

CHAPTER 8

LUBRICATION OF THE HIP JOINT

8.1 Introduction

Synovial fluid is found in a healthy natural synovial joint. Typical synovial joints are the hip, knee and shoulder. All of these joints differ in shape and size, but the lubrication mechanisms stay the same. The basic layout of the synovial joint can be described as follows and is shown in Figure 8.1.

The ends of the bones are covered with articular cartilage. The whole joint is closed up in a capsule called the fibrous capsule. This capsule is lined with the synovial membrane called the synovial capsule, and is filled with a fluid called synovial fluid or synovial, meaning “like egg white” (Sokoloff, 1978). The synovial fluid inside the synovial joint appears yellowish in colour and almost has the consistency of water.

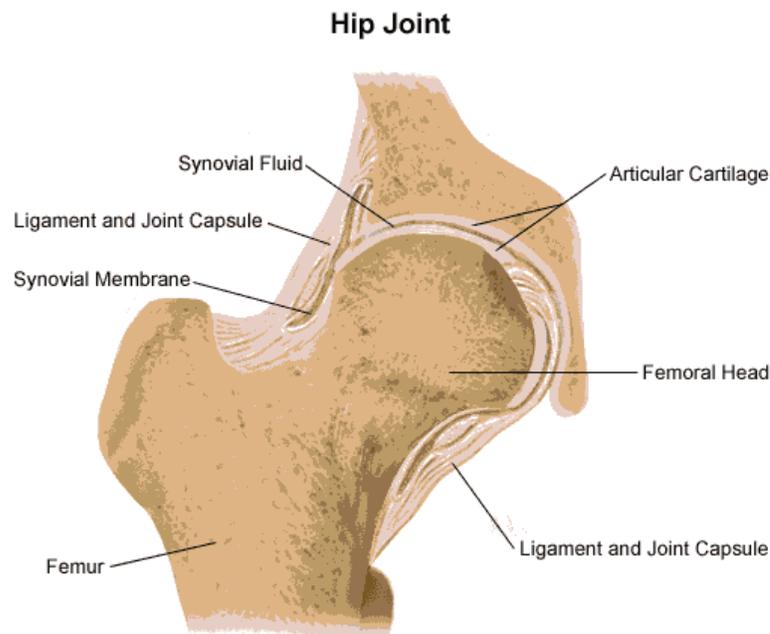


Figure 8.1: A schematic drawing of the human hip joint
(http://www.healthsystem.virginia.edu/UVAHealth/adult_arthritis/anatomy.cfm)

The synovial membrane is a thin sheet of areolar tissue as is shown in Figure 8.2. The areolar tissue is known for its richness in blood vessels and lymphatics. Its main function is that it forms a sappy tissue that lubricates and nourishes epithelial tissue in the synovial joint. It also provides strength, elasticity, support and immune system protection. (<http://science.nhmccd.edu/biol/tissue/areolar.html>). The synovial membrane has the ability to change the plasma into synovial fluid. By using this ability, the level and concentration of the synovial fluid can be monitored.

- a. Elastin fibre
- b. Collagen fibre
- c. Fibroblast cell that produces the fibres
- d. Matrix areas that appear empty and contain ground substance that is a gelatinous watery fluid

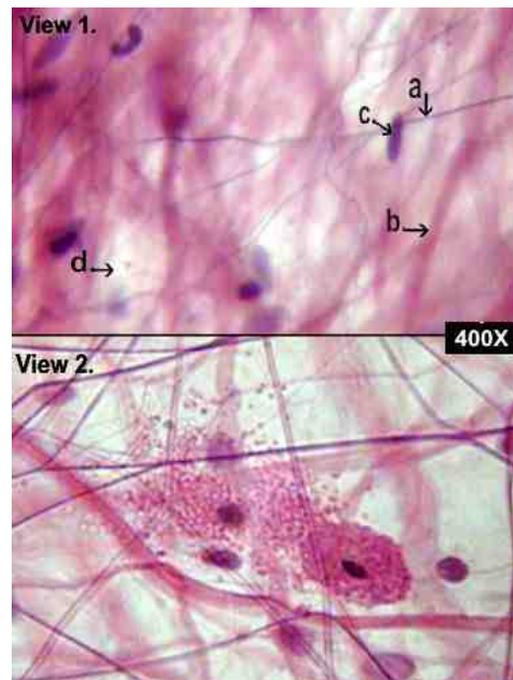


Figure 8.2: Areolar tissue (magnification x 400).
(<http://science.nhmccd.edu/biol/tissue/areolar.html>)

The synovial fluid, in the normal patient has two main functions namely:

- a. The first function is the nutrition of the joint and especially of the articular cartilage. This is necessary, because the articular cartilage

has neither blood vessels nor lymphatics. The cartilage receives all its nourishment via the diffusion of the synovial fluid into the cartilage. Sokoloff (1978) reported that cartilage not only lives in synovial fluid, but can also grow in it. During hip replacement surgery, the cartilage is, however, removed so the function of nutrition is no longer required.

