Tribological Behaviour of Ceramic Hip Replacements

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Abstract

Since 1960, when the first hip prosthesis was introduced, up to now, several implant typologies have been proposed trying to meet the increasing clinical demands of more and more active and young patients. A substantial evolution of implant design has been occurring, both in terms of materials and geometry, basically driven by their tribological performances. Indeed, the main concern of hip implants consists in the release of wear debris, which can lead to implant loosening and failure. Thus, many studies on wear and lubrication of hip prostheses have been published in the last 15 years, mainly focused on experimental researches but also on numerical/modeling approaches.

The aim of this work is to review the history of hip implants from a tribological point of view with a focus on ceramic-on-ceramic replacements, which represent the most advanced solution in terms of wear strength and chemical inertness. The main drawbacks of these implants, as the brittleness and the squeaking, are discussed and novel solutions examined.

Introduction

Artificial hip joints, though considered a surgical success, still have a limited life mainly due to the wear of articulating surfaces. In order to overcome this drawback, new materials and geometries have been proposed over the years [1,2]. The most widespread metal-on-plastic implants, used since 1960's, have been partially replaced by hard-on-hard materials: in total hip replacement (THR) metal-on-metal and ceramic-on-ceramic couplings have been introduced. More recently resurfacing hip replacement (RHR), less invasive and more similar to the natural joints, has gained renewed interest, thanks to its bigger dimension and to increased bone preservation with respect to THR.

The evolution of materials and design of THR is strongly motivated by the tribological response of these devices [1]. Although wear is the main concern, lubrication plays an important role as well, as the interaction between mating surfaces depends on the lubrication regime. In fact, as the implant is subjected to transient motion and dynamic loading conditions, the bearing coupling can experience different lubrication regimes: full-film lubrication, mixed lubrication and boundary lubrication (the surfaces are in contact through a protein monolayer). In the last two cases, abrasive and adhesive wear can arise and damage articulating surfaces, also inducing the formation of dangerous wear debris. Therefore, a primary objective in prostheses design consists in guaranteeing film lubrication condition, by means of an optimum combination of several parameters such us geometrical shape (radius and clearance), structure (monolithic or sandwich) and material (elastic modulus and Poisson's ratio).

The tribological behavior of THR is investigated both numerically and experimentally; usually lubrication is dealt with by numerical models, while wear is estimated by *in-vitro* joint simulator tests. However, experimental studies are often time-consuming and costly. Thus, many research groups have developed wear models of joint prosthesis, in order to predict wear in function of design parameters [2,3].

The aim of this work is to review the history of hip implants from a tribological point of view with a focus on ceramic-on-ceramic replacements, which represent the most advanced solution in terms of wear strength and chemical inertness.

Hip Replacements

Historical perspective. The history of hip arthroplasty started in early 19th century and has seen, throughout the ages, the development of hundreds of implant designs evolving for geometrical solutions, materials and implant-bone interface [2]. The 1st generation designs consisted in the interposition of a cup articulating with or resurfacing the acetabulum. In the 1950s, the 2nd generation designs proposed hemi-replacements, i.e. substitutes of the femoral component, both with unipolar (e.g. the Austin Moore replacements) and bipolar geometries. The 3rd generation of implants (early 1960s) introduced the modern total hip replacements, made up of head and cup components, manufactured both in metal-on-metal and metal-on-plastic material couplings. The latter became the gold standard, whilst the metal-on-metal and the more recent ceramic-on-ceramic implants (1970s) were initially abandoned because of their high unsuccessful rates. The novel concepts of biological fixation and head modularity, characterizing the 4th generation designs, spread out in the 1970-80s. From the mid-1980s until now, the 5th generation has allowed significant improvement in hip implant performances, thanks to both innovative materials, such as the highly cross linked polyethylene (HXLPE) [4] and alumina matrix composites (e.g. Biolox delta) [3], and geometries, such as the hip resurfacing replacements. Fig. 1 summarizes the design evolution of hip arthroplasty.

