CHAPTER 7

EXPERIMENTAL VERIFICATION

7.1 Simulator studies

7.1.1 Introduction

The literature study (Chapter 2) and also the results of Chapters 4, 5 and 6, indicate that acetabular cups fail principally because of excessive wear. This wear can be classified according to different modes of failure. Various simulator wear studies have been completed by McKellop et al. (2000) and Clarke et al. (1996), during which wear rates were recorded. Some temperature recordings were also made to try to quantify the temperature in the joint. From the literature available, the finding is that the typical average wear of hip implants is approximately 35 mm^3 per year or 3.5 mm^3 per 100 000 cycles (Sychterz et al., 1996; Jasty et al., 1997; Buford & Goswani, 2004). (See paragraph 2.6, page 35.) However, simulator studies reported on in the literature surveyed make use of a common experimental technique, in that the cups were removed at regular intervals (500 000 cycles) during the tests to measure the wear rates and to clean the acetabular cups and holders. This practice is in accordance with ISO 14242-1 (2002).

Using the technique to remove the acetabular cup after every 500 000 cycles to determine the amount of wear creates three basic problems which are:

a. The wear debris formed during the test, in the joint, is gradually washed out with every cleaning cycle. Although the surface defect is still present, the effect is that the test is restarted with new lubricating fluid and that the cumulative damage due to the generated debris, if any, cannot be accounted for. It was shown in paragraph 6.2.2 that severe scratches became the result of wear debris floating around in the joint area.

b. The material has an inherent plastic memory (Engineering Material Handbook, 1987). When the cup is removed from the simulator, it allows restoration within the plastic limit of the material. As indicated in Chapter 3, it was found that the creep of the UHMWPE should not be ignored. If the cups are removed from the simulator, the effect of cumulative creep is to some extent compromised.
c. The greatest problem with the technique of removing the acetabular cup to determine the mass loss is that the generated wear pattern in the acetabular cup cannot be aligned after disassembly. The net result of this is that every time the system is reassembled a new test is started.

McKellop et al. (2000) report temperatures as high as 90°C on the bearing surface in simulator testing. The bearing couple used was zirconium for the femoral head and UHMWPE for the acetabular cup. As the temperature was measured inside the zirconium femoral head, it should be remembered that the heat transfer coefficient of zirconium is so low that it can be regarded as a super isolator ($k = 0.0152\ W/m^2K$). The measured temperature was then extrapolated by means of a finite element analysis to a temperature below the surface of the ultra-high molecular weight polyethylene (UHMWPE). This is not a true reflection of the highest obtained temperature on the contact surface. Owing to the difference in heat transfer coefficients, the heat flux through the UHMWPE is much higher than through the zirconium. The temperature in localised areas can rise as high as 90°C to 100°C, but the average temperature on the bearing surface will not reach these values, otherwise the bearing will collapse.

To provide answers to the abovementioned aspects, a five poster hip simulator was built in which acetabular cups could be mounted and tested.

The main aim of the experimental verification during the course of this study was:

a. To deal with the deficiencies in the ISO procedure (ISO 14242-1 (2002)) and

b. to determine the effect of localised heat build-up on the bearing surface.

7.1.2 Design of a simulator

Simulators described in the literature, as discussed in Chapter 2, paragraph 2.10, are all hydraulically actuated with obvious advantages in flexibility, but with a high cost factor. It was decided to design a simulator where load is applied mechanically. A swing-over arm provides the necessary movement. The final concept decided upon can be seen in Figure 7.1. The basic layout of the machine is shown in Figures 7.2a and 7.2b. The basic principle is that the swing-over-arm has a length of 1 000 mm while the stem onto which the ball is mounted has a length (radius) of 300 mm. This means that when the swing arm moves through an angle θ by means of the crank, the stem moves through an angle of +30° and -30°. As the stem moves through the zero position, the cup is depressed 28 mm. The springs (Figure 7.4) on which the cups rest were designed to deliver a resisting force of 1500 N at 30° and 4000 N at 0°. This is representative of the forces on the hip during walking and corresponds to a walking speed of 6 km/h as measured by Bergmann et al. (1993). (See Figure 7.3.)

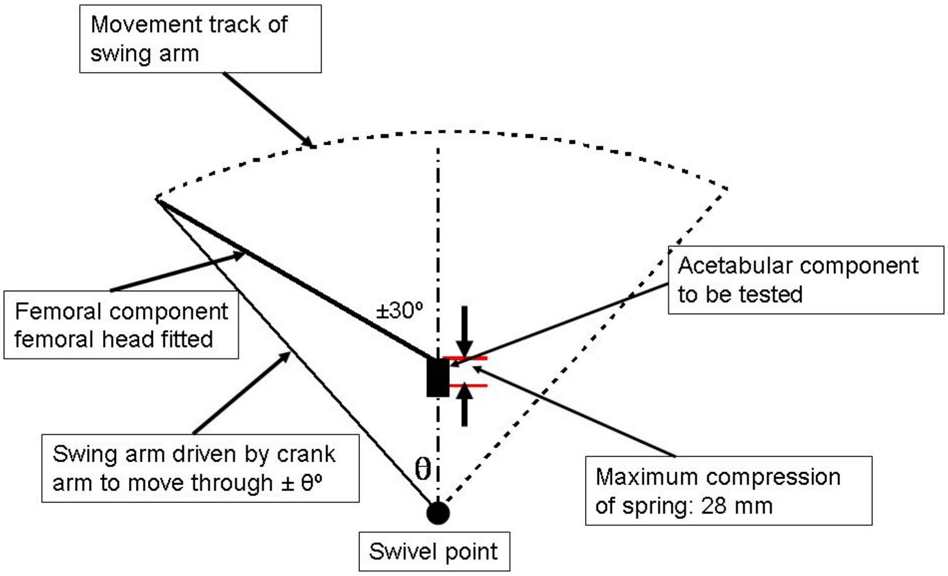

Figure 7.1: Concept for simulator movement

Figure 7.4 shows the achieved movement. The recorded force data was obtained from strain gauges mounted on the neck of the femoral stems. (See Figure 7.9.) These strain gauges were also used to set up the simulator, and to monitor the movement of the machine and determine the limits as to when to stop the machine if something should fail. A limit value of ± 5% of the applied load was decided upon. The stiffness value used in the design of the spring was 105 kN/m.

