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Review

Orthopedic applications of silicon nitride ceramics

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ABSTRACT

Silicon nitride (Si_3N_4) is a ceramic material developed for industrial applications that demand high strength and fracture resistance under extreme operating conditions. Recently, Si_3N_4 has been used as an orthopedic biomaterial, to promote bone fusion in spinal surgery and to develop bearings that can improve the wear and longevity of prosthetic hip and knee joints. Si_3N_4 has been implanted in human patients for over 3 years now, and clinical trials with Si_3N_4 femoral heads in prosthetic hip replacement are contemplated. This review will provide background information and data relating to Si_3N_4 ceramics that will be of interest to engineering and medical professionals.

1. Introduction

Silicon nitride (Si_3N_4) is a non-oxide ceramic that is rarely observed in nature, but may occur naturally, since it has been found in particles of meteorite rock [1]. Synthetic Si_3N_4 was first developed by Deville and Wöhler in 1859 [1]; but it remained little more than a curiosity for nearly a century. Commercial interest in the material increased in the 1950s, when it was developed for various refractory applications. However, it was not until the 1980s that its potential as a structural ceramic was clearly recognized. At that time, a worldwide effort was initiated to develop Si_3N_4 for use in internal combustion engines and high-temperature gas turbines. Significant improvements were made in its synthesis, processing and properties. As a result, it is now one of the most extensively studied ceramics in history. Its material properties are well understood, and its commercial use has expanded greatly.

Today, industrial uses of Si_3N_4 and its composites are well established and include high-performance bearings, turbine blades and glow plugs (i.e. applications that require a material with high fracture toughness, strength and low wear properties) [2]. Ceramic ball bearings made of Si_3N_4 are used in industrial applications where extreme strength and toughness are necessary [3]. The material properties of Si_3N_4 have led to speculation that it may have a role in biomedical fields also, since it is biocompatible [4,5] and is visible on plain radiographs as a partially radiolucent material. Because of a unique combination of material properties, Si_3N_4 has been used in spinal fusion implants, and has been developed for bearing components of prosthetic hip and knee joints.

As clinical data pertaining to the use of Si_3N_4 in orthopedic surgery become available in the future, it will be useful to have an overview of the rationale for the use of this material in biomedical applications. Cervical spacers and spinal fusion devices made of Si_3N_4 composites are presently in use, with successful short-term clinical results [6]. Surgical screws and plates made of Si_3N_4 as the source material, as well as bearings for spine disc surgery and prosthetic hip and knee joints have also been developed and tested [7–9]. This review will (1) examine the clinical rationale for using ceramic materials in orthopedic surgery, (2) summarize the limitations of existing ceramics that have been used in orthopedic surgery, and (3) review the scientific rationale for introducing Si_3N_4 ceramics in orthopedic implants.

2. Ceramic materials in orthopedic surgery

Modern biomaterials, such as titanium (Ti) alloys, polished cobalt–chromium (CoCr) and high-density polyethylene (PE) have revolutionized prosthetic replacement of diseased hip and knee joints since the 1970s, such that clinical outcomes are now predictable and durable [10,11]. However, a long-term concern related to prosthetic bearings in the human body is the adverse host biological response to accumulated, microscopic wear debris in the periprosthetic joint space, particularly PE wear particles. Less bearing wear is desirable because particulate wear in hip and knee replacements leads to localized inflammation, periprosthetic bone loss and premature implant loosening, necessitating revision surgery [12–15]. These considerations apply even more acutely

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to the younger and more active patients, who inevitably place greater demands on the prosthetic joint [16]. Strategies to reduce PE wear in the ball-and-socket joint of artificial hips, and the sliding–rolling articulation of artificial knees have been pursued vigorously by orthopedic implant manufacturers and material scientists, with varied success.

The bearing couple of a highly polished CoCr surface articulating against a PE surface led to the success of modern hip and knee replacement surgery in the 1970s [17–20]. In total hip replacements, CoCr femoral heads are still used commonly by surgeons, usually against an ultrahigh-molecular-weight or cross-linked PE liner captured inside a hemispherical metal socket. Cross-linking of PE is a manufacturing strategy designed to reduce wear [21–23]. Another wear-reduction strategy is to eliminate PE entirely from hip replacements and use a hard-on-hard bearing combination instead [24,25]. One example of such is that of CoCr-on-CoCr articulations in total hip replacement. This couple was once viewed as an ideal bearing combination, but has rapidly fallen out of favor because of adverse reactions to metal ions [26,27] and related soft tissue reactions [28,29].

Alumina (Al_2O_3) and zirconia (ZrO_2) ceramics were introduced in the 1970s and 1980s, respectively, to replace CoCr surfaces in hip and knee replacements, with the goal of offering a smoother, lower-friction surface than CoCr, so that PE wear could be reduced. Scientific evidence has shown less wear when ceramic surfaces are used in hip [30,31] and knee [32] replacement surgery, instead of CoCr. Al_2O_3 bearings are the only prosthetic hip bearings with over 30-year clinical survivorship, with no evidence of periprosthetic bone dissolution related to particulate debris [33,34]. Al_2O_3-on-Al_2O_3 total hip bearings are associated with the lowest bearing wear rates of any material used in orthopedic surgery [33,35]. In prosthetic total knee replacements, the femoral components are made of CoCr, which articulate with a PE spacer, designed to simulate the complex articular geometry of the human knee joint. Substitution of CoCr components in total knee replacements with Al_2O_3 [36–38] or ZrO_2 [39] should lead to less wear of the PE countersurface. While Al_2O_3 femoral components are used commonly in total knee replacements overseas, their use has not been adopted in the US. In the US, the closest ceramic component in knee replacements is an oxidized zirconium femoral component, in which the underlying metal alloy is transformed to a zirconia ceramic layer at the articulating surface [40,41]. Ceramic-on-ceramic bearing combinations are not feasible in total knee replacements at present, because of design and engineering limitations.