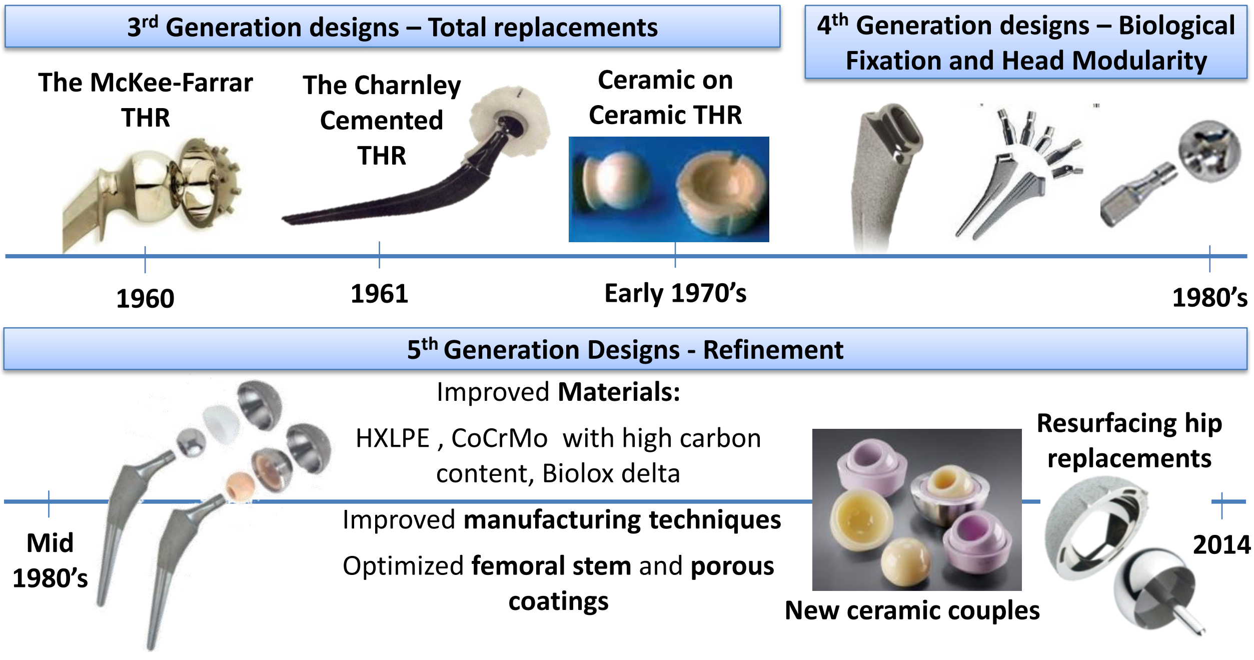


Fig. 1 Evolution of hip replacement design.

Materials and Geometry. Nowadays, hip replacements can be grouped in soft-on-hard and hard-on-hard couplings. The soft materials adopted for the acetabular cup are the ultra high molecular weight polyethylene (UHMWPE), firstly introduced, and the more recent HXLPE. Moreover, in the last years, addition of vitamin E to UHMWPE and HXLPE has allowed to improve oxidation resistance while maintaining wear resistance [5,6]. The hard materials, used for the head, can be metallic (CoCr alloys) or ceramic (Alumina and/or Zirconia composites). Depending on the head-on-cup materials, implants are classified as MoP, CoP, MoM, CoC, CoM and MoC, where M stands for metal, P for plastic and C for ceramic. The trends of such implants in the last decade are depicted in Fig. 2 [7]: MoP implants remain the most used ones, but recently CoC couplings have raised a strong interest thanks to their biocompatibility, high wear resistance and improved mechanical strength. After reaching a peak in 2008, MoM bearings, both total and resurfacing, have been largely abandoned. As far as the geometry is concerned, all implant types are available in many different sizes (i.e. different diameter D_h and diametrical clearance Cl). Recently, large heads, with diameter larger than 32 mm, have spread out [7]. Larger diameters can be reached with RHRs, available in metallic coupling only (MoM_{RHR}).

