

Tribological and surface analysis of 38 mm alumina-as-cast Co–Cr–Mo total hip arthroplasties

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Abstract: There is currently much discussion over the use of ceramic femoral components against metal acetabular cups, for use in total hip arthroplasty. The current study investigates six hot isostatically pressed alumina femoral heads of 38 mm diameter articulating against six as-cast Co–Cr–Mo metallic acetabular cups. Standard walking-cycle simulator wear testing was carried out to 5×10^6 cycles using the Durham Mark II hip wear simulator, and wear was determined gravimetrically. In addition, surface topography, using a non-contacting profilometer, an atomic force microscope, and an optical microscope, was monitored throughout the wear test. The wear of the ceramic heads was found to be undetectable using the current gravimetric method; however, a change in the surface topography was seen, as grain removal on the pole was observed through atomic force microscopy analysis. A biphasic wear pattern was found for the metallic cups, with low wear rates of $1.04 \pm 0.293 \text{ mm}^3/10^6$ cycles (mean, ± 95 per cent confidence interval) and $0.0209 \pm 0.004 \text{ mm}^3/10^6$ cycles (mean, ± 95 per cent confidence interval) for running-in and steady state wear phases respectively. Frictional measurement revealed that the joints were tending towards full fluid-film lubrication in parts of the walking cycle. The results show that the combination of hot isostatically pressed alumina and as-cast Co–Cr–Mo is a promising alternative for total hip arthroplasties.

Keywords: ceramic on metal, hip, alumina, wear, friction, surface analysis, protein

1 INTRODUCTION

The design and material combination of total hip replacements has been investigated for over 70 years, with the desire to develop the ‘perfect joint replacement’. Charnley’s low-frictional-torque small-diameter metallic head articulating against a polyethylene liner has been successfully implanted for many years [1–3]. However, periprosthetic osteolysis, caused by polyethylene particles released during the wear process, has emerged as a major factor resulting in the need for revision surgery [4–8]. Hard-on-hard bearings are thought to reduce the problems associated with osteolysis by eliminating polyethylene wear particles. An increased desire for

implantation into younger patients has resulted in a surge of interest in hard-on-hard bearings, which have emerged as a promising alternative bearing combination. The first-generation metal total hip replacements implanted in the 1960s initially indicated low wear but they were found to produce high frictional torque due to the lack of knowledge of tribological factors such as joint clearance and the requirement for high-quality metallurgical properties. Improved manufacturing techniques and the correct choice of clearances resulted in implants of superior designs during the 1990s such as the Birmingham Hip Resurfacing, which has had excellent medium-term success in young patients over a 10 year period [9]. Reports have suggested an inherent stability of the device and the likelihood that it will perform well over time [10]. However, concerns regarding the dispersion of metal ions throughout the body are also being voiced. Carcinogenic effects and hypersensitivity reactions have

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been discussed as potential adverse effects [11] but currently little evidence has been found to show that elevated metal ions result in a statistically significant increase in risk of cancer [12] or other undesirable conditions.

Because of the lack of long-term knowledge regarding metal ions, researchers are continuing to investigate material combinations in the quest to reduce the wear and volume of metal ions released. First-generation ceramic-on-ceramic (CoC) prostheses implanted in the 1970s [13] were unsuccessful owing to the large grain size, high porosity, and poor surface finish, all of which had a negative impact on the already low fracture toughness of ceramics. However, improvements in manufacturing such as hot isostatic pressing allowed more recent ceramic prostheses to be successful because of the enhanced surface finish and a reduced grain size and porosity. This promoted full fluid-film lubrication and lower coefficients of friction, both of which act to reduce wear and particle formation. Nevertheless the underlying problem of the inherent brittleness of the ceramic remains, and there are reports in the literature of catastrophic failures *in vivo* [14–16].

In recent years, ceramic-on-metal (CoM) combinations have been tested *in vitro* [17–28], with a limited number being implanted *in vivo* [29–31]. Advantages of CoM over metal-on-metal (MoM) and CoC prostheses included a reduced volume of metal wear particles [26, 31] and a reduced tendency for fracture of the ceramic component due to the softer metallic cup. The observed reduction in adhesive wear is also beneficial. An additional advantage over a polyethylene acetabular cup is that increased hardness of the cup is expected to promote a reduction in wear, since wear is inversely proportional to hardness.

The available literature regarding CoM pairings has covered a range of diameters (namely 22 mm, 28 mm, 32 mm, 36 mm, 38 mm), and 54 mm components [17–24, 28], with a range of radial clearances. Wear, friction, and particles produced during simulation have all been investigated [17–28, 31, 32].

Firkins *et al.* [20] in 2000 reported the first simulator study investigating the CoM combination. Overall for alumina of 28 mm diameter against Co–Cr alloy, a very low wear rate of $0.01 \text{ mm}^3/10^6$ cycles was found. A higher rate of $0.04 \text{ mm}^3/10^6$ cycles was found in one component after 0.5×10^6 cycles. Difficulties in measuring the wear using gravimetric techniques were noted and attributed to material transfer and the very small amount of wear itself.

Low wear rates have also been found for alumina heads of 38 mm diameter against Co–Cr–Mo cups

[17] with running-in (RI) and steady state (SS) wear rates of $1.01 \text{ mm}^3/10^6$ cycles and $0.10 \text{ mm}^3/10^6$ cycles respectively. The overall wear rate was $0.39 \text{ mm}^3/10^6$ cycles, with the majority of the wear due to the metallic cup. In comparison with their standard 32 mm MoM joints, the wear of the CoM was seen to give a fourfold reduction.

A recent study [28] compared larger-diameter (54 mm) MoM and CoM implant bearings. The combination of an alumina head against as-cast Co–Cr–Mo alloy was found to exhibit the least wear, namely $0.018 \text{ mm}^3/10^6$ cycles. In addition a differential-hardness MoM joint was investigated and compared with a ‘like’-hardness MoM pairing. The differential-hardness MoM joint was found to exhibit 68 per cent less volumetric wear than the ‘like’-hardness MoM pairing (steady state rates of $0.060 \text{ mm}^3/10^6$ cycles and $0.011 \text{ mm}^3/\times 10^6$ cycles for differential-hardness and ‘like’-hardness MoM pairings respectively). This suggests that it is advantageous to have a femoral head with a greater hardness than the cup.

