CHAPTER 6

FAILURE ANALYSIS OF RETRIEVED ACETABULAR COMPONENTS

6.1 Introduction

Detailed failure analysis of retrieved acetabular components to determine the root cause of failure provides the designer with invaluable information regarding the input to a new design of an acetabular cup.

In Chapter 5 the observations regarding 47 retrievals and the defects found were described. Various techniques were used to identify these defects and to determine the extent of the defects found. In this chapter, the cause of the failures present is discussed while the experimental verification of the stated postulate (paragraph 6.6) follows in Chapter 7.

6.2 Cracks in acetabular components

During the retrieval study various acetabular components with cracks in the base material were identified. The cracks appear in various locations within the cup, but the cracks fall into one of the following two categories, namely:

a. Cracks on the rim of the cup
b. Cracks inside the bearing area.

The failure analysis of the two different categories is dealt with separately.

6.2.1 Cracks on the rim of the cup

Various metal back acetabular components fitted with UHMWPE liners where cracks were visible on the rim of the cup were retrieved as shown in Figure 6.1. Apart from the cracks on the rim of the cup, delamination in the area where the rim meets up with the body of the cup was also visible. This delamination varied from small localised areas to a single retrieved cup where this delamination was on the complete circumference of the cup. A cross section of a cup with this delamination visible is shown in Figure 6.2

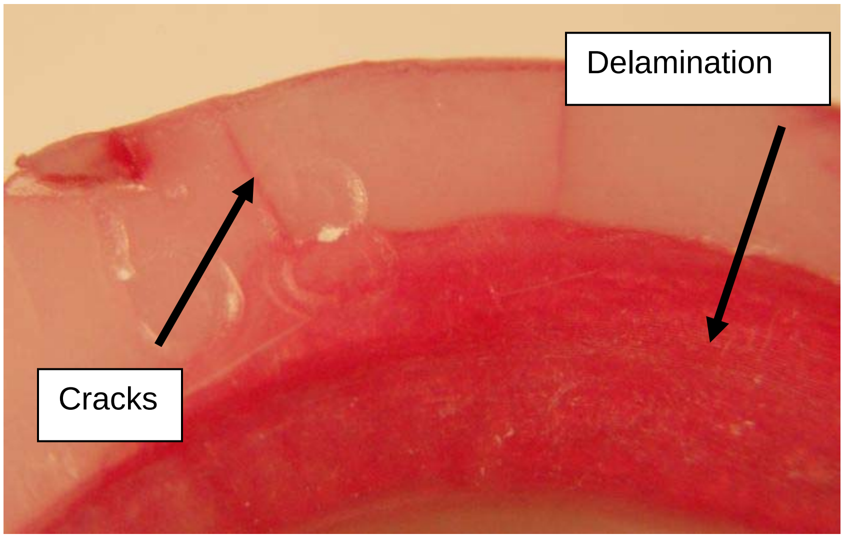

Figure 6.1: Metal back acetabular cup with cracks and delamination on rim of cup

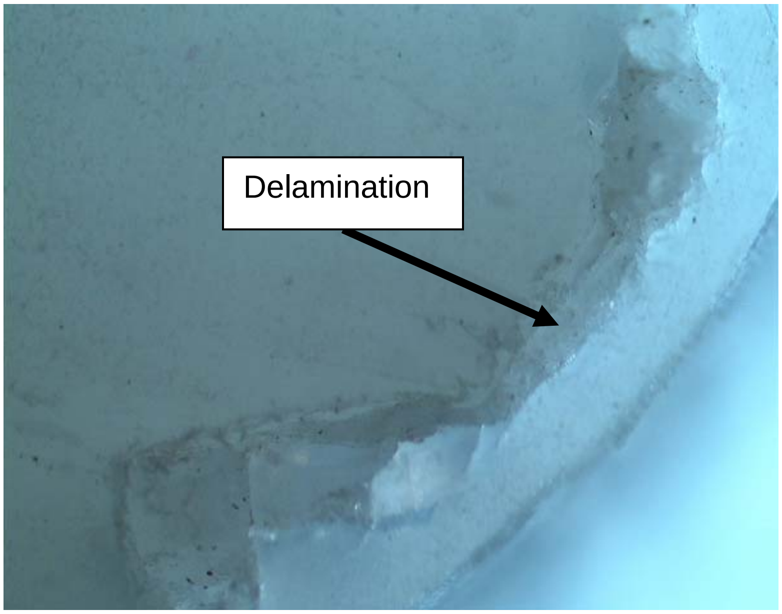

Figure 6.2: Cross section of acetabular cup showing delamination on the rim of the cup (magnification x 20)

This failure of cracks and accompanying delamination on the rim of the cup were only seen in metal back cups and also only in the metal back cups from one specific manufacturer. On closer inspection, it was noted that the UHMWPE liner does not fit snugly into the metal backing allowing the resultant forces in the hip joint to be transmitted into the pelvis via the rim of the UHMWPE liner only. This principle is schematically shown in Figure 6.3.

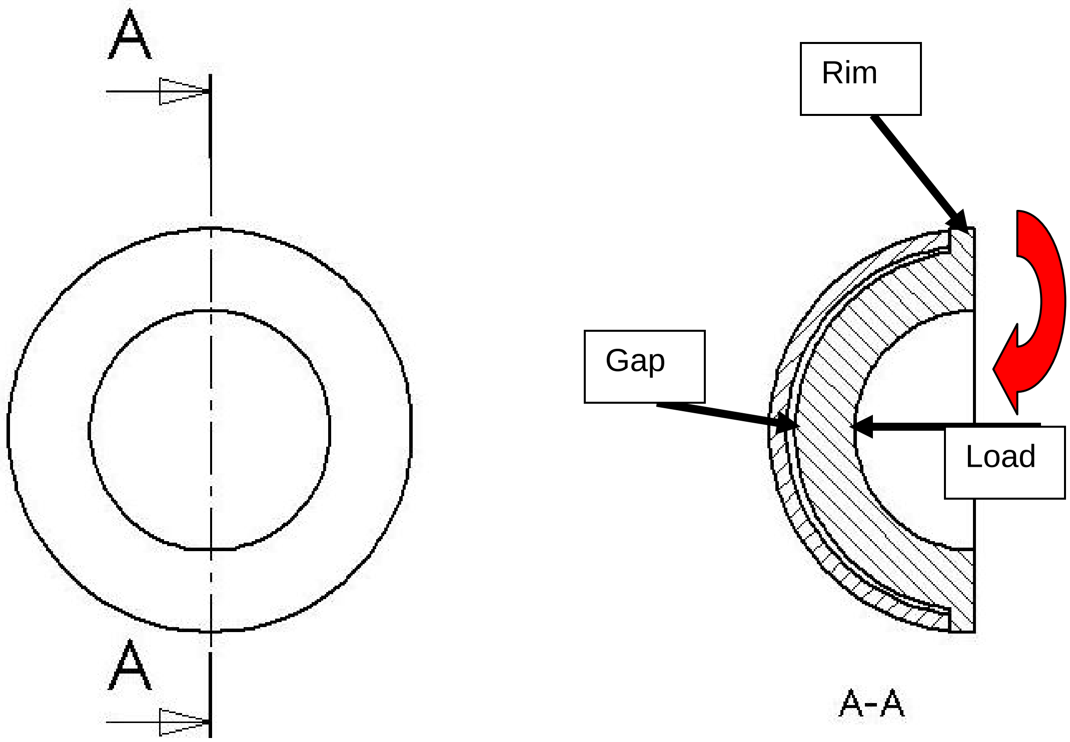

Figure 6.3: Schematic layout of UHMWPE liner not fitting snugly into metal backing

As can be seen from Figure 6.3, there is a small gap between the UHMWPE liner and the metal backing. The load coming into the bearing area will now deform the cup resulting in a bending moment with the corresponding bending stress in the rim of the cup. As the patient is walking, this load will vary according to the load profiles defined in Chapter

2 (Paul, 1976; Bergmann et al., 1993; ISO 14242-1, 2002), resulting in a dynamic load input into the rim of the UHMWPE that can lead to the fatigue failure that is manifested in the form of cracks and the delamination of the rim interface.

