Chapter 11
What Do the Retrievals Really Tell Us?

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Retrieval analysis is an important tool in orthopedic research to understand the clinical performance of joint replacements [1]. Many retrieval studies have been conducted on metal-on-metal (MoM) hips, especially in the light of the recent high failure rates due to adverse local tissue reactions caused by metallic wear and corrosion products. Ideally, retrieval analysis includes the investigation of periprosthetic tissue in addition to the analysis of the artificial device. Generally, one could approach the subject in two ways and ask: “Why did the device fail?” or “Why did the device work?” [2]. In order to address the former question, devices retrieved for cause during revision surgery are an appropriate source, while for the latter, devices retrieved postmortem are more suitable [3]. It is important to not only focus on failures but also learn from the successful designs. In the case of MoM, retrieval analysis helped to gain a more fundamental understanding on why some MoM hip joints developed dissatisfying results over time despite positive results with the earlier, small-headed implant design (the so-called second MoM generation) [4]. Retrieval analysis helps to improve the judgment for revision surgery of current MoM patients. Further, it is hoped that the lessons learned are applicable to designs with other bearing combinations as well.

Recovered and analyzed correctly, retrievals can provide clues about the specific materials used, their manufacturing process, the host response, the occurring wear

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modes of the device together with the underlying wear mechanisms, and the presence or absence of corrosion.

In this chapter, the authors will give an overview on the outcome of MoM hip retrieval analysis and the vital knowledge obtained so far. Although device fracture is known to occur in some rare cases due to overload or poor metallurgy, one of the main causes for clinical failure is related to wear and corrosion by initiating adverse local tissue reactions [5]. Therefore, focus is given to damage caused by wear and corrosion. First, the authors will demonstrate how insight into the retrieved material itself (i.e., cobalt-chromium-molybdenum (CoCrMo) alloy) can be obtained through appropriate tools. This is followed by an introduction to wear analysis, paying particular attention to the specifics of CoCrMo. Retrieval analysis ideally follows the principle of "from macro to nano". For this approach, global damage features should be evaluated first by photo documentation and macroscopic (magnifying glass) analysis techniques followed by microscopic (light microscope, white light interferometry) and nanoscopic (electron microscopy, atom force microscopy) methods. Since not only the emission of wear particles but also the release of ions is of concern, corrosion will be discussed as well. Emphasis is given to the use of modularity in femoral components, in particular the head–neck taper junction. The chapter closes with conclusions and recommendations on the handling of retrieved implants.

Type and Quality of Alloy

Every retrieval analysis should begin with the identification of the exact type of device (model, manufacturer, lot number) that is being evaluated. Also, all clinical information is of relevance and should be documented. Such information includes patient age, gender, body mass index, original diagnosis, clinical assessment scores, duration of implantation, and reason for revision. Further, detailed information about the alloy composition is warranted, which can be attained through energy dispersive X-ray analysis (EDX), if unknown. MoM hip prostheses are usually made from CoCrMo alloy, typically consisting of cobalt as the base, 26–30 % chromium and 5–7 % molybdenum, along with 0.05–0.4 % carbon and < 0.05 % nickel [6, 7]. CoCrMo alloy has been known for its wear and corrosion properties for a long time and has been used in the automotive and tooling industry first before it made its appearance in the dental field as Vitallium in the 1930s [8] and later in orthopedics in the 1940s [9]. CoCrMo is a highly abrasion-resistant material, in part due to its hard phases, which are distributed throughout the CoCr matrix and along the grain boundaries. The high corrosion resistance is provided by the high amount of chromium and molybdenum within the alloy. Chromium enables passivation by the formation of a protective chromium oxide film on the surface, which typically has a thickness of a few nanometers [10, 11]. During implant articulation, this film changes its composition and becomes a metallo-organic compound consisting of wear debris, proteinaceous and graphitic material [12, 13] as will be outlined in more detail further.

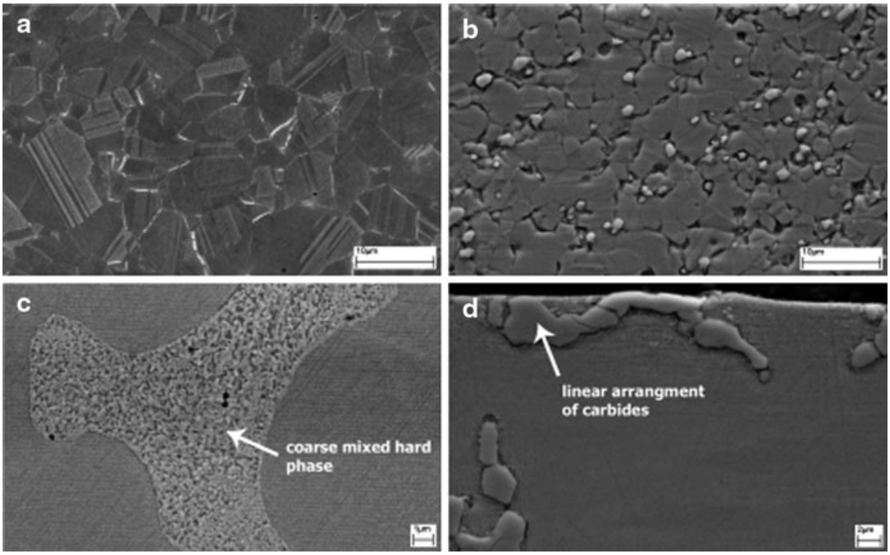


Fig. 11.1 SEM images of different CoCrMo alloy microstructures and hard phases. **a** Low-carbon wrought alloy, fine grain size, high twin density, minimal amount of hard phases. **b** High-carbon wrought alloy, fine grain size, evenly distributed fine and compact carbides. **c** As-cast alloy with coarse mixed hard phases. **d** HIPed cast alloy, linear arrangement of carbides