Experiments other than simulator wear tests have also provided corroborative evidence. A very short study investigating a Co–Cr–Mo pin articulating against an alumina plate over 90 000 cycles [25] and a further pin-on-plate study [32] testing both MoM and CoM combinations found a decreased overall wear rate and metallic ion release for the CoM combination compared with the MoM pairing.

Two retrieval studies have been published regarding CoM pairings. These were a Metasul cup against a Biolox alumina head [29] and a stainless steel head against an alumina cup [30], both of which were revised owing to pain. The latter was replaced 1 year after the primary operation by a metal-on-polyethylene (MoP) joint owing to pain and a growing mass on the proximal thigh. The Biolox head of the Metasul–Biolox combination was inserted on revision 1 year after the primary operation. After 1 year and 6 months, a polyethylene inlay and metal head were inserted owing to pain and the detection of noises by the physician on examination. Following the failure of the Metasul socket against the Biolox aluminium oxide ceramic head, Hinrich and Griss [29] expressed concerns over a number of issues regarding CoM combinations. They felt that the wear pattern raised suspicions that sphericity and matching of the heads and cups may be more important than in MoM and CoC. They also questioned what would happen to CoM components when an incorrectly positioned component was implanted, and recommended that further research and development of CoM components should be undertaken. Although

these reports highlighted negative results for CoM combinations, a detailed study by Williams *et al.* [31] has revealed promising *in-vitro* and *in-vivo* wear results for the CoM combinations. Short-term studies of 31 people at 6 months after implantation showed lower metal ion levels in those with a CoM joint in comparison with those having MoM bearings. Also the cumulative volumetric wear of MoM was found to be greater than those of CoC and CoM pairings where no difference in volumetric wear was found.

2 MATERIALS AND METHODS

2.1 Materials

The prostheses used in this study consisted of six Recap® Co–Cr–Mo as-cast acetabular cups of 38 mm diameter, and six hot isostatically pressed alumina femoral heads supplied by Biomet UK. The heads were mounted onto poly(methyl methacrylate)-coated stainless steel tapered stems, and the cups mounted into ultra-high molecular weight polyethylene (UHMWPE) holders for simulator and friction measurement. Components were matched to give similar radial clearances of approximately 100 µm, as shown in Table 1.

2.2 Lubricant

A solution of new-born calf serum (Harlan Sera-Lab Limited; total protein content, 7.5 g/dl) was diluted to 25 per cent using distilled water with additions of both 0.2 per cent sodium azide to prevent bacterial growth and 20 mM ethylenediaminetetraacetic acid (EDTA) to prevent calcium phosphate precipitation onto the bearing surfaces [33]. Friction tests were carried out using viscosities of bovine serum (BS) mixed with carboxymethyl cellulose (CMC) of 0.125 Pa s, 0.0315 Pa s, 0.0085 Pa s, and 0.0039 Pa s, and 25 per cent diluted BS with a viscosity of 0.0013 Pa s. Aqueous solutions of CMC were also used as a lubricant at viscosities of 0.092 Pa s, 0.0275 Pa s, 0.0095 Pa s, 0.0030 Pa s, and 0.001 Pa s.

CMC was chosen because of its similar rheological properties to synovial fluid. The joints were cleaned between friction tests using a weak solution of Neutracon, followed by propan-2-ol. The same batch of lubricant was used throughout all tests to reduce variability.

2.3 Wear simulator experiments

Wear experiments were carried out on the Mark II Durham hip wear simulator, which has two axes of motion: flexion–extension and internal–external rotation. This was achieved using a crank and connecting-rod arrangement driven by an a.c. motor at 1 Hz, to oscillate the femoral component with an approximate sinusoidal motion through +30° and –15°. A second similar mechanism directly drove the internal–external rotation drive bar, causing the acetabular component to oscillate with approximate sinusoidal motion in the internal–external rotation plane through ±5°. A square-wave loading cycle (a minimum and a maximum of 300 N and 2600 N respectively) was applied across the joint. The direction of load varied as the angle of flexion–extension. Acetabular components were mounted at 33° to the horizontal in all five articulating wear stations as well as the loaded soak control station.

Wear tests were carried out to 5×10^6 cycles, interrupted at 0.5×10^6 cycle intervals to measure gravimetric wear of both the acetabular and the femoral components. The protocol to clean the prostheses ensured total protein removal from the components between measurements. Briefly, the components were removed from the wear simulator, and bulk contaminants removed by flushing with water. Following this a series of washes in an ultrasonic bath was carried out. The middle time period used a weak solution of Neutracon to remove any grease or dirt from the surfaces. After this, the joints were rinsed in propan-2-ol and dried in a vacuum oven at 40 °C for 30 min. The components were allowed to acclimatize to room temperature in the metrology laboratory before being weighed using a precision balance. Throughout the cleaning protocol a soft brush was used on the back of the

Table 1 Ceramic heads against metal cup pairings and clearances

Station	Co–Cr cup number	Alumina head number	Clearance (µm)
1	9	4	100
2	6	2	98
3	5	9	99
4	2	35	98
5	3	6	97
Control	4	10	99

acetabular cups, and lint-free paper on the head and cup bearing surfaces to remove protein adsorbed onto the surfaces. The loaded soak control was used to take account of any variation due to fluid absorption and environmental changes such as changes in humidity and temperature. Volumetric wear rates were calculated using $3.980 \times 10^{-3} \text{ g/mm}^3$ and $8.287 \times 10^{-3} \text{ g/mm}^3$ for the densities of the alumina femoral head and the Co–Cr–Mo alloy acetabular cup respectively.

2.4 Friction: theoretical and practical

Results of friction measurements using the Durham hip function simulator were used to indicate the lubrication regime under which the joints were operating, through Stribeck analysis. The friction factor was plotted against a modified version of the Sommerfeld number which was calculated using

$$z = \frac{\eta u r}{L} \quad (1)$$

where η is the viscosity of the lubricant, u is the entraining velocity, L is the load, and r is the radius of the femoral head. A falling trend in friction factor is indicative of mixed lubrication, and a rising trend of full fluid-film lubrication. The friction factor itself is given by

$$f = \frac{T}{rL} \quad (2)$$

where T is the frictional torque generated between the bearing surfaces, r is the radius of the femoral head, and L is the applied load.