From the data presented, it can be accepted that this failure is due to an error either during the design or during the manufacturing process of the metal backing or the UHMWPE liner. As this defect is not a result of the wear mechanism active in-vivo, this defect will not be investigated further.

6.2.2 Cracks inside the bearing area

Cracks inside the bearing area can lead to the catastrophic failure of an acetabular component as can be seen in Figure 6.4.

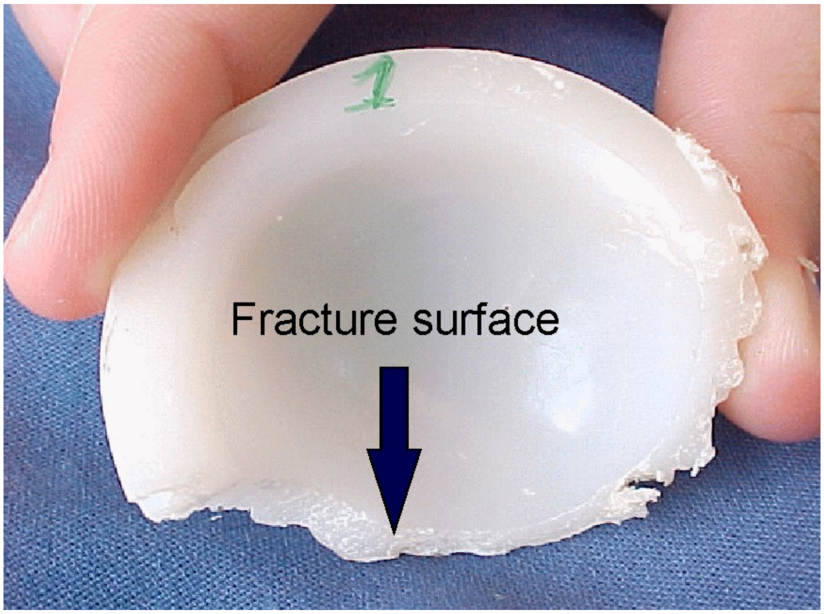

Figure 6.4: Acetabular component after catastrophic failure

From the data presented in Chapter 5 it is evident that cracks in the bearing area are fairly common as can be seen in Figure 6.5. On closer examination, making use of dye penetrant spray and the use of an electron microscope, the origin of these cracks can be established. The cracks originate in areas where severe adhesion wear has taken place. A crack starting from an area of adhesion wear can be seen in the electron microscope picture as presented in Figure 6.6.

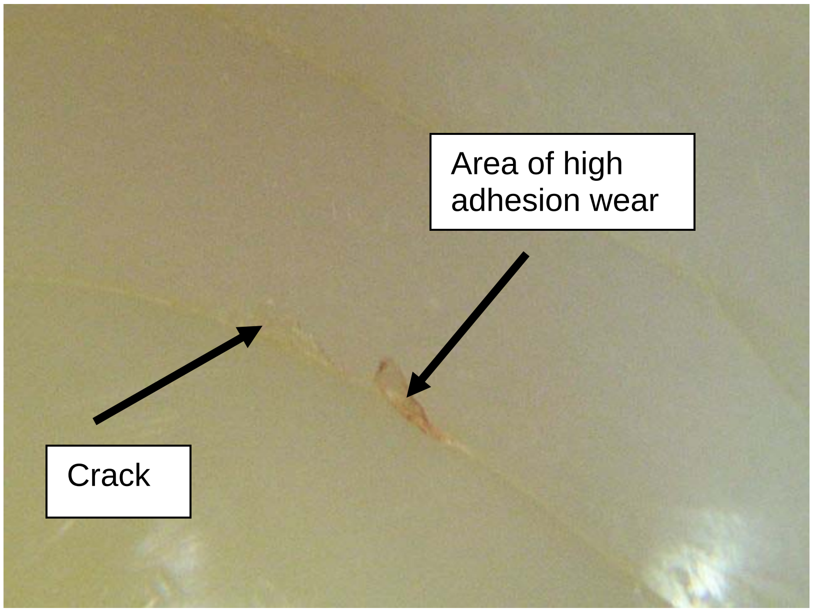

Figure 6.5: Crack on inside of acetabular cup

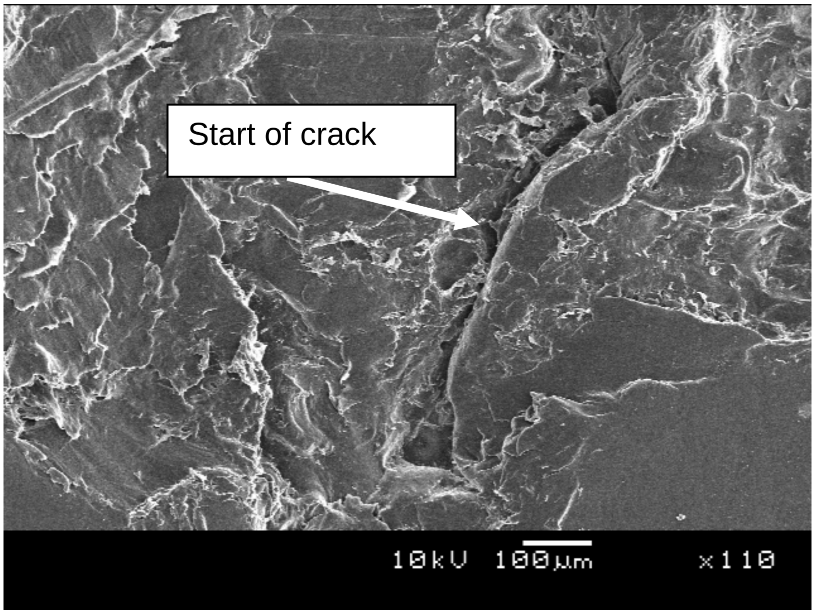

Figure 6.6: Electron microscope analysis of adhesion wear area (magnification x 110)

Under the electron microscope (Figure 6.6), it became clear that as the top layer of the material is being ripped away from the base material by adhering to the femoral head, craters are formed giving rise to areas with high stress concentrations. A crater under the surface after the removal of the top layer of material can be seen in Figure 6.7. Under the dynamic loading conditions, these stress raisers will lead to the formation of long cracks, which can lead to catastrophic failures of the acetabular component.