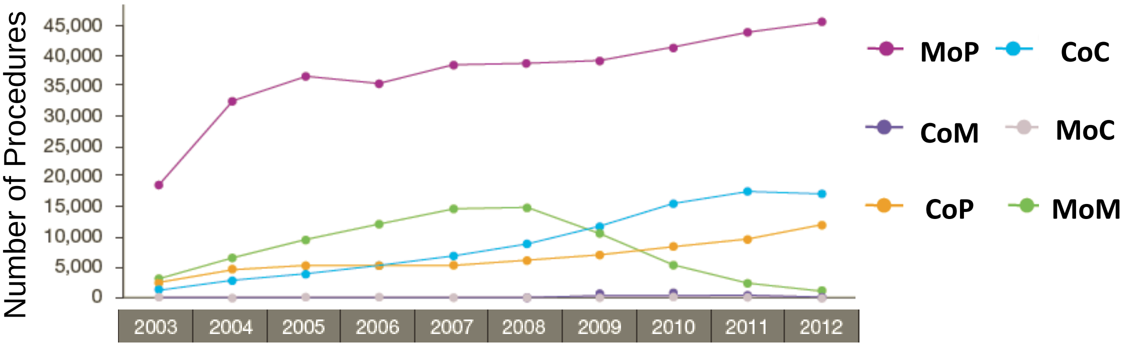


Fig. 2 Trends of hip replacements from 2003 to 2012 in the UK [7].

Tribology of Hip Replacements

The tribology of such a complex system like hip replacements, would require to address many issues, from contact mechanics to lubrication and wear, which are strongly interconnected [1,8,9]. In this section only a brief overview is provided.

Artificial joints, lubricated by a periprosthetic synovial fluid, can experience different lubrication regimes, including the boundary one, and thus are typically affected by wear. Their tribological behavior depends on materials, kinematic and loading conditions. Consequently, it should be considered that for each implant type, such features vary both during a single activity and the implant lifetime. As a reference task, simplified walking conditions are considered in standard tests (e.g. ISO 14242).

Lubrication and friction. Lubrication studies on hip replacements are commonly theoretical and numerical, as reviewed in [10]. The minimum film thickness h_{min} is predicted by means of complex numerical models or empirical formulas (e.g. [11]), assuming in both cases an iso-viscous elasto-hydrodynamic lubrication. The value of h_{min} is then exploited for predicting the dimensionless film thickness λ, and thus evaluating the lubrication regime. On the other hand, experimental studies addressed to the measurement of the coefficient of friction (CoF) in hip simulators can provide indications on the lubrication regime by reconstructing the Stribeck curve [12,13]. Table 1 summarizes lubrication and friction characteristics of hip replacements. Soft-on-hard bearings are characterized by a boundary lubrication regime (λ<1 and the CoF trend almost constant). An improved lubrication is observed in all hard-on-hard bearings: MoM implants can span all lubrication regimes (λ up to 3), MoM_{RHRs} undergo manly mixed-full film lubrication, and CoC replacements always experience full film regime (λ>>3 and coefficient of friction increasing with the Sommerfeld number S). These results are in agreement with the lubrication principles: indeed soft materials promote high film thicknesses thanks to their large elastic deformation, but are also characterized by high surface roughness, which results in low λ. On the other hand h_{min} is lower for hard couples, whose lubrication takes advantage from their smooth surfaces, particularly for ceramics. Lubrication is strongly affected also by the implant geometry: more conformal bearings, characterized by larger D_h or lower Cl, promote the lubrication as proved by the better performances of MoM_{RHR} compared to MoM replacements.

Although the elasto-hydrodynamic lubrication theory is the standard approach to the study of hip implants and is very useful for evaluating implant performances and comparing different design, its validity has been recently call into question. According to some experimental studies on MoM implants, the synovial fluid, which is a protein-containing solution, does not obey to Newtonian models [14]: firstly its proteins form a protective layer on the metallic surfaces; secondly its viscosity is not constant but rather variable with the shear rate. Further studies are necessary to clarify lubrication mechanisms.

