3.5 Reducing Wear Using the Ceramic Surface on Oxidized Zirconium Heads

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Introduction

Wear-related complications remain a major cause of revisions following total hip arthroplasty. Oxide ceramic modular heads were introduced as an alternative to metallic cobalt-chromium (CoCr) heads because their surfaces are more abrasion-resistant and produce less friction, thereby reducing abrasive and adhesive wear of the opposing polyethylene[1]. The use of oxide ceramic heads can reduce wear by 25 to 50% [2-5]. Oxidized zirconium (OxZr) was introduced as a way to provide these advantages in wear performance without the risks associated with brittle fracture of monolithic ceramics[6]. Thermally driven oxygen diffusion transforms just the metallic zirconium alloy surface into a durable, stable, low-friction oxide[7-9]. Thus, OxZr provides the benefits of ceramic wear behavior along with the mechanical properties of metal[10, 11]. This study assessed the wear properties of OxZr and CoCr heads against highly crosslinked polyethylene (XPE) that was irradiated at 10 Mrad and melt-annealed, as well as non-crosslinked polyethylene (NPE) that was not irradiated.

Materials and Methods

The NPE and XPE acetabular liners (32 mm, Reflection™, Smith & Nephew) were made of GUR1050 ultra high molecular weight polyethylene (Poly-Hi Solidur, Ft. Wayne, IN) and terminally sterilized using ethylene oxide. Half of the OxZr (Oxinium®) and CoCr heads (32 mm, Smith & Nephew) were tested with smooth surfaces (out of the box) and the rest were pre-roughened by tumbling in alumina particles in order to simulate the abrasive conditions of some clincally retrieved heads[12-15]. Both R_a and R_{pm} were used to measure the surface roughness. The thickness of the OxZr ceramic surface was monitored periodically during testing. Two measurements were made at the apex of the head and four were made 45° from the apex using a Fourier Transform Infrared (FTIR) spectrometer (Nexus 470, Nicolet, Madison, WI).

Simulator testing was conducted on a 12 station physiological hip simulator (AMTI, Watertown, MA) at 1 Hz in 450 ml of 100% bovine serum per station. Three specimens were tested per condition with soak-controls for fluid absorption correction. All conditions were tested to at least 5 Mcycle, and the OxZr with XPE combinations were continued to 20 Mcycle. Loading curves alternated between ISO and Bergman every 0.1 Mcycle[16,17]. Gravimetric measurements of polyethylene wear were corrected for fluid absorption and then used to calculate linear rates of volumetric wear using the density of the ultra high molecular weight polyethylene (0.93 g/cm^3). The wear debris was characterized using techniques described previously[18]. Statistical significance was determined using analysis of variance.

Results

In comparison to the smooth heads (<0.04 μm R_a), the pre-roughened heads appeared hazy with multi-directional scratches. The measurements of R_a (0.17 ± 0.1 mm) and R_{pm} (2.6 ± 0.35 μm) on the roughened CoCr heads were similar to those of some retrieved heads [12-15]. They were also significantly greater ($p<0.01$) than the measurements of R_a (0.06 ± 0.01 μm) and R_{pm} (0.16 ± 0.03 μm) on the roughened OxZr heads.

For the XPE liners during the first 5 Mcycle of testing, the OxZr heads in both the smooth and roughened conditions produced no detectable volumetric wear. The CoCr heads produced no detectable XPE wear in the smooth condition, but roughened CoCr produced 15.4 ± 4.1 mm^3/Mcycle of XPE wear (Fig. 1).

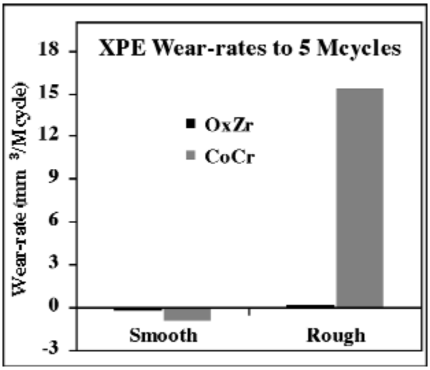

Figure 1:
Wear-rates of XPE articulating against OxZr and CoCr in both smooth and roughened conditions for a duration of 5 Mcycle.

Particle analysis of the XPE wear debris showed that significantly fewer particles ($p=0.03$) were produced by smooth OxZr heads (1.6 ± 0.8 million/cycle) than by smooth CoCr heads (2.2 ± 0.5 million/cycle). In the roughened condition, significantly fewer XPE particles ($p<0.01$) also were produced by OxZr (3.3 ± 1.2 million/cycle) than by CoCr (8.9 ± 3.3 million/cycle) heads (Fig. 2).

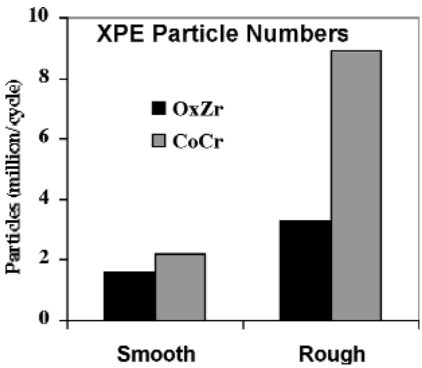

Figure 2:
Number of XPE particles generated when articulating against OxZr and CoCr in smooth and rough conditions for a duration of 5 Mcycle.

For the NPE liners during the first 5 Mcycle of testing, wear rates were significantly less ($p<0.01$) for smooth OxZr (21 ± 0.23 mm^3/Mcycle) than for smooth CoCr (38 ± 0.58 mm^3/Mcycle), and for roughened OxZr (30 ± 0.36 mm^3/Mcycle) than for roughened CoCr (76 ± 3.8 mm^3/Mcycle) heads (Fig. 3).