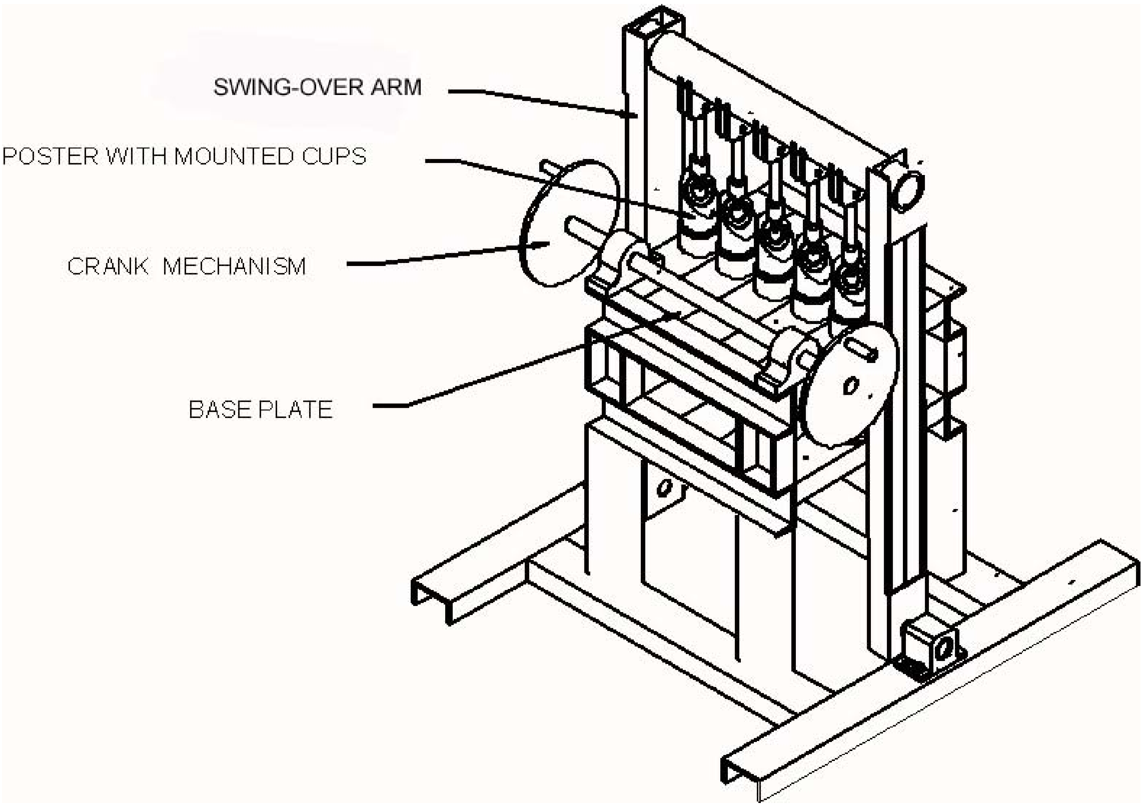

Figure 7.2a: Schematic layout of the simulator

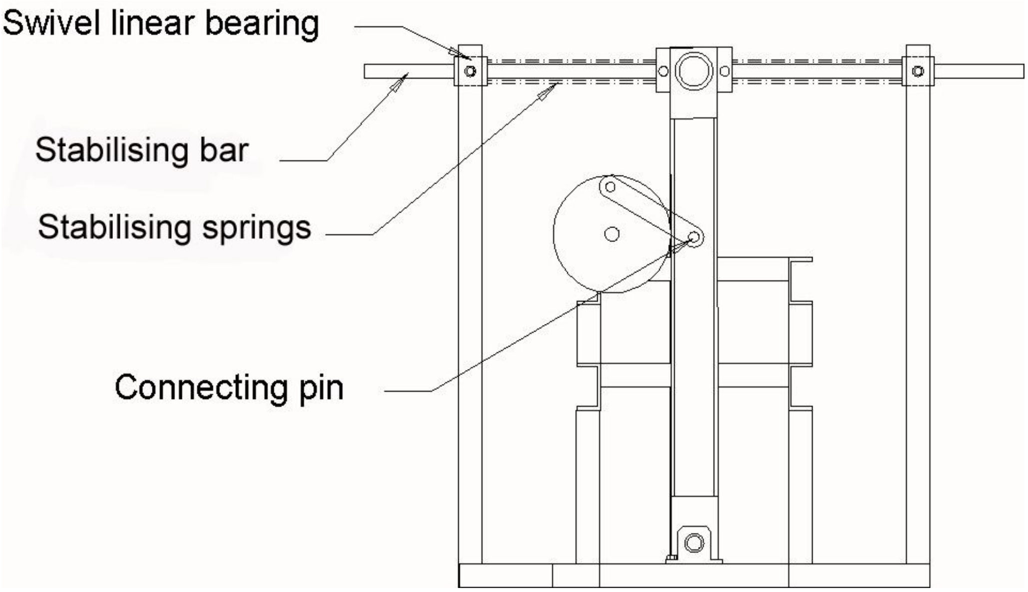

Figure 7.2b: Schematic layout of the simulator: Side view

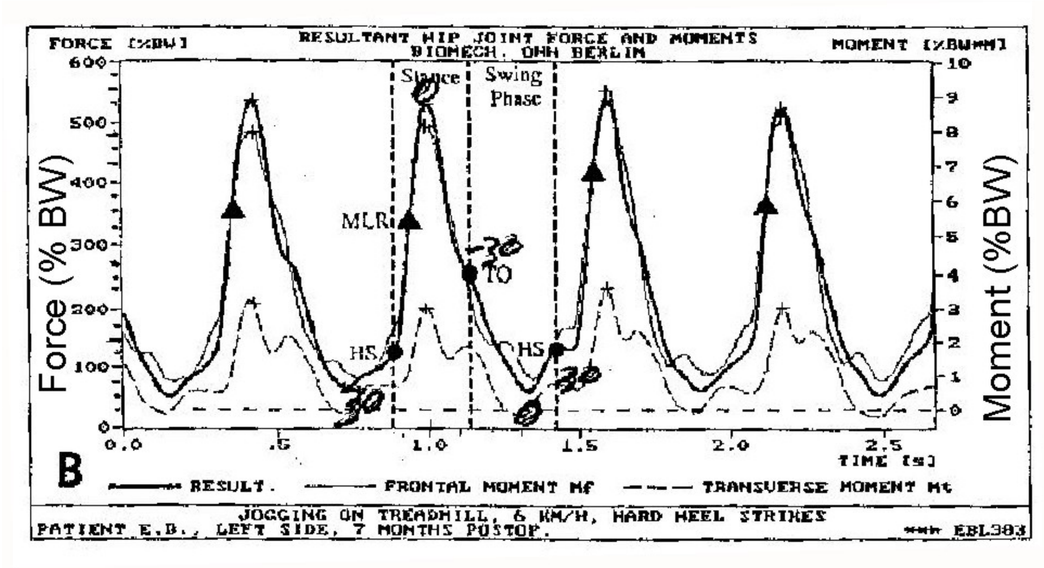

Figure 7.3: Hip movement as measured by Bergmann et al. (1993)

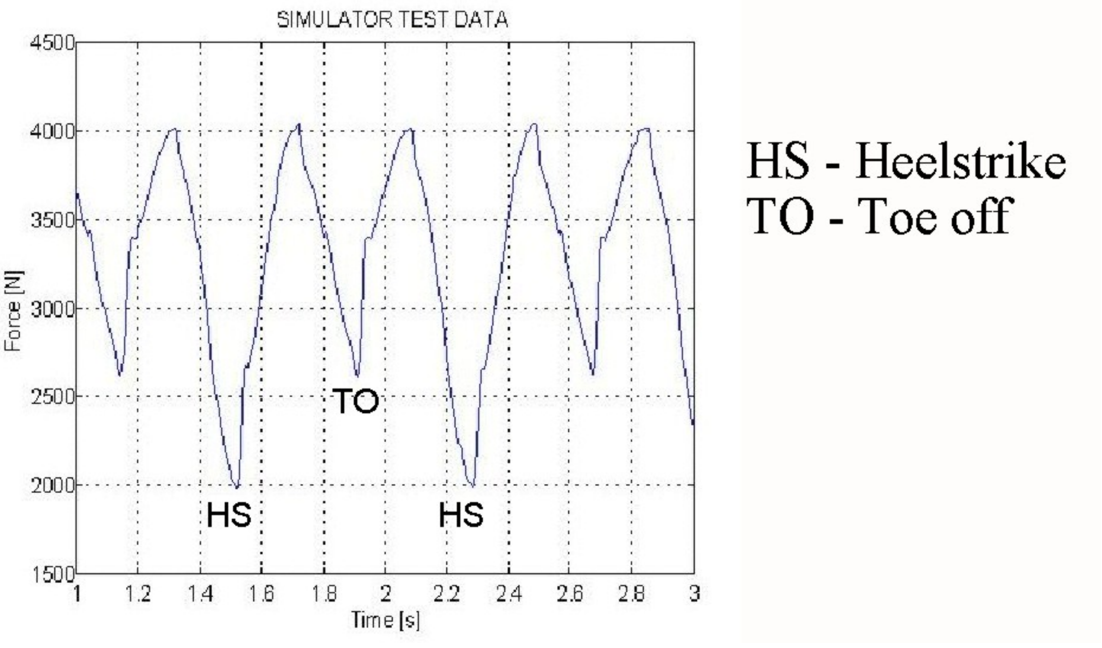

Figure 7.4: Recorded force/time graph of the simulator

The springs were manufactured and then calibrated to achieve the required stiffness for each spring. In the design of the simulator, provision was made for an adjusting plate (Figure 7.5) on which the springs are mounted. The purpose of these plates is to permit final adjustment after assembly to ensure an exact and equal loading on each post. Top dead centre is taken as the zero point. The swing-over arm is driven with an electric motor via a crank mechanism as shown in Figure 7.2. Also shown are the stabiliser bars mounted at the side, fitted with two springs on two corners to smooth out the high accelerations at the end of each cycle. (See Figure 7.6 for a photograph of the stabilising spring assembly.)

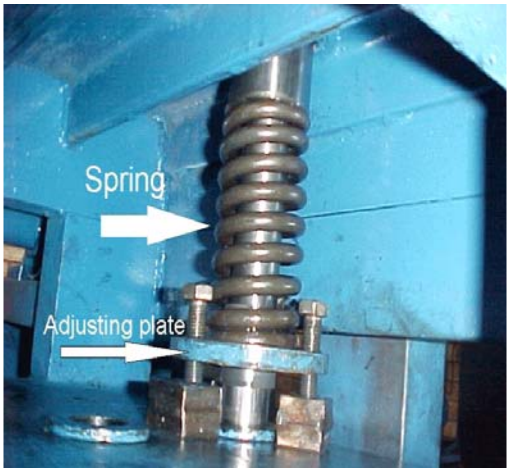

Figure 7.5: Loading spring with adjusting plate

Figure 7.6: Assembly of stabilising springs

A model of the dynamic response of the simulator was prepared. The purpose of this model was to determine the size of the stabilising springs mounted on the corners. The model was used to determine the resultant force on the pin connecting the connecting rod to the swing arm. Figure 7.7 is a graphical presentation of the effect of the stabilising springs. The stiffness finally determined was 20 kN/m. (See Figures 7.2b and 7.6 for the position of these springs.)

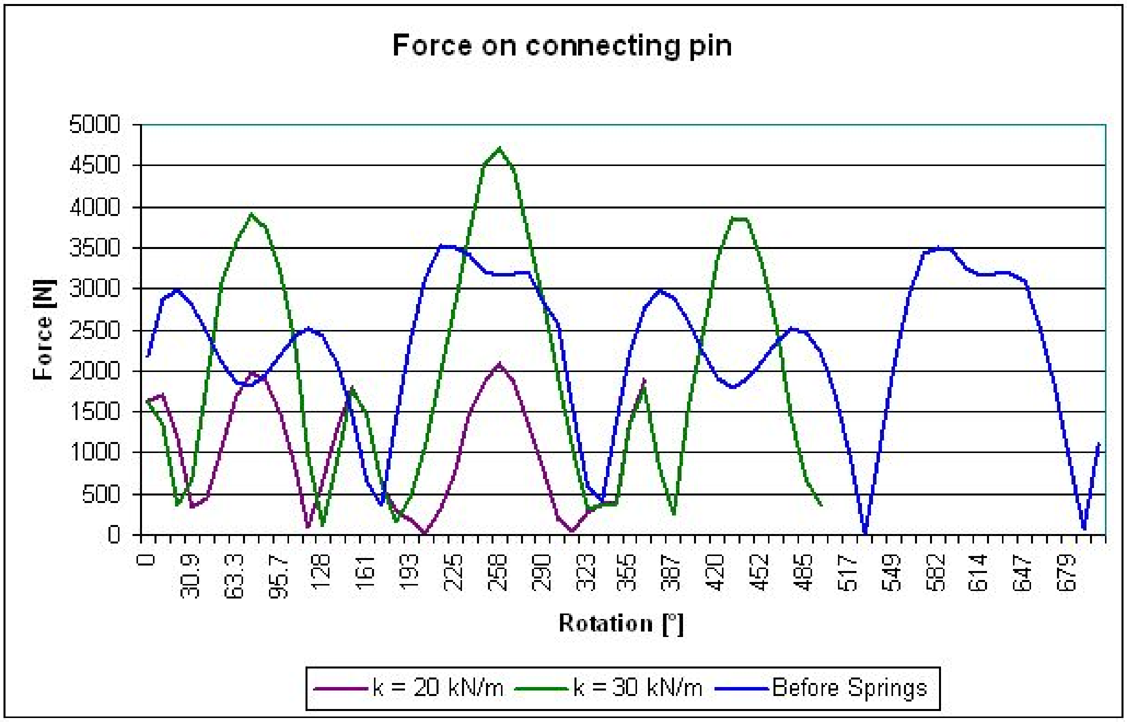

Figure 7.7: Graphical presentation of the forces on the connecting pin

The design of the simulator also makes provision for 5° adduction/abduction rotation.

The femoral head is connected to the swing-over arm with rod ends in which the ±5° movement can be achieved. The rotation of the femoral stem is mechanically activated at the end of each cycle by a deep groove ball bearing connected to the stem, stopping against an adjustable stopper. This rotation simulates adduction/abduction rotation at heel strike and toe-off. The detail is shown in Figure 7.8.