Head/ Cup	h_{min} (nm)	CoF	CoF trend	λ
MoP	65–144	0.062	Cost-Decr	0.1–1
CoP	76–107	0.056	Cost-Decr	0.05–1
MoM	20–61	0.12	Cost-Decr	0.5–3
MoM_{RHR}	82–49	0.098	Decr-Incr	0.9–4.6
CoC	35–45	0.04	Incr	5.5–28

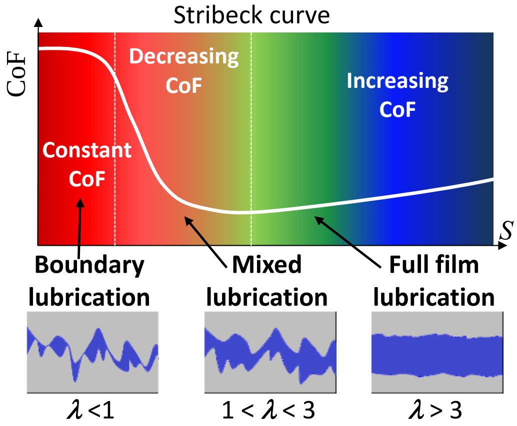


Table 1 Theoretical estimation of $h_{\min}$ according to the empirical formula for iso-viscous EHL reported in [11], assuming typical implant sizes. Experimental estimations of the COF assume a 25% bovine serum solution [12,13].

Wear. Wear is certainly one of the most important tribological features of hip replacements as it is recognized as the main cause of hip implant failure. The literature counts hundreds of thousands of wear studies [10], both experimental and numerical, aimed at characterizing and quantifying it in terms of volumetric and linear wear rates. Such investigations are distinguished in clinical and non-clinical. In the former case, implant wear is studied *in-vivo* (e.g. radiographically) and in *ex-vivo* (retrieved implants) conditions, providing a clinical insight of the implant bio-tribology. In the latter case, experimental wear tests are carried out in hip wear simulators by reproducing physiological-like conditions; this kind of results are fundamental, although they are extremely demanding from an economic and time perspective. Consequently, wear tests are typically supported by numerical analysis, i.e. finite element or analytical wear models, which implement the Archard wear law [10]. Wear models can be exploited to analyse how the wear is affected by implant geometrical features and loading/kinematics conditions [15,16]. Nevertheless, also this approach has some drawbacks: numerical models need experimental investigations for the estimation of the wear coefficient k that is a hard task, considering that k depends on the system conditions and thus varies with geometry, loading/kinematic conditions, as well as is affected by the overall wear process.

Although experimental observations reported in the literature agree in considering adhesion and abrasion as the main wear mechanisms for all implant types, in agreement with the hypothesis of the Archard wear law, some recent findings have shown further complex aspects of the wear behaviour of implant surfaces. Firstly, the wear of MoM couples seems to be partly due to a tribo-corrosion mechanism, still under investigations [17]. On the other hand the cross-shear effect has been demonstrated to strongly affect the wear of UHMWPE in multi-directional sliding against harder surfaces [18]. The local reorientation of the molecular chains entails a change in surface wear resistance. Consequently new expression of k, as well as new wear laws have been proposed for MoP implants, as discussed in [15].

Typical clinical wear rates estimated from simulator tests are reported in Fig. 3. The volumetric wear rate of MoP implants, even with the most performing HXLPE, is up to 100 times higher than MoM. CoC implants exhibit extremely low wear rates, much lower than 1 μm. Such wear rates are in agreement with the predictions of the lubrication regime. Particular attention has to be drawn to MoM_{RHRs}. Although the predicted lubrication regimes for these implants span from mixed to full film lubrication, some clinical wear studies have reported very high wear rates, identified as the cause of early and risky failures. Indeed large amount of metallic ions release has been demonstrated to cause pseudotumors [19]. In MoM_{RHRs}, one of the main causes of high wear rates is attributed to excessive cup abduction angles, which would lead to edge loading and lubricant disruption.

