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Alumina–tantalum composite for femoral head applications in total hip arthroplasty

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ABSTRACT

Dense composite laminates of alumina (Al_2O_3) and tantalum (Ta) were fabricated by hot pressing and tested *in vitro* for potential use as a femoral head material in total hip arthroplasty (THA). Al_2O_3–Ta composite laminates hot pressed at 1450 °C and 1650 °C had flexural strengths of 940 ± 180 MPa and 1090 ± 340 MPa, respectively, which were far larger than the values of 420 ± 140 MPa and 400 ± 130 MPa for Al_2O_3 hot pressed at 1450 °C and 1650 °C, respectively. The interfacial shear strength, determined by a double-notched specimen test, was 310 ± 80 MPa for the composite laminate hot pressed at 1650 °C, indicating strong interfacial bonding between Al_2O_3 and Ta. Scanning electron microscopy (SEM), energy dispersive X-ray (EDS) analysis, and X-ray mapping of polished sections of the hot-pressed laminates showed the presence of an interfacial region formed presumably by diffusion of O (at 1450 °C) or O and Al (1650 °C) from Al_2O_3 into Ta. Composite femoral heads of Al_2O_3 and Ta could combine the low wear of an Al_2O_3 articulating surface with the safety of a ductile metal femoral head.

1. Introduction

Total hip arthroplasty (THA) articulations consist of a femoral head (ball) rotating inside a hemispherical acetabular shell (socket). Typical bearing materials are cobalt–chromium alloy (CoCr) for the femoral head, and ultra-high molecular weight polyethylene (UHMWPE), for the socket. After 10–15 years *in vivo*, polyethylene wear particles lead to localized inflammation in the hip joint, periprosthetic bone resorption, and ultimately, aseptic loosening of the prosthetic components. Repeat hip surgery is morbid, risky, and costly. It accounts for about 25% of the nearly 250,000 THA operations performed annually in the U.S. and Europe [1].

Increased wear resistance of THA bearings can favorably impact implant durability. Crosslinking of polyethylene leads to better wear properties in polyethylene sockets [2–4]. Substituting Al_2O_3 femoral heads for CoCr also decreases wear [5,6]. Al_2O_3 heads can also be used with sockets of the same material. The resulting Al_2O_3–Al_2O_3 (hard-on-hard) articulations have the lowest wear of any THA bearing combination [7–9]. At intermediate follow-up, THA with Al_2O_3–Al_2O_3 articulations is associated with less femoral bone loss than THA with metal-on-polyethylene bearings [10]. Ceramic bearings contribute to the longevity of THA by dramatically reducing bearing wear, and, hence, the likelihood of revision (repeat) THA surgery [11,12].

Despite its wear advantage, Al_2O_3, like other ceramics, is brittle. Catastrophic failure of Al_2O_3 femoral heads *in vivo*, while rare, is a serious complication. The incidence of catastrophic failure *in vivo* is 1 in 5000–10,000 [13], and this risk has persisted during the last decade or so despite many improvements in Al_2O_3 starting materials, design, manufacturing, and quality control [14]. Another concern with Al_2O_3–Al_2O_3 hip articulations is audible noise or squeaking [15,16], which has an overall occurrence in the range 0.5–10% [16]. Squeaking has been the subject of considerable investigation and discussion in the last 5 years, but the mechanism of squeaking is not clear [15,16].

The design of modular femoral heads in THA is outlined schematically in Fig. 1a. The articulating surface, which must be polished and smooth to minimize friction, is loaded in compression. Femoral heads have a modular taper bore, in order to allow attachment to a matched Morse taper on the metal femoral stem. Taper depth allows intra-operative control of leg lengths. Once installed during surgery, the modular taper–bore junction is mechanically stable, but micro-motion can occur which can lead to fretting wear and corrosion [17,18]. When a compressive stress is applied to the femoral head during physiological activity, it gives rise to a tensile (or hoop) stress component in the taper bore. Ceramic taper bores typically have much larger and more numerous surface flaws from drilling than the smooth articulating surface. Catastrophic failure of ceramic bearings *in vivo* commonly results from slow crack growth, under the static and repetitive loading experienced in the body, until fracture occurs.