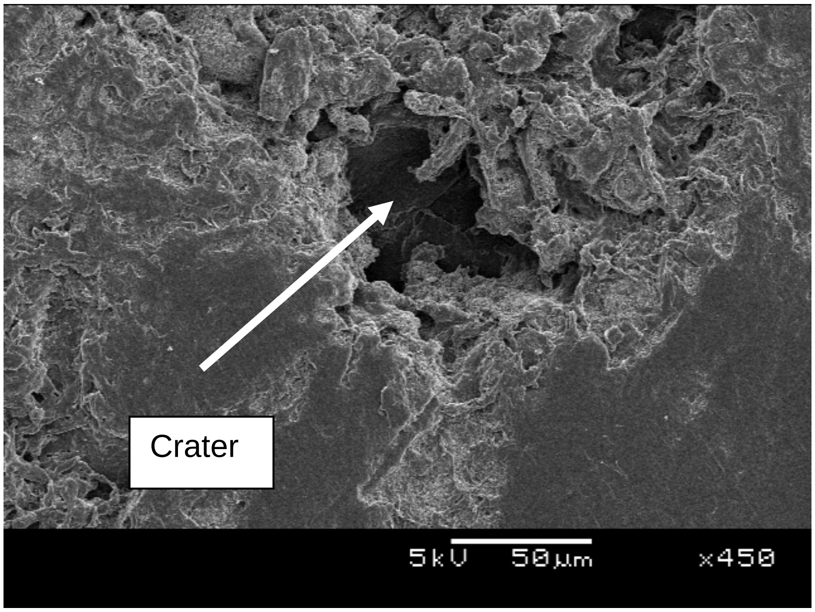

Figure 6.7: Crater under the surface after adhesion wear (magnification x 450)

From the data presented it is clear that the root cause for the formation of the cracks on the bearing area is the uneven removal of the surface of the bearing area by means of adhesion wear. This uneven removal will result in stress raisers in the form of craters which under the continuous dynamic loading will result in the formation of cracks.

It can be concluded that the cracks on the bearing surface are secondary to the formation of areas of uneven material as a result of adhesion wear. The formation of these areas is investigated further and will be discussed in paragraph 6.5.

6.3 Scratches

The scratches found on the bearing surface of the retrieved acetabular cups can again be classified into two categories namely:

a. Scratches caused by third-body wear particles

b. Scratches formed by normal UHMWPE wear products.

The failure analysis to establish the root cause for the formation of the scratches will be dealt with separately.

6.3.1 Scratches caused by third-body wear

The entering of foreign particles into the bearing is not that uncommon. These particles normally originate from the PMMA cement with which the implant is fixated. An acetabular cup with severe signs of third-body wear is shown in Figure 6.8. In this specific case glass ionomer cement was used for the fixation of the implant. This type of cement is no longer in use and has been replaced with PMMA cement.

Figure 6.8: Acetabular cup with severe scratches on inside

This type of defect is not a direct result of the active wear mechanism in the acetabular cup and is therefore not investigated further.

6.3.2 Scratches formed by normal UHMWPE wear products

In all the acetabular components retrieved, scratches as a result of the normal wear products floating around in the bearing area can be seen. The majority of these scratches are too small to see visually and it can only be seen under a magnifying glass. Throughout the literature reference is made to multidirectional fine scratches (Jasty et al., 1997; Schmalzried et al., 1999; Haraguchi et al., 2001), which are not easily visible to the naked eye. An acetabular cup with multidirectional fine scratches under a magnification of 20X can be seen in Figure 6.9. (Note that the machining marks are also visible in the Figure.)

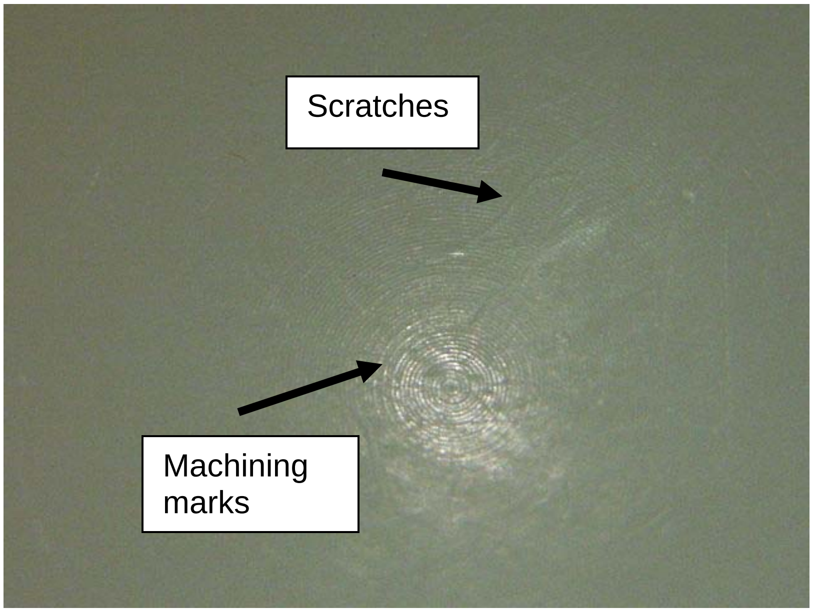

Figure 6.9: Acetabular cup with multidirectional fine scratches and with machining marks still visible (magnification x 20)

Scratches visible to the naked eye are also seen in some of the retrieved acetabular cups. When inspecting the acetabular components with a magnifying glass, treating it with dye penetrant spray and investigating under an electron microscope, the size and magnitude of these scratches become evident. The first impression is that this type of scratch must be the result of a third-body particle floating around in the bearing area. An acetabular cup with this type of scratch is shown in Figure 6.10.

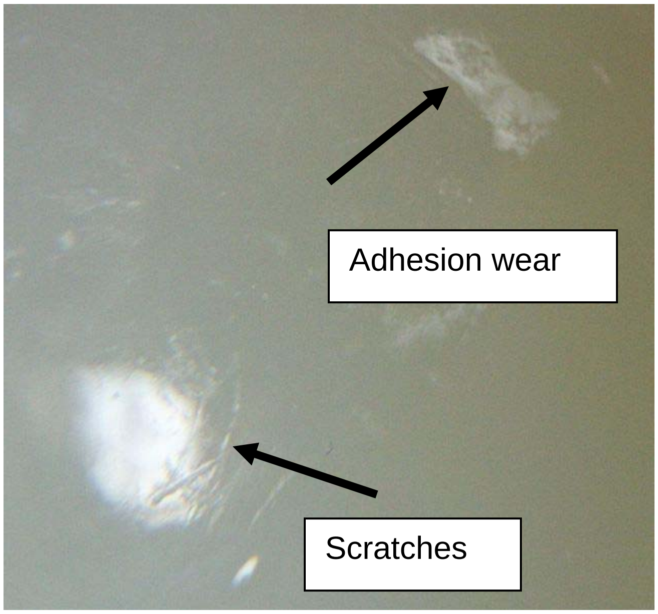

Figure 6.10: Bearing area with signs of large scratches and area with adhesion wear

Under the electron microscope, it is clear that these scratches are not fine, multidirectional scratches, but are scratches that had been formed by debris floating around in the joint. The scratches as indicated in Figure 6.10 under higher magnification in the electron microscope can be seen in Figure 6.11. The scratches have been encircled to facilitate the finding of scratches under the electron microscope. In the area of the scratches, a number of white dots are visible, which would appear as if they are pieces of PMMA cement that had entered the bearing area causing the resulting damage. In Figure 6.12, the path of one of these particles can be seen under higher magnification with the end clearly visible where the particle came to a standstill. The final path of the particle is visible in Figure 6.13 clearly showing the ploughing marks of the particle as it was destroying the bearing surface.