- b. The second function is the lubrication of the joint. This is one of the principal interests for this research project.

From the above discussion, it can be seen that to have synovial fluid in a joint, a healthy fully functional synovial membrane is required to produce the synovial fluid. During hip replacement surgery, the synovial membrane needs to be cut to gain access to the joint. (See Figure 8.1.) It is not known as there is no reference in the available literature whether the synovial membrane can function correctly after surgery. This raises the question whether or not the fluid present in the joint after arthroplasty really is synovial fluid and whether the fluid present still has enough lubricating capabilities to support the artificial joint.

As already stated, the function of lubrication is threefold. At sufficiently high speeds, low enough surface pressure and sufficient lubricant, the surfaces can plane over each other without mechanical contact. This applies at high speeds as with motor car engine bearings. If the two surfaces do not plane over each other, mechanical contact occurs, the asperity peaks (as shown in Figure 8.3) are deformed and heat is generated. The first function is therefore to prevent contact between the two surfaces. The second function of the lubricant is to act as surface contaminant to prevent the peaks from welding together. If they are allowed to weld together or adhere sufficiently, the weaker one will be ripped out leaving a crater on one surface and a build-up on the other. The third function of the lubricant is to act as a coolant as the welding process becomes less effective at lower temperatures (Hutchings, 1992).

In metal bearings, a lack of lubrication can easily cause localised temperatures in excess of 1 000°C, that will allow welding or even melting of the metal peaks.

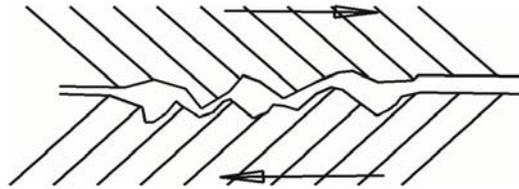


Figure 8.3: Schematic layout of surface roughness.

The main aim of this part of the research has been to establish the quality of the lubricant (synovial fluid) present in the synovial joint after total hip replacement. The lubricity of the synovial fluid is defined as the ability of the lubricant to support lubrication (Hutchings, 1992). Two parameters were used to quantify the lubricity, namely the load at failure and the average coefficient of friction over the test period. The effects of an increasing temperature were also investigated by testing at temperatures in the range of 38°C to 60°C.

The joint fluids of 12 patients were retrieved during revision surgery. Each sample was analysed for lubricity at 38 °C, 50 °C and 60 °C.

8.2 Apparatus used

Lubricity testing was conducted on a linear-oscillating test machine also known as the Optimol SRV machine (ASTM D5706-97). The outcome of a lubricity test was the load (Newton) at which breakthrough of the lubricating film occurred, as well as the average coefficient of friction measured at the breakpoint. (A schematic layout of the Optimol SRV machine is shown in Figure 8.4.)

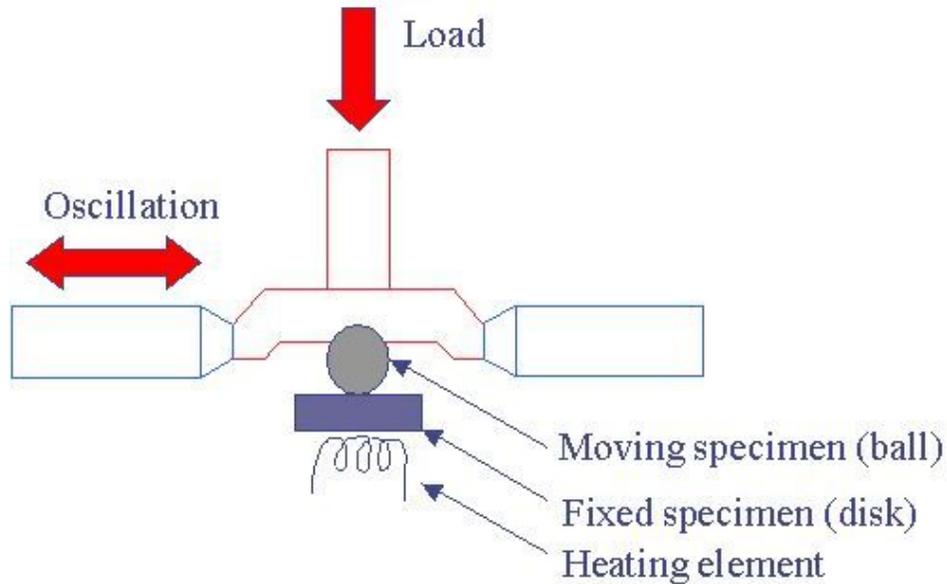


Figure 8.4: Schematic layout of the Optimol SRV machine

A specimen, known as the moving specimen, is clamped into the head of the machine; this prevents the moving specimen from rotating relative to the fixed specimen, ensuring only a sliding effect. The fixed specimen is placed on a heating element to regulate the temperature of the test sample. An oscillation motion is generated with an actuator. The frequency and stroke length of this motion can also be controlled.