Despite their encouraging wear performance in orthopedic bearings, ZrO_2 and Al_2O_3 ceramics have demonstrated their drawbacks. Yttria-stabilized ZrO_2 (YSZ) is an unstable material that can undergo phase transformation in vivo, leading to catastrophic failure; this material has been withdrawn from the biomedical market for its unpredictable outcomes [42]. Also, in comparison studies with CoCr, ZrO_2-based femoral heads have not shown consistent, superior wear reduction in total hip replacements [43,44]. Al_2O_3, in composite form, is the most widely used ceramic in orthopedic surgery today, but despite its wear reduction and long-term durability, sporadic cases of catastrophic alumina bearing failure continue to be a clinical concern [45,46]. The mechanical properties of alumina can also restrict design options in orthopedic bearings, thereby limiting surgical flexibility to precisely reconstruct the diseased joint [47,48].

Mixed composites of ZrO_2 and Al_2O_3 have also been marketed and used in hip replacements. This material, known as a "zirconia-toughened alumina" (ZTA), has shown encouraging early success [49], although the long-term in vivo outcomes of ZTA are yet unknown [50,51]. While the advantage of ZTA ceramic bearings relates to a tougher material than previous generation Al_2O_3, with higher fracture strength and essentially equivalent wear, a potential drawback is that ZTA is still an unstable, ZrO_2-based material. ZTA derives its strength and toughness from the same mechanisms that resulted in catastrophic failure of the ZrO_2-based orthopedic bearings [52,53], and there is evidence that spontaneous hydrothermally induced phase transformation will occur with it as well [54]. Material degradation of ZTA may be delayed in comparison with ZrO_2, but it may manifest nonetheless [55,56]. YSZ and ZTA derive their strength and toughness from the presence of a metastable (i.e. thermodynamically unstable) tetragonal zirconia phase that transforms to its stable monoclinic form in the presence of an advancing crack. The volume expansion associated with this transformation arrests crack propagation. Simply put, YSZ and ZTA achieve their remarkable properties through phase instability of the material itself, rather than by microstructural engineering. It is well known that such phase instability is exacerbated by warm temperatures and moist environments, (i.e. conditions readily found in the human body). As the material transforms, the component may lose its strength and toughness such that, over time, it is essentially no stronger than conventional alumina.

Given the limitations of existing ceramics used in orthopedic surgery today, there is a need for even tougher and more reliable ceramic materials that can outlast the lifespan of a patient, with sub-clinical wear rates. Joint replacement surgery is expanding in newly prosperous Asian markets, where smaller-sized bearings are used more commonly, demanding stronger, tougher ceramic materials that allow surgical flexibility with a wide range of bearing sizes and configurations. In developed countries as well, major joint replacement surgery is being performed in younger and more active patients. These individuals expect to enjoy ever longer lifespans, creating a demand for implants and bearings that will withstand several decades of cyclic loading.

3. Material properties of silicon nitride

During the 50-plus years that Si_3N_4 has been used in industrial applications, its mechanical properties have been improved by refining processing methods and using additives to create composite structures. Of the different processing methods used to make Si_3N_4, there are three typical strategies, known as reaction bonding, sintering and pressure-assisted sintering, respectively. Reaction-bonded Si_3N_4 processing is a method of producing the ceramic material by nitridation of a porous-shaped article formed from silicon (Si) powder. In the reaction bonding process, the shaped article is typically heated in N_2 at a temperature in the range 1200–1400 °C, where the Si reacts with N_2 to form Si_3N_4 and bonds the particles together. An attractive feature of the method is that the reaction-bonded Si_3N_4 product has almost exactly the same external dimensions and geometry as the shaped Si article, which leads to lower fabrication costs. This method was developed in the 1950s for refractory articles, but later in the 1980s it was further developed with the goal of producing internal combustion and turbine engines with hot-zone components made entirely from ceramics [1]. The resulting material has relatively low density, high porosity (typically 15–20%) and low strength (i.e. flexural strength of 200–300 MPa).

In sintering, Si_3N_4 powders mixed with additives (typically Y_2O_3 and Al_2O_3) are compacted and heated in an N_2 atmosphere of 10–20 MPa pressure at temperatures $>\sim 1700$ °C. The additives react with the native SiO_2 layer on the Si_3N_4 powder to form a liquid phase that surrounds the Si_3N_4 particles and aids the densification process. On cooling, the liquid phase solidifies to form an amorphous (glassy) or a partially crystallized glassy phase at the boundaries of the Si_3N_4 grains.

Hot pressing and hot isostatic pressing (HIP) are the common methods of pressure-assisted sintering, and these are used to address inadequate densification of sintered Si_3N_4. In pressure-assisted sintering, the powder (with additives) is placed in a graphite die (hot pressing) or encapsulated in a metal can (HIP) and subjected to high applied pressure (~50 MPa in hot pressing; 150–200 MPa in HIP) at high temperature (>1700 °C). Si_3N_4 made in this way gains improvements in strength, although at a higher manufacturing cost [57]. A compromise is to combine the sintering and HIP technologies (sinter-HIP) such that Si_3N_4 can be made by sintering to a stage when the pores become isolated, then HIPed (without encapsulation in a metal can) in order to achieve a relatively high strength, and at a fraction of the cost of Si_3N_4 fabricated by encapsulation in a can and HIP.