Two basic types of alloys have been used for orthopedic bearing applications: cast and wrought CoCrMo alloy. When a component is directly casted to its final shape, one speaks of cast alloy. After solidification of the alloy the component undergoes only surface finishing and in some cases heat treatment [14, 15]. Wrought alloy is first manufactured to bar stock. Its microstructure can be refined by forging as well as other methods, for example, vacuum induction melting [16]. It is usually more homogenous than cast alloy and has a smaller grain size. The chemical composition and mechanical properties of cast and wrought alloy are specified in ASTM F75 and ASTM F1537, respectively [6, 7]. These standards, however, do not set precise guidelines for the alloy microstructure. Hence, the quality between standardized materials fluctuates tremendously, the grain size in particular, as well as size and distribution of hard phases are not sufficiently standardized [17]. For retrieval analysis, knowledge of the microstructure is important since it is often not only directly related to material properties (e.g., hardness, yield strength) but also wear features on the surface. For example, since wrought alloy typically has a smaller grain size than cast alloy, it exhibits higher strength. Since grain size is inversely related to hardness, and metal hardness correlates directly with abrasive wear resistance, wrought CoCrMo alloys perform better under sliding conditions [16]. In order to visualize the microstructure of retrieved components, standard metallographic methods may be applied. A small section of the device has to be cut off, grinded, polished, and etched. Depending on the etchant, the hard phases, grain boundaries, or even both can be stained and visualized by light microscopy and/or scanning electron microscopy (SEM). In Fig. 11.1, a selection of observed CoCrMo alloy microstructures and hard phases is shown.

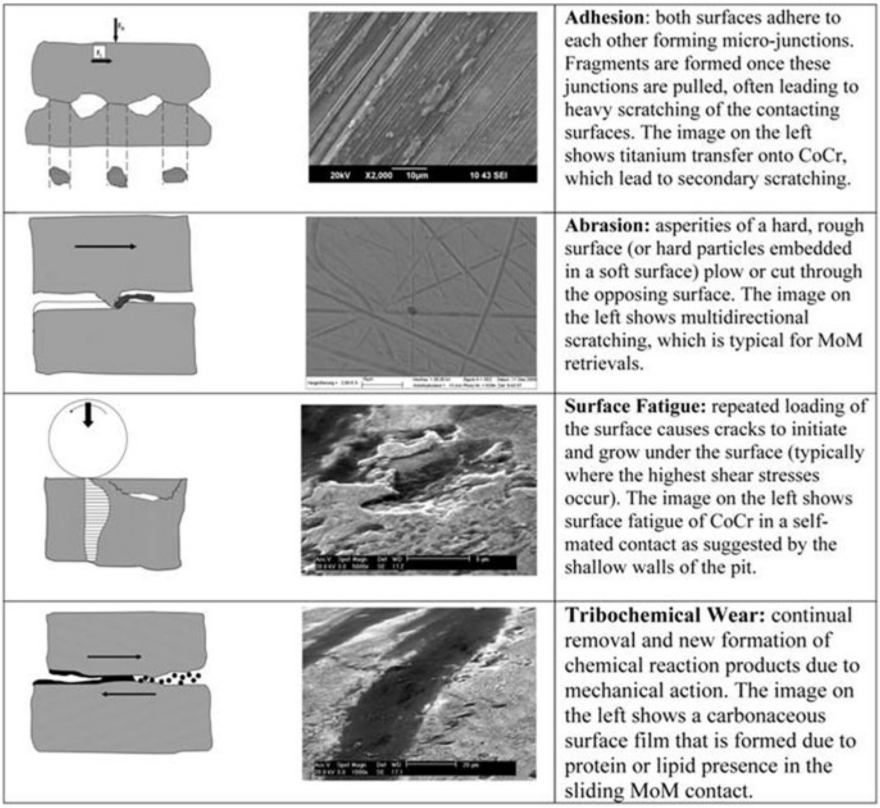
The amount and nature of hard phases depend on the amount of carbon within the alloy as well as the applied heat treatment [15, 17, 18]. As previously mentioned, the occurrence of the desired hard phases, so-called carbides (because of their chemical compound structure consisting of carbon and chromium and/or molybdenum), is directly related to the carbon content of the alloy [19]. However, a recent study has shown that not only carbides but also brittle intermetallic phases occur which can damage the bearing surfaces once they leave the metal matrix [17] (Fig. 11.1). In newer generation MoM hip joint implants, high-carbon (0.2–0.4 %) alloy is used more or less exclusively, which yields a higher amount of carbides [16]. Cast alloy implants may or may not undergo further heat treatment depending on the manufacturer. The heat treatment can have a big impact on the microstructure, especially its hard phases. The most common conditions for cast alloys are as-cast (no heat treatment), hot isostatically pressed (HIP), or double heat treatment (solution annealing and HIP). The total hard phase volume fraction can vary between 0.5 and 7 % depending on the heat treatment and solidification sequence. Based on prior studies, there is no consensus as to which type of heat treatment is preferable [15, 16, 20–22].

Wear

It appears that implant wear is directly related to the occurrence of adverse local tissue reaction and subsequent implant failure [23, 24]. Excessive wear can be design specific or to other factors, for example, malalignment [25, 26]. Thus, the focus of retrieval analysis is to understand how the components were worn, which type of wear debris was generated and how it affected the surrounding tissue. Wear analysis of orthopedic implants falls into the research field of tribology, which comprises scientific and technical aspects of friction, wear, and lubrication [27]. A hip joint is regarded as a tribological system which consists of four principal elements: body (femoral head), counter body (acetabular cup), interfacial fluid (synovial fluid), and the environment (regulated by the human body) [28, 29]. The interaction of these elements, depending on applied load, motion, and surrounding conditions (e.g. lubricant properties, local pH, temperature, etc.), results in material loss (wear debris) as well as heat and sometimes sound (squeaking).

Wear Modes and Mechanisms

In tribology research, the wear mode describes the general mechanical conditions under which a tribological system is operating. It is important to identify the wear mode and its underlying wear mechanisms during retrieval analysis. Currently, four major wear mechanisms are known, namely, adhesion, abrasion, surface fatigue, and tribochemical wear (Fig. 11.2). Knowledge of the acting wear mode and mechanisms is crucial as it provides information for appropriate wear countermeasures [28, 29].



Adhesion: both surfaces adhere to each other forming micro-junctions. Fragments are formed once these junctions are pulled, often leading to heavy scratching of the contacting surfaces. The image on the left shows titanium transfer onto CoCr, which lead to secondary scratching.

Abrasion: asperities of a hard, rough surface (or hard particles embedded in a soft surface) plow or cut through the opposing surface. The image on the left shows multidirectional scratching, which is typical for MoM retrievals.