It can be seen that most of the variables in this set-up can be adjusted or changed as found appropriate. It was, however, decided to use a test based on the ASTM D5606-97 standard for testing the film strength of lubricating fluids.

(The fixed specimen with the holder to contain the synovial fluid for testing is shown in Figure 8.5, with the moving specimen shown in Figure 8.6.)

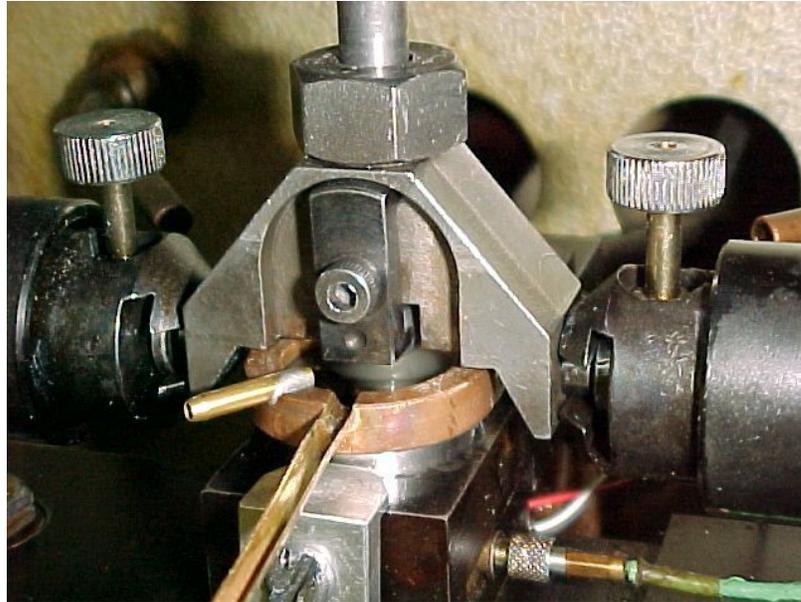


Figure 8.5: Fixed specimen in Optimol SRV machine

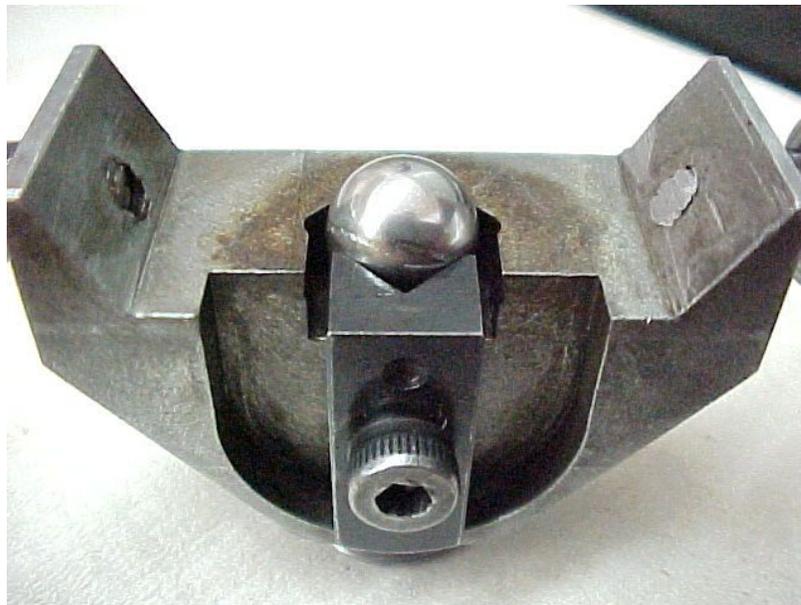


Figure 8.6: Moving specimen in Optimol SRV machine

8.3 Test method

The joint fluid used during this research was retrieved from the hip joints of the patients who underwent hip revision surgery. An orthopaedic surgeon did the retrieval of the joint fluid prior to the removal of the existing implant. The fluid was brought to the laboratory for testing within one hour of

retrieval from the patient. The joint fluid was then visually screened to identify the samples contaminated with blood. These samples were then excluded from the study. In total, six samples were excluded from this study. The retrieved synovial fluid was then centrifuged for five minutes at low velocity ($\pm 1\ 000\ g$) to separate any wear particles from the retrieved fluid.

On average, volumes of between one and five millilitres of synovial fluid were retrieved per joint. The retrieved fluids were tested individually.

Three temperatures were chosen, namely 38 °C (body temperature) 50 °C (halfway temperature) and 60 °C based on the temperatures measured in the simulator, (Chapter 7), and the work done by McKellop et al. (1997).

(Table 8.1 shows the test parameters used during the lubricity testing of the synovial fluid.)