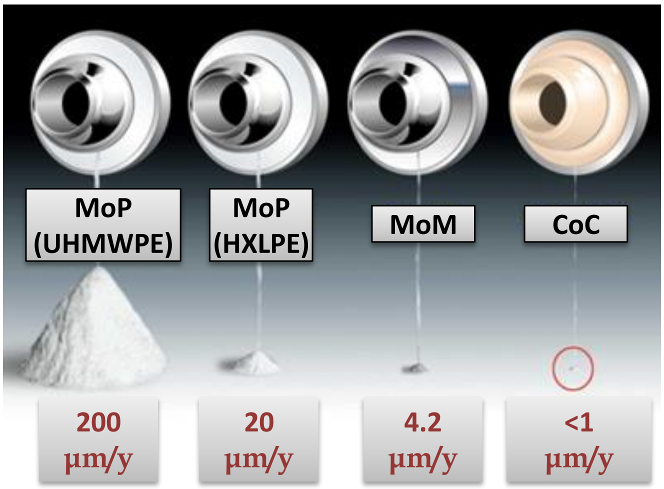
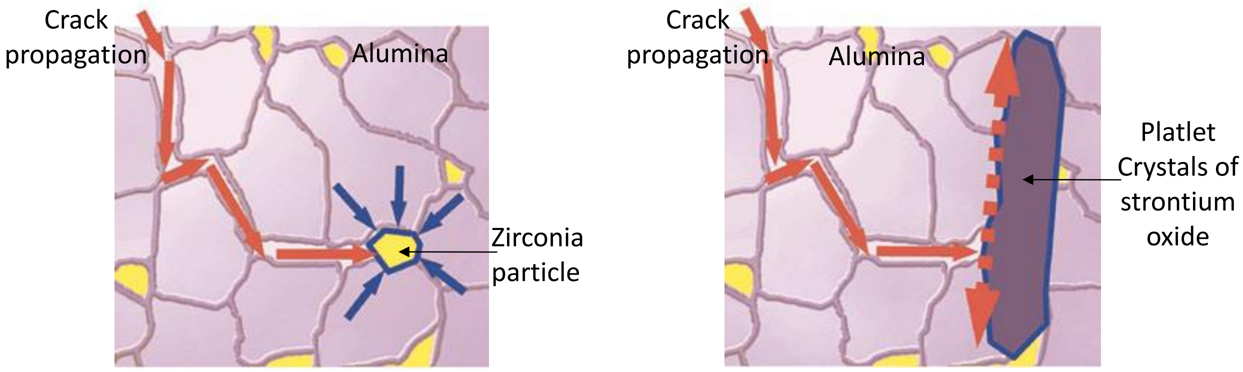


Fig. 3 Average volumetric wear rates estimated from retrieved implants. Adapted from [20].

Tribology of Ceramic Hip Replacements

The high wear rate of plastic components, as well as the low performance of the first generation of MoM implants, fostered the way for ceramics [21]. About four decades ago, Alumina ceramic (Al_2O_3, aluminum oxide) was introduced in order to improve performance and longevity of total hip arthroplasty. In addition to their high wear strength, ceramic materials offer chemical inertness and corrosion resistance, which constitute the basis for an excellent biocompatibility [21]. Thus one of their main advantages in their use is a limited incidence of osteolysis. In fact, the functional biological activity (indicator for osteolytic lesions) and the concentrations of wear particles in the periprosthetic tissue were shown to be about 20 times lower in CoC prostheses than MoP implants [22]. For all these reasons ceramic are particularly indicated for young patients with high demands.