Polished test bars with dimensions 3 × 4 × 30 mm, made of Si_3N_4 with 10 wt.% Y_2O_3 and Al_2O_3 as additives, have shown an initial bending strength of ~600 MPa, and ion implantation of the structural ceramic can increase this strength significantly, as shown by Shi et al. [58]. These investigators found increases in specimen bending strength of 56%, 66% and 35% by the implantation of Ti, Zr and Cr ions, respectively [58]. Si_3N_4, like other ceramics, is a brittle material, and typical material property tests have shown that Si_3N_4 has a Vickers hardness of 12–13 GPa, Young's modulus of 299 GPa, Poisson's ratio of 0.270, and a typical grain size of 0.6 μm [59].

The mechanical properties of Si_3N_4, particularly the fracture toughness, can be improved by an "in situ toughening" process in which the Si_3N_4, already made dense by, for example, the sinter-HIP method, is thermally treated at high temperature (>1700 °C) to grow the grains in the material into an elongated, rod-like morphology (Fig. 1a–d). In situ toughened Si_3N_4 containing large elongated (>1 μm diameter) grains were shown to have steady-state fracture toughness values approaching 10 MPa $m^{1/2}$, compared with values of ≈ 3 MPa $m^{1/2}$ for the same material composition with less elongated, sub-micrometer diameter grains [60,61]. Such improvements are possible because the grains in Si_3N_4 fabricated by the previously described high-temperature processes generally consist of the β-phase Si_3N_4 with an elongated hexagonal morphology. Typically, the Si_3N_4 powder used as a starting material consists mainly of the α-phase material (plus a small amount of the β-phase) which converts to the β-phase during the high-temperature fabrication process. The growth of the β-grains is anisotropic, with the *c*-axis growth rates of the hexagonal prisms commonly exceeding those normal to the prism faces. This elongated grain growth occurs in the presence of the viscous glassy phase resulting from the additives used in the fabrication process and the native SiO_2-rich layer on the Si_3N_4 particles, as described previously. The development of the optimum mechanical properties by the in situ toughening process depends on precise engineering of the composition of the additives used in fabricating the Si_3N_4 material (which control the composition of the viscous glassy phase) and the thermal treatment, to produce an optimized microstructure of elongated grains [61].

The elongated rod-like grains in the in situ toughened Si_3N_4 provide toughening mechanisms that are limited or absent in more conventional Si_3N_4 [62]. As a result, propagation of a crack through the in situ toughened material becomes more difficult (Fig. 2). Bridging of a propagating crack by intact rod-like grains, pullout of the rod-like grains behind the tip of the propagating crack or deflection of the crack along the boundaries of the elongated grains have been shown to provide energy-dissipating mechanisms that reduce the tendency for fast crack growth, in much the same way as a reinforcing fibrous phase in a conventionally produced composite material.

In situ toughened Si_3N_4 with 6 wt.% Y_2O_3 and 4 wt.% Al_2O_3 was fabricated to measure the mechanical strength and related properties, according to ASTM C-1161 standards, using specimens 3 × 4 × 45 mm; results showed a near 100% theoretical material

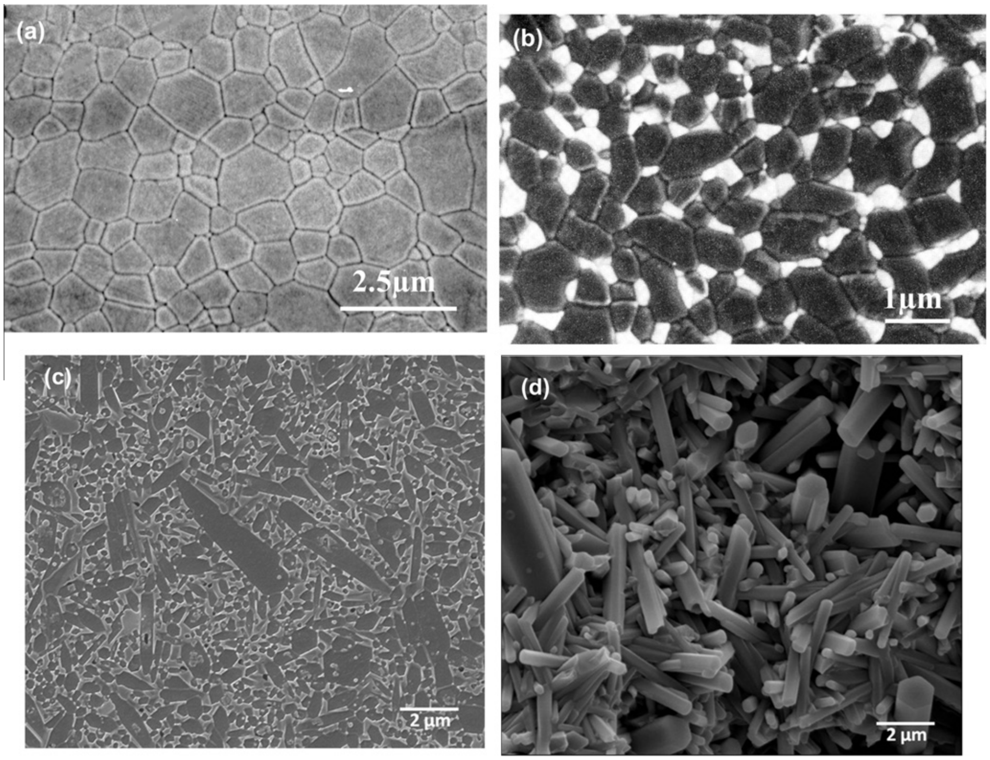

Fig. 1. SEM images showing typical microstructures of ceramic bearing materials: (a) dense, fine-grained Al_2O_3; (b) ZrO_2-toughened Al_2O_3 (ZTA). For comparison, an SEM image of in situ toughened Si_3N_4 is shown in (c); since the elongated grains in the Si_3N_4 are randomly oriented, they are cut at different angles in the polished planar view; (d) shows the as-fired surface view.