Surface Fatigue: repeated loading of the surface causes cracks to initiate and grow under the surface (typically where the highest shear stresses occur). The image on the left shows surface fatigue of CoCr in a self-mated contact as suggested by the shallow walls of the pit.

Tribochemical Wear: continual removal and new formation of chemical reaction products due to mechanical action. The image on the left shows a carbonaceous surface film that is formed due to protein or lipid presence in the sliding MoM contact.

Fig. 11.2 Pictographs describing the four major wear mechanisms and examples of their appearance on cobalt-chromium alloy surfaces. It should be noted that wear mechanisms rarely occur in isolation but often take place together affecting each other

In order to determine the wear mode, the macroscopic structure of the system and the kinematic interaction of its elements have to be analyzed. Two fundamentally different wear modes are sliding and rolling wear with different subsequent wear mechanisms [28]. The knee joint, for example, exhibits a combination of rolling and sliding wear, whereas at the hip joint, only sliding wear occurs. During sliding, depending on activity, the relative motion between head and cup can be either unidirectional or reciprocating. However, complex motion causes motion trajectories on the surface to cross each other in a way that the direction of motion on single contact spots changes frequently. This wear mode is called specifically multidirectional sliding wear and is known to influence the wear rate, especially in the case of metal-on-polyethylene bearings due to the effect of orientation-softening on the polyethylene surface [30]. In summary, the wear mode of a hip joint under well-functioning conditions can be characterized as multidirectional sliding wear.

As shown in several studies, an increase in wear is often triggered by malpositioning of the hip joint resulting in edge loading or other adverse, non-intended contact conditions (e.g., impingement) and subsequently accelerated wear [25, 31]. Therefore, the definition of wear modes for hip replacements was expanded and additional, non-intended wear contact conditions were included [32]. According to McKellop [32], there are four distinct wear modes that should be considered. Wear mode 1 describes wear conditions as intended for the implant design. Wear mode 2 is defined as contact between a bearing and a nonbearing surface. For example, this can be (a) edge loading, where the head articulates against the rim of the cup; (b) microseparation between head and cup leading to cyclic hard impact; and (c) impingement wear, which describes the contact between femoral stem and rim of the cup [25, 32, 33]. All three conditions have been observed frequently on retrieved specimens and proved particularly problematic for MoM [31, 34, 35]. In comparison to polyethylene, these "adverse wear conditions" lead to highly accelerated particle and ion release in MoM bearings often followed by catastrophic clinical failure. In hindsight, it would have been prudent to more thoroughly investigate these non-intended wear conditions for MoM hips preclinically. Wear mode 3 occurs when hard particles enter the tribological interface, and contact is established on this interfacial material. This wear mode is therefore also called "3-body wear." There is evidence from retrieval analysis [17] showing that the aforementioned brittle hard phase, break loose and enter the bearing surface. This leads to extensive scratching (and hence an increase in surface roughness) with breakdown of any occurring lubricant film and thus to increased wear. Finally, wear mode 4 has been defined as contact between two nonbearing surfaces, as for example backside wear between the metal shell and the liner of the bearing, and wear due to modular taper junctions. In particular, the latter turned out to be a tremendous problem for MoM total hip replacement with large head sizes leading to recalls of several devices on the market [36, 37]. Later in this chapter, we devote a separate section to taper wear.

Each wear mode is characterized by a specific combination of wear mechanisms, which may act in isolation or together. As mentioned earlier, knowledge of the wear mechanism provides the key for appropriate wear countermeasures. The four major wear mechanisms adhesion, abrasion, surface fatigue, and tribochemical wear have been described in detail elsewhere [28]. Briefly, adhesion leads to the formation of local junctions between the contacting surfaces, and thus has to be avoided for MoM systems to prevent catastrophic damage up to complete seizure. In well-lubricated MoM bearings, with large enough clearance, adhesion is not a problem [38]. However, the combination of a tight clearance, high contact pressure, and the absence of lubricant could provide the necessary condition for microwelding. Abrasion is characterized by hard asperities/particles cutting and plowing through softer surface. It is easily observed by the presence of scratches and grooves on the surface and occurs frequently. Its direct contribution to the overall wear loss is relatively low; however, it may have indirect effects, as for example the loss of the lubricant film, which is troublesome. Surface fatigue occurs due to repeated loading and unloading of the contacting bodies inducing small cracks underneath the surface and represents an important mechanism of wear for MoM joints [38, 39]. The cracks eventually grow and eject material fragments leading to pits or delamination. There were several reports of "micropitting" on the surfaces of MoM bearings, which could be linked to surface fatigue. Since these cracks occur in the upper zone of the surface, the volume loss due to this mechanism is relatively low and leads to mild wear. Tribochemical wear results from the continuous removal and new formation of chemical reaction products. Since this mechanism occurs in a corrosive environment in the presence of proteins, the kinetics of this process become very complex for MoM joints. The importance of tribocorrosion for MoM joints has been underestimated for a long time, and only recently has become a major field of study [10, 40].

Wear Volume and Location

Metal ions and wear particles have been described as the trigger of adverse local tissue reactions [41]. At revision surgery, the periprosthetic tissue of MoM devices often exhibits a dark color indicating the massive invasion of metal particles and/or ions, which has been defined as metalosis [42]. It is difficult (if not impossible) to measure the wear of MoM devices during follow-up using X-ray film (as it is done in the case of polyethylene). Available markers are Co and Cr blood ion levels. Threshold levels were recently set to 7 μg/L by the Medicines and Healthcare Products Regulatory Agency (MHRA) in the UK and others [43, 44]. But how much material was really removed from the surface over the entire lifetime of the implant? Metrology methods (e.g., measurements using coordinate or roundness-measuring machines) allow the precise determination of the total material loss from retrieved components [26, 31]. If the in situ time is known, a linear wear rate can be determined. For MoM bearings, the wear rate should not exceed 1–5 microns/year (approximately 0.5–1 mm^3). A higher wear rate will most likely lead to adverse tissue reactions [21, 42]. The wear rate of metal hip replacements does not follow a strictly linear evolution but wear occurs in two phases, namely, running-in and steady state [45]. As shown by simulator studies, the running-in phase exhibits a significantly higher wear rate than the steady state phase (Fig. 11.3) [45]. On average, it is estimated that the steady state phase is reached after 1 year. High wear volumes are troublesome as it has been shown that they directly correlate with high blood ion levels [23, 24] and the occurrence of adverse local tissue reactions [42, 46].