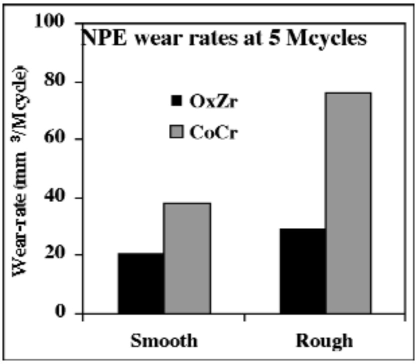

Figure 3:
Wear-rates of NPE articulating against OxZr and CoCr in both smooth and roughened conditions for a duration of 5 Mcycle.

Particle analysis of NPE wear debris showed that significantly fewer particles ($p \leq 0.01$) were produced by smooth OxZr (5.6 ± 0.6 million/cycle) than smooth CoCr (8.0 ± 1.2 million/cycle), and by roughened OxZr (5.8 ± 0.6 million/cycle) than roughened CoCr (10.5 ± 3.0 million/cycle) heads (Fig. 4).

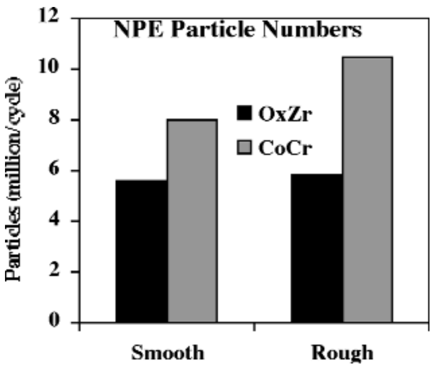

Figure 4:
Number of NPE particles generated when articulating against OxZr and CoCr in smooth and rough conditions for a duration of 5 Mcycle.

Tests with OxZr heads were continued on the simulator for another 15 Mcycle. The volumetric wear rate for XPE liners remained nondetectable with smooth OxZr heads, but by 20 Mcycle, the roughened OxZr heads produced a small amount (0.35 ± 0.04 mm^3/Mcycle) of XPE wear (Fig. 5).

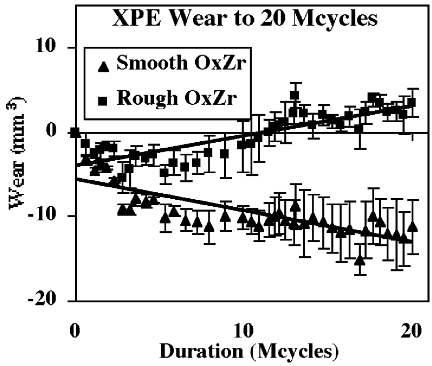

Figure 5:
Wear of XPE articulating against smooth and roughened OxZr heads for a duration of 20 Mcycle.

Measured changes in oxide thickness on the OxZr heads over the entire test duration were within the resolution of the FTIR technique, with linear regression indicating oxide wear rates of 0.0023 µm/Mcycle or less (Fig. 6).

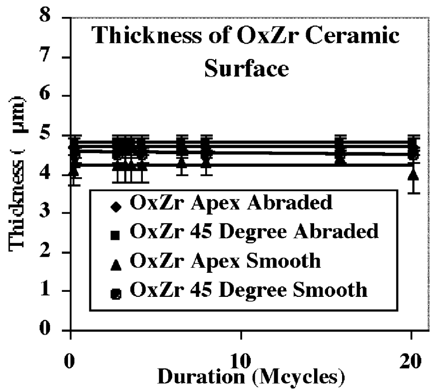

Figure 6:
OxZr ceramic surface thickness over 20 Mcycle of wear simulator testing.

Discussion

This study like previous studies has shown that XPE can provide substantial wear reductions compared to the performance of NPE [19, 20]. The volumetric wear reduction was significant when XPE was mated with a smooth CoCr surface; however, when the surface was roughened as is seen clinically with CoCr heads, the wear reduction was much less. Also important to note is that the roughened CoCr heads produced no statistical distinction (p=0.38) in the number of wear debris particles from the NPE and XPE liners. Conversely, the ceramic surface of the OxZr heads resisted roughening better than CoCr and helped maintain the superior XPE wear performance seen with smooth heads. This benefit also was demonstrated with NPE when mated with OxZr; volumetric wear rates were reduced by 45% and 61% when compared to CoCr under smooth and

Although volumetric wear of XPE couldn't be detected gravimetrically in some of these tests, it was clear that measurable wear debris was being produced. An estimation of XPE wear volume based on particle size and number was shown in a previous analysis to be approximately 1 mm^3/Mcycle for smooth CoCr heads[21]. Using this same technique for smooth OxZr heads at 5 Mcycle, the volumetric wear rate of XPE is estimated to be 0.4 mm^3/Mcycle. This indicates that OxZr produced approximately 60% less XPE wear than did CoCr. For smooth heads, it also indicates that XPE with OxZr produced about 98% less volumetric wear than was produced by NPE with CoCr.

Not only did the ceramic oxide surfaces of OxZr resist roughening better than the metallic surfaces of CoCr, but the loss of oxide thickness was negligible during the 20 Mcycle simulator tests even on the pre-roughened heads. This demonstrated the durability of the ceramic surface on the OxZr heads.

Conclusion

This study demonstrated the advantage of a low-friction and abrasion-resistant ceramic surface for articulation against polyethylene. Roughening the heads to a clinically relevant extent demonstrated that the durable oxide ceramic surfaces of OxZr heads can maintain the wear performance of crosslinked polyethylene better than the metallic surfaces of CoCr heads. These results suggest that the use of OxZr heads with XPE liners may contribute to reducing wear-related clincal complications.

References

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