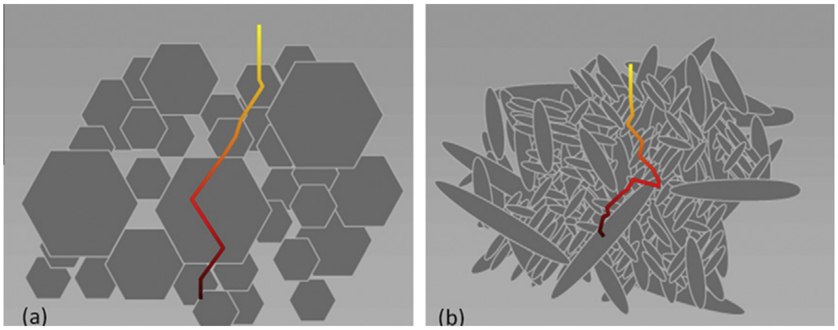

Fig. 2. Illustrations show the differences in crack propagation modes for (a) conventional ceramics and (b) in situ toughened silicon nitride ceramics.

density (3.20 g cm^{-3}), elongated grains with an average width of 1.5 μm (Fig. 1c), flexural strength 923 ± 70 MPa, with a Weibull modulus of 19 and fracture toughness 10 ± 1 MPa m^{½} [63]. Both material strength and toughness were at least two to three times higher than typical values reported for Al_2O_3, the most common ceramic bearing material in orthopedic bearings today (Table 1). The higher flexural strength and fracture toughness coupled with the large Weibull modulus indicates far higher mechanical reliability of in situ toughened Si_3N_4 compared with that of Al_2O_3. These observations for Si_3N_4 have been validated by other studies. For example, using two other compositions of Si_3N_4 with Y_2O_3 and Al_2O_3 additives, Guedes et al. [64] reported a fracture toughness of 5 MPa m^{½} and Vickers hardness values of 13 GPa.

The intrinsic material properties of Si_3N_4 make it suitable for articulation against bearing steel, which is a softer material than ceramics. Thus, Si_3N_4 has been used in rolling contact applications in the automotive, turbomachinery and power industries, where it has a significant advantage due to its low density (half that of bearing steel), low friction, corrosion-resistance and reliable performance under extreme conditions [57]. In high-performance aircraft and space vehicles, very demanding bearing operating conditions such as high vacuum (<10^{-6} torr), extreme temperatures (e.g. +230 to −150 °C), large temperature differentials, long life (both wear and fatigue life, usually 10–15 years without maintenance) and low friction are common requirements, and Si_3N_4 is a proven bearing material in these extreme performance conditions [65].

Fully densified Si_3N_4 can function under very demanding conditions; all-ceramic Si_3N_4 ball or roller bearings can operate against Si_3N_4 rolling elements and rings at temperatures up to 1000 °C, and at very high speeds. Hybrid ceramic–steel bearings also perform well under similar severe conditions. Industrial Si_3N_4 ceramic bearings have reliably met the requirements of higher efficiency, greater stiffness, higher speed, higher reliability, higher accuracy, lower friction, corrosion-resistance and non-conductivity [65] From a mechanical standpoint, therefore, Si_3N_4 ceramics easily exceed the demands placed on orthopedic bearings, whether articulating against PE, metal or Si_3N_4 itself [9]. Practical barriers to widespread adoption of this technology relate to the manufacture of most technical ceramics (i.e. material and processing costs, and the need for reproducibility, reliability and precision in manufacturing).

4. Tribological properties of silicon nitride

The suitability of Si_3N_4 for hip and knee bearings has been considered in the literature, and it is generally agreed that, in the absence of material oxidation in vivo, Si_3N_4 has the friction properties necessary to articulate against itself, even when water is the only lubricant [66]. It is also well known that Si_3N_4 bearing surfaces of various compositions and processes are subject to oxidative degradation, particularly in the presence of moisture. This has been

Table 1
Properties of in situ toughened Si_3N_4 in comparison to Al_2O_3, ZrO_2-toughened Al_2O_3 (ZTA), Y_2O_3-stabilized ZrO_2 (YSZ) and CoCr (at room temperature unless otherwise stated); properties of cortical bone are shown for reference.

Property	Si_3N_4	Al_2O_3	ZTA[a]	YSZ[b]	CoCr	PEEK	Ti-alloy	Cortical bone
Density (g cm^{-3})	3.15–3.26	3.986	4.37	6.04	~8.5	1.29	4.43	1.85
Elastic modulus (GPa)	300–320	400–450	350	210	210–250	4.2	105–115	8–12
Poisson's ratio	0.25–0.27	0.27	0.24	0.30	0.27–0.32	0.36	0.34	0.6
Strength (MPa)								
Tensile	350–400	250–300				100–110	920–980	50–130
Compressive	2500–3000	2000–3000	4300	2200	600–1800	130–140	950–990	130–190
Flexural	800–1100	300–500	1000	1050		160–180		
Fracture toughness MPa m$^{1/2}$	8–11	4–5	5.7	10.5	50–100		75	
Vickers hardness (GPa)	13–16	14–16	19.1	12.5	3–4		3.4	
Thermal expansion coefficient (10^{-6} K^{-1}) (25–1000 °C)	3.0–3.5	8.0–8.5	8.5	11	~14	47	8.6–9.6	
Thermal conductivity (Wm^{-1} K^{-1})	30–40	30	17	1.8–2.9	~100		6.7	
Surface composition	$SiNH_2$ and SiOH groups	Al_2O_3	Al_2O_3/ZrO_2	ZrO_2	CoO/ Cr_2O_3	OH Groups	TiO_2/ Al_2O_3	
Isoelectric point	9	8–9	8–9	7.5				
Surface charge at pH = 7	Lightly positive	Slightly positive	Slightly positive	Slightly positive				