Several studies demonstrated that malpositioning of MoM hip joints triggers an increase in wear rate and thus initiates failure [25, 31, 34, 37]. For this discussion, malpositioning is defined as placing the cup out of a manufacturer's defined safety window of inclination and anteversion angles. The result can be a shift of the wear mode from 1 to 2. Retrieval analysis helps to accurately visualize wear scars generated due to edge loading, microseparation, or other possible adverse contact conditions [26, 47]. The metrology data can be used to generate a wear map which shows the projection of local penetration on the articulating surfaces of head and cup as shown in Fig. 11.4. In case of well-functioning hips, the maximum penetration of the cup due to wear should be located within the primary articulating surface area and be concentrated in close proximity to the pole of the head and the superior area of the cup, but not reaching the edge [26]. The transition from a high-wear area to a

Fig. 11.3 Example of typical wear behavior in hip joints as derived from a hip simulator illustrating the difference between overall, running-in, and steady state wear rate

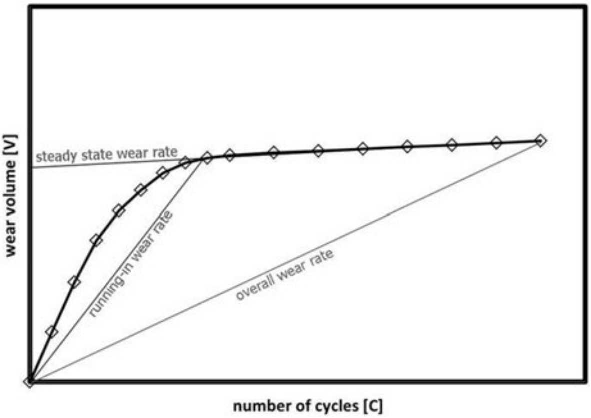
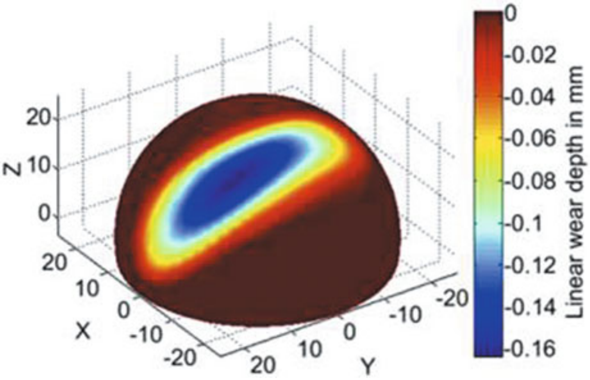


Fig. 11.4 Surface reconstruction of a femoral head based on metrology data, exhibits typical wear scar for edge loading or microseparation. (Reprinted from Langton et al. [47])



low-wear area should be smooth. During edge loading, the area of greatest wear is shifted to the edge of the cup [26]. The femoral head usually exhibits an oval wear scar, which can stretch from the trunnion up to the pole forming a stripe. Therefore, it is also referred to as stripe wear [33]. Adverse contact conditions are often displayed as clearly separated areas of damage. In the case of microseparation, the wear scar on the head exhibits numerous oriented scratches due to frequent contact with the edge of the cup as shown in Fig. 11.5.

Wear Features

Wear features or wear patterns describe the surface appearance within the wear scar. They are the direct result of the acting wear mechanism(s). Under well-functioning conditions, two wear features are most common in MoM joints: polishing and the formation of a tribofilm. Polishing can hardly be distinguished from the final surface finish process during manufacturing and is the result of fine wear particles ($\ll 1\ \mu m$)

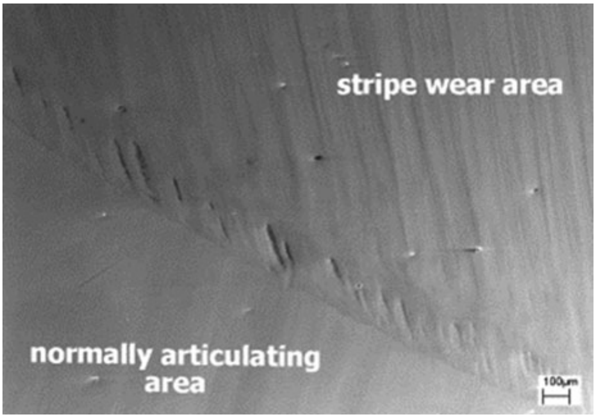


Fig. 11.5 Sharp transition zone between stripe wear area and normally articulating area on a femoral head. The stripe wear area exhibits numerous strongly oriented scratches and grooves

rolling between the articulating surfaces causing mild surface fatigue. The tribofilm forms due to combined interaction of the implant surface, fine wear particles, and protein from the synovial fluid (e.g., albumin, globulin). The resulting carbon-rich film covers parts of the articulating surface and serves as solid lubricant (Fig. 11.6). Further, it separates the two metal surfaces and thus inhibits adhesion which otherwise would increase the wear rate. On most retrievals, randomly oriented scratches can be observed as well (Fig. 11.7). Such scratches are the result of occasional abrasion due to 3-body wear. Hard abrasive particles are most likely to originate from the alloy itself due to detached hard phases. Depending on the type, size, and amount of hard phases in the alloy, the extent of occasional 3-body wear may differ. Although it is assumed that a large amount of hard phases reduces 3-body wear due to increased resistance to abrasion [14], evidence suggests that detachment of hard phases from the surface may introduce 3-body wear in the first place [17] (Fig. 11.7).

