tails after 2 million cycles articulating against CrN coated femoral head, × 500. (c) Isolated failure of CrN coated femoral head after 2 million cycles articulating against CrN coated insert, × 500.

this study to review wear of MOM hips and the simulation methods, it is worth highlighting that a range of wear rates of 0.1–1.5 $\mathrm{mm}^3/\mathrm{million}$ cycles have been reported. Chan and Medley [17] and Farrar [18] reported a range of wear rates which were generally lower than found clinically. Other authors investigated specimen orientation [19]. Chan *et al.* [20] recognizing that his simulator wear rates were lower than found in some clinical studies investigated alternative adverse load conditions associated with stop start motion. Goldsmith [21] showed higher wear rates for size 28 mm metal on meal hips. In our own simulator studies [2, 5] we found that variation in the loading conditions and the kinematic inputs influenced the wear rates [2, 5]. We chose to test under conditions that generated steady state wear of 1.2 mm^3 per million cycles in a previous study. Although this is at the higher end of the reported range, we were concerned that testing under conditions that produced low metal on metal wear, may not be an adequate test of the surface engineered bearings.

Fully surface engineered bearing systems were used in this study to reduce the wear rates for MOM prostheses and to minimize the generation of wear debris and the release of metallic ions. After 2 million cycles simulator test, the results showed that the wear rates of all of the fully surface engineered prostheses were at least 23-fold lower for the heads and 6-fold lower for the inserts than the traditional clinical MOM prostheses, which lead to at least an 18-fold reduction in the overall wear rates. The fully coated CrN on CrN and CrCN on CrCN combinations showed a 36-fold reduction in wear rate compared to the MOM control after 5 million cycles. These wear rates were also much lower than those from half coated (femoral head only) prostheses which were tested in the first part of this study [11]. The reduced wear rates have led to reduced levels of wear debris and metallic ions.

Generally, the major bearing area of the surface engineered components remained smooth and intact after the wear testing. There was a decrease in surface roughness for most bearing surfaces throughout the tests, indicating a relief polishing wear mechanism, consistent with the generation of very small wear particles. Very few areas of localized damage were found on the coatings (Figs. 8(b), 9(c), 10(b) and 11(a)), most on the heads. This localized damage mostly occurred in the first half million cycles of testing. The mechanism of this localized damage is not yet completely clear, but high localized stress due to the initial small area contact in the bedding in phase could be a cause for this damage. Separate pin on plate studies [22] have shown increased incidence of cohesive failure when contact stress was elevated. The majority of the wear debris from all of the surface engineered systems