[a] 20 vol.% ZrO_2.
[b] 3 mol.% Y_2O_3.

studied extensively for high-temperature applications (e.g. engine components) where the effluent consists of highly corrosive hot and humid gases [67]. However, these same phenomena are present in less demanding low-temperature industrial applications in liquid water or under humid conditions [68–76], and it is postulated that it may be operative for in vivo articulations as well [77–79]. Like most metallic and other non-oxide materials, Si_3N_4 is protected by a thin oxide surface coating (SiO_2) with a thickness in the range 2–5 nm [80]. When this coating is removed through erosion or wear, the surface rapidly repairs itself through re-oxidization thereby limiting its degradation.

A review of various studies of Si_3N_4 articulating against itself suggests considerable controversy associated with its friction and wear properties. For instance, a wide range in its coefficient of friction has been reported, from 0.002 [67] and 0.005 [76] to 0.6 and 0.8 [72,73]. In comparing Si_3N_4 with other ceramics, Zhou et al. [78] and later Kusaka et al. [79] found the wear rate for Si_3N_4 to be the highest of any of the materials tested. Conversely, just the opposite was reported in works by Ishigaki et al. [69] and Sasaki [77]. These diametrically opposed conclusions can be reconciled, at least in part, by different specimen preparation and testing methods. Also, the range of observed results suggests that the wear mechanism for Si_3N_4 is complex. Unlike oxide ceramics which wear solely by mechanical abrasion, Si_3N_4 has two principal wear modes: mechanical and tribochemical. As explained by Xu and Kato [73], differences in friction and wear are dependent upon which mechanism is dominant. While both mechanisms are concurrently operative, debris is primarily generated by transgranular or intergranular fracture of the oxide surface and Si_3N_4 grains in mechanical wear. The mechanical mode is operative under high loads, low speeds and stop–start conditions, which typically results in the observed high friction and high wear. Conversely, tribochemical wear occurs through the dissolution of the Si_3N_4 in accordance with the following reactions:

$$Si_3N_4 + 6H_2O \rightarrow 3SiO_2 + 4NH_3$$

$$SiO_2 + H_2O \rightarrow Si(OH)_4$$

In tribochemical wear, these chemical reactions dominate and, as reported by virtually all investigators, a hydrated silicon oxide lubricating film forms between the articulating components. Tribochemical wear is operative at lower loads, higher speeds and under continuous motion. The observed low friction and wear in the tribochemical mode is attributed to both the presence of very smooth articulating surfaces and a low-friction colloidal boundary film between the components [75,76]. This lubricating hydrated silicon oxide film is fairly effective in protecting the articulating surfaces, which results in the observed low wear of the material. Tribochemical wear is probably the dominant mode for in vitro hip simulator tests using self-articulating Si_3N_4, given the low observed wear rates [63]. However, the ability of hip simulators to replicate in vivo conditions remains controversial [81], so additional confirmatory tests using self-articulating Si_3N_4 are warranted.

To reiterate, published friction and wear data for different types of Si_3N_4 have shown variable results because of different test conditions used in various studies [82]. Prototype total hip bearings, fabricated using in situ toughened Si_3N_4 [63], have shown improved fracture toughness and strength over medical-grade Al_2O_3. When tested in a hip simulator, both CoCr and Si_3N_4 femoral heads produced low wear rates against Si_3N_4 acetabular liners that were comparable with Al_2O_3–Al_2O_3 wear rates, which are the lowest of any orthopedic bearing (Fig. 3) [63]. Other work has validated the observation that water-lubricated Si_3N_4 has very low friction when sliding against itself [83]. The in vivo environment should be more favorable yet, since human synovial fluid is an excellent lubricant, regardless of the bearing material used [84,85].

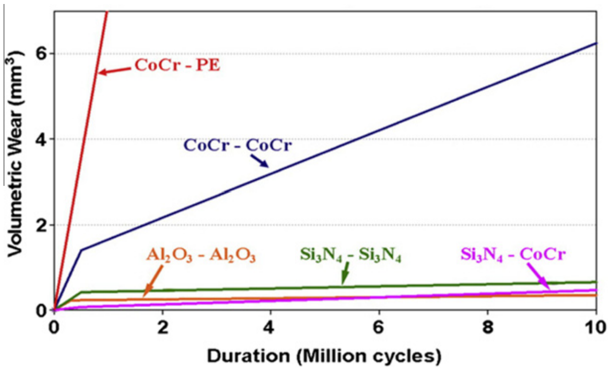

Fig. 3. Volumetric wear of Si_3N_4 hip joint bearings tested in a hip simulator, compared with Al_2O_3–Al_2O_3, CoCr–CoCr, and CoCr–PE bearing couples. From Ref. [63].