Catastrophic failure of Al_2O_3 femoral heads *in vivo* has been addressed by the development of alternative ceramic materials, such as Al_2O_3 matrix composites and silicon nitride (Si_3N_4), which have higher strength and fracture toughness than Al_2O_3, in addition to low wear [19]. However, the fracture toughness values of these alternative ceramic materials, typically lower than ~10 $MPa.m^{1/2}$, are still far below the values for CoCr alloy (50–100 $MPa.m^{1/2}$).

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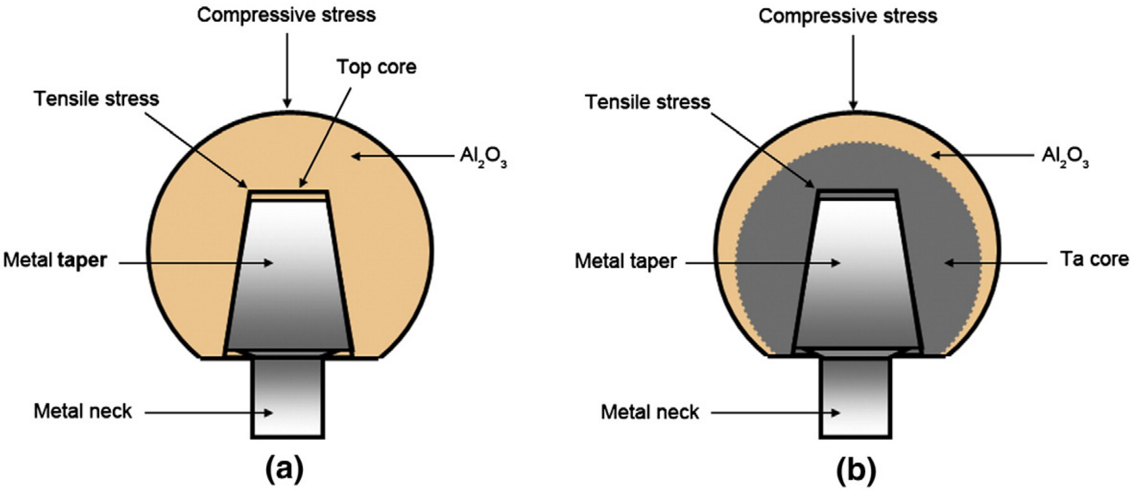

Fig. 1. Schematic diagrams of (a) Al_2O_3 femoral head on a metal taper, and (b) proposed design of Al_2O_3–Ta composite femoral head consisting of an Al_2O_3 articulating surface and a ductile Ta core.

Surface treatments such as ion implantation, thermal diffusion, or the deposition of hard ceramic coatings have been widely investigated for improving the surface hardness and, hence, the wear and corrosion resistance of metal implants [19,20]. However, many of these treatments have not proved to be successful in clinical applications, because of problems such as delamination of the coating, corrosion, poor interfacial bonding, and porosity [21,22].

Modification of the surface of a metal to form a ceramic has been successfully used in the manufacture of THA femoral heads (as well as bearings for total knee arthroplasty, TKA) from a zirconium alloy (Zr–2.5% niobium) that is oxidized by thermal diffusion to create a 5–10 µm oxidized zirconium layer [23]. The ZrO_2-based ceramic surface forms the articulating surface of the femoral head, whereas the metal substrate provides the strength and ductility to resist fracture. Oxidized zirconium has had a successful clinical experience when used as an articulating bearing against UHMWPE, providing favorable reduction in wear when compared to CoCr [24,25]. However, oxidized zirconium is not intended to be used for hard-on-hard bearing applications, whereas Al_2O_3 can be used as an articulating bearing against UHMWPE, as well as for Al_2O_3–Al_2O_3 (hard-on-hard) bearing applications.