Tests were performed with flexion–extension of $\pm 23^\circ$ at a frequency of 1 Hz. Tests were performed using simple harmonic motion of amplitude 25° and a frequency of 1 Hz. The load cycle was approximately a square wave with a maximum and minimum of 2000 N and 100 N respectively. Each test was performed in the normal and inverse directions in order to eliminate any residual error from misalignment of the bearing components. Data were logged at the 21st and 41st cycles, providing six data points each of which were an average of five points taken at the peak-load and high-velocity phase of the cycle. Each joint was tested three times and an average and standard deviation calculated for each data point [34, 35].

The theoretical lubrication mode was also calculated using the predicted minimum film thickness and recorded the average r.m.s. roughness of the

bearing surfaces, as recorded using the Zygo non-contacting three-dimensional profilometer. This yields a dimensionless parameter λ given by

$$\lambda = \frac{h_{\min}}{(\text{r.m.s.}_{q1}^2 + \text{r.m.s.}_{q2}^2)^{0.5}} \quad (3)$$

where, for $\lambda < 3$, mixed lubrication is likely and, if $\lambda > 3$, full fluid-film lubrication is predicted [36]. If $\lambda < 1$, then the bearing would theoretically operate in boundary lubrication.

The minimum-film-thickness calculation, taking into account the importance of elastic deformation of the bearing surfaces as determined by Hamrock and Dowson [37], is

$$\frac{h_{\min}}{R_x} = 2.798 \left(\frac{\eta u}{E' R_x} \right)^{0.65} \left(\frac{L}{E' R_x^2} \right)^{-0.21} \quad (4)$$

2.5 Wear track experimental detection

During wear testing, a deposit formed on the bearing surfaces surrounding the contact area. Digital images of the Co–Cr–Mo acetabular cups were taken to visualize the deposition; however, it was not visible using a digital camera on the alumina femoral heads. Because of the fluorescent nature of the deposit, an ultraviolet (UV) source and charge-coupled device (CCD) camera were used to image the heads. Images were taken through 360° to visualize the complete head and then analysed using LabVIEW 8 and a program written by the School of Chemistry, Durham University.

2.6 Surface analysis

Several surface-analytical techniques were used to monitor changes in the surface topography of the components.

Surface topography was measured throughout the test using a three-dimensional non-contacting optical interference Zygo profilometer (NewView 100, Zygo, Middlefield, Connecticut, USA). Measurements were taken at 0×10^6 cycles, 2×10^6 cycles, 3×10^6 cycles, and 5×10^6 cycles. At least ten measurements were taken in the contact area for both the head and the cups, with additional measurements taken at 2×10^6 and 5×10^6 cycles in the non-contact areas.

Optical micrographs were taken at 2.5×10^6 cycles, 3×10^6 cycles, and 5×10^6 cycles to monitor the topography of the surface throughout the wear test.

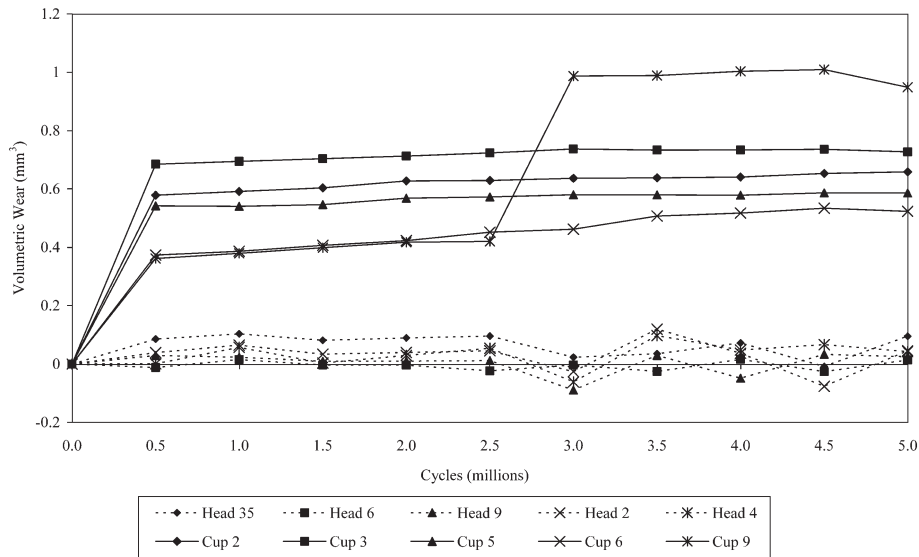


Fig. 1 Individual wear volume change of 38 mm alumina heads against as-cast Co-Cr-Mo cups worn to 5×10^6 cycles (incorporating loaded control) on a standard walking-cycle simulator

Environmental scanning electron microscopy (ESEM) and atomic force microscopy (AFM) were carried out on the alumina femoral heads after 5×10^6 cycles. Images were taken at the pole and on an unworn surface for comparison. An accelerator voltage of 20 kV and a spot size of 5 were used during imaging using ESEM.

AFM images were analysed using the WSxM image browser [38].

3 RESULTS

3.1 Wear

The volume change for the individual Co-Cr-Mo cups and alumina heads is summarized in Fig. 1. The volume losses and standard deviations for the heads were lower than the cups with greater variation in wear rates between the metal samples likely to be due to the differences in cup RI wear rates between 0 cycles and 0.5×10^6 cycles. The overall RI wear rate of $1.04 \pm 0.293 \text{ mm}^3/10^6$ cycles (mean, ± 95 per cent confidence interval) was measured; however, the heads experienced a gravimetrically non-detectable change in wear throughout the 5×10^6 cycle test. After the initial higher wear rate experienced by the cups a wear rate of $0.0209 \pm 0.004 \text{ mm}^3/10^6$ cycles (mean, ± 95 per cent confidence interval) was seen from 0.5×10^6 cycles to 5×10^6 cycles. The greater wear seen by cup 9 at 3×10^6 cycles arose because the joint ran dry, after which the joint returned to the lower wear rate.