To eliminate PMMA as a third-body wear particle creating the scratch, a back scatter analysis was performed to establish the presence of any foreign particle at the end of the scratch. The back scatter analysis is shown in Figure 6.14.

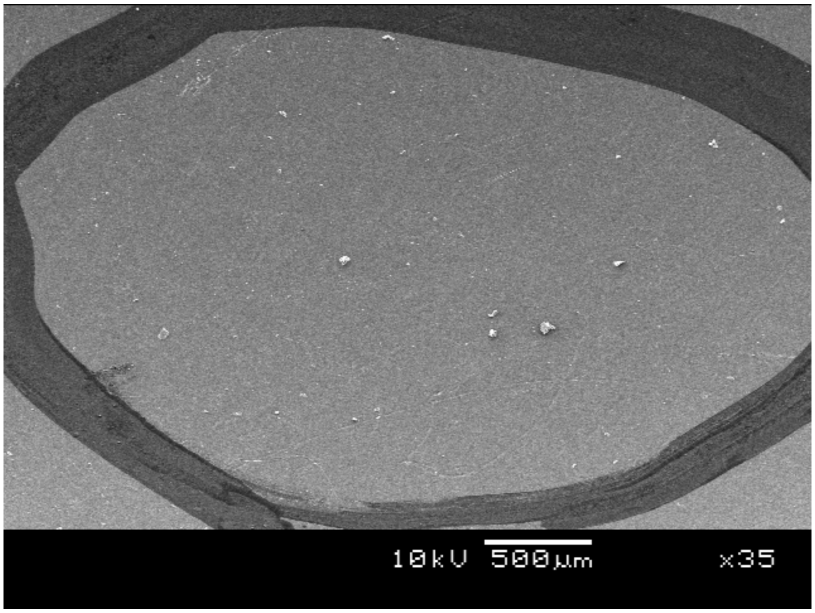

Figure 6.11: Scratches on bearing surface with white particles visible (magnification x 35)

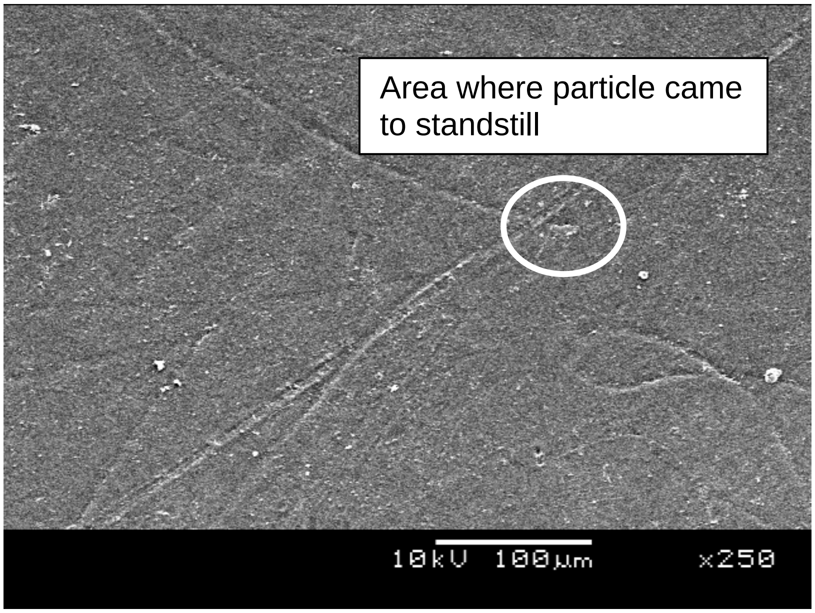

Figure 6.12: Scratch mark on bearing surface (magnification x 250)

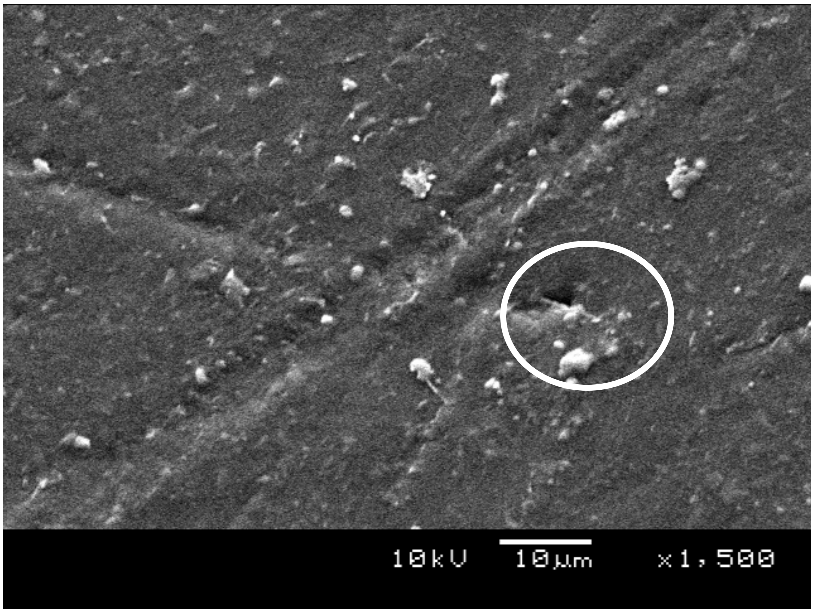

Figure 6.13: Final position of particle causing damage to bearing surface (magnification x 1 500)

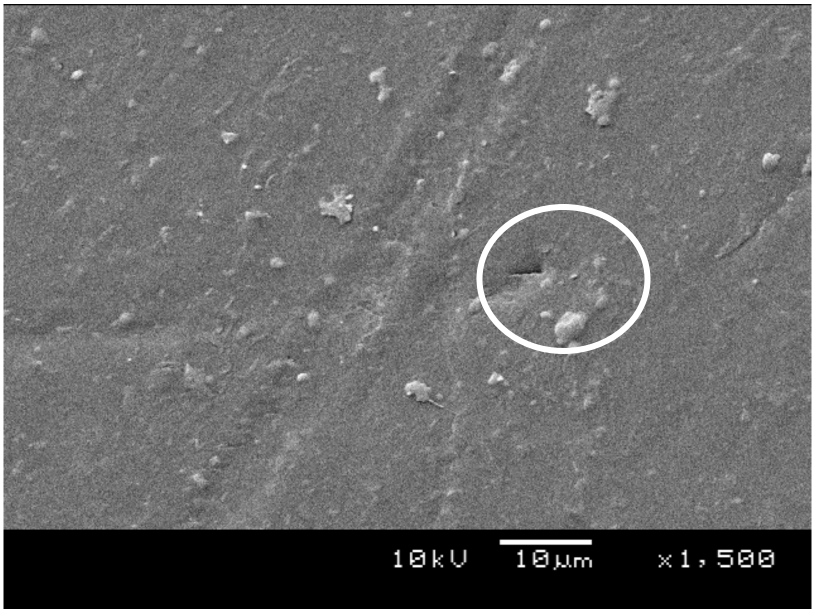

Figure 6.14: Electron microscope back scatter analysis of scratch (magnification x 1 500)

As the areas encircled in Figures 6.13 and 6.14 are compared, it is clear that there is no foreign particle present that could have caused the damage as seen. There is even wear debris trapped around the ploughing mark that is the same as the base material, UHMWPE.

