

# Pin-on-plate studies on the effect of rotation on the wear of metal-on-metal samples

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An important cause of osteolysis and subsequent loosening of replacement hip joints is the body's biological response to polyethylene wear debris. Interest has thus been renewed in hard bearing surfaces such as metal-on-metal implants. Tests were performed on a pin-on-plate machine to determine the effects of pin rotation on the wear of two different compositions of cobalt chrome molybdenum (CoCrMo) against itself (high carbon and low carbon). With reciprocating motion only, the low carbon material gave an order of magnitude higher wear than the high carbon material. The overall wear (that for both the pin and the plate) was significantly reduced with added rotation for the low carbon material but remained approximately the same for the high carbon material. However, the wear of the low carbon material was not reduced below that of the high carbon material which remained the best material in terms of wear.

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## 1. Introduction

Before the introduction of total joint arthroplasty as a solution for damaged joints, people with diseases such as osteoarthritis suffered a great deal of pain and discomfort. In many cases sufferers were confined to a wheelchair and relied on the care of others for what are normally considered as day-to-day living routines. Nowadays, with years of experience behind us, we can rely on this surgical technique to improve the lives of millions of people. However, with more and more people every year taking advantage of total hip replacement surgery, there are more hip arthroplasties performed on the younger patient. The longevity of these joints is therefore becoming increasingly important.

One of the most commonly used prosthetic hip systems is the Charnley low friction arthroplasty which incorporates a metal on ultra-high molecular weight polyethylene (UHMWPE) coupling. Currently, an artificial hip prosthesis can be expected to last on average up to fifteen years with failure due, in the majority of cases, to late aseptic loosening of the acetabular component [1, 2]. This loosening is thought to be as a result of debris induced bone resorption [3, 4]. As the femoral head articulates against the acetabular cup, wear takes place and produces, predominantly, UHMWPE wear particles. It has been suggested that it is the body's biological response to this wear debris that causes osteolysis [5]. This bone resorption results in loosening of the joint at the fixation interface.

It is now well accepted that this wear must be decreased in order to reduce bone resorption. One way of reducing this wear volume is to incorporate hard bearing surfaces such as metal-on-metal and ceramic-on-ceramic prostheses [6–8]. Early metal-on-metal joints

(such as the McKee-Farrar prosthesis) were discarded in favour of the metal-on-UHMWPE prosthesis because of the high frictional torques produced by this large diameter bearing as well as impingement problems and poor surgical technique with subsequent failure [7, 9, 10]. Despite this high incidence of failure, there have been a few reported cases of success after as many as twenty years of use with little wear [11, 12]. By designing these new generation metal-on-metal total hip prostheses to closer tolerances and by using superior metal compositions it is thought that the long-term survivorship of metal-on-metal implants can be further and more consistently improved.

Various workers have performed wear studies on metal-on-metal prostheses using hip simulators that accurately match the loading and motion cycles as experienced *in vivo* and their results reflect the clinical wear situation well [7, 13–15]. However, these types of machine are complex and expensive to produce. Pin-on-plate machines represent a simple method to screen different combinations of materials for use in artificial joints. Unlike hip simulators, the pin-on-plate machine does not attempt to recreate the *in vivo* conditions. These machines assess the wear that will occur when two materials come into contact under similar sliding speeds and contact stresses to those encountered in the body. The specimens are easier to manufacture than those for the simulators as they are just a simple pin and plate. Previous work [16–18] on both metal-on-polyethylene and metal-on-metal samples has indicated that by simply adding a rotational element to the relative motion between the pin and the plate specimens, results more in accordance with clinical wear factors can be obtained.

In this study tests were performed on a pin-on-plate machine to determine the effects of pin rotation on the wear of two different compositions of cobalt chrome molybdenum (CoCrMo) against itself (high carbon and low carbon).