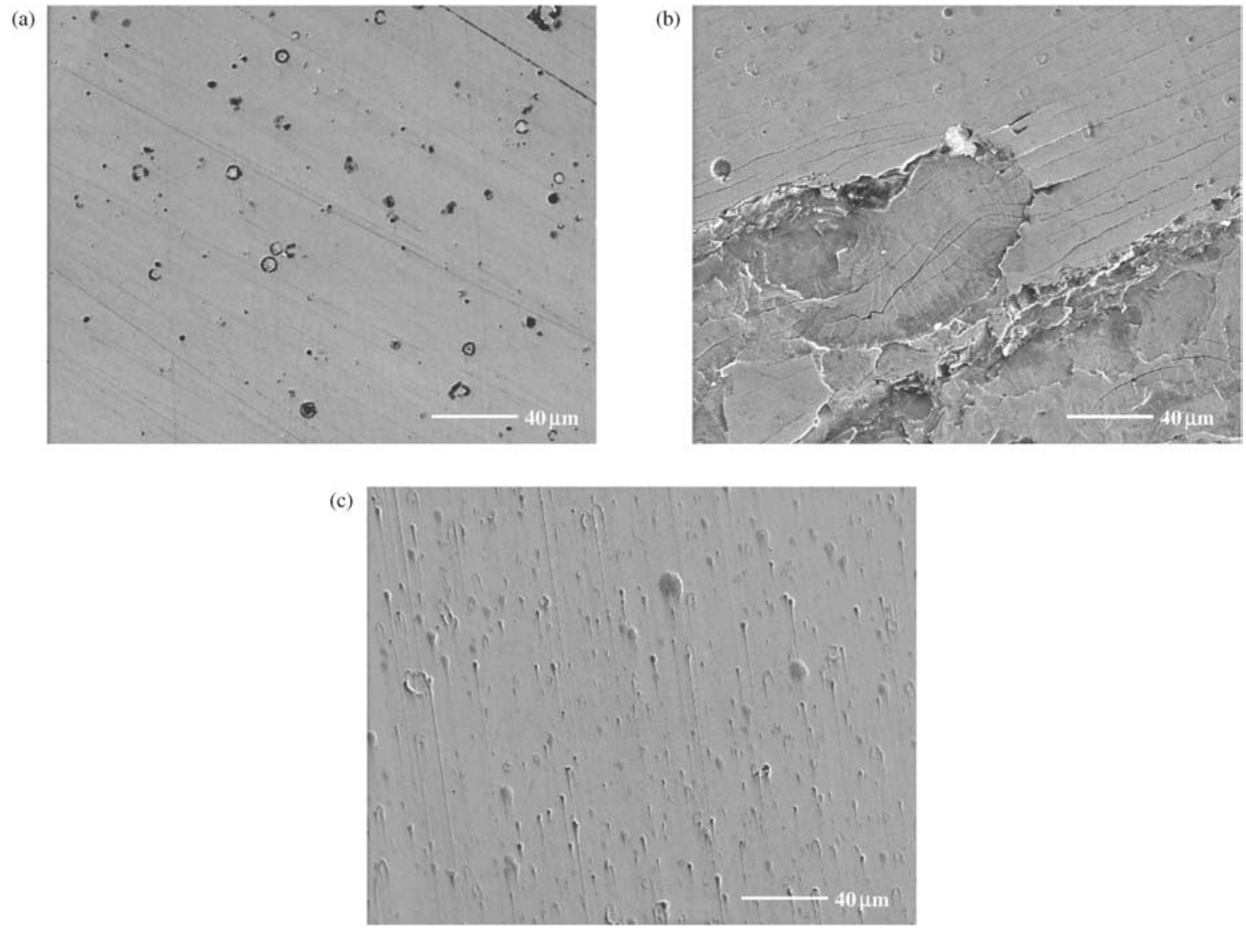

Figure 10 Central region of the contact area of a femoral head showing minor scratching of the CrCN coating, × 500. (b) Cohesive failure of CrCN coating on a femoral head along the edge of the wear area which associated with heel strike after 2 million cycles, × 500. (c) CrCN insert showing characteristic comet tails after 2 million cycles articulating against CrCN coated femoral head, × 500.

was generally less than 30 nm in length, which is similar to the size of the wear debris seen in the MOM combination. The CrN on CrN and TiN on TiN articulations showed some larger shards of wear debris (up to 500 nm) during the bedding-in stages of the tests. These larger shards may be associated with the cohesive failure of the coatings. The occurrence of localized damage had a very limited effect on the overall volumetric wear.

Analysis of the ratio of the three elements, Co, Cr and Mo, measured from the traditional MOM prostheses were approximately the same as in the composition of the CoCrMo alloy. Since corrosion of the surface could be selective resulting in variation of the ratio of the three elements, this result suggested that the ion release could have been due to the degradation and dissolution of the CoCrMo wear debris, rather than the bulk material. The ion concentration measurements from the surface