Ceramic materials. There are four generations of medical Alumina ceramic used in the orthopaedic field, mainly produced by CeramTec (Germany), which is as the recognized manufacturer world leader company in the field of bioceramics for joint replacements [20]. In 1974 the first generation of Alumina, BIOLOX®, was introduced. The material was characterized by insufficient purity, low density and large grain size due to the long sintering process. That resulted in low mechanical strength and toughness, and early implant failures for breakage. A decade later, the BIOLOX® of 2nd generation was proposed: produced from an improved raw material, it was characterized by finer grains resulting in a better performance. A paramount advancement in Alumina properties occurred with the 3rd generation and the novel BIOLOX® forte. This material was manufactured combining the sintering with a hot isostatic pressing, which allowed to reduce grain size and to improve both mechanical strength and wear resistance. The better performance of this ceramic generation was due also to the following two factors: the replacement of mechanical engraving with laser marking for implant identification code, thus increasing the fracture load and the execution of proof tests on each implant before going into the market. The 4th generation of ceramic was launched in early 2000s with the alumina matrix BIOLOX® delta, made up of 82% Alumina, 17% Zirconia, 0.6% strontium oxide and 0.3% chromium oxide. The latter is responsible of the characteristic pink colour. This ceramic exhibited improved mechanical properties and clinical performance [23]. Its extremely high fracture toughness is due to two mechanisms depicted in Fig. 4: crack propagation is prevented both by Zirconia particles, which act like crack arresters and absorb impact energy, and platelet-like crystals of strontium oxide, which dissipate energy by deflecting the crack. Also hardness and wear resistance are improved by chromium oxide. Thanks to these performing properties, new designs, such as bigger implants, could be explored [5]. The mechanical-chemical properties of the four ceramic generations are compared in Table 2.



(a) (b)

Fig. 4 Mechanisms responsible of the high fracture toughness of BIOLOX® delta. (a) Zirconia particles prevent crack propagation by absorbing impact energy. (b) platelet-like crystals of strontium oxide deflecting the crack. Adapted from [20].

PROPERTIES	1° GEN BIOLOX®	2° GEN BIOLOX®	3° GEN BIOLOX® FORTE	4° GEN BIOLOX® DELTA
Al_2O_3 (%)	99.7	--	> 99.8	81.6
ZrO_2 (%)	na	--	na	17
Other oxides (%)	Rest	--	Rest	1.4
Density (g/cm^3)	3.95	3.96	3.97	4.37
Grain size of Al_2O_3 (µm)	4	<3.2	1.75	0.56
Young's module (GPa)	410	--	407	358
Fracture toughness (MPa m$^{0.5}$)	3	3	3.2	6.5
Wear Volume (mm^3/Mc) 0-1 Mc	5	1	0.8	0.45
Wear Volume (mm^3/Mc) 1-5 Mc	1.1	0.5	0.5	0.25

Table 2 Comparison of the mechanical and physical properties of the four generations of Alumina produced by Ceramtec, data from [20].

Implant fracture. One of the most discussed concerns about ceramic implants is their brittleness and consequent breakage. The early generations of CoC implants reported high failure rates due to fracture. Nevertheless this problem seems to be solved with the modern CoC thanks to the significant improvement in the mechanical properties commented above (Table 2). This is supported by many studies; in particular [24] reports a fracture rate decreasing from 0.026%, through 0.014% to 0.004%, going through the first three generations of Alumina ceramic. Consequently, though a risk concern is still pertinent, ceramic implant breakage is very rare. When it happens, fatigue and impact are recognized as the main causes of failure. In particular, fatigue fracture can be due to a mismatch in the coupling with a tapered stem and neck-to-rim impingement in head and cup, respectively. Impact fractures are related to surgical aspects such as a strong impact on the head during its positioning and a misalignment between the cup and metal back. Revision of failed CoC implants can be a hard issue [25]. Indeed ceramic debris remaining in the peri-prosthetic fluid, can cause dangerous third body wear because of their hardness. Consequently, it is suggested to avoid the use of MoP and MoM implants in the revision, whilst CoC implants are extremely recommended.

Edge-loading and squeaking. Rather than brittleness, edge loading and squeaking are considered the actual main drawbacks of ceramic implants. The edge loading consists in the contact between the head and the cup rim which causes high local stress concentration and lubricant disruption, finally leading to surface damage and stripe wear. The latter, often observed in retrieved components, appears as dark narrow regions in the superior quadrant of the head and correspondent areas of the cup edge, as portrayed in Fig. 5.