A further analysis was done on another spot in the same acetabular cup as shown in Figure 6.15. This analysis was done closer to the area of adhesion wear. The main scratch can be seen in Figure 6.15 with the final damage enlarged in Figure 6.16.

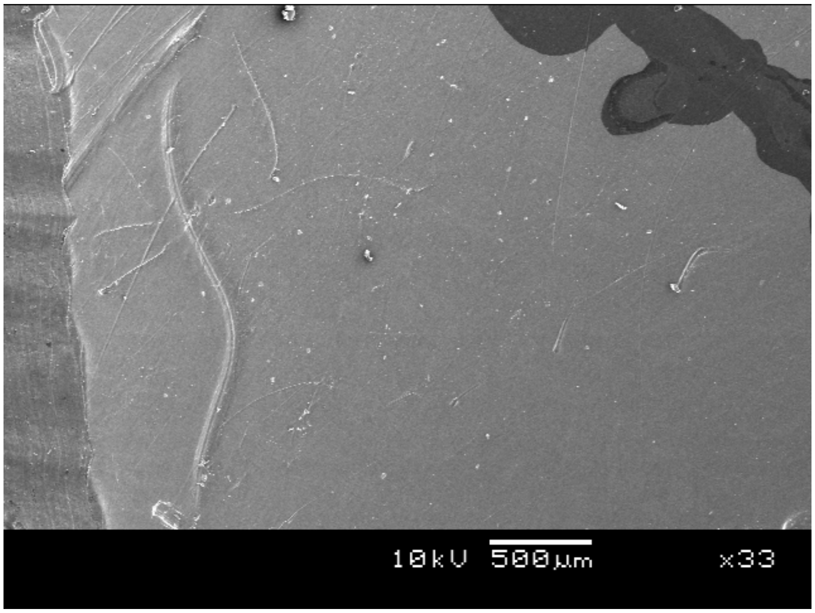

Figure 6.15: Scratch on bearing surface (magnification x 33)

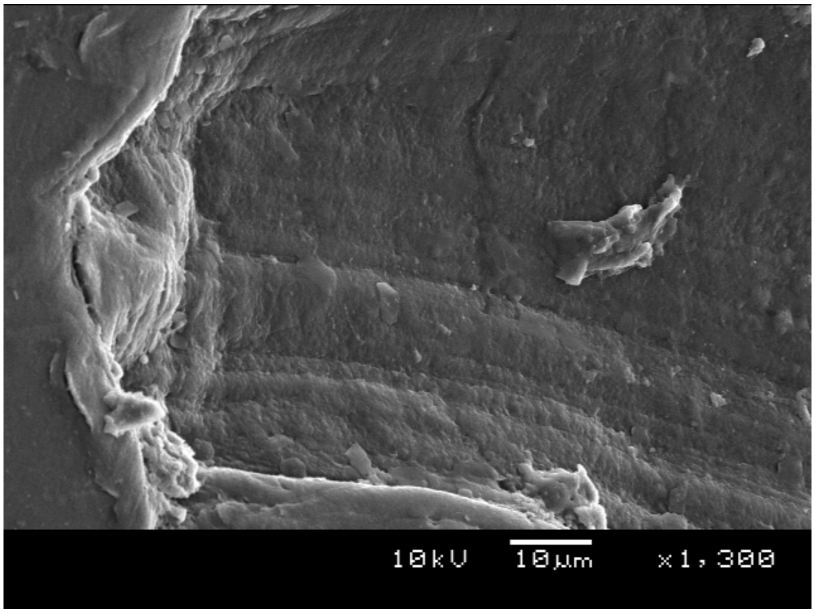

Figure 6.16: End of scratch on bearing surface (magnification x 1 300)

In both these scratch marks, the damage was not caused by a foreign body, but by a wear particle generated during the in-vivo use of the implant. The conclusion can be drawn that no foreign body is present in the wear scar. When the damage to the acetabular cup is compared to the wear debris retrieved from tissue surrounding the joint, the resemblance is clear. Typical debris retrieved from the same patient can be seen in Figures 6.17 and 6.18.

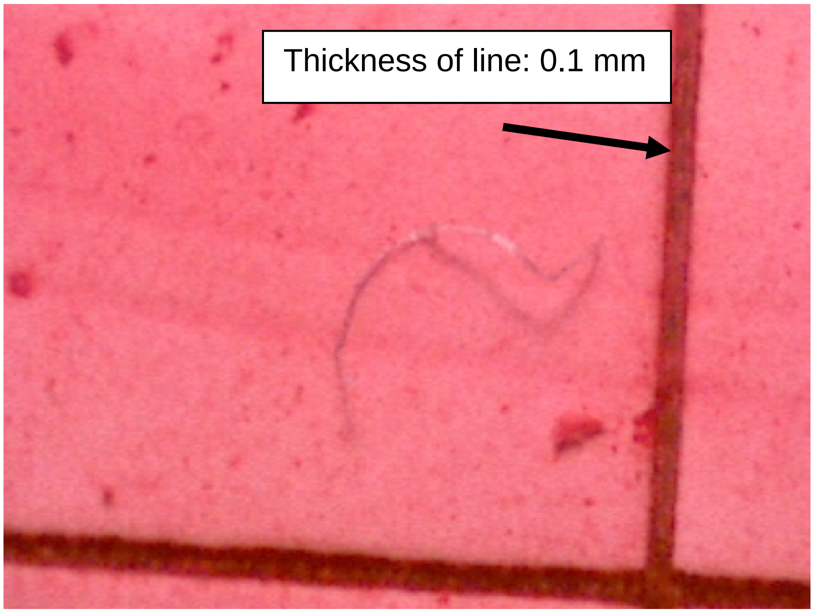

Figure 6.17: Whisker-like debris retrieved from patient (magnification x 20)

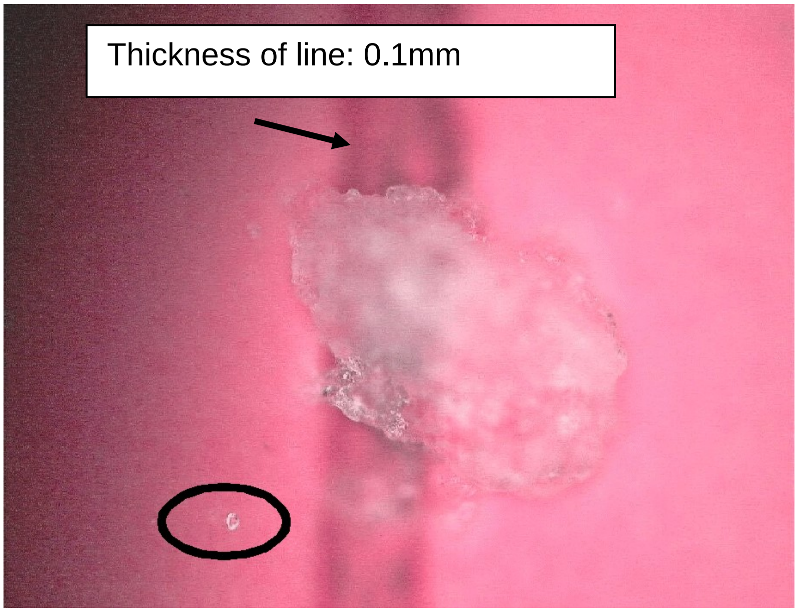

Figure 6.18: Debris retrieved from patient (magnification x 40)

The shape and the appearance of these items of debris suggest that both the whiskers and the droplets were formed under excessive heat conditions. From the literature survey, it was clear that for UHMWPE temperatures above 40ºC should be avoided, with short time (seconds) peak temperatures of 80ºC given by the manufacturers as the absolute maximum (Engineering Material Handbook 1987; Material data sheet, UHMWPE Poli HiSolidur 1999).