Table 8.1: The test parameters used to determine the lubricity characteristics of the joint fluid

Fixed specimen (Disk)	Size: Ø24 x 7.85 mm Material: AISI E 52100 Hardness: Rockwell C 60 ± 2 Surface finish: $R_z = 0.1 - 0.15$
Moving specimen (Ball)	Size: Ø10 mm Material: AISI E 52100 Hardness: Rockwell C 60 ± 2
Load	A run-in load of 50N, whereafter the load is increased by 50N every minute.
Temperature	38°C, 50°C and 60°C
Oscillation	Frequency: 50 Hz Stroke: 1 mm
Feeding mechanism	A drop of fluid was placed between the moving and fixed specimen prior to the test commencing.

8.4 Test outcome

Different test set-ups on this machine can give different test outcomes. In the test specification as given in Table 8.1, the most important factor is to determine the load at failure. According to the ASTM D5606-97 method, the load at failure is defined as the load where the coefficient of friction rises by more than 0.2 over the steady state coefficient of friction, or where total seizure occurs.

A typical result of a lubricity test is shown in Figure 8.7 with all the test results attached in Annexure H.

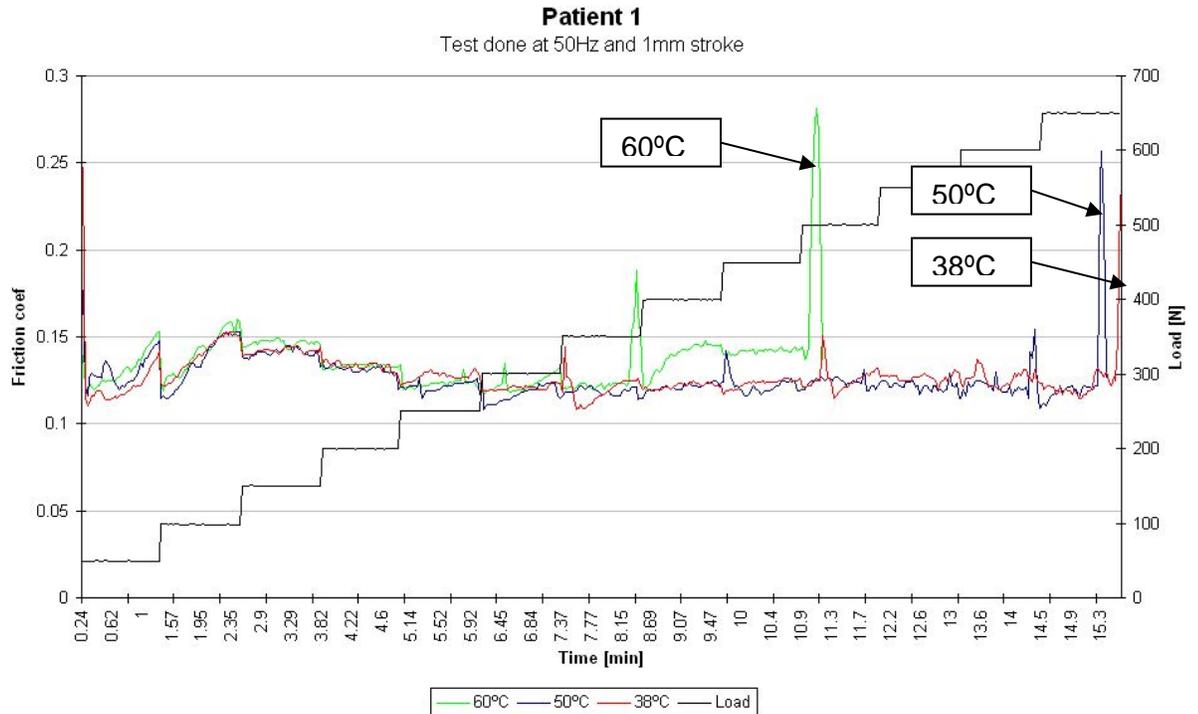


Figure 8.7: An example of a typical lubricity test result. The loads at failure are indicated on the graph

It can be seen from Figure 8.7 that the load at failure at the various temperatures was as follows:

38 ° C	650 N
50 ° C	650 N
60 ° C	500 N.

The scar on the moving specimen (ball) can be seen in Figure 8.8 with the scar on the fixed specimen (disk) shown in Figure 8.9.

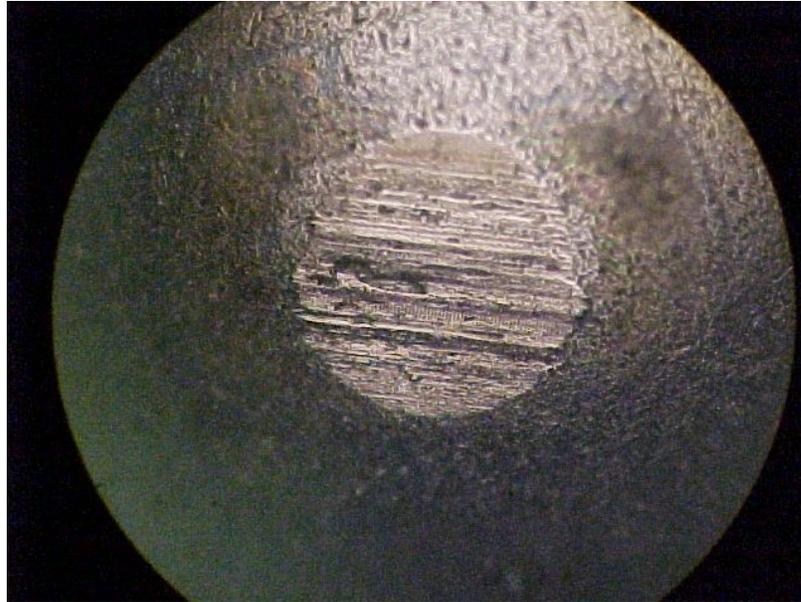


Figure 8.8: Wear scar on moving specimen (ball)