Edge loading was firstly associated to the implant malpositioning, i.e. steep cup inclinations (i.e. angles higher than 45°), due both to surgical procedure and loose cup migration. Later, as stripe wear was reported also in well fixed and positioned bearings, other hypotheses were formulated. On one hand, it was postulated that, because of soft tissue laxity caused by arthroplasty, head/cup microseparation can occur during the walking swing phase, followed, at the heel strike, by the head impact onto the cup edge [26]. Other studies support the edge loading would occur during the deep flexion, being induced by head subluxation, posteriorly [27]. In some cases edge loading occurs with neck-to-rim impingement, as proved by characteristics stripe wear areas in the exterior surface of the cup rim, at the opposite side to edge loading marks, as indicated in Fig. 5. Such a condition, can cause an increase in the wear rate, up to one order of magnitude [28,29], which however is still significantly lower than values observed in other bearing materials.

The phenomenon of the edge loading is strictly related to the squeaking, which consists in an audible sound occuring during motion. Squeaking is typically observed in CoC implants [30], even if some cases have been reported also for MoM bearings. The incidence of the squeaking depends on its definition and thus varies in the range 1-21% [30]. Basically, benign and problematic squeaking are distinguished: in the former case, the sound occurs only with specific motions, such as deep flexion, and the implant funcionality is intact; in the latter case, the sound is intrusive and not tolerated by the patient who also report pain and disability. Though, the squeaking rarely leads to implant revision. For instance, a meta-analysis on 16828 CoC implants showed an incidence of squeaking and revision for squeaking of 4.2% and 0.2%, respectively [31].

The origin of the squeaking is still to be fully understood. However, experimental findings suggest that it can be caused by a combination of factors including patient characteristics, implant features (e.g. neck/stem design) and surgical outcomes (cup inclination, hence edge-loading and impingement). For instance, squeaking seems more frequent in young patients particularly demanding because of their weight of their activity level.

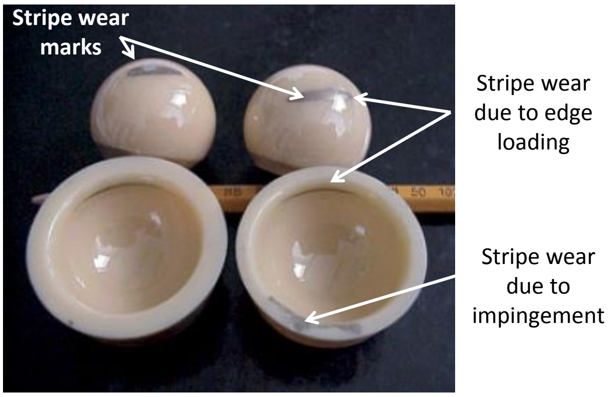


Fig. 5 Typical stripe wear observed in CoC implants, caused by edge loading and impingement. Adapted from [20].

Novel solutions for ceramic implants

Hybrid hard-on-hard coupling. The hybrid coupling composed by a ceramic head and a metallic insert (ceramic-on-metal, CoM) was proposed in the last decade [32] to the purpose of overcoming MoM and CoC limits, i.e. metal ion release and ceramic insert fracture. Recent studies have demonstrated that CoM bearings, with a BIOLOX Delta head and a CoCrMo alloy liner, undergo reduced in-vitro wear compared to MoM bearings, under both standard and adverse conditions, such as edge loading condition [33]. However, hybrid replacements are actually in limited use, as reported [7] (Fig. 2).

Metal-bulk head resurfaced by a ceramic-layer. In order to combine the strength and toughness of metallic materials, with the bio-inertness and low wear of ceramics, bio-ceramic coatings of metallic components might be a key answer. Unfortunately, such an approach is still under investigation for hip joints, mainly because of the following issues: the complex design of a strong metallic/ceramic interface that typically develops unwanted residual stresses of thermal nature; the effect of the metallic surface on the stoichiometry of the ceramic layer, e.g. the ions diffusion from the metallic to the ceramic side, which can enhance the residual stresses [34]. Recently, a novel solution has been proposed that consists in a metallic-bulk head, whose surface naturally undergoes to an oxidative process, leading to a ceramic surface layer. The latter differs from a coating as it is naturally developed and integrated with the metallic bulk, and it minimizes the typical problems at the ceramic/metal interface [34]. This type of femoral head was introduced in the market in 2003 as Oxinium®, and is characterized by a metal bulk in Zirconium alloy and a surface ceramic oxide layer, as shown in Fig. 6. Originally, it could be used with liners and cups of different materials, both hard and soft. Unfortunately the hard-on-hard option with metal liner has been recently recalled because of high failure rates [35]. Consequently, although the research direction towards ceramicised metallic surface is considered winning, further investigations are required.