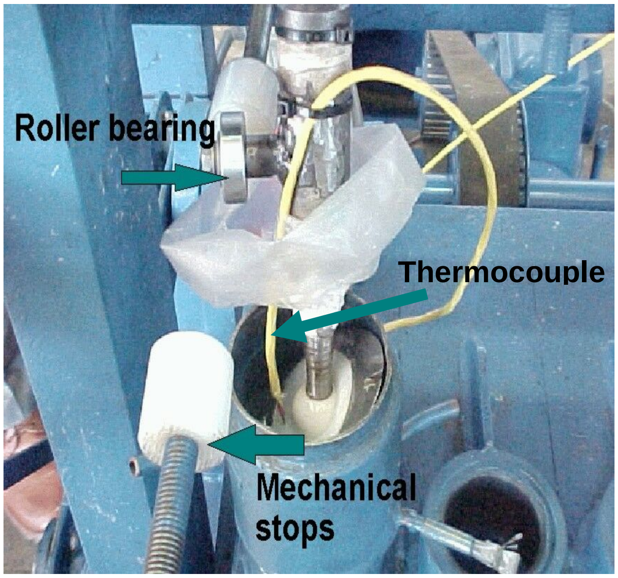

Figure 7.8: Mechanical stops to achieve ±5º abduction/adduction rotation

The steel backing of the post is mounted inside a container. Water is circulated through the jacket of the container to maintain the temperature of the lubrication fluid at 37.5°C. The temperature in each post is monitored by means of a thermocouple, as can be seen in Figure 7.8. Detail of the strain gauges as well as the detail of the cup mounted in the post is shown in Figures 7.9 and 7.10.

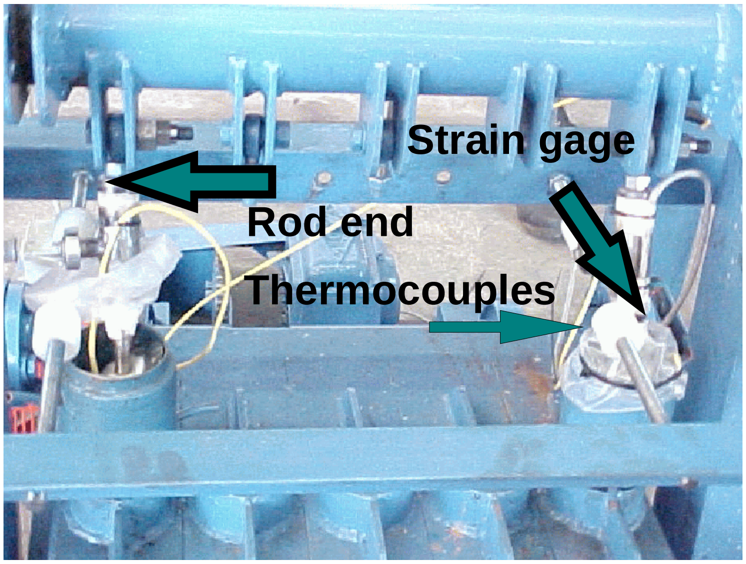

Figure 7.9: Two cups in position showing the thermocouples and strain gages

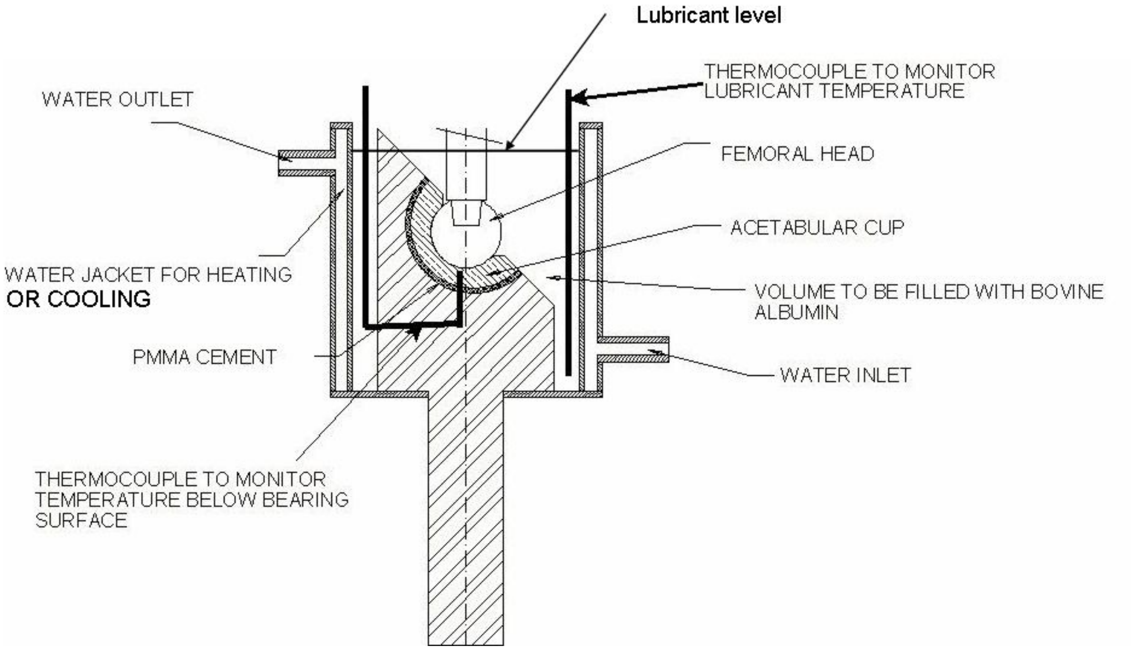

Figure 7.10: Detail of the acetabular cup in the test station

7.2 Overview of test work to be carried out

During the experimental phase of this study, a number of tests were conducted to establish the effect of overheating between the ceramic femoral head and the UHMWPE acetabular cup.

The first tests were done in the hip simulator as described in paragraph 7.1. The main aim of these tests was to establish whether the differences in the wear debris formed under the following test conditions could be detected:

a. When the simulator was running with lubricant.
b. When the simulator was running without lubricant.

In both cases, the wear debris generated was collected and compared. The temperature rise in the acetabular cup was also monitored to establish the rise in temperature against time.

Throughout the experimental phase, the control test performed was to compare the debris generated during the laboratory experiment with the debris retrieved from tissue surrounding the joint in-vivo, as this is the only way to calibrate the tests and to establish the effect of the various parameters. The design and test parameters were altered continuously until similar debris resulted.

The second set of experiments was conducted to establish what temperature was required to generate the type of wear debris as retrieved from the tissue surrounding the joint in-vivo. Two tests were designed to determine the temperature at which the debris formation starts namely:

a. Test to generate wear particles by generating frictional heat on the bearing surface between the ceramic femoral head and the UHMWPE test piece.
b. Test to generate wear particles by heating a ceramic femoral head externally and then ploughing it through the test piece.

The third set of tests was designed to determine the coefficient of friction between a ceramic femoral head and an UHMWPE acetabular cup. As friction is the main component generating heat in-vivo, it was necessary to determine the correlation between the theoretical values and the actual values as measured in an acetabular cup. The tests were performed under the following conditions:

a. Dry
b. Dry with wear debris on the surface
c. At an elevated temperature of approximately 60ºC.

7.3 Test with lubrication – test 1(a)

7.3.1 Test protocol

The simulator is operated at 1.5 Hz, similar to the simulator of McKellop et al. (1997, 2000), Wang et al. (1996) and as defined in ISO 14242-1, (2002). This corresponds to 90 cycles per minute or the equivalent of approximately 90 metres in one minute. The lubricating fluid used for the current study was 0.9% NaCl solution. The reason for using NaCl as a lubricant is that the lubricant as prescribed by ISO 14242-1, (2002) namely a 25 ± 2% calf serum solution with a minimum protein mass of 17 g/l, must be changed after every 500 000 cycles as it decomposes. Although NaCl is not a good lubricant, it will provide accelerated results, especially in view of the fact that no long-term tests were planned, but merely the determination of the rise in temperature and the nature of the particles generated. At a rate of 1.5 Hz, a life cycle test of 20 years will take approximately three months to complete.

Continuous temperature readings (Figure 7.9) were taken in and around the cup to establish the temperature of the UHMWPE just below the wear surface. (See Figure 7.9.) The loading in each femoral component was also monitored to ensure that the machine remains within the determined specification. (See Figure 7.11.)

Samples of the lubricating fluid (0.9% NaCl) were taken at every 250 000 cycles. The fluid was filtered through a 0.45μm filter. These are the same filters that were used to extract the wear debris from the tissue surrounding the joint in-vivo and retrieved during revision surgery. The filtered fluid was returned to the test station.

Figure 7.11: Test-recording equipment

7.3.2 Test results

Temperatures of up to 65°C were measured in the bottom of the cup within 15 minutes of operation where after the temperature stabilised at 65°C. The lubricating fluid in the chamber was kept at a constant temperature of 37.5°C. As described, the first sample was taken after only 250 000 cycles and the lubricating fluid was filtered through a 0.45µm filter. The same technique, as described in Chapter 5, was used, in other words colouring of the filter paper enabled the wear particles to become visible against the coloured filter paper and allowed them to be studied under a microscope. In Figure 7.12, two wear particles can be seen at 40 times magnification.

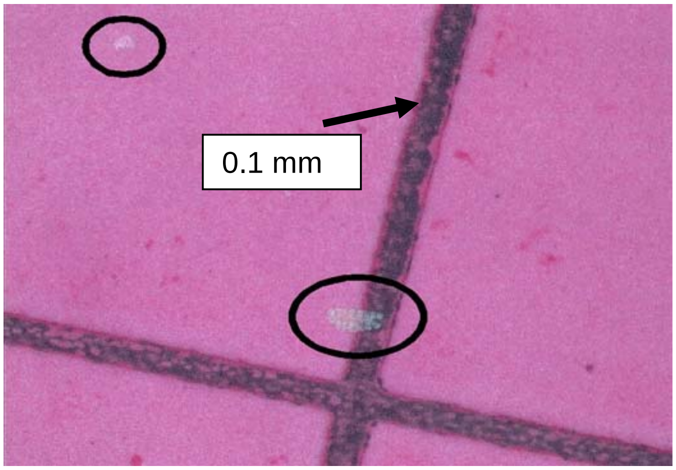

Figure 7.12: Wear particles on filter material (magnification x 40)

In Figure 7.13, the larger particle is shown under a magnification of 100 times. From this photograph (see the enclosed CD for better clarity), the extruded edges are clearly visible. The shape of the wear particle indicates that the temperature at localised spots rises sufficiently to allow the particle to be transferred or to be extruded. The same particle but under 900 x magnification is shown in Figure 7.14.

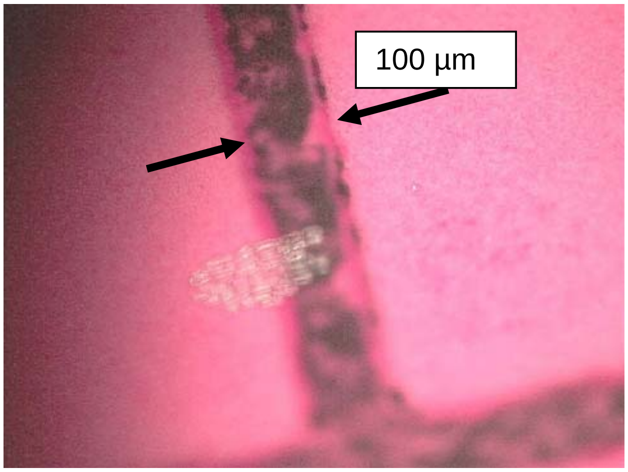

Figure 7.13: Wear particle retrieved from simulator (magnification x 100)

Figure 7.14: Retrieved wear particle from simulator (magnification x 900)

In total, four samples were drawn through the test of 1 000 000 cycles, all with the same shape and size of wear debris.