Under adverse contact conditions (wear mode 2 and 3), wear features may change drastically. For example, under edge loading or microseparation, wear is clearly more mechanically dominated and abrasion becomes the most dominant wear mechanism

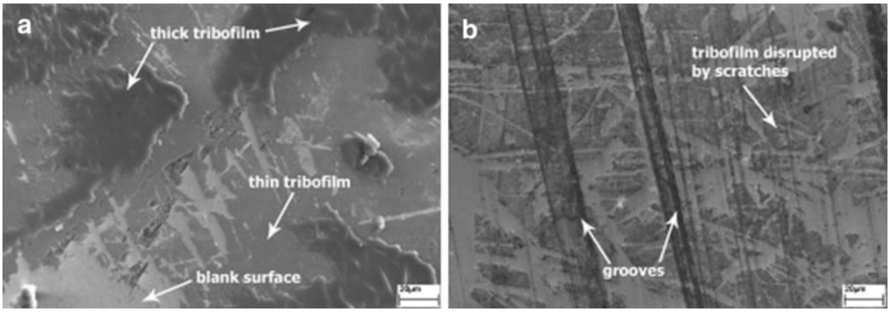


Fig. 11.6 Carbon-rich tribofilm on the articulating surface of a femoral head **a** under normally articulating conditions (wear mode 1) and **b** after edge loading/microseparation conditions (wear mode 2)

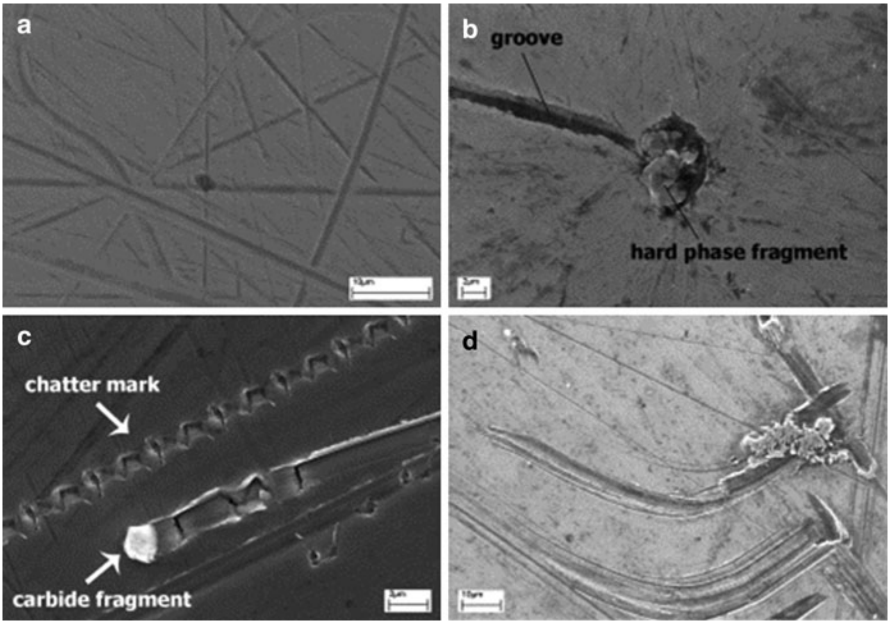


Fig. 11.7 SEM images of wear features caused by abrasion. **a** Randomly oriented scratches due to 3-body wear. **b** Groove caused by plowing hard phase fragment. **c** Chatter mark and grooves caused by carbide. **d** Grooves and scratches

(Figs. 11.5 and 11.7). In the affected areas, oriented scratches and deep (> 1 µm) grooves can be observed. Around the main wear area also, an increased amount of randomly oriented scratches can be found due to the wear particles generated in the edge loading/stripe wear areas, which are now introducing increased 3-body wear. A tribofilm may form as well in some areas, but it appears patchy and cannot unfold its beneficial influence on the implant wear behavior (Fig. 11.6). Several other wear features have been reported for adverse contact conditions which can be characterized as subgroups of those reported here.

Wear of metal devices not only causes morphological alterations on the articulating surface but also has impact on the immediate subsurface microstructure. Such alterations occur within the first few micrometers underneath the surface. Retrieval analysis of a group of well-functioning MoM hip replacements has shown that CoCrMo alloys undergo distinctive changes in the primary articulating zone [48]. Here within the first 400 nm, a nanocrystalline subsurface zone forms that gradually increases in grain size throughout depth. Also, the lattice structure of the alloy changes from the common face-centered cubic (fcc) lattice to the hexagonal close-packed (hcp) lattice. The grain size in this zone lies somewhere between 30 and 80 nm, and thus is significantly smaller than the bulk alloy [48]. Moreover, in some areas the nanocrystalline metallic surface shows incorporation of carbonaceous material, which originates from the earlier described tribofilm. Overall, the resulting metallo-organic composite material has beneficial influence on the wear

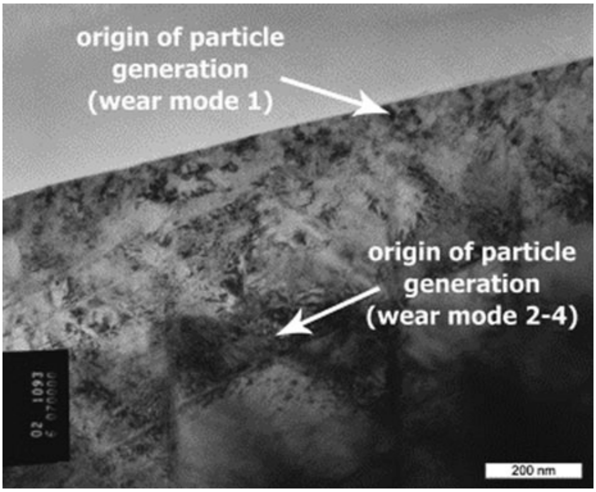


Fig. 11.8 TEM cross-section image of a femoral head articulating subsurface zone. On *top* a thin nanocrystalline layer can be seen. Under wear mode 1, nanoparticles are generated only within this area. Under adverse contact conditions, particles detach underneath that layer resulting in larger particles

and corrosion behavior of the bearing [13, 49]. If edge loading or microseparation occurs, the subsurface microstructure exhibits a slight but distinctive difference: The nanocrystalline subsurface zone is very thin (100 nm) and displays a sharp boundary with no transient changes to the underlying bulk microstructure.

The in situ alteration of the CoCrMo alloy subsurface microstructure is an important component in the understanding of MoM hip wear. However, its analysis requires sophisticated techniques, most importantly the use of a transmission electron microscope (TEM), which is not always available. Besides, sample preparation is time consuming and requires skilled personnel. Implant surface samples need to be locally thinned to a thickness of < 100 nm. This can be achieved with dimple grinding and ion milling [39], or with a focused ion beam (FIB) device paying close attention not to alter the existing microstructure. Once a sample has been prepared, an electron beam can be transmitted through the sample in the TEM. Many TEMs are further equipped with EDX or EELS (electron energy loss spectroscopy) which provide additional information of the local chemical composition and structure. Sample preparation and analysis have to be handled with great care to avoid the introduction of artifacts that could lead to wrong interpretation. Overall, such analysis gives valuable information, but it is time consuming and destructive and therefore should be applied to the most representative components available.