3.2 Friction

Figure 2 shows a typical Stribeck plot of an alumina head against a Co-Cr-Mo cup worn to 5×10^6 cycles in a standard wear simulator. The joint was lubricated in a range of viscosities of both CMC fluid and BS with the addition of CMC fluid. After 5×10^6 cycles of wear testing, the friction factor of the prostheses when lubricated in BS was found to be higher than when lubricated in CMC fluids. A distinct difference could be seen between the friction factors resulting from lubrication with the two different fluids. The friction factor in 25 per cent BS was 0.052 and with distilled water was 0.017. The shape of the curves, in addition to the friction fac-

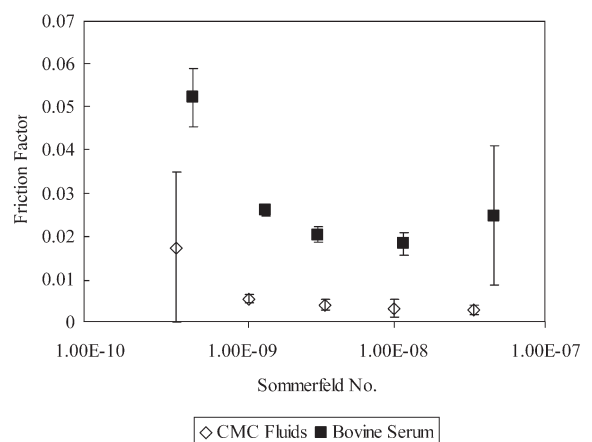


Fig. 2 Stribeck plot for a 38 mm alumina head against Co-Cr-Mo alloy cup worn to 5×10^6 cycles in a standard walking-cycle simulator

tors, indicate that the joint is working close to full fluid-film lubrication in parts of the walking cycle.

The theoretical lubrication modes shown in Table 2 support the experimental results. The calculations show that the joints were operating close to or within full fluid-film lubrication for the majority of 5×10^6 cycles of standard walking-cycle wear. This is supported by both the wear rates and the topography images, which show low wear on both the bearing surfaces.

3.3 Surface analysis

Analysis of the bearing surfaces during wear simulator testing revealed a white deposit on both components, as shown in Figs 3 and 4. The deposit on the ceramic heads was difficult to see by eye and therefore was visualized using a UV light and a CCD camera. The deposit was clearly visible on the metallic cups and therefore was recorded using a digital camera. The deposit was situated on the pole of the head, leaving a clear circular contact area where no deposit was present. Many abrasive scratches protruded into the deposit, revealing the underlying ceramic material. There was no evidence of deposited material on the surface of the loaded control sample.

Surface analysis of the ceramic heads using a white-light profilometer showed minimal wear or surfaces changes. Small quantities of metal transfer could be seen on the heads, the majority deposited outside the contact area, which is a result of setting up the simulator. Analysis showed the transfer to be nanometres thick. ESEM analysis of the heads revealed visible grains in the centre of the wear patch with occasional grain removal (Fig. 5(a)). Faint multi-directional scratches were also visible. Regular directional scratching was seen outside the wear patch; however, the grains were much less obvious unless a single grain or cluster of grains had been pulled out (Fig. 5(b)).

Grain pull-out could clearly be seen when the surface ceramic femoral head was analysed with an

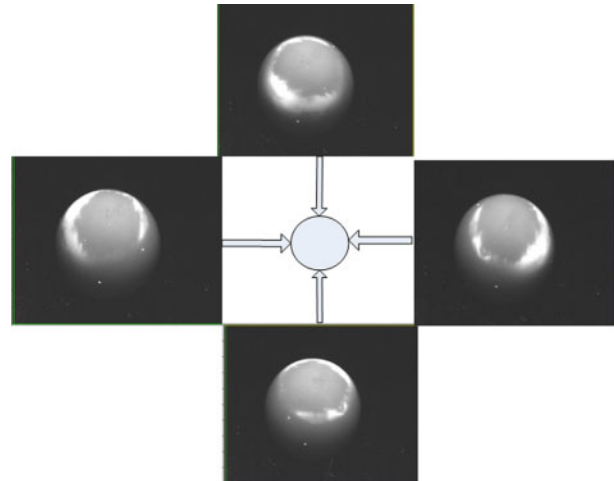


Fig. 3 UV images of deposition on a 38 mm alumina head after 0.5×10^6 cycles of wear testing in a standard walking-cycle simulator



Fig. 4 Digital image of the deposit left on the Co-Cr-Mo alloy cup after 0.5×10^6 cycles of wear testing in a standard walking-cycle simulator

atomic force microscope. Micrographs were taken in the wear patch on the pole of the head. Figure 6(a) shows a $100 \mu\text{m}$ scan of the surface on the pole in which pulled-out grains appear to be to $5 \mu\text{m}$ in size. Figure 6(b), which is at a higher magnification,

Table 2 Predicted lubrication modes ($\eta = 0.0013$)

Number of cycles ($\times 10^6$)	Head r.m.s. roughness (μm)	Cup r.m.s. roughness (μm)	h_{\min} (μm)	λ	Friction factors of the following	
					CMC*	BS†
0	0.010	0.016	0.07	> 3	—	—
2	0.013	0.017	0.07	> 3	—	—
3	0.009	0.017	0.07	> 3	—	—
5	0.009	0.017	0.07	> 3	0.017	0.052

*CMC, $\eta = 0.001$ Pa.s.

†BS, $\eta = 0.0013$ Pa.s.