Studies on the tribological behavior of ceramics have shown that wear mechanisms also depend on contact conditions during laboratory testing. In most structural ceramics such as Si_3N_4, wear occurs through a small-scale surface fracture process if the contact load exceeds a threshold value specific to that material. Another mechanism, alluded to earlier, whereby wear can be generated is surface oxidation of the material. In laboratory testing with pure Si_3N_4, both mechanisms of wear have been confirmed [82]. Accordingly, for stable, long-term steady performance of Si_3N_4 orthopedic bearings, a chemically inert material composition that is impervious to surface oxidation is mandatory. Precise control of the starting powders and processing parameters is critical in manufacturing bearing components with predictable, reliable in vivo behavior that can outlast the remainder of a patient's lifespan.

Laboratory investigations using finite element analyses support the use of Si_3N_4 in load-bearing hip resurfacing components. Hip resurfacing differs from hip replacement in that the arthritic host femoral head is resurfaced with a prosthetic cap, rather than being surgically excised and replaced [86]. Stress distributions in the proximal femur bone with implanted Si_3N_4 hip resurfacing prostheses are similar to those of intact, healthy bone. Mazzocchi et al. [87] investigated Si_3N_4 ceramics for their potential use in orthopedic implants, and validated several properties that are critical to biomedical applications, such as wetting behavior and wear performance, which simulate conditions typical of a hip joint prosthesis. In three different Si_3N_4 ceramic materials prepared, these investigators found a lower contact angle of water when compared with oxide ceramics such as Al_2O_3 and ZrO_2 (Fig. 4). Also, very low friction coefficients were consistently measured with undetectable surface modifications and wear tracks in the Si_3N_4 materials tested, using a disc-on-ball model of wear detection [87].

5. Material stability of silicon nitride

A key concern relating to in vivo implantation is the long-term stability of the material, (i.e. a lack of corrosion, oxidation and other chemical alterations that can affect material properties). Si_3N_4 in its raw unimplanted form, when exposed to flowing oxygen, rapidly forms oxides on the surface that are populated with cracks and pores. Additives of other materials can dramatically change this surface corrosive behavior, such that the resulting composites are suitable for long-term material stability, with imperviousness to oxidative degradation.

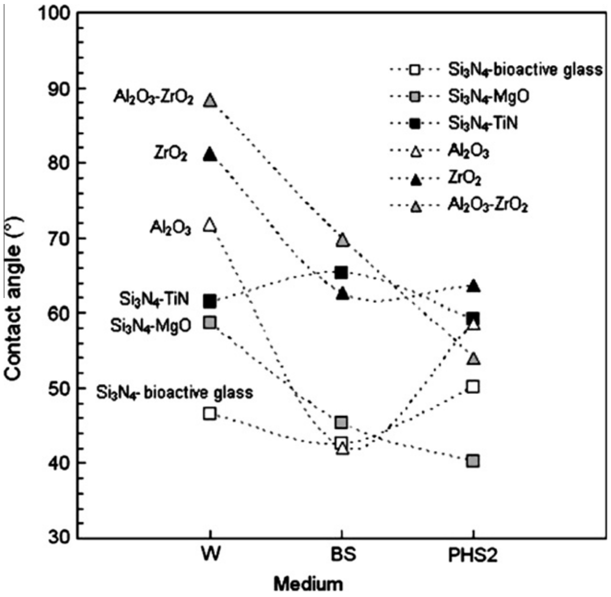

Fig. 4. Contact angle of deionized water (W), diluted bovine serum (BS) and Hank's balanced salt solution (PHS2) on three Si_3N_4-based ceramics and three oxide ceramics, Al_2O_3, Y_2O_3-stabilized ZrO_2 (3 mol.% Y_2O_3) (denoted ZrO_2), and an $Al_2O_3-ZrO_2$ composite containing 20 wt.% ZrO_2. The starting compositions for the Si_3N_4 ceramics consisted of: (1) 10 vol.% silicate bioactive glass; (2) 8.7 vol.% MgO; (3) 65 vol.% of an Si_3N_4-based material (2 wt.% Al_2O_3 + 5 wt.% Y_2O_3) and 35 vol.% TiN (denoted Si_3N_4-TiN). From Ref. [87].

Surface modifications for different Si_3N_4 material preparations were investigated for a duration of 45 days, using water and isotonic physiological saline solution [87]. Both weight changes in the specimens and scanning electron microscopy (SEM) examination of the exposed surfaces were conducted to identify morphological and chemical modifications. These experiments showed a very limited surface modification related to exposure to oxygen-containing media. The newly formed phases were limited to the boundary zone, in the nano-scale [87]. Si_3N_4 ceramics contain, besides Si_3N_4 grains, the grain boundary phases formed by sintering additives (typically an yttrium–aluminum–silicate glass or a glass–ceramic) and a SiO_2-rich layer on the surface. Independent of additives, during sintering, SiO_2 partially decomposes, forming surface gradients, or even leads to metallic Si inclusions in the ceramic. The often-used additive Al_2O_3 partially dissolves into the Si_3N_4 grains by a chemical reaction; the resulting boundary phase has a decisive influence on the mechanical properties and oxidative behavior of the bulk ceramic. Different Y_2O_3/Al_2O_3-containing Si_3N_4 ceramics with amorphous grain boundaries exhibit varying degrees of corrosion-resistance, even to acids [88].

Aluminum (Al) implantation into raw Si_3N_4 is another strategy for controlling material oxidation that is mediated by sodium [89]. The beneficial role of Al is in surface modification of the ceramic, so that sodium-accelerated oxidation processes can be reversed. In addition, the surface morphology and phase characteristics of the oxides are enhanced, resulting in smooth and glassy oxide layers, which may play a protective role during oxidation. Aluminum ion implantation is a novel method for essentially preparing a functional gradient material. There are several other functional gradient oxidation control strategies that may be available, including various coatings. For instance, Tsarenko et al. [90] reported on the preparation of Si_3N_4 with a sol–gel alumina coating which was effective in preventing oxidation; and Salgueiredo et al. [91] investigated diamond-like carbon coatings on Si_3N_4 in an attempt to further reduce friction, presumably by elimination of oxidation through both mechanical and tribochemical wear.