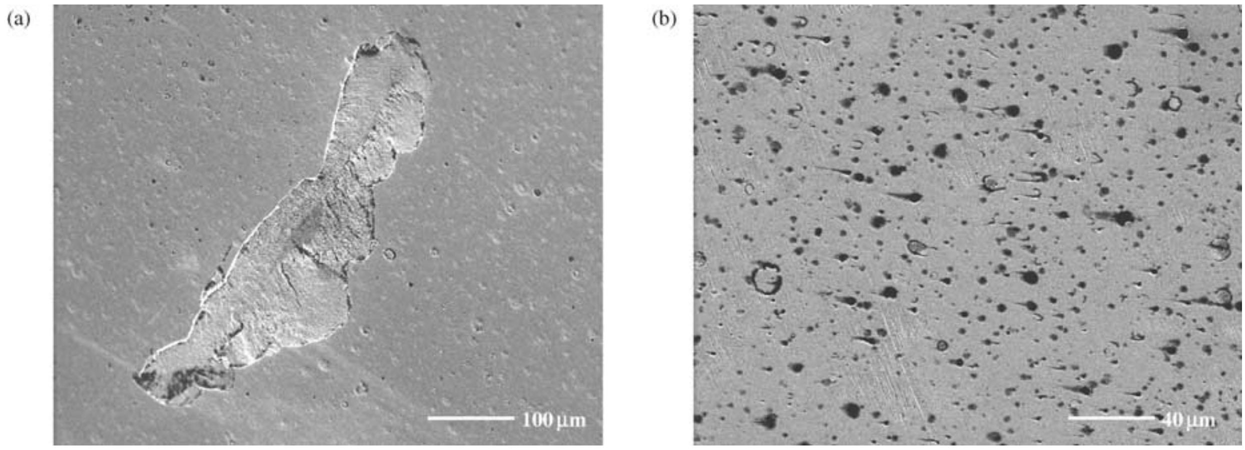

Figure 11 (a) Isolated cohesive failure within a smooth CrN coating on a femoral head after 2 million cycles articulating against TiN coated insert, × 200. (b) TiN insert showing characteristic comet tails after 2 million cycles articulating against CrN coated femoral head, × 500.

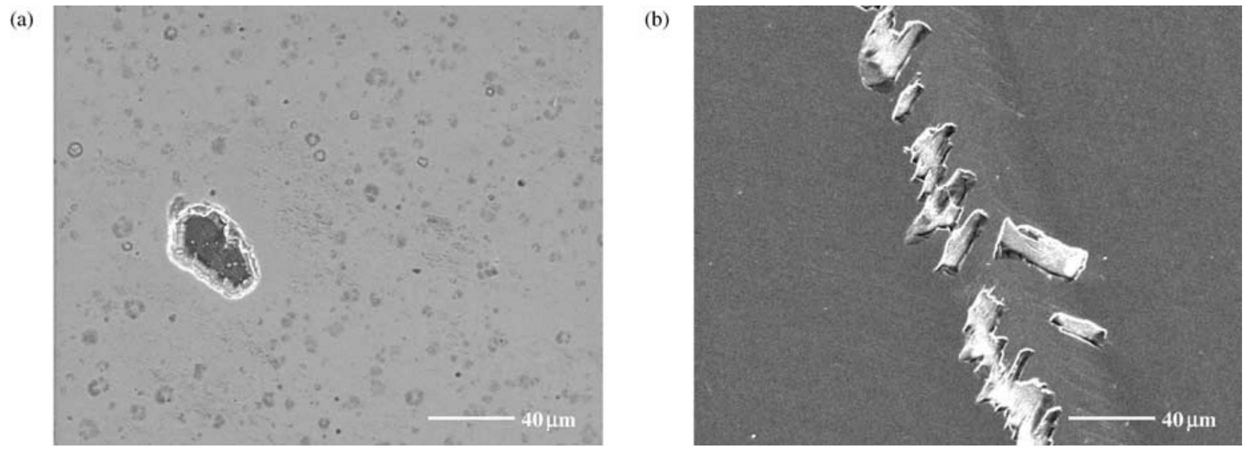

Figure 12 (a) Smooth CrN coated femoral head after 2 million cycles articulating against DLC coated insert. The hole in the coating is an isolated area of localized adhesive failure between the coating and substrate, × 500. (b) Cracking of the DLC coated insert after 2 million cycles articulating against CrN, × 500.

