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Thin Hard Crest on the Edge of Ceramic Acetabular Liners Accelerates Wear in Edge Loading

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Abstract

Ceramic acetabular liners may exhibit a small, sharp crest - an artifact of discontinuous machining steps - at the junction between the concave spherical surface and the interior edge. On three ceramic liners, this crest was found to form a 9–11° deviation from tangency. Edge loading wear tests were conducted directly on this crest and on a smoother region of the edge. The crest elicited 2–15 times greater volumetric wear on the femoral head. The propensity of the crest to rapidly (<2000 wear cycles) cause elevated wear under low contact force (200 N) suggests that the crest artifact of prevailing machining protocols might be a root cause of stripe wear and squeaking in ceramic acetabular bearings.

Introduction

The manufacturing process commonly employed to machine the inner surfaces of hard acetabular liners suffers a possible shortcoming that may be a root cause of some clinically observed wear modes. The inner surfaces typically comprise a concave sphere (the *ID*) and a convex *edge* that forms a transition between the ID and the liner's face. Commonly, these surfaces are machined in separate, discontinuous steps, and it is difficult to merge these steps to create a smooth and tangent junction where the ID and edge meet. Consequently, the liner may exhibit a small but distinct artifact - a "crest" - where the ID and edge surfaces meet [1].

The femoral head may sublux (or "piston") out of the liner during common activities [2]. Such motion leads to edge loading, with the head bearing upon the liner's edge rather than the ID. In hip simulator wear tests, motion patterns including small subluxation to induce edge loading have elicited greater wear rates than ordinary motion patterns having only ideal, fully reduced head-liner contact [3]. The increased wear from edge loading has been explained as resulting from non-conforming contact that induces elevated contact stresses that increase surface damage [1]. Ceramic-on-ceramic hips may commence squeaking after

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several months of noise-free service [4]. Such squeaking has been linked to wear damage by retrieval analysis [4] and by laboratory wear tests [5].

Since edge loading in general causes elevated contact stresses, we hypothesized that edge loading on a distinct, sharp feature located upon the edge would have particularly damaging effects. This study reports the results of a wear test that isolated the damaging effects of the crest artifact by comparing the wear from small sliding across the crest with wear from small sliding across a smoother region of the liner's edge.

Materials and Methods

Three ceramic liners were examined: a Ø36 mm alumina matrix composite (AMC, BioloX Delta), a Ø36 mm aluminum oxide (Al₂O₃, BioloX Forte), and a Ø28 mm Al₂O₃ (all: Ceramtec, Germany). On each, the crest was palpable by dragging a fingernail across the ID-edge junction, or by lightly rubbing a femoral head across the same. Each liner's crest was measured with a stylus profilometer (SJ401, Mitutoyo, Japan) by tracing a 2.5 mm long profile across the ID-edge junction.

The wear test was designed to create edge loading with short distance sliding contact. The tests were conducted using custom fixtures in a fatigue test machine. The fixtures included a horizontal spring that pressed the equator of the femoral head into the liner's edge with a 200 N force. For a crest trial, the initial head-liner contact point was directly on the crest, and for a smooth trial, the contact point was on a smooth portion of the edge ~1 mm above the crest. Each liner was paired with a head of the same size and material. The liner was reciprocated vertically (*i.e.*, along the test machine's axis) by ±0.5 mm at 1 Hz for 2000 cycles, while the head could pivot on a swing arm to maintain edge contact. The 2000 cycle endpoint was sufficient to elicit measurable roughening on the femoral head. The contact point was lubricated by a drip feed of 50% diluted bovine serum. The dimensions of the femoral head wear scar were measured using a stereo-microscope. The volumetric wear was quantified using an optical surface profilometer (NewView, Zygo Corp., CT); further details are given in the following section.

Results

The stylus profilometer traces (Fig. 1) show the crest on each liner. The angle at the crest was measured graphically and scaled appropriately to quantify the crest's "sharpness". Table 1 provides the dimensional and volumetric wear results. Each trial produced a plainly visible wear scar on the femoral head. The optical surface profile scans of the smooth trial wear scars were 1.5×1.5 mm; 3.0×1.5 mm scans were used for the crest trial scars, yet even these wider scans left some of the scar width outside of the scanned area (*cf.* Table 1). Figure 2 compares these measurements from the Ø28 Al₂O₃ wear scars. These 3D surface models come from subtracting the original scanned surface data from a sphere best-fit to the unworn portion. In the resulting data, the unworn portion appears approximately as a plane, and the worn portion appears as surfaces in relief. The volumetric wear was numerically computed as the volume contained between the relief surfaces and the mean plane through the unworn portion.

Discussion

If the ID-edge junction were ideally smooth and tangent (*i.e.* without a crest), then head-liner contact at the crest's present location would be more conforming than at the smooth location; hence, the test would be expected to cause lower contact stress and less wear at the crest location. Since the opposite occurred – the crest trials produced 2–15 times greater

wear volume than the smooth trials – it appears that the crest itself was responsible for the increased wear.

The initial contact positions in the smooth and crest trials were associated with head-liner separations of 4.7 and 2.0 mm, respectively, for the Ø36 pairs. Although 4.7 mm is beyond the typical range of in-vivo measured subluxations, 2.0 mm is within the reported range. Subluxation as small as 0.08 mm can instigate edge loading [6]. Since the crest is the first edge feature that a subluxing head would contact beyond the ID, in-vivo subluxation in the range 0.08 - 2 mm would likely result in crest loading such as that examined in this study.

Little is yet known about the magnitude of head-liner contact forces during subluxation events. Even so, the 200 N contact force used in this study appears to be low compared with that applied (500 N) in micro-lateralization simulator tests [7]. The onset of crest-incited wear in <2000 cycles in the present study has implications for longer term damage. Early post-operative generation of ceramic wear debris from crest loading damage could lead to 3rd-body wear conditions at the head-ID interface. This may partly explain a 1–2 yr. post-operative onset of ceramic hip squeaking [4].

Since edge loading can occur even with minute subluxation, the liner's bearing surface should be regarded holistically as including *all* of the inner surfaces. To enhance wear resistance, manufacturers should implement smooth, tangent junctions between all adjoining geometric segments of this whole bearing surface. Surgeons should anticipate that edge loading may occur and should implement techniques such as proper joint tensioning and prosthesis alignment to minimize its occurrence and magnitude.

Acknowledgments

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Fig. 1. Profilometer traces encompassing each liner's ID and edge, with the crest at the junction. The profile height is exaggerated by the differing horizontal and vertical scales; the stated angles are suitably scaled values.

Fig. 2. Worn surfaces on Ø28 Al₂O₃ head: a) Smooth trial, b) Crest trial. The spherical form has been removed, so the wear volume appears as the region in relief to a plane. The depth scale is magnified to emphasize the surface texture; actual peak depths are approximately 1.3 µm in a) and 3.5 µm in b).

Table 1

Femoral head wear scar measurements

Bearing	Volume (mm ³)		Height×width (mm)	
	Smooth	Crest	Smooth	Crest
Ø36 AMC	0.087×10 ⁻³	1.362×10 ⁻³	0.90×1.79	1.11×4.17
Ø36 Al ₂ O ₃	0.235×10 ⁻³	0.527×10 ⁻³	0.87×1.43	1.05×2.71
Ø28 Al ₂ O ₃	0.338×10 ⁻³	5.080×10 ⁻³	0.90×1.41	1.00×3.70