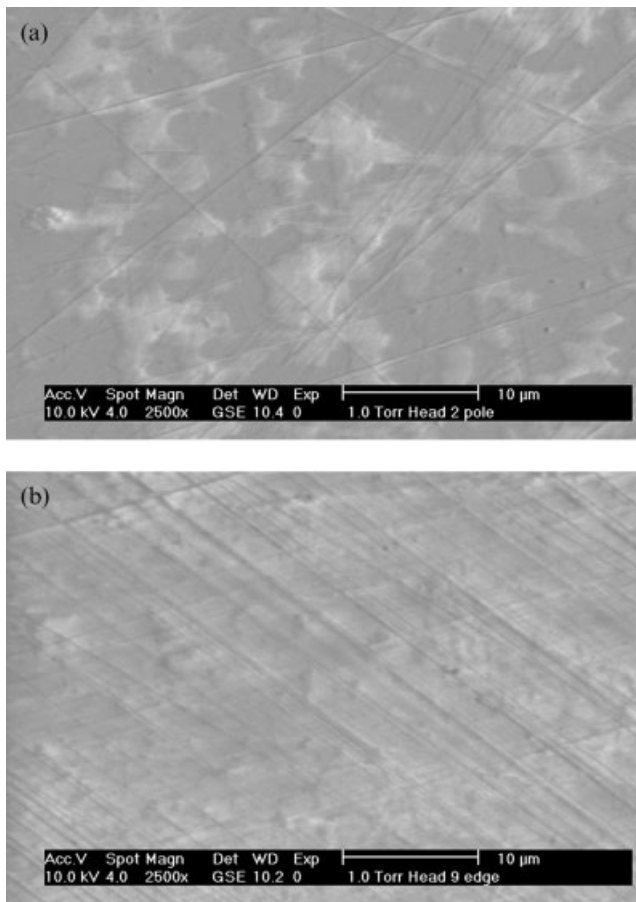


Fig. 5 Typical ESEM images of the alumina head (a) in the wear track and (b) out of the wear track

confirms this and clearly shows abrasive scratches. The grains were clearly visible on the pole of all heads but generally not away from the wear track. Images of the loaded control head and unworn areas of the worn components revealed multi-directional polishing scratches, where grains were not visible and grain pull-out was not observed. This is illustrated in Fig. 6(c).

Pitting, carbide pull-out, and matrix removal were progressively seen in the metallic cups throughout the wear testing, with increased amount of scratches seen in the wear track. The width of the scratches appeared to be similar in size to the pits formed during material pull-out. By contrast, images taken out of the wear patch remained constant throughout the test.

3.4 Surface measurements

The average r.m.s. roughness (Fig. 8) of the ceramic heads at 0 cycles was $0.010\ \mu\text{m}$, which was almost invariant throughout the wear test. Similarly, the r.m.s. roughness for the cups maintained a relatively

constant value between $0.016\ \mu\text{m}$ and $0.017\ \mu\text{m}$ up to 5×10^6 cycles (see Table 2).

The peak-to-valley values (Fig. 9) for both the head and the cup were initially similar because the manufacturing finishing process produces a microscopically smooth surface. At 2×10^6 cycles and 3×10^6 cycles, the cups revealed a greater peak-to-valley value than the heads; however, at 5×10^6 cycles the peak-to-valley value of the heads was considerably greater than that of the cups.

The cups initially had a positive skewness value (Fig. 10); conversely the heads had a negative skewness. As the test progressed the skewness of the worn cup became consistently negative; however, the control cup remained positive. The head skewness did not change much until 5×10^6 cycles whereas both the control and the worn heads became noticeably negatively skewed, which indicates deeper valleys than peaks.

4 DISCUSSION

The aim of this study was to carry out a thorough examination of the wear and friction of six alumina heads of 38 mm diameter against Co–Cr–Mo alloy cup total hip replacements provided by Biomet UK. Wear was determined gravimetrically up to 5×10^6 cycles in an attempt to indicate the performance of CoM combinations. Various surface-analytical techniques were undertaken to monitor the changes in the surfaces throughout the wear test. Friction measurements were used to determine the lubricating mechanism prevalent between this material combination as indicated by the Stribeck plot, in which a falling trend in friction factor with increasing Sommerfeld number is indicative of mixed lubrication, and a rising trend is indicative of full fluid-film lubrication. The optimum result would be a material combination which exhibits full fluid-film lubrication; this would then be likely to exhibit lower wear.

Knowledge of CoM prostheses is growing rapidly, and the majority of work to date has revealed a positive outcome for CoM combinations. Joint diameters from 28 mm to 54 mm have been investigated, giving steady state wear rates in the range of $0.01\text{--}0.1\ \text{mm}^3/10^6$ cycles. Ranges of diametrical clearances, types of simulator, and lubricants have been used, all of which result in similar wear rates. In the current study the five pairs of joints were found to experience similar wear rates throughout the test. However, the wear of the femoral heads was found to be undetectable using the current gravimetric

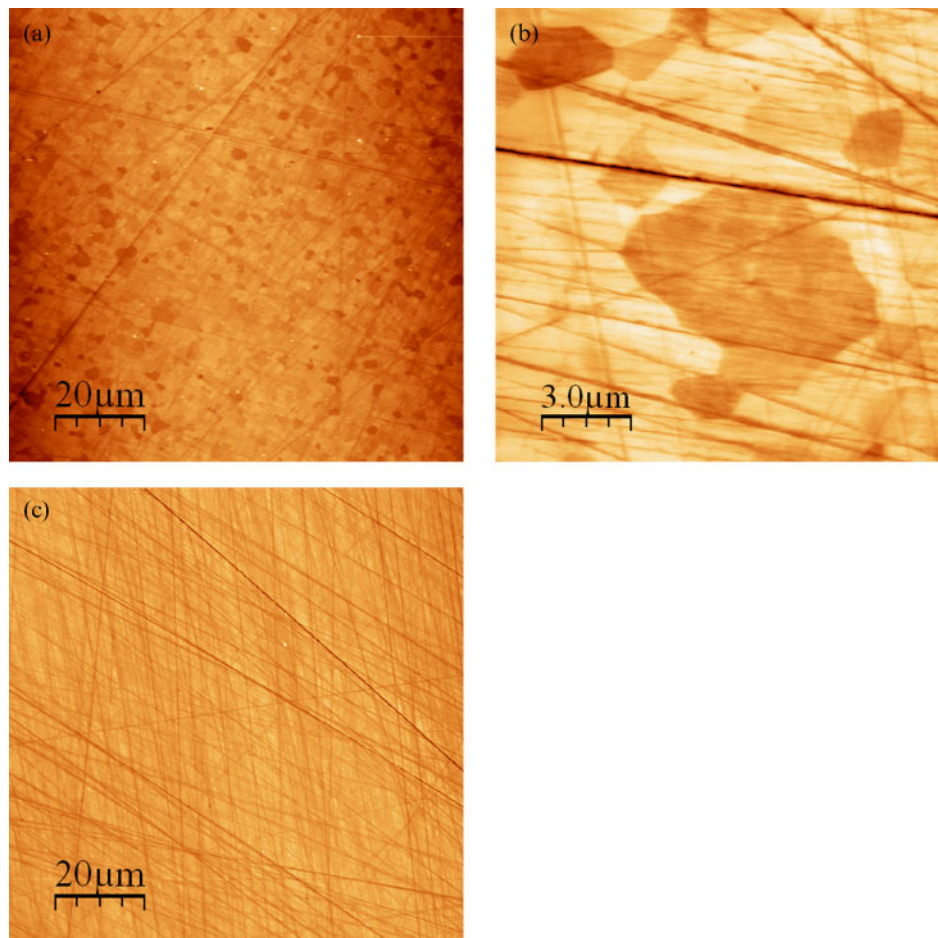


Fig. 6 AFM image of a ceramic head (a) in the wear track (pole) showing individual grain removal, (b) at a greater magnification in the wear track (pole) showing individual grain removal and abrasive scratches, and (c) in an unworn area of the head