Wear Particles and Adverse Tissue Response

In well-functioning metal hips (wear mode 1), during steady state, it can be expected that the origin of particle detachment is strictly limited to the nanocrystalline zone (Fig. 11.8) [39, 49]. Thus, the particle size correlates with the immediate subsurface grain size. This can be observed on retrievals since polishing as a wear feature

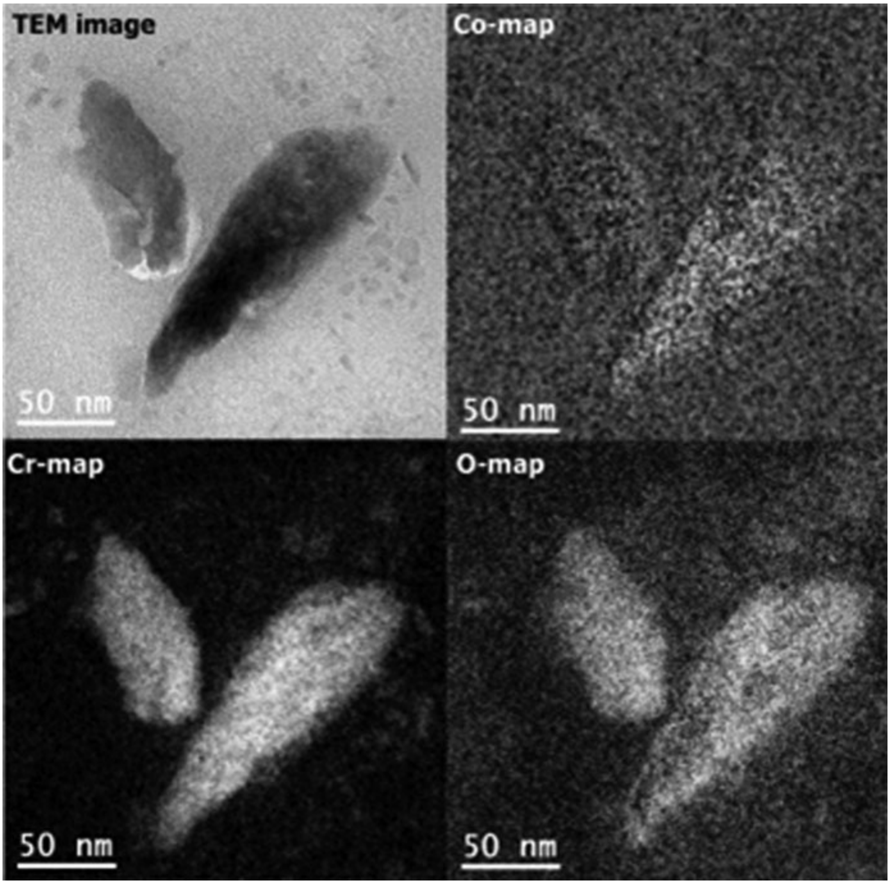


Fig. 11.9 TEM image and elemental maps (measured by EFTEM) of wear particles generated in a hip simulator. It can be seen that wear particles consist mainly of Cr and O, indicating the presence of chromium oxide. Remains of cobalt occur only locally in particles with a size > 50 nm. (Modified from Pourzal et al. [52])

indicates that most particles are very small, so they act more like a polishing paste rather than abrasive particles. Also, particles observed within the tribofilm were in the same size range [49]. This was confirmed by earlier studies of wear particles which were isolated from hip simulator wear-testing fluid (bovine serum) [50, 51]. It showed that such particles are in a size range of 30 to 80 nm. In general, particles of that size (< 100 nm) are considered nanoparticles and known to be highly reactive, especially in a biological environment. Indeed, energy-filtered TEM (EFTEM) analysis of such wear particles showed that the majority of wear particles consists of chromium oxide with almost no remains of cobalt (Fig. 11.9) [52]. Most of these particles are small (< 40 nm) and only a few, larger particles (> 60 nm) still contain cobalt. Thus, it must be assumed that these particles are highly reactive (pyrophoric) resulting in fast formation of small chromium oxide particles and cobalt ions. Under adverse contact conditions, as for example edge loading and microseparation, abrasion takes

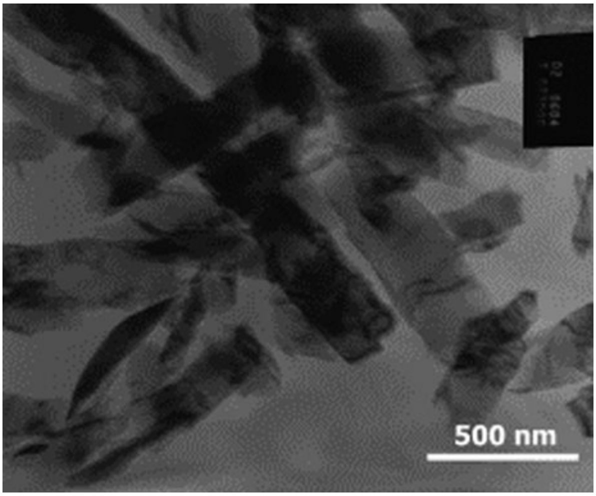


Fig. 11.10 TEM image of wear particles generated under adverse contact conditions. The particle size reaches from 200 to 800 nm. (Modified from Pourzal et al. [52])

stage as most dominant wear mechanism resulting in excessive scratching due to 3-body wear (Fig. 11.7). Under such conditions, as illustrated in Fig. 11.8, particles are no longer generated within the nanocrystalline zone but well below it. This leads to larger particle sizes up to 1 μm (Fig. 11.10). Such wear particles are chemically significantly more stable than nanoparticles. It was shown by Pourzal et al. [52] that the crystal structure of these particles is the same as that of the alloy subsurface zone. Just like the bulk alloy, the particle is protected by a chromium oxide passive film, which inhibits corrosion and thus chemical alteration.