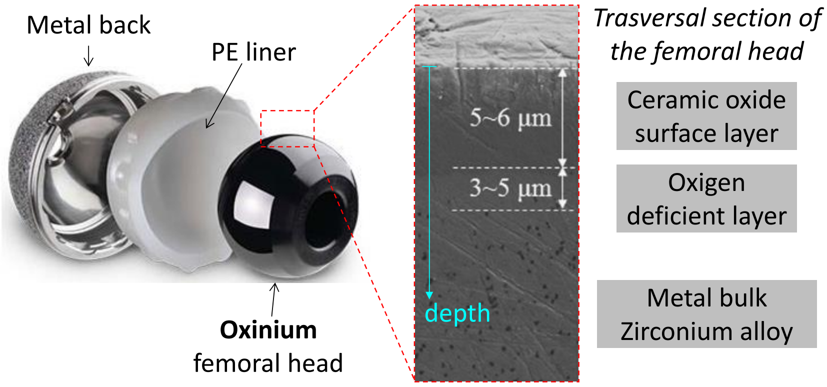


Fig. 6 Oxinium® femoral head, characterized by a metal bulk and ceramicised surface, provides wear resistance without brittleness. Adapted from [34].

Non-oxide ceramics for resurfacing ceramic implants. A further research direction consists in investigating new ceramics with higher mechanical strength and toughness which would allow new designs, and in particular ceramic resurfacing implants recommended for young active patients. Silicone nitride ceramics, belonging to the non oxide ceramic grades, are known to have improved mechanical features compared to the Alumina-based ceramics. Moreover, some recent studies have proved their chemical stability, wear resistance and, mostly, cytocompatibility [36]. Consequently, silicone nitride ceramics have been suggested to be employed in CoC resurfacing implants [37].

Conclusions

The present paper depicts a brief overview of hip implants from a tribological perspective, with particular attention to ceramic couplings. The evolution of material and geometrical features is described on the basis of lubrication and wear performances, which are the main concerns of these devices. Actually, lubrication and wear are strictly interconnected, so that improving the lubrication regime also reduces wear loss. For this reason, the trend is towards more conformal large head implants, so that the standard 28 mm head diameter is now replaced by 32/36 mm size.

Nowadays, many material couplings are available for hip joint prosthesis, differing both in mechanical and tribological behaviour, and biocompatibility. However, a general trend is fairly recognized: while MoP coupling still remains the most widespread solution, in the last years a remarkable increase of CoC implants has been noticed mainly due to improvements in ceramic materials. Indeed, ceramics are highly biocompatible and show the lowest wear rate, and thus are suitable to young and active patients, whose number is extremely increasing in the last decade. In fact, according to [7], about 20% of people undergoing primary hip replacements has less than 60 years. The expected life of an implant can be in the range of 15-20 years, but follow ups at such time interval are not yet available for the new implants/materials. One recent study [38] reports satisfactory results for 94 hip replacements (head diameter 36 mm), for an average of 6.5 years follow up, without any complications such as squeaking or fracture. However, one of the main drawbacks of CoC articulations remains their high cost, so that hybrid solution as CoP might be considered as a valuable alternative, offering similar tribological performances [39].

Ongoing research activities are focused on the development of new materials (e.g. non oxide ceramics) and design solutions (e.g. ceramic resurfacing) aimed at optimizing the tribological performance of hip implants. Furthermore, many studies are devoted to identify the most suitable in-vitro tests able to reproduce in-vivo conditions and to offer more reliable predictions. Also numerical tools are under remarkable development, since they can reduce the need/number of experimental tests which are time consuming and expensive.

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