method; therefore the wear rates are presented for the metallic cups only.

Opinions are divided as to whether a biphasic wear pattern is observed for wear of CoM combinations. Firkins *et al.* [20] presented the first simulator study regarding CoM pairings and did not find an RI phase. Smith *et al.* [18] reported a biphasic wear rate only for the larger-diameter (28 mm rather than 22 mm) prostheses and suggested that the RI phase was faster in the CoM pairing than in the MoM replacements. It was proposed that this was due to both the replacement of the metallic head with a ceramic component, which introduced an initially smoother material that was not likely to undergo a RI phase, and accelerated polishing of the metallic cup by the smoother harder ceramic component. However, Ishida *et al.* [17] presented a biphasic wear pattern for 38 mm and 32 mm CoM joints tested in an orbital simulator to 3.5×10^6 cycles using α calf serum as the lubricant. In the current study a higher wear rate was found for the metallic cups between

zero and the first measurement at 0.5×10^6 cycles, compared with the rest of the test. This RI phase was likely to be due to polishing of the metallic cups by the ceramic head, causing flattening or removal of the carbides and raised matrix material of the metal cup during wear. Initially the theoretical calculations of λ gave values between 3.3 and 3.7, indicating little asperity contact with behaviour towards full fluid-film lubrication. As wear progressed, the theoretical calculations indicated a move towards full fluid-film lubrication.

The wear of the CoM pairings was found to be similar to fully ceramic replacements presented in the literature, a selection of which is shown in Table 3. The low wear of CoM joints as shown in this study is an attractive option for total hip replacements, as the replacement of the ceramic cup with a metal cup reduces the chances of fracture or chipping of the ceramic when *in vivo*.

The current study revealed the ceramic head wear rate to be too small to measure using the gravi-

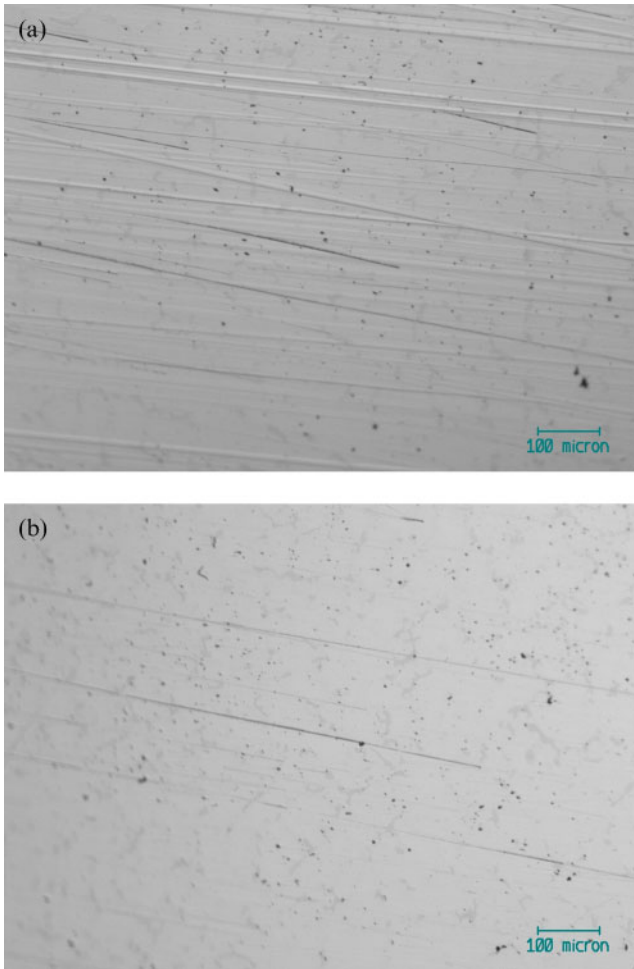


Fig. 7 Optical image of a Co-Cr-Mo alloy in the wear track after 5×10^6 cycles in a standard walking-cycle simulator showing (a) abrasive wear where the carbides in the matrix can be seen faintly and (b) pitting of the matrix and abrasive wear where the flattened carbides can be seen faintly

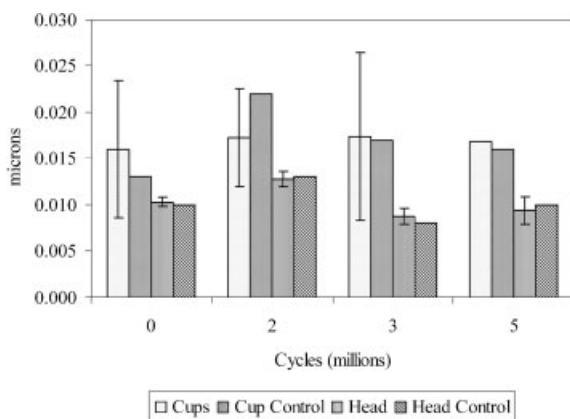


Fig. 8 Average change in r.m.s. roughness with number of cycles of the 38 mm alumina against Co-Cr-Mo alloy joints worn in a standard walking-cycle simulator