Related work has identified the optimal concentrations of aluminum ion implantation necessary for the optimization of the oxidation resistance of Si_3N_4 ceramics [92]. Accelerated aging in vivo was modeled using autoclaving of prototype Si_3N_4 bearings; the autoclave environment is used for surgical disinfection and exposes the material to high temperatures and humidity. Despite exposure to autoclaving for 100 h, in situ toughened Si_3N_4 fabricated using Al_2O_3 and Y_2O_3 additives showed no phase changes on X-ray diffraction, and the material maintained its superior flexural strength [9]. Thus, while phase changes and material degradation are a concern with implantable materials, and the history of catastrophic failures of Y_2O_3-stabilized ZrO_2 bearings in total hip replacements [93–95] is cautionary, existing evidence concerning the properties of Si_3N_4 and the successful use of Si_3N_4 in critical industrial environments attest to the stability of this material, and to its suitability for use in the in vivo environment.

6. Biocompatibility of silicon nitride

Any material used for in vivo applications must be bioinert (i.e. the material must not demonstrate toxicity or reactivity in bulk or particulate form, once implanted in the body). Oxide ceramics, such as stabilized ZrO_2 and Al_2O_3, were used as ceramic materials in orthopedic applications because of their excellent biocompatibility, in addition to their wear resistance. Recent evidence with cytotoxicity assays, summarized below, shows that Si_3N_4 ceramics have a similar, favorable biocompatibility profile. Furthermore, Si_3N_4 has been implanted in spinal surgery for over 3 years without adverse effects, and results from the complete spectrum of ISO 10993 biocompatibility testing have validated its biocompatibility.

Not only are Si_3N_4 ceramics non-toxic, but the material may encourage cell adhesion, normal proliferation and differentiation. Neumann et al. [5] investigated Si_3N_4 ceramics with different surface properties, with Ti alloy as a reference; cytotoxicity testing, cell viability and morphology assessment were performed, applying the L929-mice fibroblast cell culture model in a direct contact assay. These investigators reported favorable results with all Si_3N_4 materials tested; cell growth, viability and morphology were comparable with Ti, and polished Si_3N_4 surfaces appeared to promote cell growth. Further investigation compared industrial-grade Si_3N_4, using the L929-cell culture model, with Al_2O_3 and Ti alloy as controls [96]. Again, Si_3N_4 ceramics showed no cytotoxicity and favorable physicochemical properties. Investigators concluded that Si_3N_4 ceramic is suitable for biomedical applications.

The biocompatibility of Si_3N_4 has also been assessed in an in vitro model using the human osteoblast-like MG-63 cell line [97]. Results showed that Si_3N_4 has a non-toxic, biocompatible ceramic surface for the propagation of functional human bone cells in vitro. Its high wear resistance in polished form, and its ability to support bone cell growth and metabolism in porous form make Si_3N_4 an attractive candidate for orthopedic surgery. Cappi et al. [98] performed mechanical investigations and cell culture tests with mouse fibroblast cells (L929) and human mesenchymal stem cells on Si_3N_4; excellent cytocompatibility was demonstrated by live/dead staining for both types of cells [98]. Furthermore, the human mesenchymal stem cells were able to differentiate towards osteoblasts on all Si_3N_4-based ceramic materials tested. Guedes et al. [99] implanted Si_3N_4 ceramic constructs into rabbit tibiae for 8 weeks, and found no adverse reaction, with bone ingrowth occurring into and around the implants. In a separate investigation, the authors also found that Si_3N_4-based ceramics did not elicit any toxic response when tested with standard cell culture models [64].

Howlett et al. [4] investigated the effect of Si_3N_4 on rabbit marrow stromal cells and their differentiation when grown in vitro and in vivo. In vitro, marrow stromal cells attached to the ceramic discs, and fresh marrow stromal cells formed cartilage, bone and fibrous tissue, whether implanted with or without Si_3N_4, into the intraperitoneal cavity of rabbits. When inserted into living bone, Si_3N_4 promoted the formation of a cuff of bone, which contributed to osseous stability, and the material remained unchanged during the animal's life, with morphologically normal tissue found adjacent to the implant upon autopsy [4].

7. Silicon nitride in orthopedic surgery

During the several decades that ceramic materials have been used in orthopedic surgery, their advantages over CoCr alloy in terms of low friction and improved wear qualities have been confirmed and reviewed extensively [100,101] Si_3N_4-based ceramics are markedly different from the existing Al_2O_3-based ceramics presently used in orthopedic surgery worldwide. While polished Al_2O_3, and oxidized zirconium are used presently in the bearings of total hip [102–105], and total knee replacements [41,106–108], an attractive property of Si_3N_4 ceramics pertains to its ability to be formulated into both a porous substrate and a hard bearing surface. In porous form, Si_3N_4 can support direct, appositional bone ingrowth that is necessary for durable biological fixation to the skeleton. Si_3N_4 could therefore be used to make orthopedic implants with a smooth articulating surface on one plane, and a porous ingrowth surface on another plane, within the same implant. This ability opens the door to several novel skeletal applications of Si_3N_4. Examples of Si_3N_4 arthroplasty and spinal reconstruction products designed for human application are shown in Fig. 5.