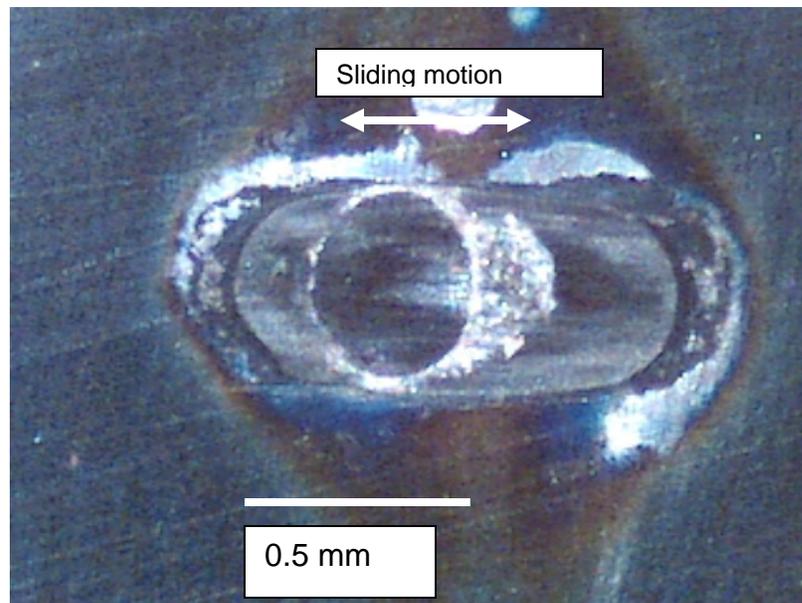


Figure 8.9: Wear scar on fixed specimen (disk) (magnification x 60)

From Figure 8.9, the visible imprint from the ball as it was cold welded to the surface and then, when disassembled, tore away. The size of the wear scar is a function of the load at which the lubricant failed.

A typical wear scar size on the ball for a load at failure of 550N is 0.65 mm in the direction of sliding motion and 0.7 mm across the direction of the sliding motion.

8.5 Lubricity properties of patients

The synovial fluids retrieved from a total of 12 patients were tested. The results of these tests are shown in Table 8.2 and Figure 8.10.

Table 8.2: Tests results to determine lubricity characteristics for 12 patients

Patient	Breakthrough load [N]		
	38°C	50°C	60°C
1	650	650	500
2	750	700	550
3	450	650	500
4	400	450	350
5	800	500	600
6	650	550	600
7	600	500	550
8	500	600	550
9	600	550	500
10	600	650	500
11	650	500	450
12	650	550	500
Average	608	571	513

From the data presented in Table 8.2, it can be seen that the average load of failure is as follows:

38 °C: 608N with a standard deviation of 114.48N

50 °C: 571N with a standard deviation of 78.21N

60 °C: 513N with a standard deviation of 67.84N.

The results as presented in Figure 8.10 indicate that the lubricity of the synovial fluid decreases with increase in temperature.