The objective of the present work was to explore the feasibility of developing an Al_2O_3–metal composite system which would address concerns about catastrophic failure of Al_2O_3 femoral heads *in vivo*. The composite is intended to combine the low wear rate of Al_2O_3 with the safety of a ductile metal femoral head (Fig. 1b). This design differs from that of oxidized zirconium in that the ceramic articulating layer has a far higher thickness (2–3 mm). In addition to the low wear of dense Al_2O_3, the thick articulating layer can also contribute substantially to the strength of the composite femoral head. The composite femoral head is intended to provide an alternative to Al_2O_3 articulating against UHMWPE, as well as Al_2O_3–Al_2O_3 (hard-on-hard) bearings. The work reported here explored the fabrication of Al_2O_3–Ta test specimens, and the evaluation of the microstructure and mechanical properties of the composite specimens.

Al_2O_3 has been used in orthopaedic applications for decades [19]. Tantalum was selected as the metal because of its biocompatibility, corrosion resistance, and engineering properties. Tantalum is being increasingly used for a variety of orthopaedic applications, and porous Ta has shown the ability to support cell and tissue ingrowth [26]. Because of the existence of a stable passivating oxide layer on its surface [27], Ta has low electrochemical potential and high corrosion resistance. Tantalum (density = 16.6 g/cm^3; melting point = 2996 °C) has a tensile strength of 420 MPa, and an elastic modulus of 186 GPa in tension at 20 °C [28]. The average coefficient of thermal expansion of Ta in the range 20 °C–1000 °C is 6.73×10^{-6} °C^{-1}, compared to a value of 8.44×10^{-6} °C^{-1} for Al_2O_3, so thermal mismatch stresses and, presumably, the risk of delamination at the interface between the two materials should be small.

2. Experimental procedure

2.1. Preparation of Al_2O_3–Ta composite laminates

The starting materials were high-purity Al_2O_3 powder (A16SG; average particle size ≤ 0.4 µm; Almatis, Leetsdale, PA) and Ta powder (−325 mesh; purity = 99.8%,; Atlantic Equipment Engineers, Bergenfield, NJ). Composite laminates of Al_2O_3–Ta with the shape of disks (35 mm in diameter × 3 mm) were prepared by hot pressing in a graphite die, the contact surfaces of which were coated with boron nitride to limit reaction between the composite and the die. The thickness of the Al_2O_3 and Ta layers in the laminate was approximately the same.

The required mass of Ta powder was poured into the graphite die, and the system was vibrated to settle the powder into a layer with a nearly uniform thickness. The process was repeated for the Al_2O_3 layer on top of the Ta layer. Hot pressing was performed for 30 min in flowing Argon gas (~60 cm^3/min) at 1450 °C or 1650 °C (heating and cooling rates = 10 °C/min) under a pressure of 35 MPa. The pressure was applied when the temperature reached 1200 °C. On cooling after the hot pressing, the pressure was released at 1100 °C. For comparison, Al_2O_3 disks were hot pressed under the same conditions.

2.2. Mechanical testing

The flexural strength of the Al_2O_3–Ta laminates was determined in four-point loading and compared with the value determined for Al_2O_3. Mechanical testing in flexure is commonly used to measure the strength of (brittle) ceramics, and the main goal of the flexural strength testing was to determine the strength of the Al_2O_3–Ta composite laminate relative to that of Al_2O_3. The interfacial shear strength between Al_2O_3 and Ta in the hot-pressed composite laminates was measured using a double-notched coupon test [29,30]. This method was chosen because it has been shown to be more reliable than the short-beam shear test [30,31]. Furthermore, the specimen preparation is simple, and no extensive set-up or fixture is required for the test.

2.2.1. Measurement of flexural strength

Hot-pressed disks of Al_2O_3–Ta composite and Al_2O_3 were sectioned and diamond-machined to give rectangular beams (25.0 × 2.0 × 1.5 mm) corresponding to the dimensions of ASTM C1161-02c 'Standard A' bars. The thicknesses of the Al_2O_3 and Ta layers in the composite bars were