## 2. Materials and methods

The pin-on-plate machine used in this study was based on the existing four station reciprocating pin-on-plate machines at the Centre for Biomedical Engineering at the University of Durham. As with the existing machines, the sledge reciprocated along two fixed parallel hardened steel bars. The heated bed and stainless steel plate holder were positioned on top of this sledge. The plate holder consisted of six wells into which the plate specimens fitted exactly. The lubricant was contained within these individual wells and heated to a temperature of 37 °C by resistors within the bed. This was controlled by a thermocouple. Only four of the stations were loaded, the remaining two were available to be used for soak control specimens although these were not necessary for the metal samples as fluid absorption would be negligible. Two of the four loaded stations incorporated rotation and reciprocating motion, the other two had reciprocating motion only. All four loaded pins were held in stainless steel holders. The pins were notched to provide good location in the pin holders. The holders were held in the pin arm and those pins with rotational motion were held within a polyacetyl bearing within the pin arm. The loads were applied to the specimens via a lever arm mechanism. Level sensors made from platinum wire were attached to each loaded station to allow the lubricant to be maintained at an almost constant level. This was topped up at each station from a common reservoir. An electronic counter was connected to the reciprocating sledge. The sledge was driven by a 0.18 kW, d.c. motor, with the motor speed controlled using a variable voltage supply. Stroke length was altered by adjusting the crank radius of the drive shaft. Rotation was incorporated into the pin-on-plate machine in the form of full rotation provided by small 6.25 W motors attached to the appropriate stations. A perspex cover with removable top and front panels was placed over the entire rig to prevent dust contamination from the atmosphere. A schematic diagram of the pin-on-plate machine is shown in Fig. 1.

Two pins and plates of low carbon (0.06%) wrought CoCrMo alloy (samples 1 and 4) and two pins and plates of high carbon (0.25%) wrought CoCrMo alloy (samples 2 and 3) were provided by Biomet Merck Ltd. Both material compositions were manufactured to meet the requirements of ASTM F1537 and ASTM F799. Each of the pins were flat ended, circular cylinders with a length of 19 mm and a diameter of 5 mm. Two stations applied reciprocating motion only, one to the high carbon material combination and the other to the low carbon combination. Whilst the other two stations applied both reciprocation plus rotation, one to the high carbon material and the remaining station to the low carbon material combination.

The recommendations set out in the ASTM Standard Practice F 732-82 [19] were followed with regard to the

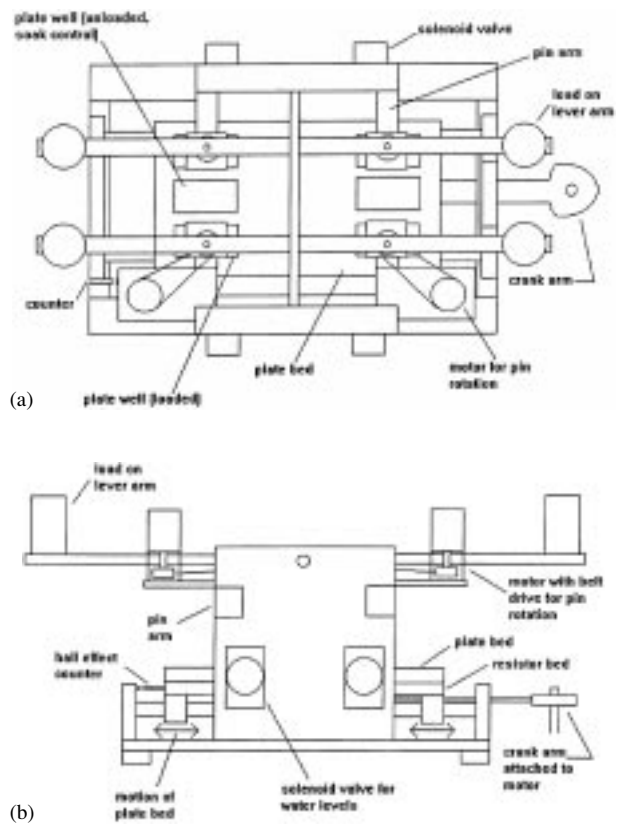


Figure 1 (a) and (b): Schematic representation of the pin-on-plate machine.

motion, sliding speed, lubricant and temperature. The pin-on-plate wear tests were carried out at a temperature of 37 °C, at 60 r.p.m. with a 25 mm stroke resulting in a sliding speed of 50 mm s<sup>-1</sup>. A load of 40 N was applied vertically to each pin to allow for direct comparisons with previous work carried out in the Centre for Biomedical Engineering at the University of Durham. Thirty percent bovine serum with 0.2% sodium azide was used as the lubricant which was topped up with distilled water to counteract any loss of fluid due to evaporation. Where applicable a constant rotation of approximately 60 r.p.m. was applied to the pins.