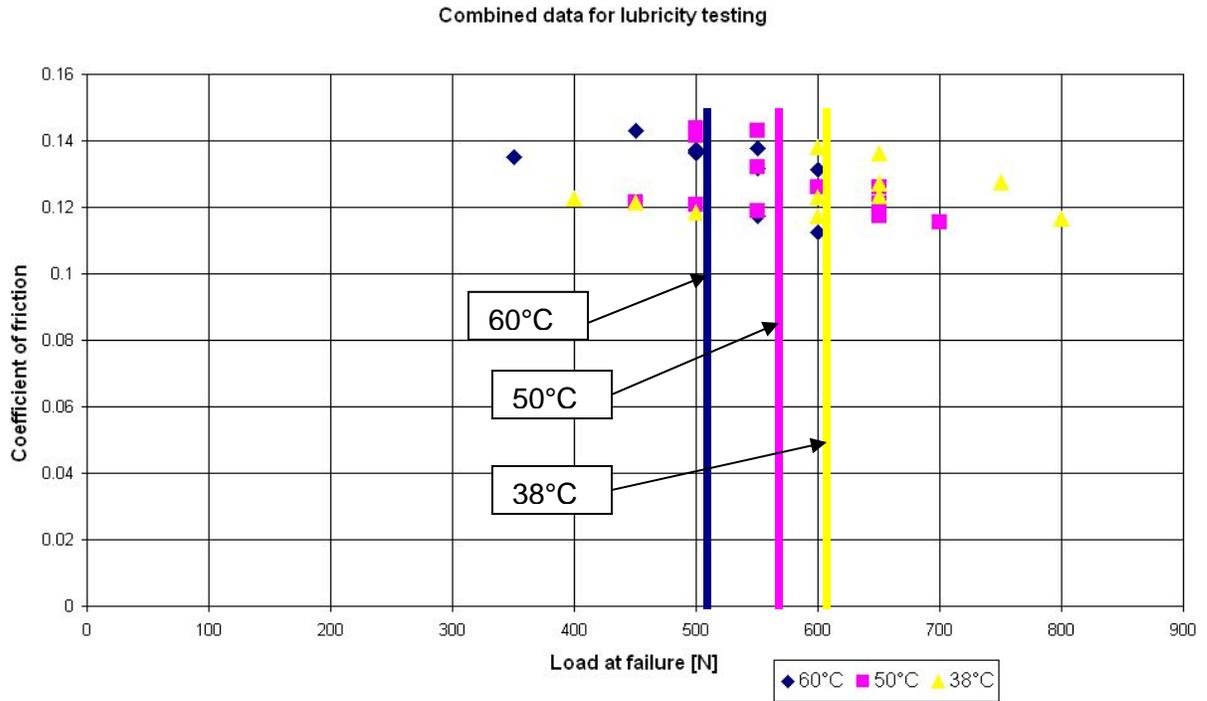


Figure 8.10: Combined lubricity data for 12 patients as tested with averages as indicated

8.6 Discussion

The average coefficient of friction as tested, does not differ a great deal between the three temperatures used for the lubricity testing. A small decrease can be seen in the load at failure, but if one takes into account the fact that the tests were done in 50N increments, it is realised that the difference can be neglected and can be ascribed to experimental error.

The surface defects of the acetabular components, as typically shown in Figure 8.11, Chapters 5 and 6 and in Annexure E are consistent with a lubricant with inadequate lubricity characteristics. The result of the inadequate lubrication is a heat build-up on the bearing surface between the UHMWPE acetabular cup and the ceramic femoral head resulting in the UHMWPE adhering to the femoral head and particles being ripped from the base material, as shown in Figure 8.11.

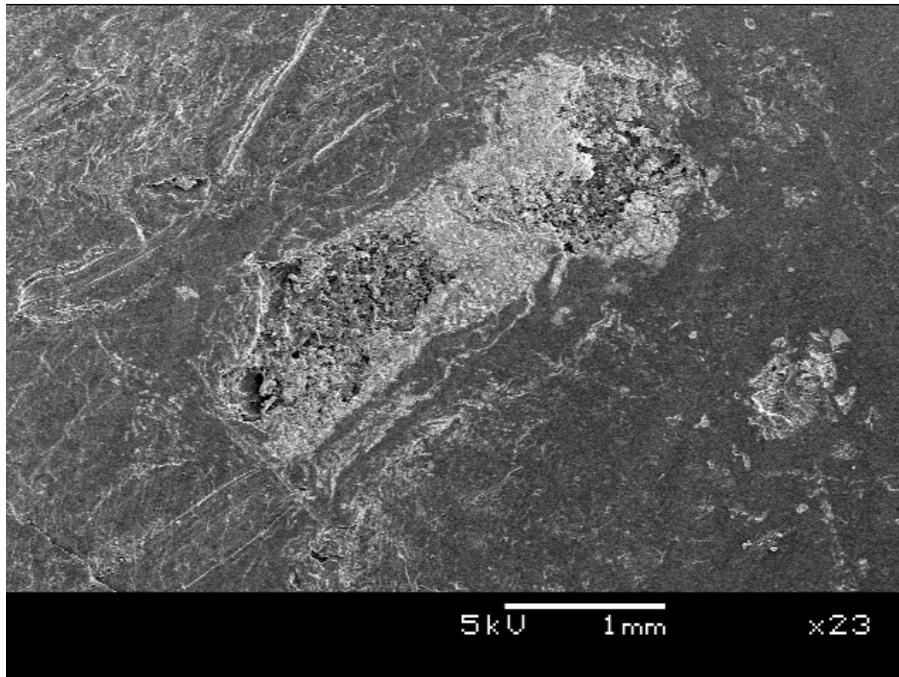


Figure 8.11: Adhesion wear on bearing surface of retrieved acetabular cup

The wear debris retrieved from the scar tissue as presented in Figures 8.12 and 8.13, as well as in Chapters 5 and 6 was also consistent of wear debris generated in a bearing where there was inadequate lubrication.