Prosthetic hip and knee replacement bearings require biomaterials with low wear rates and favorable frictional coefficients that remain stable in vivo for several decades of service life. Si_3N_4 articulating against itself, metal or PE seems to satisfy this requirement, since under test conditions, the contact surface of Si_3N_4 becomes ultra-smooth as a result of tribochemical polishing, and the friction becomes very low at increasing sliding distances [66]. Thus, Si_3N_4 should be an excellent material for prosthetic hip and knee bearings, especially in light of very favorable tribological properties when this material articulates against itself in water. In theory, if oxidation were a significant concern, non-oxide ceramics like Si_3N_4 should not be suitable for hip and knee bearings, but as studies have demonstrated, surface oxidation can be controlled or eliminated by doping as-fabricated Si_3N_4 with selected additives, thereby increasing its resistance to oxidation [63,109].

Osteofixation using plates and screws, such as in maxillofacial surgery is another potential application of Si_3N_4. An advantage of Si_3N_4 is that the material is partially radiolucent, which means that the implant, adjacent bone and the implant–bone interface can be visualized easily on plain radiography. Such is not the case with metal implants, which being radio-opaque, can block radiographic visualization of the underlying tissue. Furthermore, Si_3N_4 is non-magnetic, which enables magnetic resonance imaging (MRI) examination of soft tissues proximal to Si_3N_4 implants with no artifact. In contrast, examination of soft tissue proximal to metal implants can be problematic owing to the presence of MRI-related artifacts [110].

Reaction-bonded porous Si_3N_4 yields an implant material suitable for fusion surgery of spinal intervertebral bodies and, in this application, Si_3N_4 has been in clinical use in Australia for over 15 years, with no reports of adverse effects [111]. Furthermore, dense Si_3N_4 has been implanted in spinal applications in the US for over 3 years now, with no adverse reports concerning any implant. Other potential biomedical applications of Si_3N_4 include drug-release devices, microelectro-mechanical systems (Bio-MEMS), and traumatic reconstructions of otorhinolaryngologic skeletal defects [7,112–114]. A cancellous-structured porous Si_3N_4 composite ceramic is in commercial use as a spinal fusion implant, and bone ingrowth rates are similar to those reported for porous Ti, indicating that porous Si_3N_4 is an excellent substrate for implants designed for direct, biological skeletal fixation [115]. New bone forms even in the cortical region of the rabbit tibia and around silicon nitride implants, suggesting that the material is osteoconductive and promotes stable osseous fixation [116].

8. Conclusions

Ceramics have remarkable properties that have fueled excitement about their potential applications in the biomedical field, where the need for improved biocompatibility, strength, low wear, endurance, reliability and related properties is especially acute in skeletal reconstruction. Oxide ceramics such as Al_2O_3 and stabilized ZrO_2 have a lengthy history in prosthetic hip and knee replacements; and the favorable outcomes and the limitations of these ceramics are well known. Today, Al_2O_3 is the most common ceramic bearing used in orthopedic surgery, and oxidized zirconium has replaced stabilized ZrO_2 as a bearing surface. Composites made of Al_2O_3 and ZrO_2 have been designed to provide tougher orthopedic bearings with low wear properties.

Dense Si_3N_4 ceramics prepared by in situ toughening have mechanical properties that are superior to the Al_2O_3-based ceramics and composites currently used as bearings for total hip and knee joint replacement. In situ toughened Si_3N_4 has a flexural strength approaching 1 GPa, a Weibull modulus of $\sim$20 and a fracture toughness of $\approx$ 10 MPa $m^{1/2}$, which are indicative of long-term mechanical reliability under complex loading. When articulating against itself or CoCr alloys, Si_3N_4 has a wear rate comparable with that of Al_2O_3-on-Al_2O_3 bearings, which have the lowest wear rates of any bearing material used in orthopedic surgery.

Unlike metals, Si_3N_4 is semitransparent to X-rays and being non-magnetic, it enables MRI of soft tissues proximal to Si_3N_4 implants. Si_3N_4 is biocompatible, and porous Si_3N_4 has been shown to

Fig. 5. Examples of Si_3N_4 arthroplasty and spinal reconstruction products designed for human application. Courtesy of Amedica Corp., Salt Lake City, Utah, USA.

support bone ingrowth at rates comparable with those reported for porous Ti surfaces when implanted in a large animal (ovine) model.

Si_3N_4 has been used to promote bone fusion in spinal surgery, and to develop bearings that can improve the wear and longevity of prosthetic hip and knee joints. As the world population increases, the demand for maintaining an active, healthy lifestyle has increased and will probably do so for the foreseeable future. Consistent with this demand, the need for artificial hip and knee replacements has continued a steady upward trend, especially in economically developed nations [117,118]. The limitations of the materials used in orthopedic joint reconstructions are evident in the significant number of repeat surgeries, with attendant increases in costs and morbidity associated with total hip and knee replacements that have failed owing to bearing wear [118,119]. Improved materials, such as Si_3N_4 composites, when thoroughly investigated in terms of their mechanical properties and suitability for in vivo implantation, may play a role in the development of future orthopedic implants that can relieve human suffering and dysfunction in the years to come. A half century after industrial Si_3N_4 ceramics were developed, this remarkable material may yet fulfill its promise in the biomedical field.

9. Disclosures

Corresponding author B. Sonny Bal is advisory surgeon to Amedica, developer of synthetic silicon nitride for orthopedic applications, and serves on the Board of Directors of Amedica, Salt Lake City, UT. Co-author Mohamed N. Rahaman has no disclosures for this article.

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Appendix A. Figures with essential colour discrimination

Certain figures in this article, particularly Figs. 2 and 3 are difficult to interpret in black and white. The full colour images can be found in the on-line version, at http://dx.doi.org/10.1016/j.actbio.2012.04.031.

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