The wear was assessed gravimetrically. At least twice a week (approximately 0.2 million cycles) the machine was stopped to allow for cleaning and weighing of the samples. Any excess lubricant was syringed from the lubricant baths and the pins and plates removed. The samples were then cleaned with Gigasept disinfectant and then acetone. The pins and plates were then weighed three times on a Mettler AE 200 balance (accurate to 0.1 mg) and an average weight recorded. The machine was then reassembled and the lubricant refreshed. The wear tests were performed up to five million cycles.

Surface topography measurements were performed using a Zygo NewView 100 non-contacting 3D profilometer. At least five measurements of  $S_a$  (three dimensional average surface roughness,  $\mu\text{m}$ ) were taken of the pins and plates of each material composition prior to testing. The surface measurements were then performed at one million cycle intervals until the end of the five million cycle test. Further surface analyses were conducted at regular one million cycle intervals using the light microscope.

The wear volumes were plotted against sliding distance and the gradient of the line through the data (determined by linear regression analysis) provided the wear rate. The wear rate was then divided by the load to determine the wear factor,  $k$  (material specific wear coefficient,  $\text{mm}^3 \text{N}^{-1} \text{m}^{-1}$ ).

### 3. Results

The results obtained from the pin-on-plate tests are shown in Table I and graphically in Figs. 2 and 3. The final wear factors were taken over the full duration of the test.

Both the pin and the plate wear were drastically reduced when rotation was incorporated into the motion as well as reciprocation for the low carbon material. The plate wear of the high carbon material was also reduced significantly with both rotation and reciprocation, however, the pin wear remained about the same. The overall wear (that for both the pin and plate combined) was significantly reduced with added rotation for low carbon CoCrMo but remained approximately the same for high carbon CoCrMo.

Initially, all the surface roughnesses were very similar ( $S_a$  10 nm or less). Once the wear had started there was little difference between the surface roughness measurements throughout the test for both the pins with rotation and reciprocation. Both pins remained very smooth to

TABLE I Wear factors for metal/metal samples with and without rotation

Sample	Material	Wear factor ( $\text{mm}^3/\text{N m} \times 10^{-6}$ )
Plate 1 (rotation)	Low carbon	0.61
Plate 2 (rotation)	High carbon	0.063
Plate 3	High carbon	0.22
Plate 4	Low carbon	4.5
Pin 1 (rotation)	Low carbon	0.55
Pin 2 (rotation)	High carbon	0.78
Pin 3	High carbon	0.53
Pin 4	Low carbon	1.9

both the eye and in terms of surface roughness measurement. The wear tracks on the plates with rotation varied considerably throughout the duration of the test. The surface roughness measurements for both plates with rotation and reciprocation also fluctuated throughout the tests. There were both highly polished areas and areas of light to moderate scratching seen on the plates. The position and amount of this scratching on the wear track varied during the course of the test.

As soon as the reciprocation motion started, the wear of both pins and plates with reciprocation only established as unidirectional scratching in the direction of motion. The surface roughness of the wear track increased with duration of sliding.

### 4. Discussion

The wear factors compare well with those found by other workers [7, 18]. The low carbon material resulted in higher wear rates than the high carbon material under both the conditions of reciprocating motion alone and reciprocation plus rotation. This marked reduction in the wear of high carbon CoCrMo against itself when compared to low carbon CoCrMo against itself has also been shown by Schmidt *et al.* (1996) [7]. They found that with reciprocating motion alone the low carbon pairing gave wear factors of between five and twelve times the high carbon pairing.

The addition of the rotational motion to the low carbon material significantly reduced the wear. This effect on the high carbon material, however, was far less pronounced than for the low carbon material. The plate wear reduced but the pin wear was not significantly changed. Tipper *et al.* (1999) [18] also found that the introduction of a second axis of motion to metal-on-metal wear samples decreased the wear of the low carbon content material significantly but not that of the high carbon content material. Overall the wear order is specified below and can be seen in Fig. 4.