7.4 Test without lubricant – test 1(b)

7.4.1 Test protocol

The same test protocol as for the UHMWPE acetabular cup, with lubricant, was used. The test was done without any lubricant to obtain accelerated wear and to establish the shape of the wear particles generated. The purpose was to obtain particles generated under the most extreme conditions and then to study their shape, and the damage caused to the bearing surface. It was expected that under these extreme conditions the acetabular cups would fail very quickly and therefore no temperature recordings were made. Another problem is that the failure due to overheating is localised, which makes it almost impossible to measure in the current test configuration. It was decided that the rise in temperature would be determined later on with a different test configuration. (These results are presented in paragraph 7.3.)

7.4.2 Test results

Failure occurred after about 10 minutes, at 90 Hz, when strands of plastic were forced out from the bearing surface in the acetabular cup. The surface, after failure, can be seen in Figures 7.15 and 7.16.

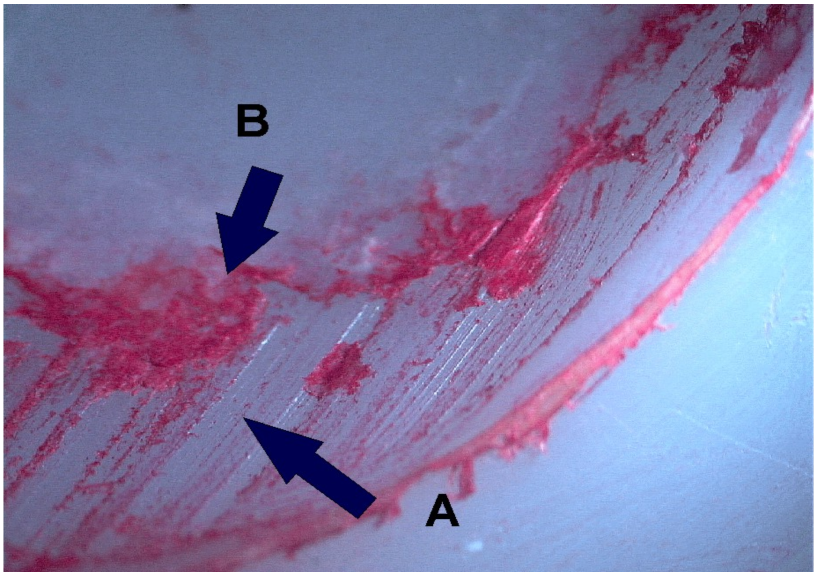

Figure 7.15: Wear surface on the inside of the cup (magnification x 10)

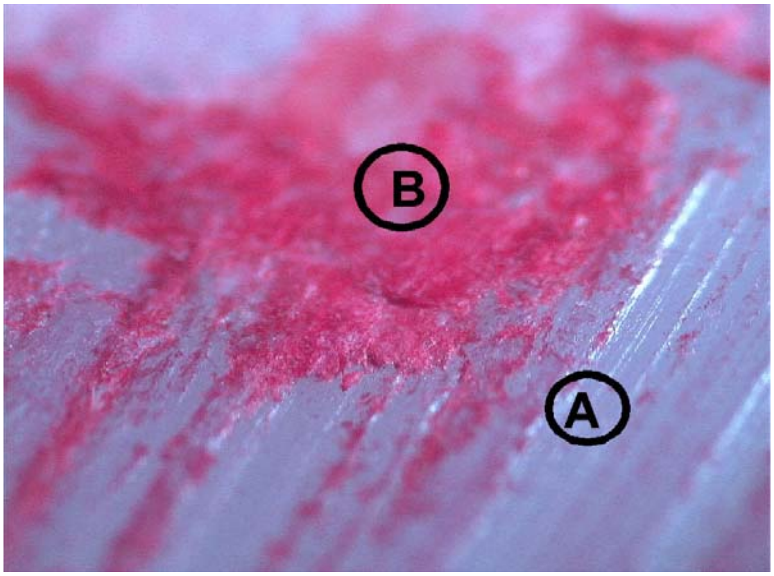

Figure 7.16: Wear on inside of a cup (magnification x 20)

On close examination of the wear surface, the following two aspects are visible:

a. An area is visible where it appears as if the material was torn out of the base material, leaving what looks like scratch marks. (See A in Figure 7.15 and enlarged in Figure 7.16 also marked by an A)

b. On the edge of the high-wear area, extrusions are visible. This is marked with a B in Figure 7.15 and enlarged in Figure 7.16.

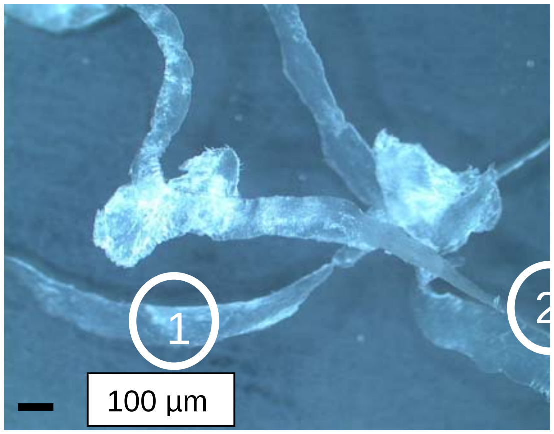

Figure 7.17: Wear debris retrieved from an acetabular cup on simulator (magnification x 20)

c. If one looks closely at the retrieved wear debris, Figures 7.17, 7.18 and 7.19, signs of waviness on the edges are visible, suggesting formation at an elevated temperature. The extruded whiskers, as described in paragraph 5.8.2, are also visible.

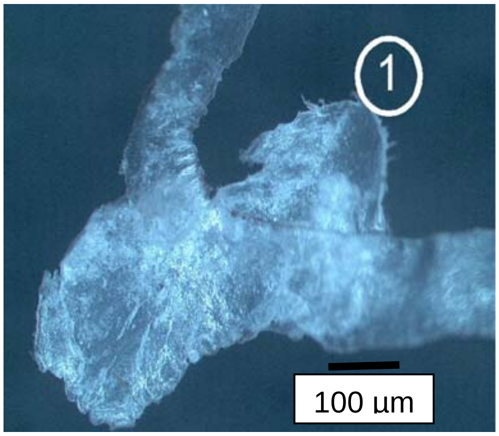

Figure 7.18: Wear debris retrieved from an unlubricated acetabular cup in a hip simulator (magnification x 40)

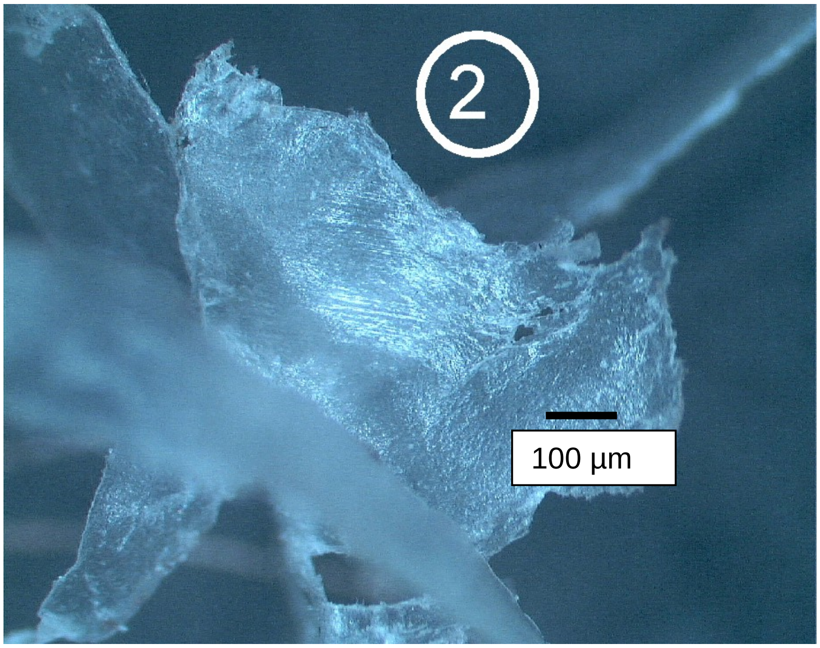

Figure 7.19: Wear debris retrieved from an unlubricated acetabular cup in a hip simulator (magnification x 40)

7.5 Test to generate wear particles by generating frictional heat on the bearing surface – test 2(a)

7.5.1 Purpose of the test

Various wear particles were retrieved throughout the course of this study whether from fresh retrievals from patients or from tests done on the hip simulator in the laboratory. All of the retrieved debris showed signs of extrusion. The temperature at which failure had occurred was still unknown. Therefore, this experiment was performed to enable manufacturing of wear debris and to determine the temperature at which the debris started forming.

7.5.2 Test protocol

A very simple test was designed to try to manufacture wear debris similar to that found in the tissue retrieved during revision surgery. A ceramic femoral ball was mounted on a steel stem. The combination was then pressed against a block of UHMWPE in a milling machine. The basic layout is shown in Figure 7.20. The femoral ball was rotated at high speed (2 900 rpm) allowing frictional heat to be generated on the bearing surface between the ceramic and the UHMWPE test piece. The test was monitored and when the first wear debris started to appear the ball was quickly removed from the bearing surface and the temperature was immediately measured using a laser-guided infrared thermometer. The advantage of the infrared thermometer is that temperatures can be measured instantaneously and, at the distance used, the object diameter of the temperature reading is about 0.4 mm in diameter.

The wear debris generated was collected for further analysis.