Excessive generation of wear particles and release of metal ions from MoM bearings can induce adverse local reactions in the periprosthetic tissues [53]. The type and occurrence of local adverse tissue reactions differ depending on the nature of the wear particles, especially with respect to their size [54]. In vitro studies have suggested which particles or ion species might be primarily responsible for tissue necrosis [55–59]. High concentrations of Co^{2+} are toxic to macrophages and other cells. Cr^{3+} as well as chromium oxide may be comparably less harmful [57, 59]. This can manifest as a macrophage foreign body response to metallic particles or, in some patients, as a lymphocyte-dominated inflammatory response [60], leading to widespread necrosis of soft tissues, osteolysis, and failure of an arthroplasty. One or the other reaction may be present, or in some cases, both the foreign-body macrophage and the lymphocyte-dominated inflammation can be observed in the same specimen. A detailed description of the histopathology is presented in this volume in Chap. 9 by Bauer.

Corrosion

Corrosion is the gradual destruction of a material due to chemical interaction with its environment. Unlike wear, the material loss occurs mainly by ion release instead of particle formation. CoCrMo alloy is considered a corrosion-resistant alloy mainly

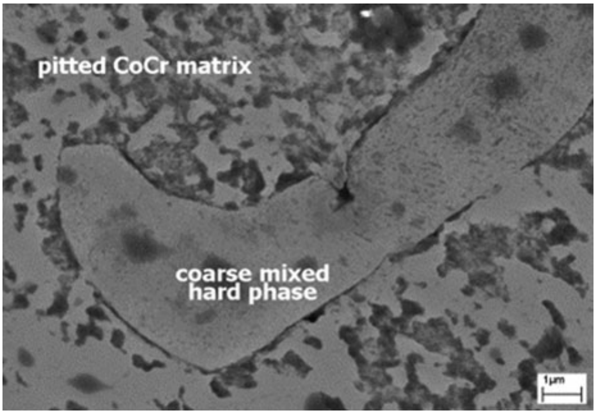


Fig. 11.11 Excessive pitting corrosion on the articulating surface of an as-cast alloy hip resurfacing femoral head. Pitting mainly occurred locally in the direct proximity of coarse mixed hard phases

due to the formation of a continuous passive film that consists primarily of chromium oxide (Cr_2O_3). It has to be stated that corrosion can never be separated from metal wear. Wear can usually cause local disruption of the passive film resulting in corrosion of the surface. Alloys like CoCrMo are able to rebuild the passive film rather quickly. However, there is always a contribution of corrosion during the wear process. The study of the combined interaction of wear and corrosion is subject of the field of tribocorrosion [10, 40].

Bearing Surface

Under well-functioning conditions of the implant, corrosion plays only a minor role on articulating surfaces and no specific damage pattern can be observed. However, in some rare cases, so-called pitting corrosion occurred leading to high blood ion levels and adverse tissue reactions [61]. This excessive type of corrosion is characterized by numerous pits, which can spread several micrometers. An example is shown in Fig. 11.11. The reason for the occurrence of pitting corrosion may be local galvanic elements that occur due to inconsistent metallurgy of the alloy or pairing of two different alloys between head and cup. Inconsistent metallurgy can be best observed by metallographic analysis as previously mentioned. The occurrence of excessive pitting corrosion is very rare on the articulating surface. A more prominent source of high ion release due to corrosion is the modular taper junction of total hip replacements.

Corrosion of Modular Junctions and Adverse Tissue Response

The investigator of retrieved implants should be aware that the bearing surface is not the only potential source of metallic particle generation and metal ion release in MoM total hip arthroplasty. For this reason, all surfaces of retrieved devices should be thoroughly examined for evidence of wear and corrosion with particular attention to the mating surfaces of modular junctions. Marked corrosion has been reported at modular head–neck junctions [62] and at the junction between dual modular necks and femoral stems [63]. A lymphocyte-dominated adverse local tissue response similar to that seen with MoM bearings may occur when one or both components of a corroded modular junction are made of CoCr alloy.

The nature of corrosion, the identification of solid corrosion products, and the serum cobalt and urine chromium concentrations associated with modular head–neck junctions have been studied extensively in earlier generation devices with metal-on-polyethylene bearings using SEM, EDX, X-ray diffraction, EELS, and atomic absorption analysis [64–68]. Corrosion attack of modular CoCr components included preferential dissolution of cobalt, pitting, and intergranular corrosion [64]. Serum cobalt and urine chromium concentrations were significantly elevated in patients with moderately or severely corroded tapers [66]. At the corroded modular connections, solid corrosion products were found at two locations [67]. A thin, friable interfacial layer of highly crystalline mixed oxides and chlorides of chromium and molybdenum was present within the crevice formed by the mated head and neck components. Thicker deposits identified as amorphous chromium phosphate were present around the opening of the crevice. Migration of brittle chromium phosphate corrosion products to the bearing surface was demonstrated throughout the periprosthetic tissues [65] and to para-aortic lymph nodes [69].

Contemporary modular head–neck junctions of improved design and the more recently introduced dual modular CoCr necks demonstrate same types of corrosion and corrosion products (Fig. 11.12) as earlier modular head–neck designs described previously [62, 63]. Both foreign-body macrophage and lymphocyte-dominated inflammation can be observed in the periprosthetic tissues from contemporary modular junctions (Fig. 11.13). Corrosion of these devices may not be immediately apparent on gross examination of the retrieved component or when using reflected light microscopy, even under moderate magnification. A slight dulling of the surface, a matted surface appearance, or a bright surface with the presence of corrosion products may be the only indication of corrosion. In such specimens, examination with SEM can reveal extensive pitting corrosion (Fig. 11.14) or intergranular corrosion of modular junctions. Modular head–neck and CoCr dual modular necks can be sources of metallic particle generation and metal ion release in addition to the bearing surface in MoM total hip devices and should be carefully examined when assessing retrieved components and relating their retrieved condition to the clinical performance of an arthroplasty.