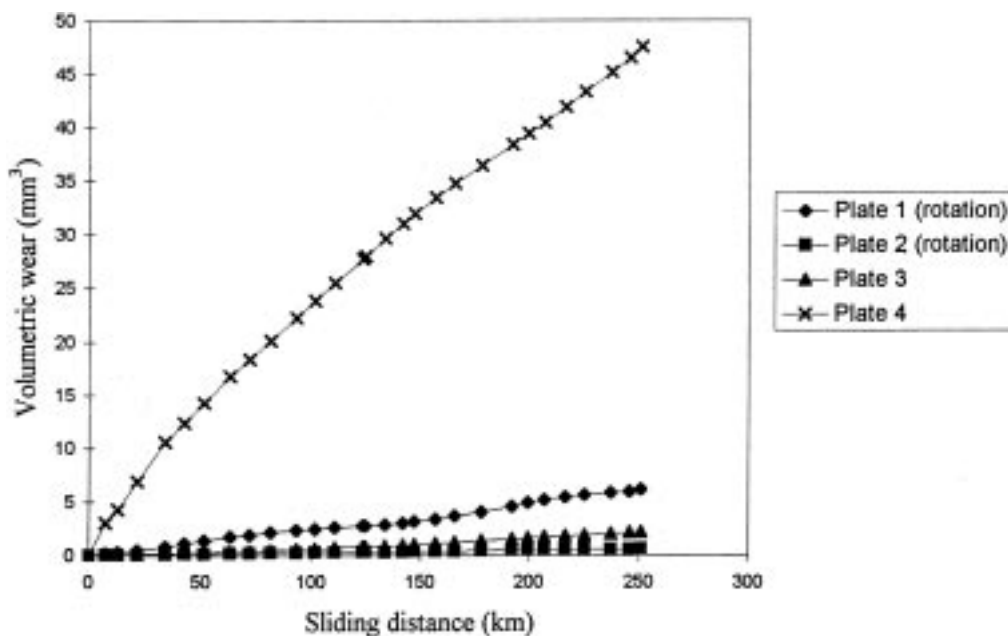


Figure 2 Volumetric wear versus sliding distance for the CoCrMo plates.

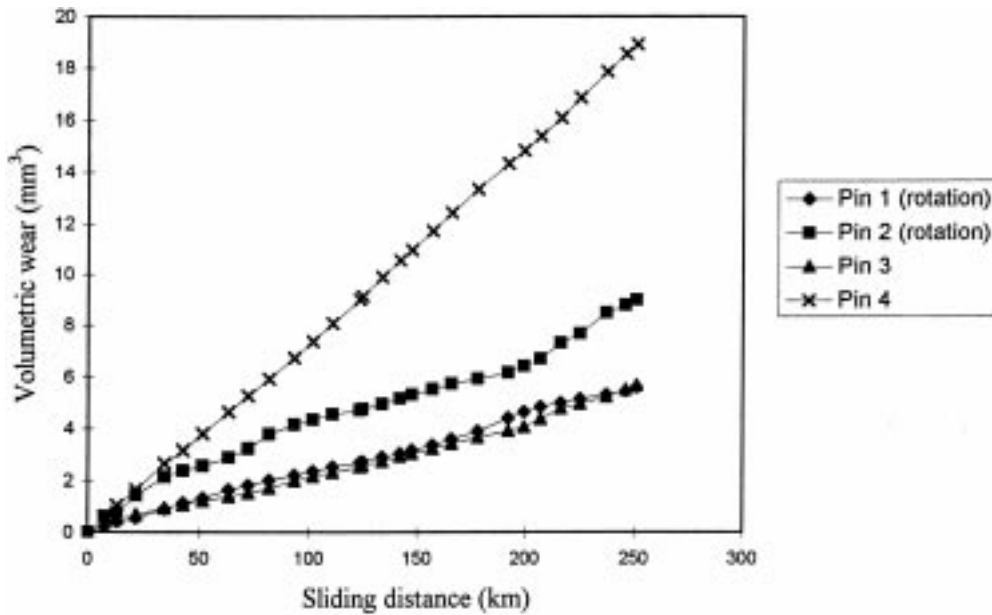


Figure 3 Volumetric wear versus sliding distance for the CoCrMo pins.

Wear of high carbon (with rotation) = wear of high carbon < wear of low carbon (with rotation) < wear of low carbon.