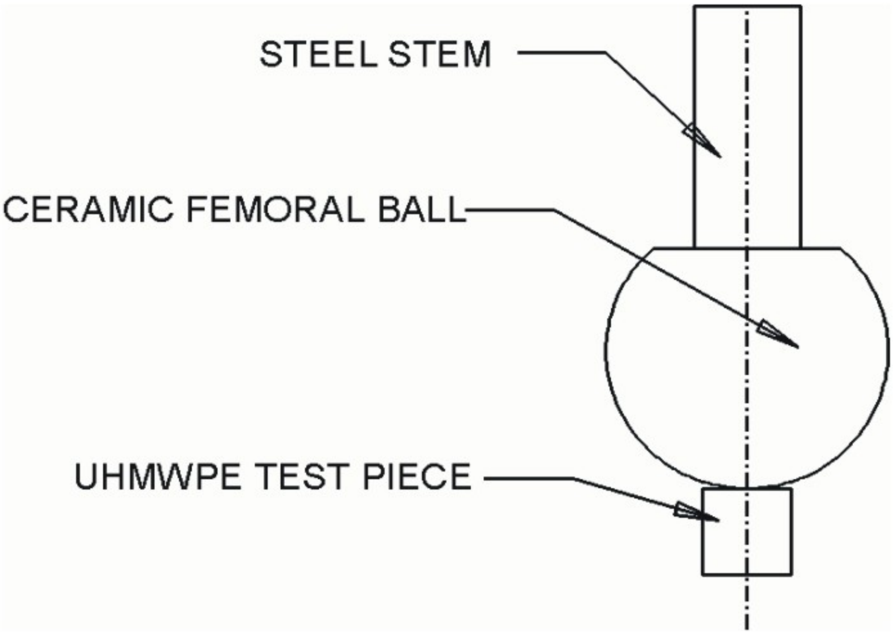

Figure 7.20: Test layout to manufacture wear particles with frictional heat

7.5.3 Test results

A temperature of 105°C was measured on the surface of the UHMWPE test piece at the onset of debris formation. The resulting damage on the UHMWPE test piece can be seen in Figures 7.21 and 7.22.

In Figure 7.23, the wear debris adhering to the ceramic femoral ball is also visible. The extruded edges, as presented earlier, are also visible on the debris that had formed during the test.

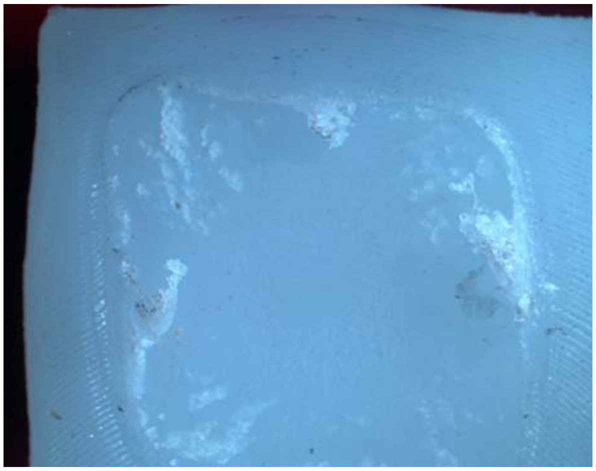

Figure 7.21: Area of damage on a test piece

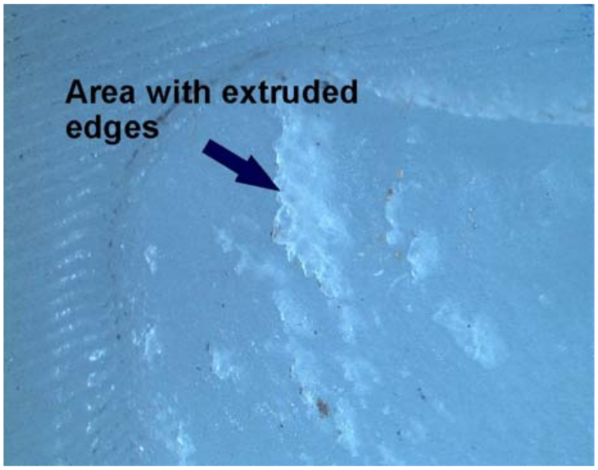

Figure 7.22: Surface damage on UHMWPE test piece (magnification x 20)

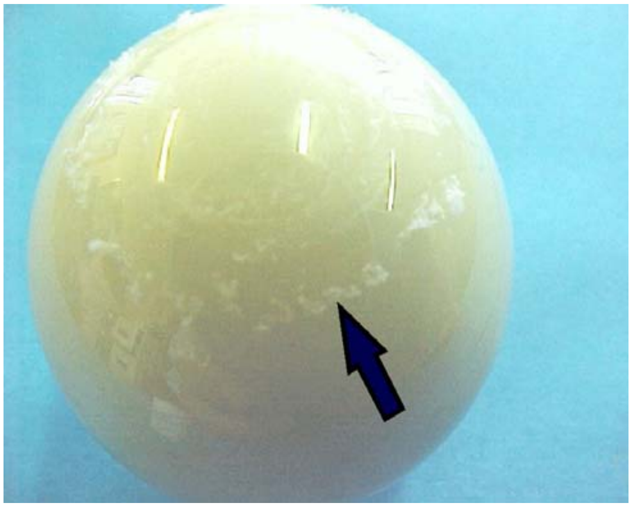

Figure 7.23: Wear debris adhering to femoral ball — indicated with an arrow

The wear debris was retrieved and then examined under a microscope. The same colouring procedure was used as described earlier to see the debris on the filter paper. The resulting debris is presented in Figures 7.24 and 7.25.

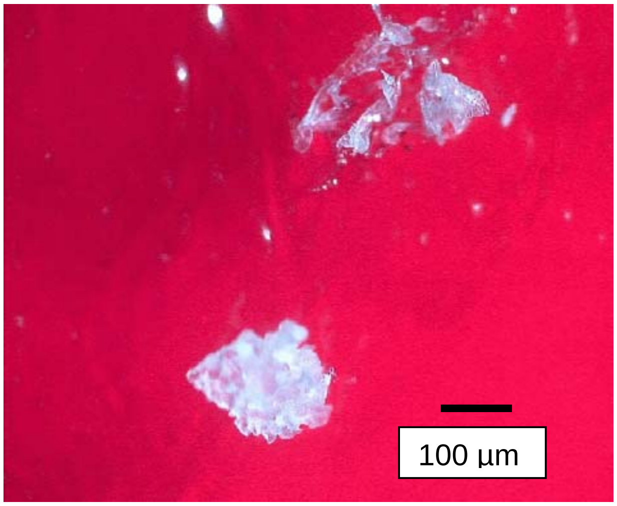

Figure 7.24: Wear debris generated by frictional heat at a measured temperature of 105°C (magnification x 40)

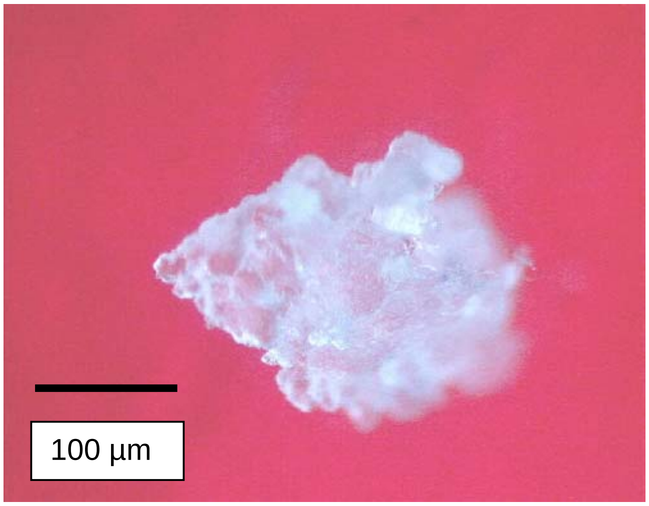

Figure 7.25: Wear particle at higher magnification (magnification x 100)

The particle shows evidence that it heated up sufficiently to adhere to the ceramic femoral head and to be ripped from the base material.

In this investigation, a laser-guided infrared thermometer was used to measure the surface temperature in known hot spot areas. It would, however, be a mistake to assume that the microscopic hot spots can be picked up by the instrument. To explain the principle of uneven surface asperities, a very brief summary of surface action is given here as the phenomenon is well documented in text books on bearing materials (Hutchings, 1992).

Despite the best surface preparation, all surfaces have remaining waviness or surface roughness. When two surfaces are moved relative to each other, as shown in Figure 7.26, the peaks collide and deform. In the case of a well-prepared acetabular cup, the surface peaks are in the order of 2 to 4 µm, compared to a human hair typically having a thickness of 50 µm. The surface peaks that collide are where the biggest temperature rise due to friction is going to take place, although it is almost impossible to measure the exact temperature rise, as already stated.

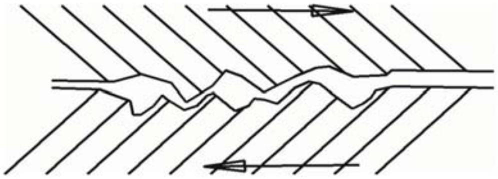

Figure 7.26: Schematic layout of surface roughness

The laser-guided infrared thermometer used in this investigation has an object diameter of only 0.4 mm at the distance used. Although this object diameter is much better than that which can be achieved by thermocouples, this spans approximately 200 surface peaks. The best that can therefore be achieved is to measure the average temperature of a known hot spot.

7.6 Test to generate wear particles by externally heating up a femoral head – test 2(b)

7.6.1 Purpose of the test

The purpose of the test was to generate wear debris under conditions where the ceramic femoral head was preheated to a specific temperature. This enabled the generation of wear debris between the ceramic femoral head and the UHMWPE test piece as verification for the debris generated by means of frictional heating.

7.6.2 Test protocol

The test set-up designed and built for the frictional heating test was again used (Figure 7.20). The ceramic femoral ball was preheated to temperatures of 70, 80, 90 and 100°C, respectively, to enable verification of the temperature measurement at which debris formation started during the frictional heating test. After heating the femoral ball, the machine was set into motion allowing the heated femoral ball to penetrate the material. The femoral ball was rotated at only 50 rpm to virtually eliminate heat generated by friction.

7.6.3 Test results

At 100°C, the surface of the test piece again showed evidence of the femoral head adhering to the UHMWPE and then ripping out and extruding particles from the base material. This phenomenon was not expected at 90°C or lower in this short duration test, as the temperatures measured during the frictional heating test were above 100ºC. (See Figures 7.27 and 7.28 for the damage on the UHMWPE surface and Figure 7.29 showing the wear particles adhering to the femoral ball.)