If the data obtained from the electrophoresis and mass-spectrometric analysis (Chapter 5) of the brown discolouration on the inside of the acetabular cups is taken into account, it can be concluded that during the in-vivo service of these implants temperatures of at least 60ºC were generated. It must be accepted that these high temperatures will only be generated in localised areas where the asperities due to machining are the highest. The complete acetabular cup will not be at this elevated temperature.

During the experimental phase of this study it has been proven that the type of damage as explained in this paragraph, with the accompanying wear debris, can only be generated if enough heat is applied under the prevailing pressure during walking to allow the extrusion of the whisker-like debris or the adhesion of particles to the femoral head.

6.4 Plastic flow

In the observations discussed in Chapter 5, areas of material that had plastically flowed under the prevailing pressure were identified. An acetabular cup with the type of plastic flow mentioned is shown in Figure 6.19. Under higher magnification, making use of the electron microscope, a number of these areas of plastic flow were identified. (See Figures 6.20 and 6.21.)

If the higher creep data at elevated temperatures (Chapter 3) together with the analysis of the brown discolouration is taken into account with the resulting conclusion of localised elevated temperatures, it is clear that the only way this type of plastic flow can occur is that the material at elevated temperatures is squeezed out of the high pressure area to an area of lower pressure.

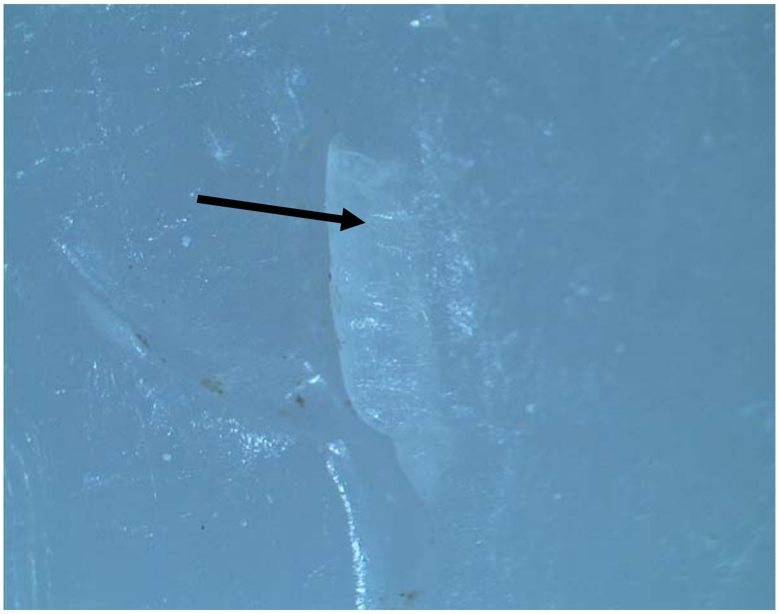

Figure 6.19: Plastic flow of material visible in cup (magnification x 10)

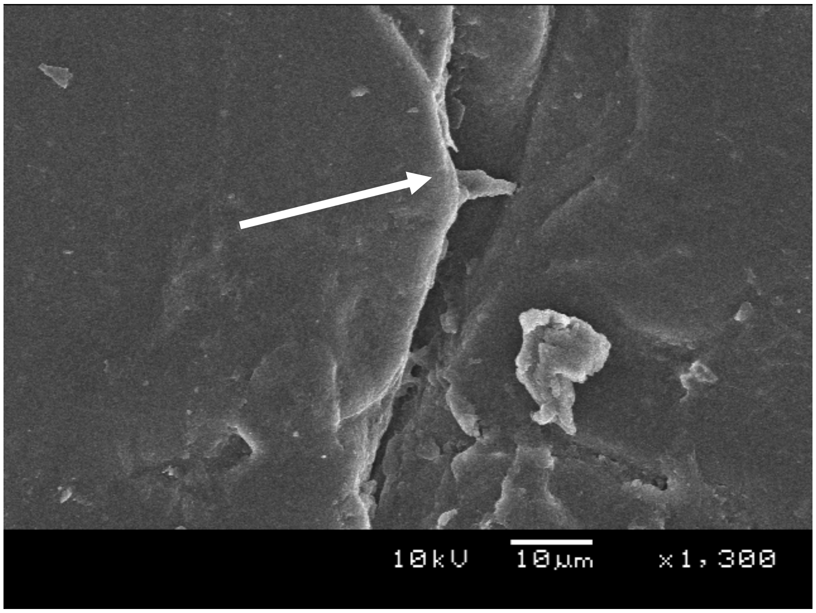

Figure 6.20: Plastic flow in acetabular cup (magnification x 1 300)

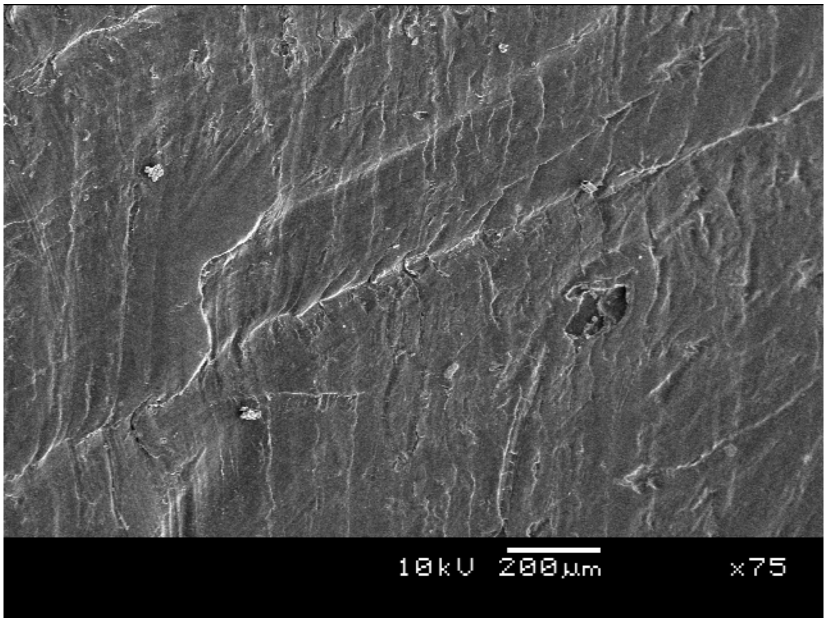

Figure 6.21: Area with plastic flow lines visible (magnification x 75)

During the experimental phase of this study, plastic flow similar to the plastic flow shown in Figures 6.19 to 6.21 was generated in the laboratory. It is shown that the only way to simulate this type of plastic flow under the equivalent prevailing pressure is at an elevated temperature.

6.5 Adhesion wear

In the observations done in this chapter, areas of adhesion wear were identified. These areas were first identified during the visual examination of the retrieved components as shown in Figure 6.22. When the components were treated with dye penetrant spray, these affected areas became clearly visible, as shown in Figure 6.23. The areas were characterised by a typical butterfly shape as described by Wang et al. (1997), where the surface of the bearing area seemed to be broken up. In some of the cups, the machining marks are also still visible under higher magnification, as shown in Figure 6.24. The edges of these areas are very rough and this is indicative of the temperature under which the removal of the material took place.