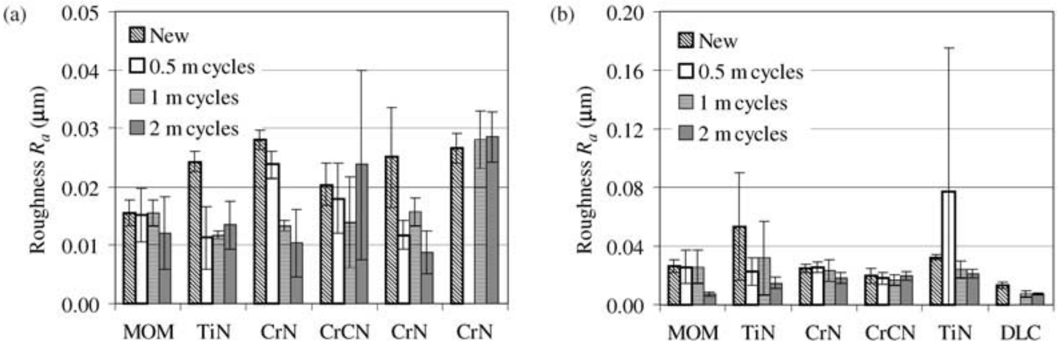

Figure 13 (a) Surface roughness of the femoral heads at different stages of the wear test. (b) Surface roughness of the inserts at different stages of the wear test.

engineered prostheses showed a substantial reduction (at least 20-fold) compared to the traditional MOM hip prostheses. As elevated metal ion levels remain a concern clinically [22, 23] in MOM hips, this reduction in ion levels provides an important advantage for these surface engineered bearings.

Surface coatings have previously produced variable results when used in joint replacements. The use of TiN coatings on titanium bearing surfaces articulating against UHMWPE in patients with nickel sensitivity met with limited success [24–26]. DLC has also been used to coat femoral heads articulating against polyethylene, to give improved wear resistance [27–29], however, concerns have been expressed about elevated friction and wear [30]. Our previous research experience also showed that thin (1–2 μm) DLC and TiN coatings can wear through very quickly. This may have been due to local penetration and wear up to a depth of 1–3 μm in the bedding-in phase, due to the designed radial clearance and the variation in sphericity of the components. This present study, therefore, primarily focused on thick AEPVD coatings, with a thickness greater than 8 μm. This is the first report on the use of CrN and CrCN coatings as bearing surfaces in orthopaedics. These coatings generally have better cohesive strength and toughness compared to TiN, with only slightly reduced hardness. Future work will focus on more longer term simulator studies and the improvement of the coating quality to reduce the number of droplets and spikes, and hence to reduce occurrence of pits after polishing. This study, together with the previous study on half coated bearings [11], shows that the application of thick CrN and CrCN AEPVD surface engineering technology has considerable potential to reduce wear, wear debris and ion release in metal on metal bearings.