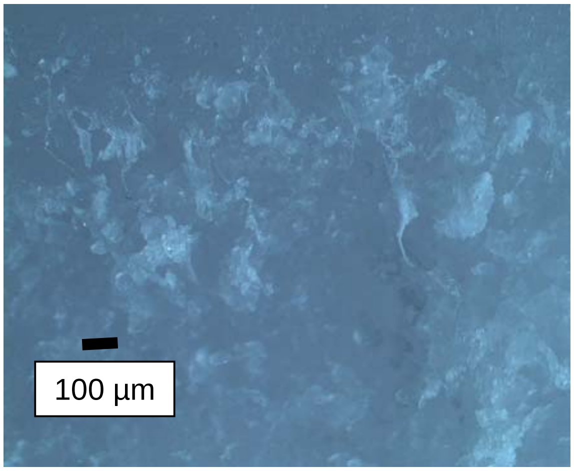

Figure 7.27: Surface of a test piece after damage by preheated femoral head (magnification x 10)

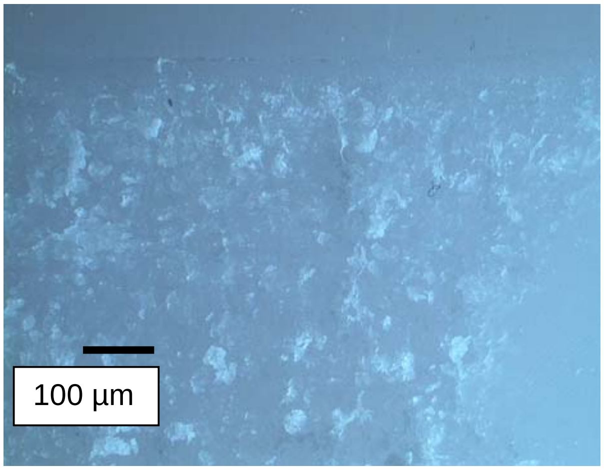

Figure 7.28: Damage surface of UHMWPE test piece (magnification x 20)

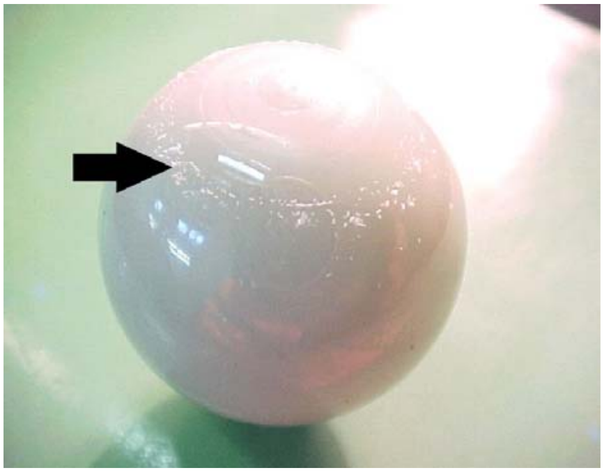

Figure 7.29: Wear particles adhering to femoral ball — indicated with an arrow

The wear debris was again collected for further analysis under the microscope making use of the same technique as described in Chapter 5. (The findings can be seen in Figures 7.30 to 7.32.)

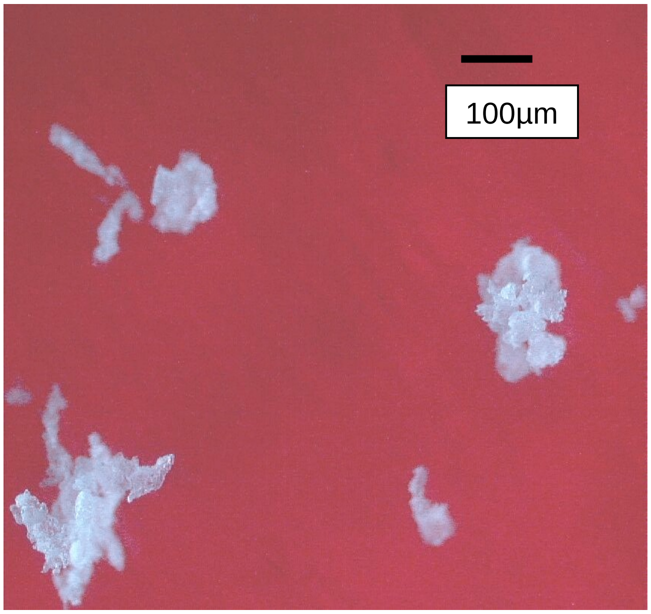

Figure 7.30: Retrieved wear debris from preheated ball test. Ball temperature 100°C (magnification x 20)

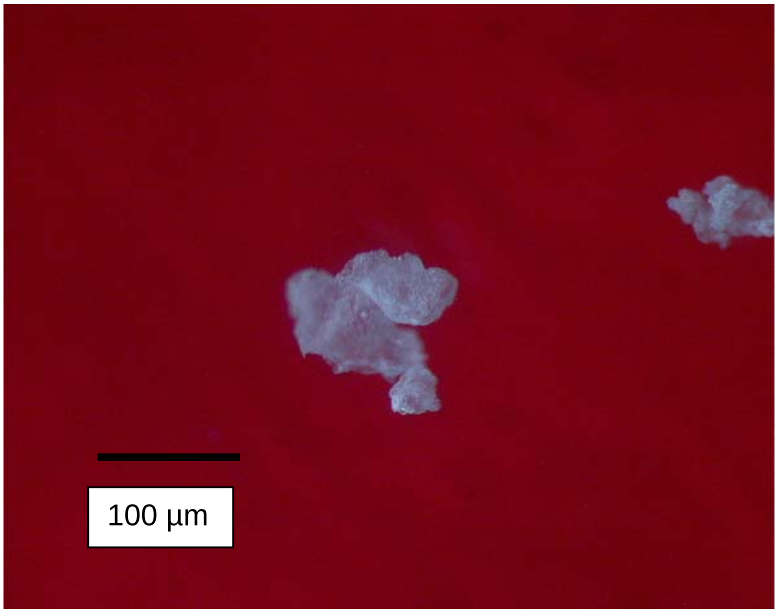

Figure 7.31: Wear particles retrieved from externally heated femoral head at temperature of 100°C (magnification x 40)

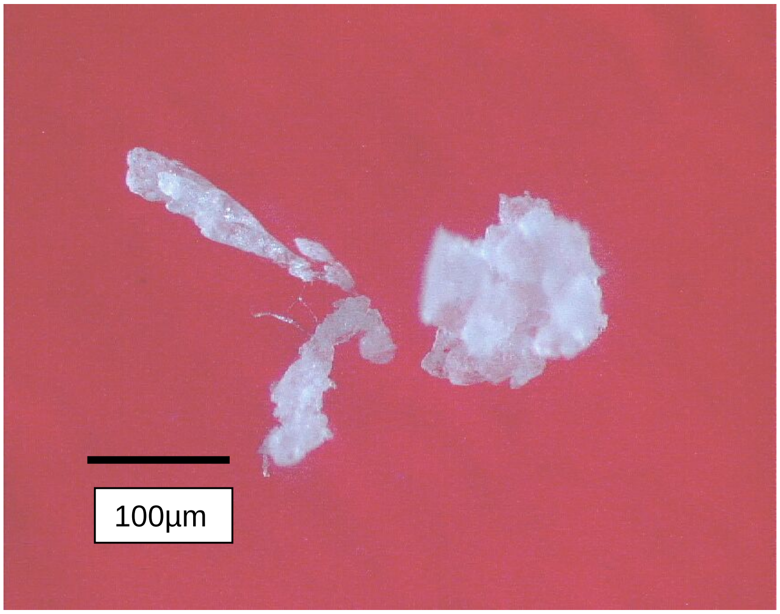

Figure 7.32: Wear particles retrieved from externally heated femoral head at a temperature of 100°C (magnification x 40)

7.7 Test to determine the coefficient of friction on the inside of an acetabular cup – test 3

7.7.1 Purpose of the test

The purpose of the test was to gain an indication of the coefficient of friction between a zirconium femoral ball and the acetabular cup under various conditions. These values are needed to explain the influence of the coefficient of friction on the heat generated in-vivo.

7.7.2 Test protocol

A very simple test was designed to determine the static coefficient of friction between a zirconium femoral head and the acetabular component as shown in Figure 7.33. The femoral head was mounted inside the cup with a weight at the bottom to accomplish the loading. The experiment was designed in such a way that only the friction between the femoral ball and the acetabular cup is measured. This was achieved by having the weight applied to the femoral head going through the centre of the femoral head and thereby the system could be balanced without external fixation that could influence the results.

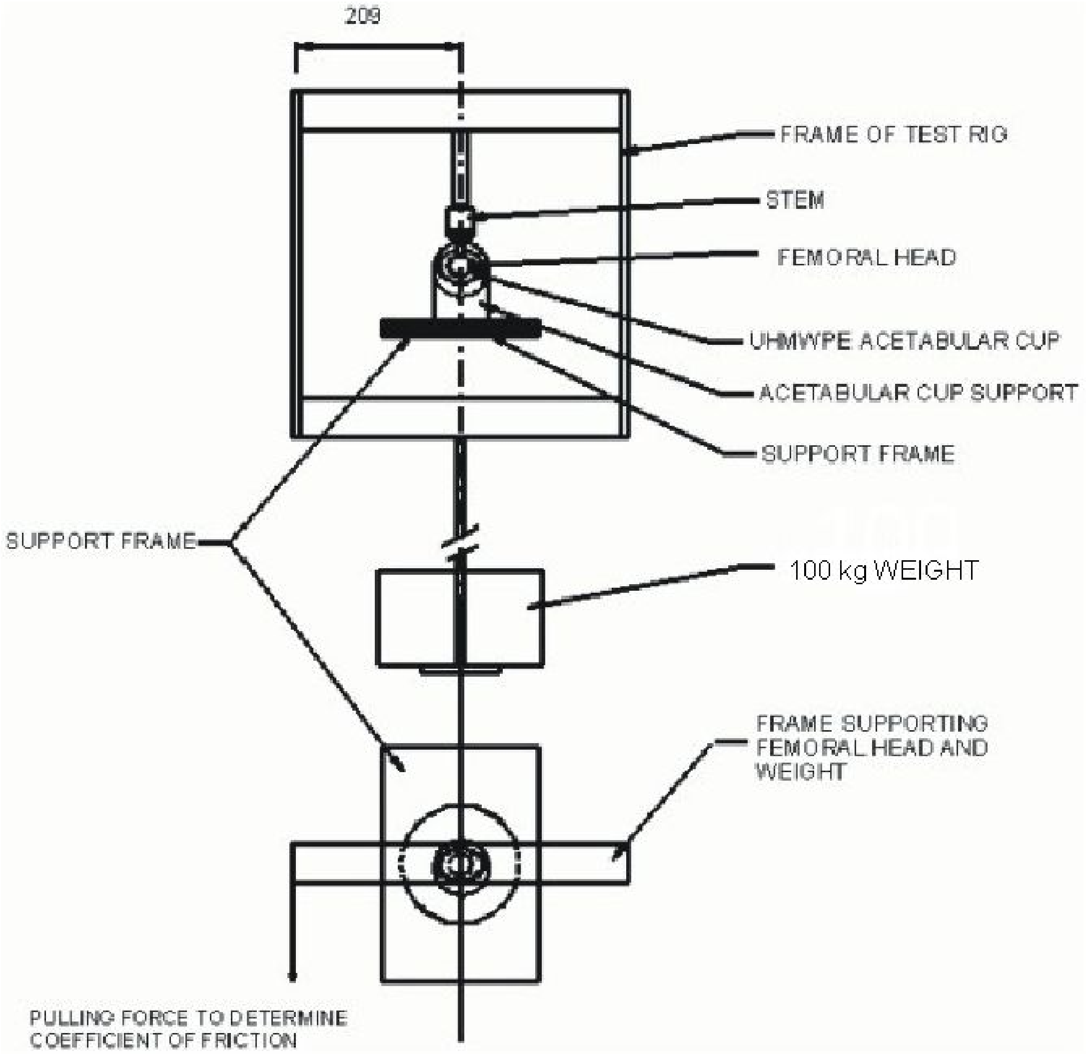

Figure 7.33: Test set up for determining coefficient of friction between ceramic femoral head and UHMWPE acetabular cup

The experiment was repeated a number of times to gain an indication of the coefficient of friction for the following conditions:

a. Dry.
b. Dry with wear debris on the bearing surface.

c. Lubricated with one drop of water on the bearing surface.

d. At a temperature of approximately 60°C. Owing to the fact that the UHMWPE was preheated, the temperature was limited to 60°C to prevent the bearing from collapsing.