Therefore, although the addition of rotation decreased the wear of the low carbon material dramatically, it did not decrease it below the wear of the high carbon material with reciprocating motion alone ( $1.15 \times 10^{-6} \text{ mm}^3/\text{Nm}$  cf.  $0.75 \times 10^{-6} \text{ mm}^3/\text{Nm}$ ). High carbon CoCrMo is therefore the best in terms of wear.

It is hypothesized that the reduction in wear factor with the addition of rotational motion is due to multidirectional polishing of the metal surfaces. With reciprocation alone the metal surfaces are scratched in the direction of sliding. When rotation is added some of the “built up edge” surrounding the scratch (because the metal is ductile) may be folded back into the wear track making it less likely to become an abrading asperity but

also making it less likely to be removed as a wear particle. Multidirectional polishing of metals in this type of test has also been discussed by Tipper *et al.* (1999) [18].

When calculating the wear factors only the reciprocating sliding distance was taken into account, no alteration was made to the sliding distance due to the rotation of the pin in those tests which incorporated both reciprocation and rotational motion. This is a somewhat simplified method of calculating the wear factor. Calculations were performed to determine what effect, if any, the rotation had on the overall sliding distance [20]. It was shown that rotation increased the average sliding distance (depending on which position on the pin the calculations were performed with respect to, the sliding distance was either increased or decreased) but only by about 2.1%. It was therefore deduced that using

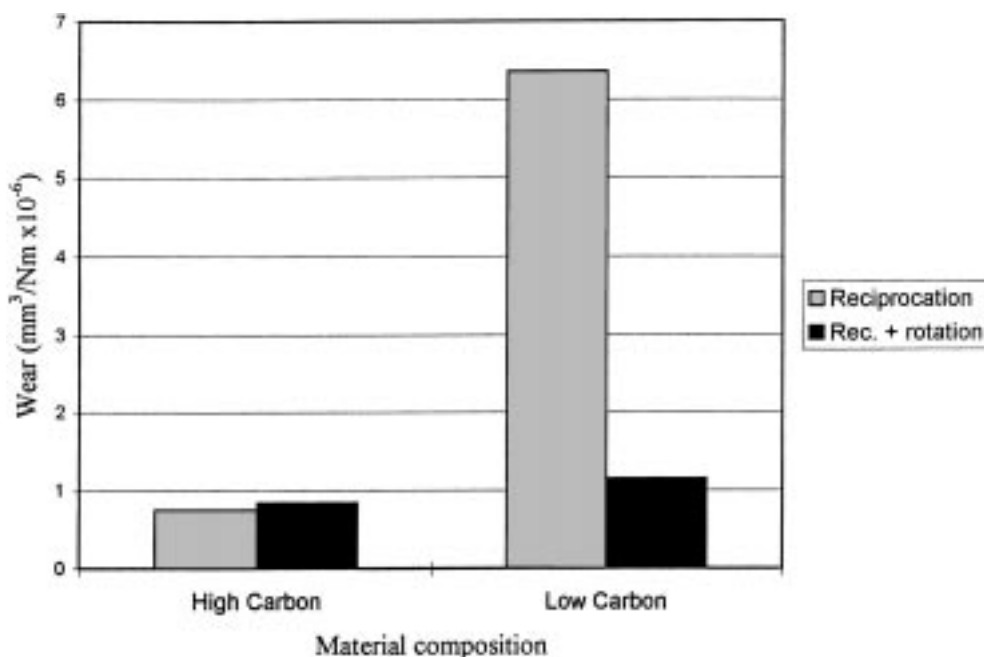


Figure 4 Total wear of the metal-on-metal pins and plates with and without rotation.

the reciprocating sliding distance in the calculations of wear factor was, indeed, a good approximation to the sliding distance.

## 5. Conclusions

High carbon CoCrMo has been proven to be a better material in terms of wear than low carbon CoCrMo. Also, the addition of rotational motion to the simple reciprocating pin-on-plate machine reduced the wear in the metal-on-metal samples more closely to that found clinically. The pin-on-plate machine with rotation is therefore considered to be a more accurate method of comparing the wear of different material combinations than the simple reciprocating machines. It is also considered to be a cheap and simple solution for comparing these material combinations before testing them on simulators that more accurately match the loading and motion cycles within the body.

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