Third-body Wear Damage Produced in CoCr Surfaces by Hydroxyapatite and Alumina Ceramic Debris: A 10-cycle Metal-on-Metal Simulator Study

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Abstract

Ceramic particles are believed to be particularly abrasive due to their extreme hardness. Ceramic debris has been reported in retrieved total hip arthroplasty (THA) due to chipping and fracture of alumina components or by flaking of hydroxyapatite from implant coatings. However there appears to be no abrasion ranking of such particle behavior. The hypotheses in this study were, i) alumina particles would create large scratches in CoCr surfaces and ii) hydroxyapatite would produce very mild scratching comparable to bone-cement particles. Hydroxyapatite beads came in two types of commercial powders while the flakes were scraped from retrieved femoral stems. Alumina beads came in two commercial powders and flakes were retrieved from a fractured ceramic head. Particle morphologies were determined by SEM and CoCr surface damage by interferometry and SEM. Six 38-mm MOM were mounted inverted in a hip simulator and run with ceramic particles inserted for a 10-second test. Surface-roughness ranking after 10-second abrasion test revealed that bone cement and hydroxyapatite produced least damage to CoCr surfaces while alumina produced the most. Alumina increased surface roughness 19-fold greater than either hydroxyapatite or bone-cement particles. The alumina debris produced numerous scratches typically 20-80 μm wide with some up to 140 μm wide. Surprisingly the alumina beads and flakes were pulverized within the 10-second test interval and remained adherent to the CoCr surfaces. Additionally, the hydroxyapatite although also a ceramic had no more effect on CoCr than the bone-cement debris. Use of well-characterized and commercially available alumina and hydroxyapatite powders appeared advantageous for abrasion tests. These new data indicated that such ceramic powders have merit.

Keywords: ceramic hydroxyapatite alumina debris CoCr, 3rd-body abrasive wear, MOM hip arthroplasty, simulator

Level of Evidence: AAOS Therapeutic Level III

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Introduction

There are many risks in total hip arthroplasty (THA) that may trigger adverse wear, including; impingement, [1,2] subluxation, [3,4] dislocation, [5,6] “edge wear”, [7-9] and micro-separation. [10-12] Unfortunately there is little understanding with regard to which patients may be at risk [5,6,13-21] and uncertainty as to which events may trigger a major particle release. [22,23] Acetabular cups combined with metal and ceramic liners may incur additional risks due to, (a) the cup rim plastically deforming the femoral head, [24] (b) 3rd-body abrasion created by liberated metal particles, [25,26] and (c) smearing of metal alloy contaminants onto CoCr bearings. [6,27] There are also varying opinions on how hard a particle has to be to damage metallic bearings (Fig.1). These data are important for understanding material interactions between hard particles, [28,29] designing laboratory wear studies, [30-34] and understanding the implications of 3rd-body wear in vivo. [3,12,25,26,35]

Abrasion models have included a) particles inserted between bearing surfaces, [29,30] b) particles added to lubricants to produce abrasive slurries, [31,32,34,36-38] and c) mathematical modeling of debris interactions. [28,29] A MOM simulator study introduced titanium (Ti) particulates [30] that dramatically increased wear rates. Another study used a high concentration of hydroxyapatite powder (HA) in the test lubricant but this had no measurable effect on MOM wear. [31] Our prior simulator study contrasted abrasion potential of large particles of CoCr and Ti6Al4V versus bone-cement flakes (PMMA) in a 10-second simulator test. [39] The large PMMA particles had no visible effect on CoCr surfaces whereas the metal debris increased surface roughness by approximately 20-fold. The resulting scratch profiles ranging 20-108 μm wide and 0.5-2.8 μm deep. The scratch aspect ratio (Fig. 2) averaged 0.3, indicating that the large metal particles had plastically deformed to create wide but shallow scratches in CoCr surfaces. Such abrasion tracks appeared identical to those reported on retrieved MOM bearings. [25] Ti6Al4V particles produced abrasion tracks similar to CoCr particles but also clearly demonstrated an ability to fragment and adhere to CoCr surfaces. [39] Such varied debris interactions in MOM bearings illustrated that we have little understanding of the life history of debris that circulates in the human hip joint.