The wear debris generated during the previous two tests (frictional heating between femoral head and UHMWPE test piece and the external heating of the femoral head) was placed on the bearing surface to simulate the wear debris generated over a period of time in-vivo.

To determine the static coefficient of friction, the force needed to cause the test rig to move was measured. The force was applied over a pulley system to cause the minimum deflection of the system. Small weights were suspended on the rope attached to the frame providing the input force, enabling the calculation of the coefficient of friction. (See Table 7.1 for the different weights as measured.) A dial gauge was used to indicate the point at which the static friction was overcome.

7.7.3 Test results

Table 7.1: Values for masses needed to cause movement

Condition	Mass (gram)
Dry	405
Dry with wear debris on bearing surface	385
Lubricated with one drop of water on the bearing surface	306
At a temperature of approximately 60°C	505

To calculate the coefficient of friction, a mean friction radius of 7 mm was assumed as is shown in Figure 7.34. In this case, a 28 mm femoral head was used. This friction radius is determined by the tolerances during manufacturing.

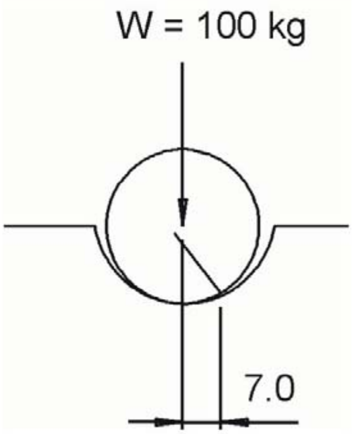

Figure 7.34: Data used for the calculation of coefficient of friction

With a moment arm of 209 mm (Figure 7.33) and a given load, the coefficient of friction was calculated as follows:

$$F.r = \mu.W.r$$

$$\mu = \frac{F.r}{W.r} = \frac{0.405x0.209}{100x0.007} = 0.12$$

If this result is compared with the data found in the relevant literature, (Chapter 2), a value of 0.1 - 0.22 is given for a polished steel ball on UHMWPE with a ceramic/UHMWPE couple having a coefficient of friction of approximately 0.01–0.03. (http://www.utahhipandknee.com/history.htm).

(The results of the estimated coefficients of friction are shown in Table 7.2.)

Table 7.2: Values for estimated coefficient of friction under various conditions

Condition	Coefficient of friction determined experimentally	Values from literature (Engineering materials Handbook, 1987)
Dry	0.12	0.1 - 0.22
Dry with wear debris on bearing surface	0.115	---------------
Lubricated with one drop of water on the bearing surface	0.09	0.05-0.1
At a temperature of approximately 60°C (Dry)	0.15	----------------

From the data, as presented in Table 7.2, it can be seen that wear debris accumulated on the bearing surface has virtually no effect on the coefficient of friction. What is interesting is the 25% increase in the coefficient of friction at the elevated temperature of 60ºC. Lubrication in the form of water caused an almost 30% decrease in the friction coefficient.

7.8 Conclusion of experimental results

7.8.1 Simulator study

The simulator studies were conducted with the following aims:

a. To get an indication of the temperature below the bearing surface in the acetabular cup while in operation.

b. To generate wear debris and to compare the shape of the wear debris to the shape of the debris retrieved from scar tissue surrounding the joint in-vivo.

The tests were performed with and without lubrication to enable an accelerated test.

7.8.1.1 Temperature in acetabular cup

The temperature in the cup was measured by inserting a thermocouple approximately 0.5 mm just below the bearing surface of the acetabular cup. It must be accepted that the thermocouple will not be able to measure the temperature on the surface peaks, as explained in paragraph 7.5.3. The temperature reported will be an average value over a larger area of approximately 3 mm as the diameter of the thermocouples is 1 mm.

The temperature recorded after 15 minutes of continuous operation, with 0.9% NaCl as lubricant, was 60ºC. The temperature fluctuated, but stabilised between 60º and 65ºC. The temperature measured during the current study actually correlates very well with the values reported by McKellop et al. (2000), although in the test done by the McKellop group, the thermocouple was inserted in the ceramic femoral head and not in the UHMWPE acetabular cup. In the study done by the McKellop group, the measured temperature was extrapolated to the surface and a value of 90ºC was reported.

The test without any lubrication failure of the acetabular cups, as shown in Figures 7.15 and 7.16, happened so quickly that no temperature readings were possible.

7.8.1.2 Wear debris retrieved from simulator

During the simulator test, with lubrication, wear debris was retrieved every 250 000 cycles without stripping the assembly. A sample of the lubricant was retrieved and filtered through 0.4 µm filters before investigating the filter paper under a microscope to determine the shape and size of the wear debris. The procedure for retrieving the debris and investigating the filter paper under the microscope is the same as discussed in Chapter 5.

An example of the wear debris retrieved from the simulator is shown in Figure 7.35.

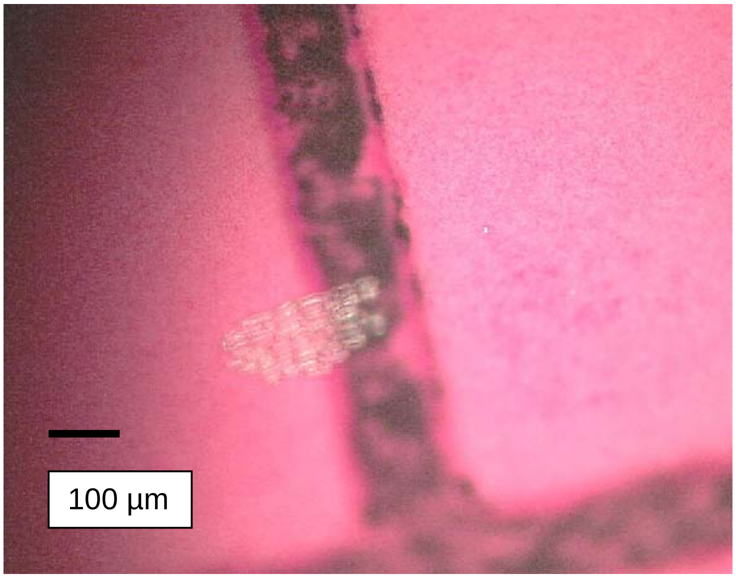

Figure 7.35: Wear debris retrieved from simulator (magnification x 100)

If the wear debris in Figure 7.35 is compared with wear debris retrieved from the scar tissue, as shown in Figure 7.36, as well as the particle still attached to the acetabular cup as shown in Figure 7.37, a similarity in shape and size between the different debris is visible.

All the debris retrieved from simulator and tissue, showed signs of the bumpy surface where the particles were ripped from the base material after adhering to the femoral head. This failure is only possible if the localised temperature in the acetabular cup is high enough for the material to be sufficiently softened to enable the adhesion of the UHMWPE to the femoral head with the consequent ripping of the material from the base material. The temperatures measured during the current study showed that localised temperatures in excess of 60ºC have been achieved resulting in the damage as explained in Chapters 5 and 6 and verified in Chapter 7.

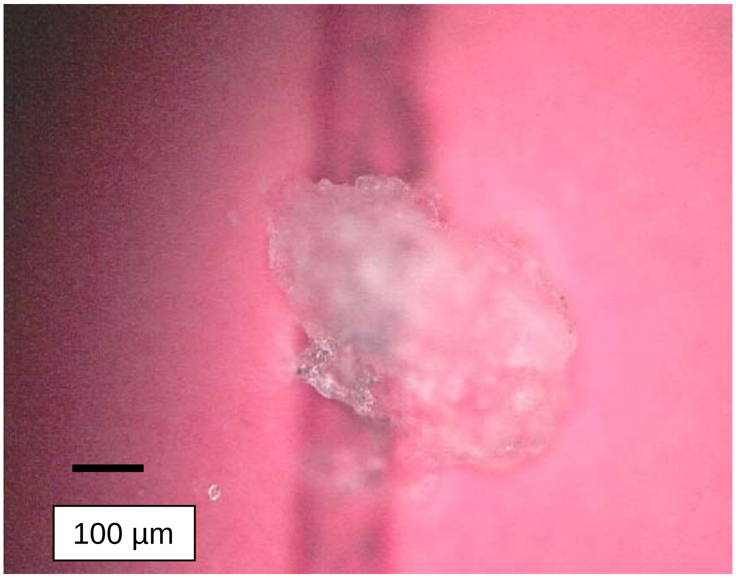

Figure 7.36: UHMWPE wear debris retrieved from scar tissue (magnification x 100)

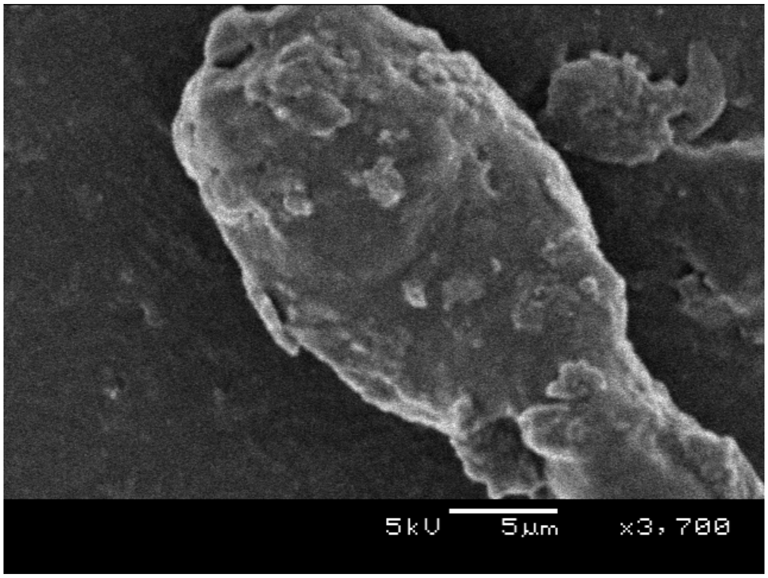

Figure 7.37: UHMWPE wear particle still attached to base material (magnification x 3 700)

The same procedure can now be followed in comparing the wear debris retrieved from the simulator test that had run without lubrication, as shown in Figure 7.38, to the debris retrieved from the scar tissue shown in Figure 7.39.