Summary and Recommendations on Retrievals Handling

In this chapter, we have shown that retrieval analysis can provide helpful information on the failure mechanism of specific implants. Macroscopic and microscopic techniques help to identify the wear mode(s) under which the implant had operated

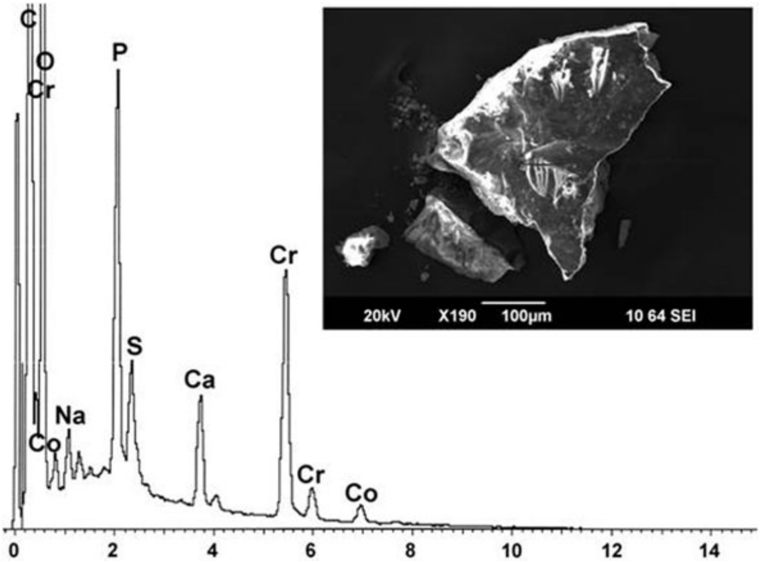


Fig. 11.12 Energy dispersive X-ray analysis spectrum of an approximately 350 µm particle (*inset*) from a contemporary head–neck junction with intergranular corrosion is high in chromium, phosphorous, and oxygen with a trace of cobalt and is typical of chromium phosphate corrosion product. The device was removed after 83 months for infection

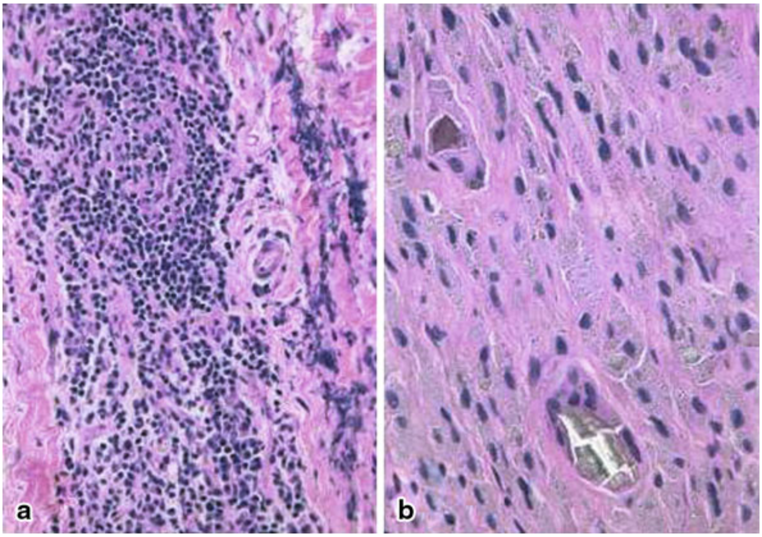


Fig. 11.13 **a** Lymphocyte-dominated inflammation in joint pseudocapsule surrounding contemporary CoCr/CoCr head–neck junction with intergranular corrosion (H & E, × 400). **b** Histiocytes and multinucleated giant cells laden with minute particles of chromium phosphate corrosion product adjacent to a contemporary CoCr/CoCr head–neck junction with intergranular corrosion (H & E, × 600)

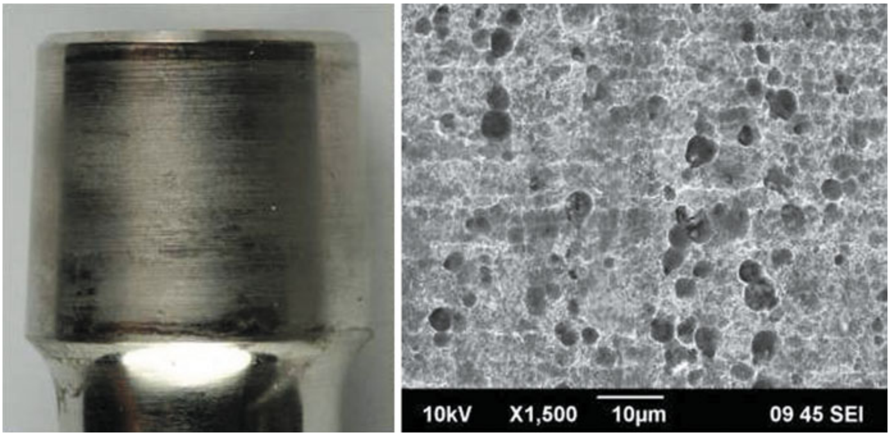


Fig. 11.14 Severe pitting and etching was observed on a contemporary CoCr neck taper mated with a ceramic head (*left*, gross appearance; *right*, scanning electron micrograph). The device was removed for lymphocyte-dominated local adverse tissue response 16 months following primary implantation

and determine the active wear mechanisms from the resulting wear features. Knowledge of the microscopic wear features enables the investigator to estimate the size of wear particles transported to the periprosthetic tissue and qualitatively estimate the amount of wear debris. This knowledge helps to better understand the biological response and histological findings and possibly avoid failures in the future. Retrieval analysis of well-functioning implants clearly demonstrated that MoM articulations can work satisfactorily. This knowledge should build the foundation for potential design changes.

It is important to treat the available retrievals with great care to avoid secondary damage during or after retrieval. Therefore, we want to encourage operating surgeons to support retrieval analysis and close this chapter with a few recommendations on retrieval handling. First of all, any damage to the articulating surface should be kept to a minimum if the course of the surgery allows it. It is recommended to place marks on nonarticulating parts of head and cup which determine the orientation of the components in vivo. Such marks will make the interpretation of wear scares (e.g., stripe wear) and wear features (e.g., oriented scratches) easier. Further, it has been shown that tribochemical reactions can play an important role for the longevity of MoM hip replacements. Therefore, it is of great importance not to perform any form of intensive cleaning directly after implant removal. Mechanical cleaning and the use of detergents should be avoided. Ideally, the retrieval is rinsed in distilled water and stored in formalin. Thus, tribofilms and other deposits (e.g., chromium phosphates), which may carry important information regarding the failure mechanism, will not be lost. After proper analysis and documentation of such films, they may have to be removed to analyze underlying morphological wear features on the articulating or taper junction surfaces.

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