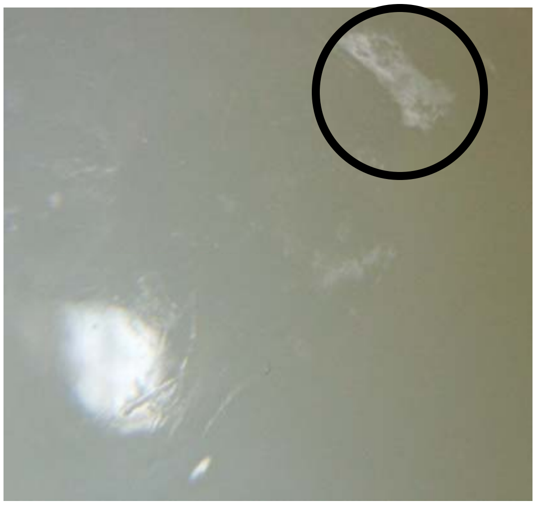

Figure 6.22: Visible adhesion wear in acetabular cup

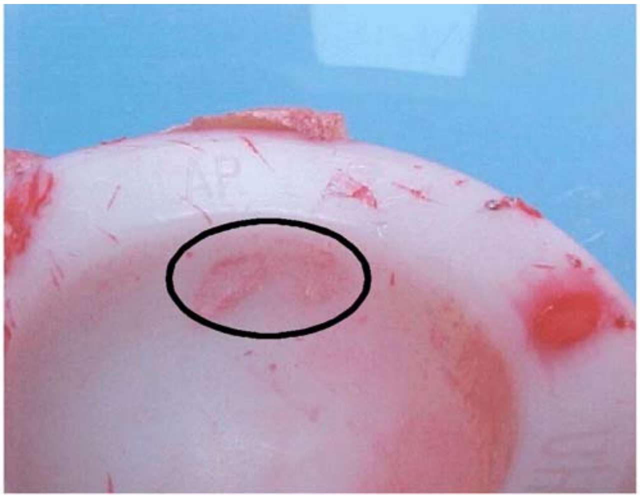

Figure 6.23: Butterfly wear pattern on inside of acetabular cup

Figure 6.24: Area with adhesion wear (magnification x 40)

The area with adhesion wear, as indicated in Figure 6.21, was then further investigated making use of the electron microscope. From the data obtained from the electron microscope, as presented in Chapter 5, it is evident that in this area adhesion of the material to the femoral head took place. The surface of the bearing was subsequently ripped, exposing the deeper part of the base material as is shown in Figure 6.25.

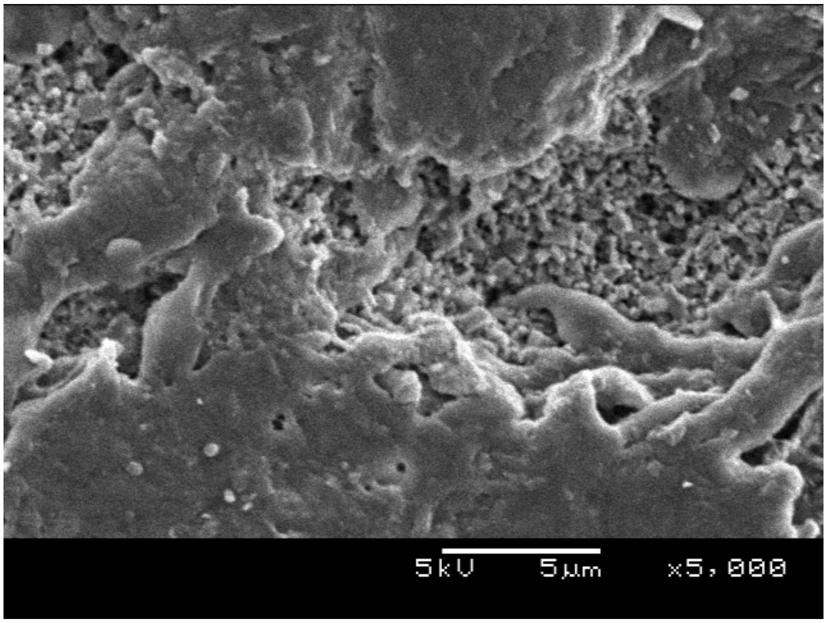

Figure 6.25: Area with adhesion wear exposing the base material of the acetabular cup (magnification x 5 000)

The typical particle that was dislodged from the bearing area is shown in Figure 6.26. This is also the type of particle that can result in the scratches, as shown in Figures 6.15 and 6.16. Examining the particle closely in Figure 6.26 actually reveals a number of smaller particles that were dislodged and is now adhering to the outer part of the bigger particle. The rest of the pictures can be seen in Annexure E. It must be noted that although the particle shown in Figure 6.26 was worked out of the high-pressure high-temperature area of the bearing, it was again attached to the base material when the pressure and temperature dropped sufficiently.

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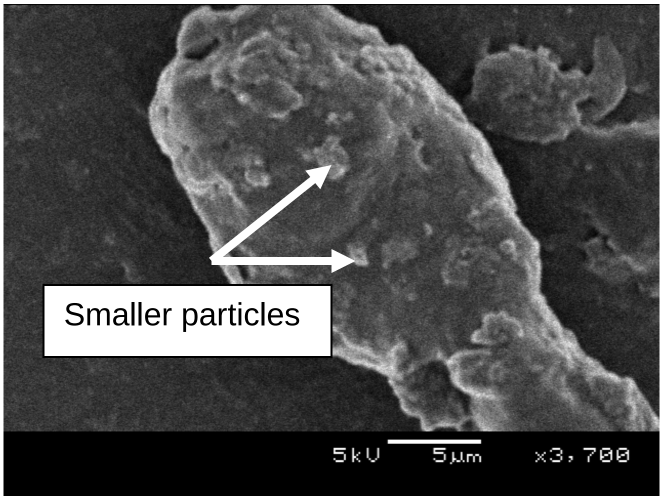

Figure 6.26: Wear particle with smaller particles attached to it (magnification x 3 700)

The mechanism for the formation of this type of particle can therefore be described as a snowball effect where the smaller particles, which were sufficiently softened by the prevailing head and pressure, adhere to the bigger particle as this was rolling or skidding along on the inside of the acetabular bearing.

A second type of adhesion wear was identified where the surface layer of the acetabular bearing is ripped off in what looks like tile-shaped wear debris, as shown in Figure 6.27.

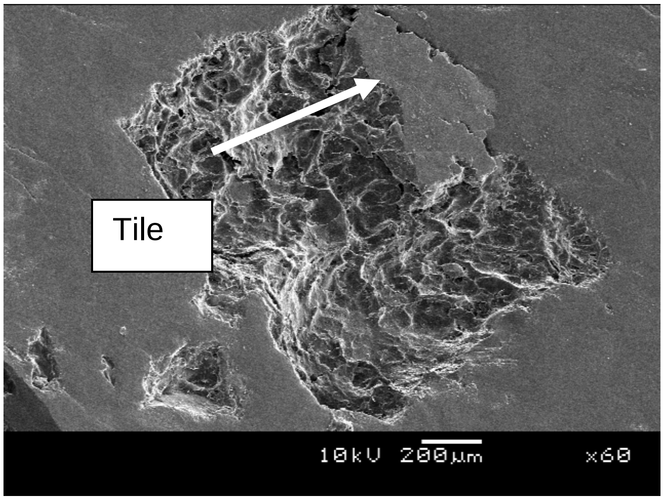

Figure 6.27: Area with adhesion wear (magnification x 60)

If the defect as shown in Figure 6.27 is investigated further under higher magnification, it appears that the tile, as shown in Figure 6.28, is almost completely loose and is only attached at the one corner. The moment this tile is dislodged, it will be wear debris that floats around in the joint area.