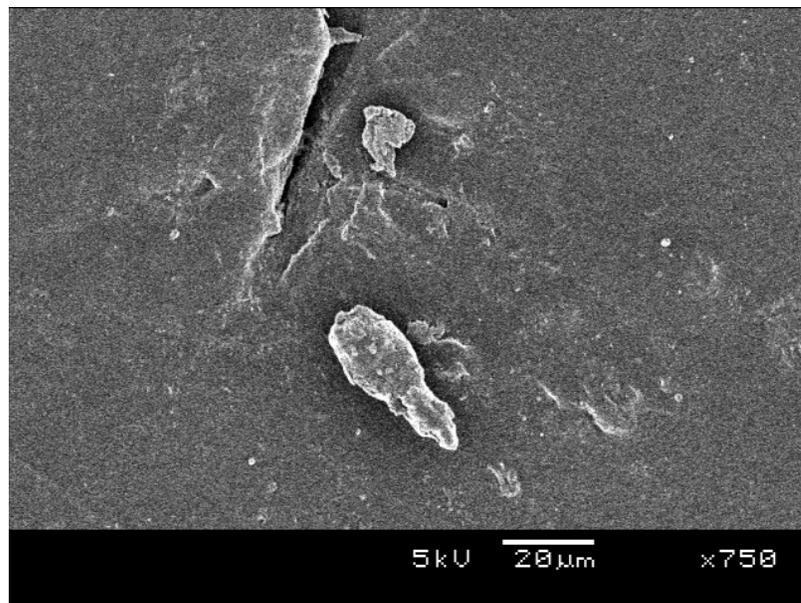


Figure 8.12: Wear particle still attached to UHMWPE acetabular cup

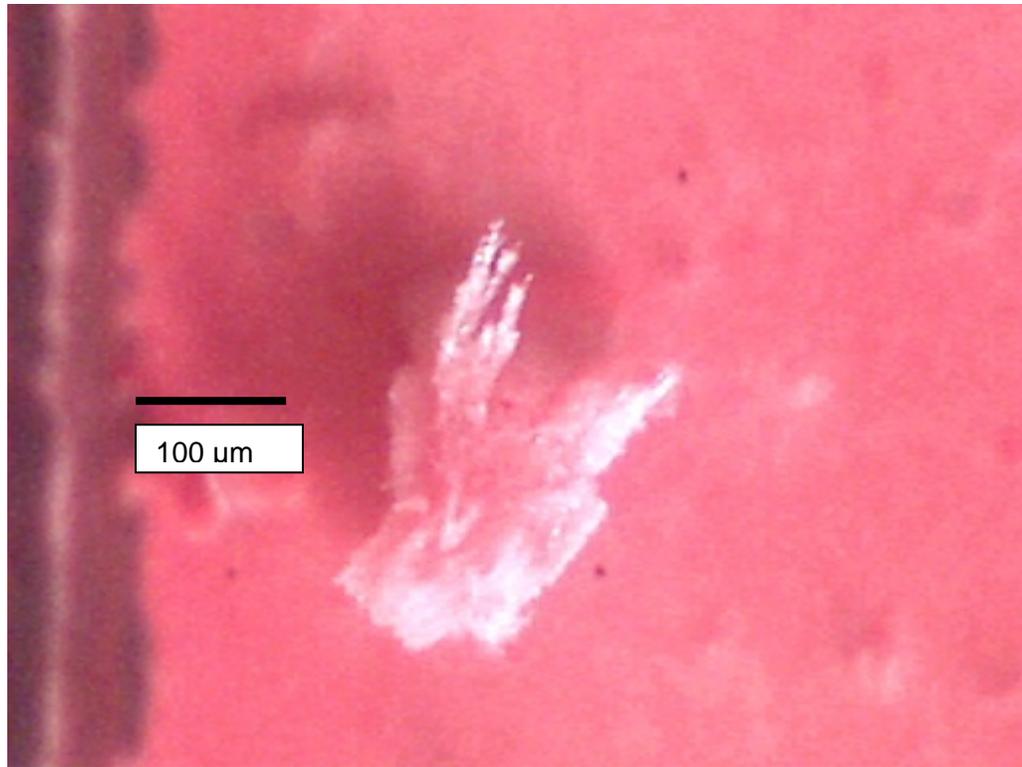


Figure 8.13: Wear debris retrieved from patient no. 5 (magnification x 200)

If the work, as presented in Chapters 5, 6 and 8 is analysed, the only conclusion that can be reached is that the main reason for mechanical failure of the UHMWPE acetabular components is overheating as a result of inadequate lubrication.

CHAPTER 9

CONCLUSION AND RECOMMENDATIONS

9.1 Conclusion

Owing to the crippling nature of arthritis, surgeons have been trying for well over a century to successfully treat this debilitating disease. Since the early 1970s when Sir John Charnley started with total hip replacement (THR) as a solution to this ever-increasing problem many different designs have been developed, but all of the designs revolved around a femoral stem, femoral head and acetabular component. Independent of the design, longevity of the implant remains a problem. The major cause of replacements, according to various hip registers (Chapter 1), is aseptic loosening due to osteolysis.

The main aim of this study has been to determine the root cause of mechanical failure of the acetabular cups and to discover the origin of the excessive amount of UHMWPE wear debris floating in the joint resulting in osteolysis.