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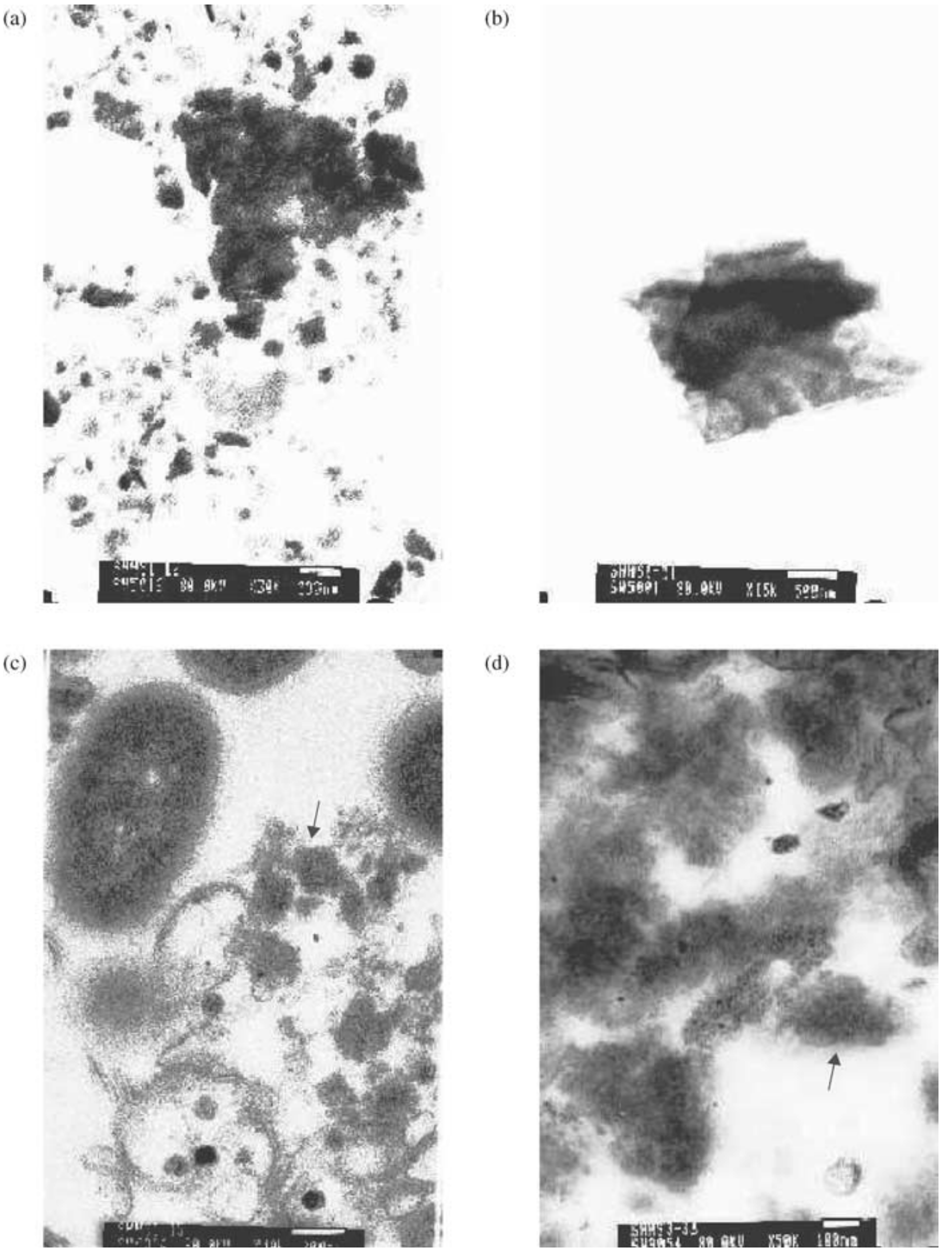

Figure 14 Transmission electron micrograph of wear debris. (a) LC head and HC insert at 0.3 million cycles. The majority of wear debris was less than 30 nm, clumps of these small particles form aggregates (electron dense areas), small particles are sized at the edge. (b) CrN couple at 0.3 million cycles. There was a low incidence of shards (> 100 nm), one is shown in this figure. (c) CrCN couple at 2 million cycles. The majority of particles are less than 30 nm. An arrow marks an aggregate of debris. (d) CrN head and TiN insert at 2 million cycles. The majority of particles are less than 30 nm. An arrow marks an aggregate of debris.

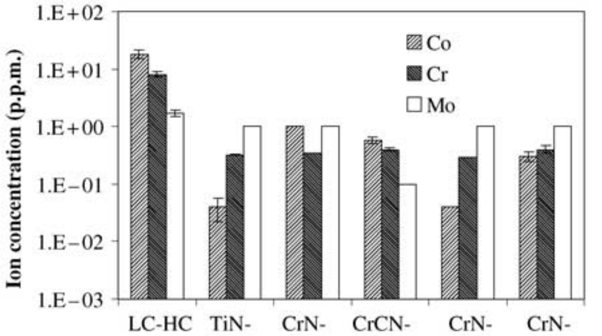

Figure 15 Metallic ion concentration in the serum lubricants from different prosthesis combinations. *titanium < 1 ppm.

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