The aim of this study was to characterize 3rd-body abrasion effects of ceramic particulates in MOM bearings. Ceramic debris has been reported in retrieved THA, either from implant coatings such as hydroxyapatite [40-46] or following chipping or fracture of alumina compo-

Figure 1. Ranking of material hardness for bone cement, metal alloys and ceramics.

nents. [47-50] However there appears to be no ranking of ceramic particles in hip simulator models. Our two hypotheses in this study were that i) alumina particles would plow into CoCr surfaces creating scratches > 40 μm wide, comparable to damage created by large CoCr particles [39], and ii) hydroxyapatite particles would produce very mild scratching on CoCr surfaces, comparable to the results with PMMA particles. [39,51]

Methods

Hydroxyapatite particles for our study were provided in powder form by two orthopedic vendors (Table 1). The flakes were scraped from retrieved Ti6Al4V femoral stems archived in the DARF Center. A ceramic vendor provided two alumina powders and we retrieved alumina flakes from a THA case that featured a fractured ceramic head. Size and shape distributions were determined by scanning electron microscopy (SEM: EVO MA15; Zeiss, Thornwood, NY). Energy dispersive x-ray imaging was used to characterize material types and to detect contaminants (EDS: X-flash detector 4010, Bruker AXS, Madison, WI). Particle numbers per 5mg allotments were determined mathematically using volume approximations and material densities (Table 1). Control data (PMMA and CoCr particles) were taken from a prior simulator study run under identical conditions.

The six 38-mm MOM bearings were wrought high-carbon, CoCr alloy, identical to those used in the prior study (DJO Global Company, Austin, TX). [39] Cups were mounted inverted in an orbital hip simulator (Shore Western Manufacturing, Monrovia, CA). [39,52] The simulator

Particle type	Range (dia)	Average (dia)	Ratio	Particle model (#)
HA powder-2	5-55	21	0.17	370,000
HA flakes	10-65	23	0.19	NA
HA powder-1	5-60	26	0.21	189,700
Al ₂ O ₃ powder-1	5-80	33	0.27	65,600
Al ₂ O ₃ powder-2	5-170	48	0.39	22,300
Al ₂ O ₃ flakes	5-330	87	0.71	3,600
CoCr control	45-180	103	0.84	900
PMMA control	30-250	122	1.00	6,800

Table 1. Ceramic particles ranked in order of size and compared to PMMA and CoCr controls

test mode used dynamic loading of 0.3–3 kN for 10 simulator cycles (10-second test). Cleaning protocols were same as previous study. Only the femoral heads were characterized for roughness using white-light interferometry (WLI; NewView 600; Zygo, Middlefield, CT). Head roughness was compared using standard indices (Ra, PV) with 12 fields measured at each site. SEM and EDS imaging were used to study surface topography and detect contaminating elements. Surface scratches were characterized by their cross-sectional profiles (N=12 per site), noting widths and overall depth (Fig. 2: W, Z). Data analysis was performed by statistical review using one-way ANOVA and Dunn's multiple comparisons.

Fig2 Scratch Profile TH16

Figure 2. Profile showing scratch width (W) and depth. For field data on scratch depths, roughness assessment used the peak-to-valley parameter (PV) while profiles of individual scratches provided measurement-Z. The aspect-ratio comparisons used PV/W and Z/W.

Results

Size range of the ceramic particles averaged smaller than either PMMA or CoCr controls (Fig. 3). Both types of HA powders presented spherical beads of size range 5–65 μm (Figs. 4a, b). The beaded morphology of alumina powder-1 (Fig. 5a: 5–80 μm) appeared quite similar to the

HA powders whereas alumina powder-2 contained more irregular globular shapes with double the size range (Fig. 5b). The particles collected from a retrieved ceramic case ranged still greater in size with some irregular fragments

Figure 3. Ranking of particle sizes by equivalent circle diameter (ECD).

A) Beads in hydroxyapatite powder-1

B) Beads in hydroxyapatite powder-2

Figure 5. SEM imaging of alumina particles, (A) alumina powder-1, (B) alumina powder-2, (C) low magnification of alumina fragments, and (D) alumina fragments of size 500–900 μm .

(Figs. 5c) having with well-defined edges (Fig. 5d).