During the study, various techniques have been used to investigate the acetabular components to try to establish the root cause for mechanical failure.

These techniques include:

1. Visual inspection
2. Investigation making use of dye penetrant spray
3. Investigation under stereo microscope
4. Investigation making use of a scanning electron microscope
5. Electrophoresis
6. Mass-spectrometric analysis
7. SRV analysis of the synovial fluid.

The wear debris retrieved from the scar tissue surrounding the joint of a number of patients, were also analysed.

Apart from the obvious defects such as mechanical damage due to impingement, the main focus of this study is on the wear patches found on the inside of the acetabular components.

The wear areas presented as areas where the surface layer of the UHMWPE was ripped off by adhering to the rotating femoral head. This mechanism of failure is only possible if localised overheating takes place, which results in the material either adhering to the rotating femoral head or the material being squeezed out under the prevailing pressure. Both these mechanisms were confirmed by the wear debris retrieved from the scar tissue. This wear debris was identified as either droplets of UHMWPE or whisker-like wear products as shown in Chapters 5 and 6.

To confirm the fact that conditions with elevated temperatures exist, the brown discolouring on the inside of the acetabular cups was analysed, making use of electrophoresis, mass-spectrometric analysis and scanning electron microscope analysis. In this part of the study, it was confirmed that it was possible that the localised temperatures on the bearing surface had reached at least 60°C during in-vivo service. This temperature was confirmed by inserting a thermocouple just under the surface of an acetabular cup and then measuring the temperature while performing in-vitro testing on the hip simulator (see Chapter 7).

The wear debris as retrieved was also duplicated in the laboratory while the temperature on the surface was monitored. It was established that wear particles similar in shape and size were formed at temperatures in excess of 90 °C (see Chapter 7). At temperatures above 50 °C, the UHMWPE had shown extensive increase in creep, indicating that at these temperatures the material softens sufficiently for this type of debris to be generated (see Chapter 3).

The overheating as described can also only occur if there is a lack of lubrication in the bearing couple. The synovial fluid from 12 patients was retrieved during revision surgery. This synovial fluid was then tested on an SRV test machine to determine the lubricity characteristics of the synovial fluid as retrieved. It was discovered that the load-carrying capability of the synovial fluid did not comply with the minimum requirements for a fluid to function as a lubricant (Chapter 8). The lubricity characteristics of healthy synovial fluid were not assessed as it is very difficult to retrieve enough fluid from a healthy human being for a test.

The effect of crosslinking and irradiation was also determined on the creep characteristics of the UHMWPE. During these tests, it was determined normal irradiation as used during sterilisation has almost no effect on the creep properties. The biggest influence on the creep characteristics of the UHMWPE was obtained when the test material was crosslinked in a hydrogen atmosphere. A reduction of 82% was achieved at 60°C for crosslinked material.

The final conclusion of this study is that excessive amounts of wear debris are generated due to the localised overheating of the bearing couple as a result of insufficient lubrication. The localised heat build-up results in excessive amounts of wear debris being generated and deposited in the joint area causing osteolysis.

9.2 Recommendations

During the course of this study, a number of problem areas regarding the design of acetabular cups were discovered. The following recommendations are made to assist in follow-up studies in this field:

- a. It has been shown that there is excessive heat build-up on the bearing surface. To enable designers to accommodate this heat build-up, a more detailed analysis to determine the material properties of UHMWPE at elevated temperatures is required. These properties include creep and impact strength, as well as creep in retained bearings as found in an acetabular cup. Another area that warrants further investigation is the influence of an alternating load on the creep behaviour of UHMWPE.
- b. A better understanding of the mechanism feeding the lubrication into the joint will have to be developed. With the poor lubricity characteristics, it is vital to get enough of the lubricant into the joint to fulfil the necessary functions.
- c. As indicated, the ceramic femoral heads do not have the ability to conduct heat away from the bearing surface resulting in premature failure. A suitable alternative material must be identified and tested over a substantial period of time to enable the analysis of the accumulated wear effect.
- d. More conclusive comparative testing between the different materials and processes will have to be conducted. The materials that will have to be evaluated are virgin and crosslinked UHMWPE, stainless steel, chrome Cobalt, alumina and zirconium femoral heads. These tests will have to be done over a longer period than 500 000 cycles to be able to better assess the effect of third-body wear due to the wear products floating around in the joint.
- e. The best alternative currently available is a crosslinked cup fitted in a metal backing, provided that the UHMWPE liner fits snugly into the metal backing. The advantage of this combination is that a thinner liner can be used resulting in better heat transfer to the surrounding bone, as well as better restraint to creep. As illustrated, the crosslinked material provides better creep resistance at elevated temperatures with the added increase in wear resistance.

- f. A thorough investigation will have to be conducted to develop a lubrication model giving an even better correlation between in-vitro and in-vivo results. The size and shape of the wear debris retrieved must be used as guidance in the development of this lubrication model.