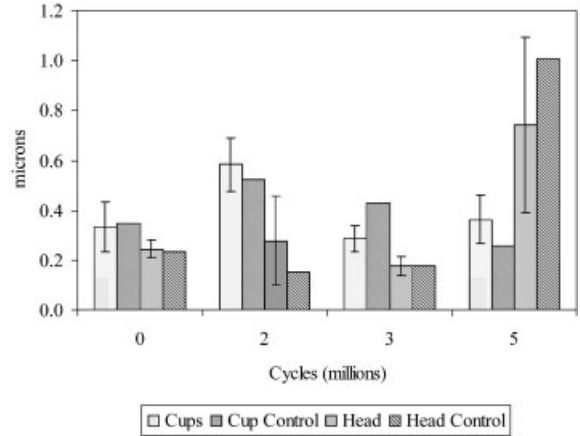


Fig. 9 Average change in peak-to-valley height with number of cycles of the 38 mm alumina against Co-Cr-Mo alloy joints worn in a standard walking-cycle simulator

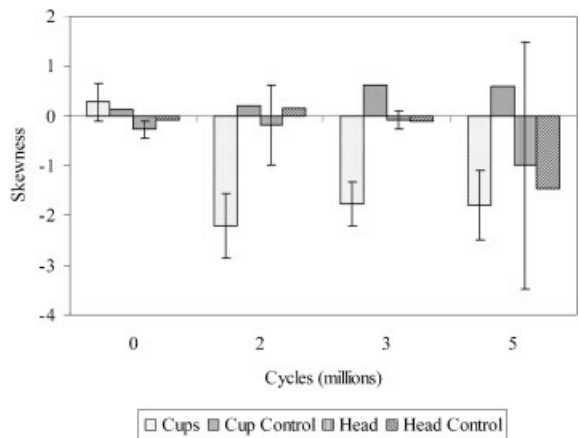


Fig. 10 Average change in skewness with number of cycles of 38 mm alumina against metal joints worn in a standard walking-cycle simulator

metric method; however, a change in surface topography was noticed, indicating that some wear had occurred. A change in r.m.s. roughness was not observed; however, a change in skewness was noticed when analysed using a profilometer. Grain pull-out and a change in the orientation and regularity of the scratches was found during ESEM and AFM analysis, indicating wear, albeit an extremely small amount. The wear that did occur was important, as some generated third-body wear of the metallic cups.

In the current study, a white deposit was also noticed on both the ceramic head and the metallic cup. Digital images were taken of the cups, in which the deposit can be seen in the superior quadrant of all cups, with the exception of the control, where no deposition was found. The wear patch can clearly be

Table 3 CoC literature review

Study	Materials	Size (mm)	Clearance (μm)	Steady state ($\text{mm}^3/10^6$)
Nevelos <i>et al.</i> [39]	Alumina:alumina	28	32	0.08
Smith and Unsworth [40]	Alumina:alumina	28		0.097 ± 0.039
Clarke <i>et al.</i> [41]	Alumina:alumina	28	≤ 80	0.004 ± 26 per cent (average over 14×10^6 cycles)
Essner <i>et al.</i> [42]	Alumina:alumina	32	25	0.04 ± 0.03

seen in the centre, where contact has occurred and no deposit is observed. Scratches protrude into the deposit, showing that abrasive wear was occurring; however, these scratches are not noticeable on the underlying metallic surface. The deposit was located on the top of the ceramic heads in a u-shaped pattern which was evident on all heads except the control. As with the cups, scratches were visible in the deposit but not the actual ceramic surface. The area with no deposition on the cup corresponded to the area on the head and was therefore expected to be the wear patch. On the cups, the wear patch was evident owing to visible carbide pull-out and abrasive wear. This can be seen from the optical images of the cup where the carbide and matrix material was pulled out, and corresponding scratching of the matrix material is obvious (Fig. 7(a)). It could be concluded that third-body particles may have caused the damage, as these are possibly due to carbides or alumina grains removed from the femoral heads. The scratches seen were continuous over the harder carbide components within the matrix; therefore a material of similar or greater hardness is likely to have caused the damage. The parallel regular scratches in the pole indicated that wear was due to repetitive movement during simulation, which was not present outside the wear patch (Figs 7(a) and (b)).

For the ceramic femoral heads, no noticeable changes in surface roughness were found throughout the tests, indicating little wear. Although ESEM and AFM images showed occasional grain pull-out in the wear track (e.g. Figs 6(a) and (b)), there was no macroscopic damage on any worn head. Grains were visible on the wear patch but, outside the wear patch, multi-directional polishing marks resulting from manufacture were observed (Fig. 6(c)). Changes in the surface topography were found. The peak-to-valley value of the cups was greatest at 2×10^6 cycles (Fig. 9). This may be due to carbide pull-out during the first stages of the wear testing. A small decrease between 3×10^6 cycles and 5×10^6 cycles was probably caused by polishing of the metal cup by the harder ceramic head. Conversely the ceramic heads were found to have their greatest peak-to-valley value at 5×10^6 cycles, possibly owing

to grain pull-out in the wear track. As polishing is less likely to occur on the ceramics, the holes left by pulled-out grains would remain at the original depth, therefore resulting in a large peak-to-valley value. However, it must be noted that small defects on the surface can lead to artificially large peak-to-valley values; the peak-to-valley value is not an average of the surface, but the largest distance between the highest and lowest points within the examination area. A low surface roughness with a large peak-to-valley value can indicate an individual feature on the head, rather than the large peak-to-valley value representing the dominant surface feature. The skewness values were as expected, with initially both head and cup showing skewness values close to zero (Fig. 10), indicating that the surface is equally as likely to have asperities above and below the mean line. However, as the test progressed, the skewness values for the metallic cups became more negative, indicating deep troughs compared with shallow peaks. This is consistent with the proposal that carbides are pulled out of the surface during wear testing. The ceramic heads produced low skewness values throughout testing until 5×10^6 cycles, where the worn heads became largely negatively skewed. This is consistent with the increase in the peak-to-valley value, and the observation of some grain pull-out, causing an increased change in the surface topography generally below the mean line. The standard deviation of the skewness of the worn heads at 5×10^6 cycles is large, and some heads had positive skewnesses. The result for the control at 5×10^6 cycles is surprising.