Surface-roughness ranking after the 10-second abrasion test revealed that bone cement and hydroxyapatite ceramics produced least damage on CoCr surfaces while the alu-

Debris	Ra (nm)	Ra ratio	PV (nm)	PV ratio
PMMA control	11 (7-19)	1.0	340 (131-725)	1.0
HA powder-1	14 (10-20)	1.3	362 (256-453)	1.1
HA powder-2	17 (9-30)	1.5	551 (244-994)	1.6
HA flakes	54 (34-89)	4.9	1287 (613-1805)	3.8
CoCr control	203 (38-628)	19	2003 (823-3721)	5.9
Al ₂ O ₃ powder-1	365 (143-630)	33	2720 (1378-4278)	8
Al ₂ O ₃ powder-2	475 (236-870)	43	3291 (1971-4635)	10
Al ₂ O ₃ flakes	532 (127-1234)	48	5897 (3199-8034)	17

Table 2: Roughness indices measured on CoCr surfaces

mina ceramics produced most (Table 2: Ra). Hydroxyapatite and bone-cement particles provided minimal damage to CoCr surfaces, average (Ra) indices being typically less than 0.01 μ m (Fig. 6). The hydroxyapatite flakes created

Figure 6. Ranking of CoCr surface damage (Ra: average roughness parameter) produced by particle types.

5-fold greater roughness than PMMA particles. Although suspected, particle imaging by SEM and EDS did not identify any metal contaminants (Ti, Al, V). Alumina and CoCr particles raised surface roughness to greater than 0.2 μ m on average (Ra), 19-fold greater than produced by bone-cement particles. Maximum peak-to-valley roughness indices (PV) provided similar damage ranking but with higher magnitudes (Fig. 7).

Figure 7. Ranking of CoCr surface damage (PV: peak-to-valley parameter) produced by particle types.

SEM imaging after 10-seconds of abrasive wear with hydroxyapatite particles revealed CoCr surfaces that were typically featureless (background scratches $\pm 0.1 \mu$ m) with an occasional scratch 0.25 μ m deep in some fields of view (Fig. 8). In contrast alumina beads produced numerous scratches typically 20-80 μ m wide (Figs. 9a, b) with occasional scratches up to 140 μ m wide by 3 μ m deep (Figs. 9c, d). These scratches averaged aspect ratios of 0.03. Thus a 50 μ m wide scratch would typically have 1.5 μ m depth in the CoCr surface (Table 3). Equally conspicuous were 100-500 μ m size areas of surface contamination. These as verified by EDS were layers of pulverized alumina particles, ranging 1.2-1.9 μ m thick on CoCr surfaces. Alumina flakes produced the greatest surface damage, with numerous large scratches 80 – 100 μ m wide surrounded by numerous pits (Fig. 10). There was also abundant evidence of pulverized alumina layers, typically adjacent to the larger scratches (Fig. 10b).

Sampling of individual scratches to characterize width

Figure 8. SEM and Zygo imaging of CoCr surface scratched during hydroxyapatite test, (A) surface scratch, (B) oblique image of scratched surface, and (C) profile of surface scratches.

Figure 9 SEM and Zygo imaging of CoCr surface scratched during alumina bead test, (A) SEM image of 20-200µm size plaques of alumina contamination, (B) 80µm wide scratch with 20-200µm size plaques of alumina contamination, (C) oblique Zygo image of scratched CoCr surface, and (D) large scratch profile.

Figure 10. SEM imaging of CoCr surface scratched during alumina flake test, (A) 100µm wide scratch in pitted surface and (B) 30µm and 80µm wide scratches surrounded by plaques of alumina contamination (numbered 1-8).

Measure-ments	Debris	Lip width (W µm)	Scratch depth (PV µm)	Aspect ratio (PV/W)
N=24	PMMA control	8 (3-23)	0.12 (0.04-0.32)	0.02
N=12	HA powder-1	3 (2-5)	0.16 (0.13-0.20)	0.05
N=12	HA powder-2	4 (2-6)	0.18 (0.06-0.28)	0.04
N=12	HA flakes	12 (5-28)	0.73 (0.14-1.37)	0.06
N=24	CoCr control	54 (26-108)	1.44 (0.48-2.62)	0.03
N=12	Al ₂ O ₃ powder-1	59 (16-92)	1.59 (0.67-2.17)	0.03
N=12	Al ₂ O ₃ powder-2	75 (39-134)	1.99 (0.64-3.6)	0.03
N=18	Al ₂ O ₃ flakes	54 (13-98)	4.97 (1.58-11.21)	0.09

Table 3: Profile measurements of scratches in surfaces of CoCr heads.

and depth (Fig. 2. W, Z) revealed virtually the same ranking as the roughness indices provided by the interferometry assessment (Ra, PV). Scratch widths produced by bone cement and hydroxyapatite particles were the smallest and those produced by CoCr and alumina particles were the largest (Fig. 11). Similarly with scratch depths, bone cement and hydroxyapatite particles produced the shallowest scratches while CoCr and alumina particles produced the deepest damage (Fig. 12). Aspect ratio of profiled scratches (Fig. 2: ratio Z/W) produced by alumina and CoCr beads averaged 0.03. The alumina flakes were noticeably different from the rest of the particles, producing a higher aspect ratio averaging 0.09 (Table 3).