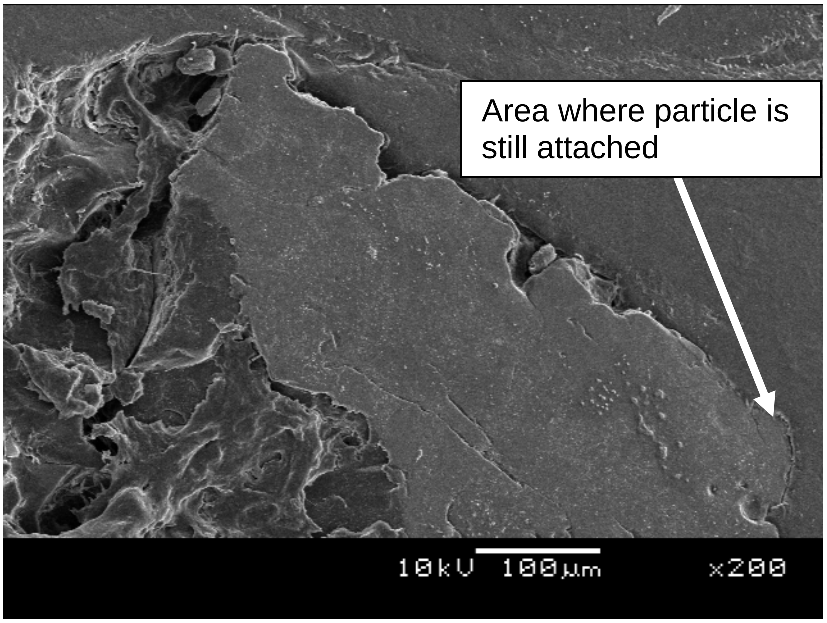

Figure 6.28: Adhesion particle about to be broken out (magnification x 200)

During the experimental phase (Chapter 7), this type of failure will be simulated in the laboratory, showing that the root cause for failure is due to excessive heat build-up on the bearing surface giving rise to adhesion of the surface layer to the femoral head.

6.6 Postulate for mechanical failure of acetabular cups

The shape of the particles as well as the shape of the small craters with the resulting scratches and plastic flow observed can readily be explained as follows: If the bearing load plus the rate of movement is not too high, the temperature will be relatively low and excellent bearing life will be obtained. The heat input into the bearing is determined by the product of load and speed (PxV) (Hutchings, 1992). If the PV value increases the surface temperature at the point of highest loading increases accordingly. As the temperature goes up, adhesion between the femoral ball and the socket increases with a resultant higher heat input in the high-stress area. (See Figure 6.29(A).) A point is reached where the material has softened sufficiently and the adhesion has increased to the point where the bearing material is dragged along by the ball, in a similar manner to a wear particle being dragged along by a shaft in a rotating plain bearing couple. This leaves behind a crater, with the displaced material trapped between the cooler edges of the crater and the femoral head. Loading will flatten the material removed (see Figure 6.29 (B)) into a wafer with irregular edges as shown by the retrieved particles in Figures 6.26 and 6.28. If, on the other hand, a scratch exists under the wafer, there will be a tendency to extrude material along the scratch as a fibre or whisker as shown in Figure 6.17. It should be noted that the pressure in the wafer of removed material will be very high as the wafer will, in effect, be forced between the ball and the cup, effectively raising the ball relative to the cup with the load being mainly supported by the wafer. (Note that the flattened wafer can be forced into the bearing surface.) The particles will with time migrate through the bearing to the surrounding tissue.

A further aspect to consider is that after a crater has been formed, the edges of the crater will be bearing the highest load, as shown in Figure 6.29(C). The process described above will be repeated during the dynamic loading, with the result that the crater will grow in size and in depth, as is commonly observed in retrieved acetabular cups.

The rate of particle migration is expected to be very slow, because of the slow oscillating movement of the femoral head. It can also be seen from the experimental results (Chapter 7) that the coefficient of friction of the bearing as a whole is not affected by the presence of loose bits of bearing (UHMWPE) material on the bearing face. The difference in the coefficient of friction was too small to measure with the existing techniques. The process described above must therefore not be regarded as rapid and catastrophic but rather as slow and eventually catastrophic. This is a slow process that is largely activated by high PV incidents.

Inadequate lubrication will accelerate the build-up of heat and therefore will accelerate the wear process. It is shown in the experimental work done on lubrication of the hip joint (Chapter 8), that the average lubricating capabilities of the synovial fluid retrieved from ten patients do not meet the standards of a basic lubricant. This lack of lubrication will definitely result in accelerated heat built-up on the bearing surface with the consequential damage as shown in Chapters 5 and 6.

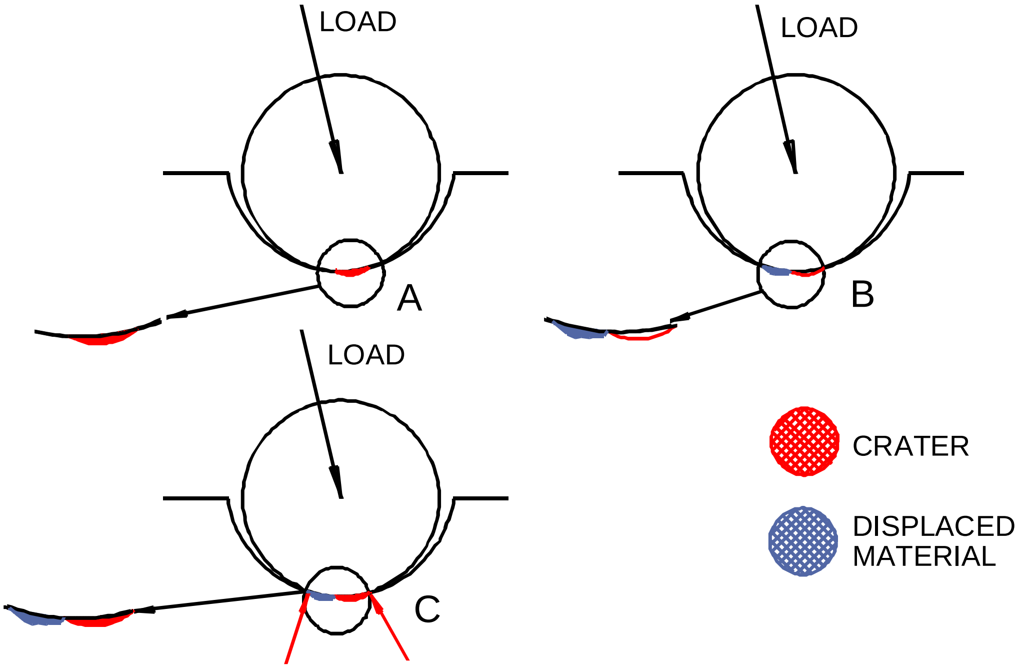

Figure 6.29: Steps in wear debris formation in acetabular cup