The present study observed some material transfer onto the ceramic heads; however, currently no analysis of the elemental composition has been undertaken. It is thought that the deposition revealed in the current study is not composed of calcium phosphate, owing to the addition of EDTA to the BS which acts to bind the calcium in solution, therefore preventing deposition of calcium onto the surfaces. Thus deposition is likely to be predominantly due to albumin and α , β , and γ globulins. Scholes [43] reported the deposition of protein on MoM, MoP, and CoC material combinations, which was analysed using sodium dodecyl sulphate poly-

acrylamide gel electrophoresis [43]. However, the analysis was carried out on the deposition which occurred during soaking in bovine serum for 24 h, and not on the deposition caused during wear simulation. Therefore the composition of the two depositions may differ. In previous studies, Firkins *et al.* [20] reported that surface analysis showed no signs of wear or changes in surface roughness after testing; however, metal transfer (less than 20 nm thick) and calcium phosphate deposits were found at the edge of the contact area. It was concluded that, as this was not in the wear track, it had no effect on the wear of the bearing surfaces. Energy-dispersive X-ray analysis confirmed that it was Co–Cr alloy with an elemental composition similar to that of the main matrix; however, it was found that it did not appear to accelerate the wear of the metal cups.

Friction was used to indicate the lubrication regime which was prevalent in the joints under investigation. The CoM combinations worn to 5×10^6 cycles showed low friction factors below 0.052 with a curve shape indicating that the joints were likely to be operating in full fluid-film lubrication. The joint showed a decrease in friction factor from 0.052 ± 0.007 , when proteins were present, to 0.017 ± 0.017 in the absence of protein (Fig. 2). The results when employing CMC fluids as a lubricant are similar to that found for CoC joints, which typically produced friction factors of 0.002 compared with 0.004 for CoM (except for distilled water, which was 0.017 ± 0.017) [44, 45].

It has been hypothesized that the proteins which adsorb onto the surface are responsible for the change in lubrication, in addition to the surface topography of the bearing contact. Scholes and Unsworth [46] investigated the effects of proteins on the friction and lubrication of hip joints. They compared the hip material prostheses of MoP, MoM, and CoC lubricated in CMC fluids, and BS, with the addition of CMC. Their results showed that, for MoM, BS produced the lower friction factors between 0.09 and 0.15, while the CMC fluids produced friction factors between 0.2 and 0.3. Conversely the CoC components produced friction factors less than a hundredth (0.001–0.006) of the values given by MoM pairings when proteins were absent. When proteins were present, the friction factors were found to be between 0.02 and 0.06. Their reasoning for the CoC result was that, when protein was absent, the bearing surfaces, having $\lambda > 3$, allowed full fluid-film lubrication, and so the friction in the joint was due to shearing of the lubricant film. When proteins were introduced into

the lubricant, they adsorbed onto the surface, introducing a molecule which is greater in size than the fluid film thickness; therefore the proteins adsorbed to the surface were sheared in addition to the proteins and constituents of the lubricant film. Currently, to the present authors' knowledge, there are no published data which quantify the size of the protein layer which adsorbs to the surface during simulator testing that uses BS as a lubricant. A report by Spikes [47] in 1996 discussed that adsorbing polymer solutions are able to form viscous surface layers at least 20 nm thick, which is thought to interact during boundary lubrication conditions. Although these data are not known, it can be hypothesized that the adsorbed proteins created a greater friction factor than when the friction was solely caused by shearing of the CMC lubricant film. In addition, adsorption of proteins onto the surface may act to alter the surface properties, reducing the hydrophilic nature of the ceramic surfaces, and therefore reducing the effectiveness of the lubrication. By contrast, the MoM joints were found to have lower friction factors when the proteins were present. The interactions between asperities was a mixture of metal against metal and protein against protein, which lowered the friction produced (compared with just metal-against-metal contact).

The results of the present study support these hypotheses. The metallic cups had a low average surface roughness; therefore the CoM pairing showed results with the same trend as CoC pairings, with an increase in friction factor when proteins were present. Grain pull-out seen on the alumina femoral head and carbide pull-out of the metallic acetabular cup provided a topography with a negative skewness, which is more favourable than a positive skewness towards fluid-film lubrication. The friction factors for CoM are higher than CoC joints, owing to the small amount of metal-against-ceramic asperity interaction which occurred. These friction factors were lower than with MoM joints as the adhesive forces between metal-against-metal interactions are much greater than those of ceramic-against-metal interactions. It must be noted, however, that the difference between the friction factors when protein is or is not present is considerably less than that seen for other material combinations

5 CONCLUSIONS

The wear rate of the metallic cups was discovered to be $1.04 \pm 0.293 \text{ mm}^3/10^6$ cycles and $0.0209 \pm 0.004 \text{ mm}^3/10^6$ cycles for the RI and SS phases respec-

tively. The as-cast metallic cups showed very low wear, with small amounts of carbide pull-out. This pull-out is likely to cause the decreased surface roughness and the scratching in the wear track. The smooth surface finish and greater hardness of the ceramic component are likely to have caused polishing of the scratches during continued wear testing, therefore resulting in a lower surface roughness than may be expected for metal in MoM combinations. The friction results of joints tested at 5×10^6 cycles suggested that the joints were tending towards full fluid-film lubrication, with the results showing a similar trend to CoC combinations with an increase in friction found when lubricated in BS compared with CMC fluids. A white deposit was seen on both components after each phase of wear testing, which was removed every 0.5×10^6 cycles to allow for gravimetric analysis. In summary, the wear of CoM components was found to be gravimetrically undetectable on the ceramic component, and very low on the as-cast metallic cups.

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APPENDIX

Notation

AFM atomic force microscopy

BS	bovine serum
CCD	charge-coupled device
CMC	carboxymethyl cellulose
CoC	ceramic on ceramic
CoM	ceramic on metal
EDTA	ethylenediaminetetraacetic acid
ESEM	environmental scanning electron microscopy
E'	elastic modulus (N/m^2)
f	friction factor
h_{\min}	minimum film thickness (m)
L	load (N)
MoM	metal on metal
MoP	metal on polyethylene
r	radius of the femoral head (m)
RI	running in
R_x	equivalent radius (m)
T	frictional torque (N/m^2)
UHMWPE	ultra-high molecular weight polyethylene
UV	ultraviolet
u	entraining velocity (m/s^2)
z	Sommerfeld number
η	viscosity (Pa s)
λ	lambda ratio = $h_{\min}/\text{r.m.s.}$