Figure 11. Ranking of scratch widths (W) profiled individually at selected damage sites.

Figure 12. Ranking of scratch depths (Z) profiled individually at selected damage sites.

Discussion

The risk of alumina particles scratching CoCr surfaces was clearly an anticipatable result. The new evidence was that such scratches typically had an aspect ratio averaging 0.03, duplicating that created by metal particles. [39]. This conformity in surface damage supported our first hypothesis. The SEM data indicated that alumina beads typically 30-50µm in size were flattened massively within a 10-second test to produce 1-2µm thick ceramic layers on CoCr femoral heads. The larger alumina flakes reacted similarly, but with scratches having a somewhat higher aspect ratio (0.09). SEM imaging of these wide but shallow scratches indicated they were made by compressed plaques of alumina plowing across CoCr surfaces (Fig. 9). These data further illustrated the complexity of abrasion studies. The interaction of hip joint motion and applied contact stresses is a dynamic process that induces unpredictable fragmentation and wear mechanisms to circulating particles, even in alumina as the hardest biomaterial (Fig. 1). Thus the interaction of bearing type and debris compressive-strength adds additional complexity.

The hydroxyapatite beads did not damage CoCr surfaces due to a combination of low compressive-strength and hardness. This was not due to particle size or shape because a similar beaded morphology in alumina powder-1 produced dramatic CoCr scratches. This surprising result for hydroxyapatite particle revealed that this ceramic had no more effect than the large plastic particles that comprise bone cement. This result was in accordance with MOM simulator wear data. Liao et al (2010) ran a 5-million cycle study using a high concentration of hydroxyapatite particles and found no adverse effects. [31] Similarly it has been suggested that some commercial bone cements may be abrasive because they contain barium sulphate (BaSO₄) or zirconia ceramic (ZrO₂), such micron-size additives having three times the hardness of CoCr (Fig.1). [55,56] Nevertheless several MPE simulator studies demonstrated that bone cement does not damage CoCr surfaces. [34,36,37,57] We used a bone-cement slurry as the lubricant in a MOM simulator study and similarly found no adverse effect. [52] Therefore, these ceramic supported our second hypothesis, that hydroxyapatite debris would be no more damaging to CoCr surfaces than bone cement.

Prior abrasion models have primarily used metal-on-polyethylene (MPE) bearings. [13,36] Clinical studies indicated that, following revision of a fractured bearing, retained alumina debris could produce adverse wear of MPE. [54] Retrieval studies also indicated hydroxyapatite debris liberated from implant surfaces may accelerate polyethylene wear. [43,44] However, use of MPE bearings in this

3rd-body wear study would have added additional complexity, the soft polyethylene surface allowing the particles to imbed in an unpredictable manner. Thus, use of MOM hip joints simplified the task of ranking ceramic damage to CoCr surfaces. Such laboratory models are further challenging due to uncertainties regarding choice of particulate morphology, dosage, and test methods. The major limitation in this study was that use of commercial ceramic powders lacked clinical relevance. It may be argued that the hydroxyapatite beads in powders-1 and 2 differed in chemical and physical composition from hydroxyapatite particles released from implanted prostheses. It was also possible that the hydroxyapatite flakes scraped from the two retrieved femoral stems were contaminated by metal particles. This was not detected in samples scrutinized by SEM/EDS but could not be ruled out for debris allotments used in the simulator studies. A further limitation in this study was that the fields of study could not be precisely duplicated between microscopic mapping with SEM and by interferometry. Thus quantitative results were presented only by the latter method.

Use of well-characterized and commercially available alumina and hydroxyapatite powders would appear advantageous in development of standardized abrasion tests. This 10-second simulator test established that alumina powders and fracture flakes damaged CoCr surfaces equally, indicating that such ceramic powders represent a valid test model. This may also be true for hydroxyapatite powders and flakes. However the evidence in this study was not considered conclusive.

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Disclosure Statement

One or more of our authors have disclosed information that may present potential for conflict of interest with this work. For full disclosures refer to last page of this journal.

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