Fabrication and Testing of Silicon Nitride Bearings in Total Hip Arthroplasty

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Abstract: Total hip arthroplasty (THA) bearings were fabricated from silicon nitride (Si_3N_4) powder. Mechanical testing showed that Si_3N_4 had improved fracture toughness and fracture strength over modern alumina (Al_2O_3) ceramic. When tested with Si_3N_4 cups in a hip simulator, both cobalt-chromium (CoCr) and Si_3N_4 femoral heads produced low wear rates that were comparable to Al_2O_3-Al_2O_3 bearings in THA. This study offers experimental support for a novel metal-ceramic THA bearing couple that combines the reliability of CoCr femoral heads with the wear advantages of ceramic surfaces. **Key words:** silicon nitride, total hip arthroplasty, wear rates, ceramics, fracture toughness.

Metal (cobalt-chromium [CoCr]) femoral heads are used widely in total hip arthroplasty (THA), usually with ultrahigh-molecular-weight or cross-linked polyethylene acetabular cups. The rationale for using ceramic femoral heads instead of CoCr is improved wear resistance; alumina (Al_2O_3) femoral heads decrease polyethylene wear in CoCr-polyethylene THA, and Al_2O_3-Al_2O_3 produces the lowest wear of any THA bearing [1-4].

Low wear is desirable because particulate wear in THA is linked to inflammation, periprosthetic bone loss, and premature implant loosening [5]. Early clinical data have shown less bone resorption in the proximal femur in Al_2O_3-Al_2O_3 THA compared to CoCr-polyethylene controls [6]. Several other clinical and laboratory data have shown that ceramic bearing surfaces can reduce wear in THA [5,7-10].

A concern with ceramic femoral heads is brittle catastrophic failure in vivo [11]. Improvements in the quality and manufacturing of Al_2O_3 have not eliminated this risk [12]. In the past, zirconia femoral heads were introduced as a stronger alternative to Al_2O_3, but zirconia can undergo phase transformation and weakening, leading to unpredictable outcomes in vivo [13]. Another strategy to reduce polyethylene wear is to modify the surface of zirconium alloy femoral heads [14]. This avoids brittle failure, but the wear reduction, surface hardness, and scratch resistance of oxidized zirconium are less favorable than Al_2O_3, and oxidized zirconium cannot be used in ceramic-ceramic articulations [15].

In this study, an alternative ceramic material was fabricated from silicon nitride (Si_3N_4) powder. Mechanical testing showed high-flexural strength, fracture toughness, Weibull modulus, and resistance to hydrothermal degradation. The Si_3N_4 cups

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produced low wear rates when tested with either CoCr or Si_3N_4 femoral heads. The purpose of this report is to describe the fabrication, material properties, and wear outcomes of Si_3N_4 THA bearings.

Experimental Procedures

Material Synthesis

The Si_3N_4 powder (average particle size, 0.5 μm), with 6 wt% yttrium oxide (Y_2O_3) and 4 wt% Al_2O_3 as liquid-phase sintering additives, was ball-milled for 18 hours in ethanol, using zirconium oxide (ZrO_2) balls as the milling media, to create a homogeneous mixture. After drying, the mixture was mechanically deagglomerated, followed by sieving and pressing in a stainless steel die (6 mm × 60 mm) at a pressure of 40 MPa to a height of 7 mm. The resulting material was cold isostatic pressed (207 MPa) to form the green-shaped article. Densification was achieved by sintering in nitrogen at atmospheric pressure at 1875°C for 30 minutes, followed by hot isostatic pressing in argon at 1775°C, at a pressure of 207 MPa for 2 hours. Acetabular inserts and femoral heads were made from near net-shaped Si_3N_4 blanks with this process; these were ground and polished to industry standards (Biomet, Warsaw, Ind).

Mechanical Properties

Weibull modulus and flexural strength were measured using standard 3-point bend test specimens (n = 6) according to ASTM C-1161 standards [16], using specimens 3 × 4 × 45 mm. Bending tests were done on test fixtures designed to minimize spurious stresses, with a nominal span of 40 mm. Bending loads were applied using a universal testing machine at a cross-head displacement speed of 0.5 mm/min.

Fracture toughness was measured using single-edge-notched beam (SENB) specimens according to ASTM-E399 standards [16]. Test bars measuring 2.5 × 5 × 25 mm were prepared, with notches of various depths. Notched specimens (n = 6) were tested in 3-point bending with a span length of 20 mm. The resultant fracture loads were converted to fracture toughness values using the ASTM-E399 protocol.

Simulated Material Aging

To rule out the possibility of material degradation that can occur with yttria-stabilized zirconia, Si_3N_4 specimens (n = 3) were placed in a surgical autoclave (250°F at a pressure of 1 atm) for 1, 5, 24, and 100 hours, respectively. The phase composition of Si_3N_4 autoclaved for 100 hours was compared to nonautoclaved controls using x-ray diffraction. The flexural strength of test specimens after autoclaving was measured as described above; mean and SDs were compared to control specimens.

Wear Properties

Calculated Contact Stresses. Wear reduction in THA is related, in part, to lower differential contact stresses between the mating surfaces of the bearing couple. Contact stresses between dissimilar bearing materials can be calculated by the Hertz equations below, which predict lower contact stress differentials for dissimilar materials with closely matched elastic modulii [17],

$$\sigma_0 = \frac{3P}{2\pi a^2} \tag{1}$$

$$a^3 = \frac{4}{3}\frac{k}{E_2}PR^* \tag{2}$$

$$\frac{k}{E_2} = \frac{9}{16}\left[\frac{1}{E_2}\left(1-\nu_2^2\right)+\frac{1}{E_1}\left(1-\nu_1^2\right)\right] \tag{3}$$

where σ_0 is the maximum Hertzian contact stress under an applied load of P; a is the contact circle; R^* is the composite radius of curvature for the 2 mating surfaces; and k/E_2 is the material parameter defined by the respective elastic modulii E_1 and E_2 and the respective Poisson's ratio ν_1 and ν_2 of the articulating surfaces.

Using published values for the elastic modulii (CoCr = 225 GPa; Si_3N_4 = 300 GPa; Al_2O_3 = 380 GPa) and Poisson's ratios (CoCr = 0.29; Si_3N_4 = 0.29; Al_2O_3 = 0.25) [18-20], the predicted Hertzian stresses for a 28-mm ball-socket bearing with a diametral clearance of 75 μm and a load of 8 kN are CoCr-CoCr = 288; CoCr-Si_3N_4 = 315; and CoCr-Al_2O_3 = 334 MPa. These calculations predict a 9% increase in contact stress for CoCr-Si_3N_4 over CoCr-CoCr vs a 16% increase in CoCr-Al_2O_3 over CoCr-CoCr. This information was the basis for testing both Si_3N_4-Si_3N_4 and Si_3N_4-CoCr couples in the hip simulator.

Hip Simulator Tests. The THA bearings (28-mm diameter) made of Si_3N_4 were fine ground and lapped to a mean R_a surface roughness value of less than 0.05 μm. Three Si_3N_4-Si_3N_4 and Si_3N_4-CoCr pairings were tested to 1 million cycles in a hip simulator using standard protocols [21,22]. In Si_3N_4-CoCr pairings, commercially available CoCr femoral heads (Biomet) were used with Si_3N_4 cups, with a diametral clearance between 100 and 200 μm.