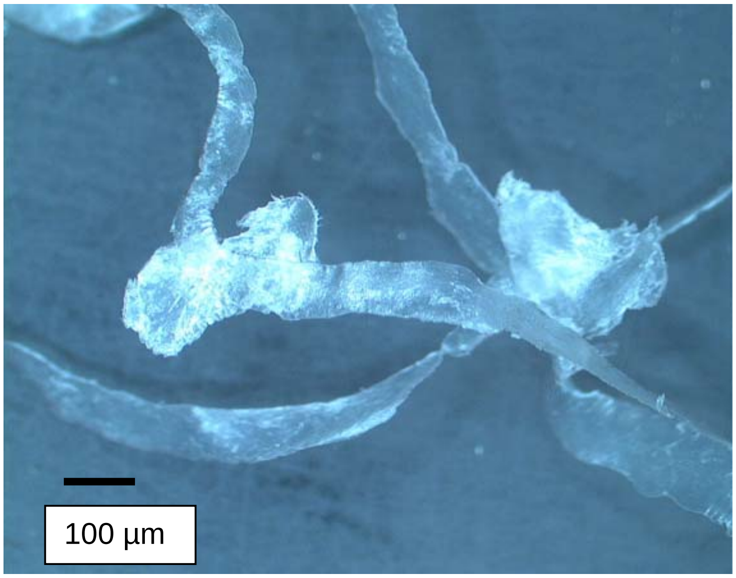

Figure 7.38: UHMWPE wear debris retrieved from simulator running without lubrication (magnification x 20)

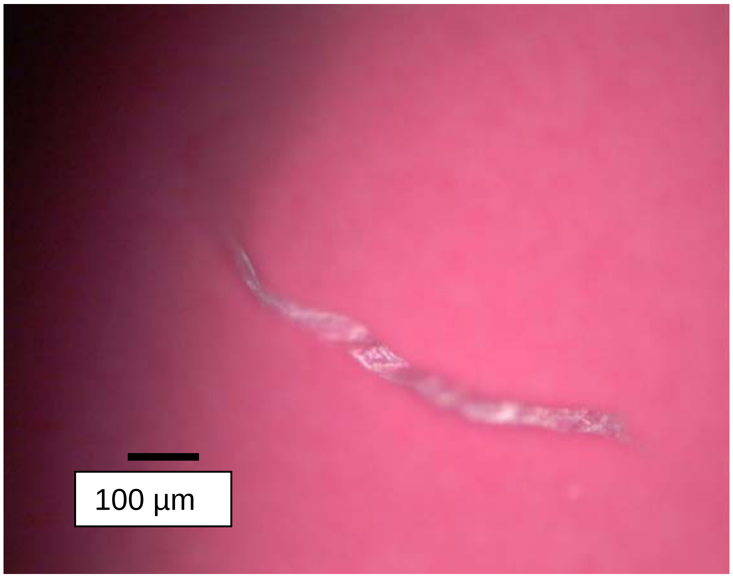

Figure 7.39: UHMWPE wear debris retrieved from scar tissue (magnification x 100)

If the debris in Figures 7.38 and 7.39 is compared again the similarities are clear, although the debris retrieved from the simulator is much bigger. (See paragraph 7.4.)

All of the retrieved debris showed signs of extruded edges. It is proof that the extruded edges are indicative of overheating on the interface between the ceramic femoral head and the UHMWPE acetabular cups. The indication in both the wear debris retrieved from the scar tissue and the debris generated in the simulator is that the material was heated sufficiently to be softened to such an extent that the material was extruded under the prevailing pressure.

7.8.2 Simulating of wear debris formation in laboratory

A test set-up was designed and built to simulate the formation of the type of wear debris retrieved from the scar tissue. The aim of this part of the experimental work was to establish a more accurate temperature at which the wear debris starts to form. Two tests were conducted namely:

a. The formation of wear debris by generating heat between the femoral head and the UHMWPE test piece by means of friction.

b. Preheating the femoral head to a predetermined temperature and the running of the femoral head through the UHMWPE test piece generating wear debris.

The wear debris generated during both of these tests was fairly similar, as can be seen in Figures 7.40 and 7.41. In both tests, the temperature generated and the preheated temperature required to form the type of wear debris as shown were in excess of 90ºC. The similarity between the wear debris generated and the debris retrieved from the scar tissue is also remarkable. A particle retrieved from the scar tissue is shown in Figure 7.42. Both pieces of material ripped from the base material after adhering to the femoral head are visible, as well as whiskers of material that were extruded under the prevailing heat and pressure. Also visible in these test results is the plastic flow of the material as described in Chapters 5 and 6. The plastic flow on the test piece can be seen in Figure 7.22.

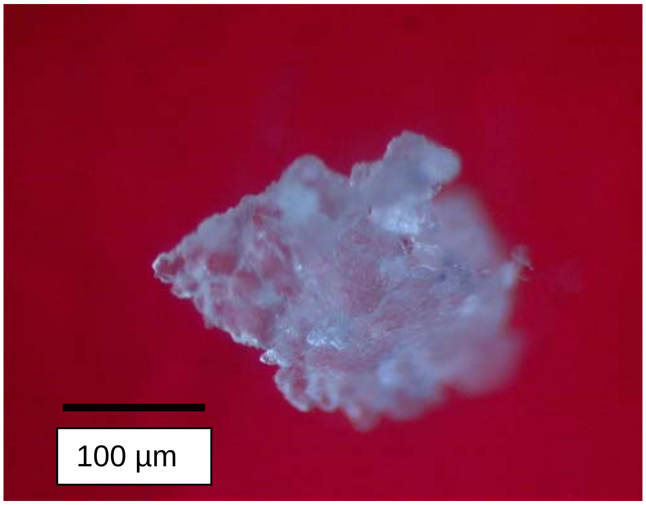

Figure 7.40: UHMWPE wear particle generated by means of frictional heating (magnification x 100)

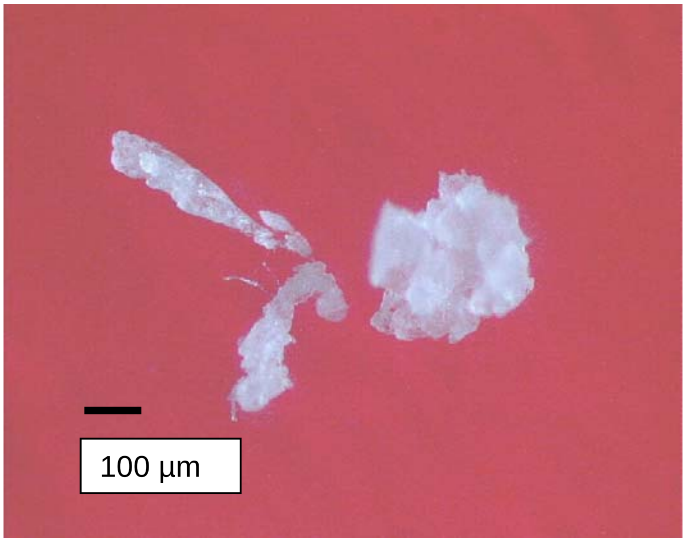

Figure 7.41: UHMWPE wear debris generated by preheating the femoral head (magnification x 40)

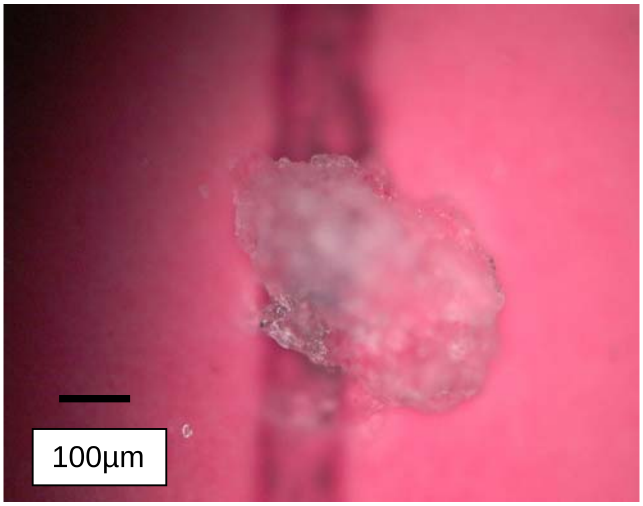

Figure 7.42: UHMWPE wear debris retrieved from scar tissue (magnification x 100)

If the data as presented is examined, it is clear that two mechanisms are responsible for the formation of the UHMWPE wear debris as shown in Chapters 5, 6 and 7. The three mechanisms are as follows:

a. The material is locally heated to a point where the material becomes sufficiently softened to adhere to the femoral head with the result that a piece of material gets ripped from the base material. The result is the typical adhesion wear marks visible in the acetabular cups as shown in Chapters 5 and 6. The cracks seen in the acetabular cups are secondary to the formation of the patches of adhesion wear resulting in stress raisers.

b. The material is locally heated to a point where the material becomes sufficiently softened to be extruded under the prevailing pressure and temperature forming whisker-like wear debris as shown. The areas where extrusion of the material had taken place will also present as scratches, similar to the scratches caused by third-body wear particles.

c. The material was sufficiently softened in localised areas by elevated temperatures to result in the plastic flow of sections of the bearing surface.

7.9 Lubrication of the hip joint

The lubrication of any bearing couple is very important as the lubrication has basically three functions (Hutchings, 1992). The three functions associated with lubrication are:

a. To keep the different bearing surfaces apart.
b. To act as surface contaminant to prevent peaks from welding to each other.
c. To cool down the contact surface between the two load-carrying components.

As the three aspects of lubrication and the lubricating characteristics of the synovial fluid are such an unexplored area, Chapter 8 is devoted to a study of the lubrication of the joint and to establish the lubricating characteristics of synovial fluid.