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Reviewing Alumina-Zirconia Composite as a Ceramic Biomaterial

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Abstract: In orthopedics, increasing the implant lifetime minimizes the need for repair surgery, which benefits the patient’s health and the practice bottom line. The quality of the materials and designs is always being enhanced to reach the ultimate objective of a single implant that would last a person their whole life. The purpose of orthopedic treatments is to enhance the patient’s ability to participate in normal activities and socialize, and the implant carrier should not be subjected to unnecessary limitations. As a result, implants are exposed to severe mechanical stress and the inherently hostile in vivo biochemical environment, which is particularly prevalent in younger and more active people. The development of hip prosthesis design and materials has taken this path in recent years. This development is one of the most challenging problems in the field of implant technology in this century. In this study, various materials, including ceramics, glass, metal alloys, polymers, metal alloys, composites, and others, were used in an effort to combine biocompatibility with fatigue resistance, stiffness, hardness, the capacity to withstand dynamic and static stresses, and excellent chemical and mechanical wear resistance. The fracture toughness of zirconia-toughened alumina composites is increased by a factor of four compared to alumina by itself. Zirconia was first included in alumina as a densifier; however, it was not until much later that zirconia was used as a reinforcement particle to increase the level of toughness in the material. The use of ZTA to improve the mechanical properties of orthopedic implants has lately been the subject of several studies, which have all just been concluded. This research includes a literature review primarily concerned with the Biolox Delta composite, its microstructural properties, manufacturing and prosthesis materials for it to identify as a bioceramic material for medical applications.

Keywords: Biolox, composites, orthopedics, hip.

回顾氧化铝-氧化锆复合材料作为陶瓷生物材料

摘要：在骨科中，延长植入物的使用寿命可以最大限度地减少修复手术的需求，这对患者的健康以及实践的底线都是有益的。为了达到使人终生使用的单一植入物的最终目标，材料和设计的质量一直在提高。骨科治疗的目的是增强患者参与正常活动和社交的能力，植入物载体不应受到不必要的限制。因此，除了固有的不利的体内生化环境外，植入物还受到严重的机械应力。这在更年轻、更活跃的人群中尤为普遍。这是近年来髋关节假体设计和材料的发展路径。它的发展是本世纪种植技术领域遇到的最具挑战性的问题之一。在这项研究中，使用了多种材料，包括陶瓷、玻璃、金属合金、聚合物、金属合金、复合材料等，努力将生物相容性与抗疲劳性、刚度、硬度、承受动态和静态的能力相结合应力，以及出色的化学和机械耐磨性。与氧化铝本身相比，氧化锆增韧氧化铝复合材料的断裂韧性提高了四倍。氧化锆首先以致密剂的形式包含在氧化铝中。然而，直到很久以后，氧化锆才被用作增强颗粒，以提高材料的韧性水平。使用 ZTA 来改善骨科植入物的机械性能最近已成为许多研究的主题，这些研究都刚刚结束。该研究包括文献综述，主要涉及复合比奥洛克三角洲、微观结构特性以及假体的制造和材料，以确定用于医疗应用的生物陶瓷材料

关键词：Biolox、复合材料、骨科、髋关节.

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1. Introduction

A major purpose of recent materials technology is the development of materials that enhance the quality and lengthen the duration of active human life. As a result, ceramic materials have stronger biological compatibility with tissues in the human body than metals and polymers. As a result, they are in high demand in medical practice [1]. The first recorded efforts at hip surgery were made in England in 1750 to cure arthritic patients. Initially, it was proposed that the hip be repaired by replacing it with a prosthesis, which was first proposed in 1840. The goal of this technique was to resurface or replace the femoral head's acetabular region. A wooden pallet was put inside both the injured regions of the hip joint for this purpose. Unfortunately, this operation turned out to be a complete failure because of the wear particles that were discharged into the body. The following biological ingredients were used to resolve the problem of compatibility: pig bladder, skin, muscular tissue, and gold foil, to name a few. The first artificial materials were utilized just a few decades after discovering the first natural ones. These included rubber, zinc, glass, wax, and silver plates [2]. As part of a series of lectures on total joint replacement in 1890–1891, surgeon Themistocles Gluck presented ivory ingredients. In 1891, the first ivory complete knee replacement was done on a 17-year-old female and was initially regarded as successful. However, his work with ivory components was later dismissed because the prostheses frequently failed due to infection. In contrast, Professor Themistocles Glück described the use of ivory to replace femoral heads in patients whose hip joints had been damaged by tuberculosis as the first known attempt at hip replacement at the 10th International Medical Conference in Germany [3–5]. Later, in the late 19th and early 20th centuries, surgeons experimented with an interposition arthroplasty, which included putting different tissues (fascia lata, skin, pig bladder submucosa) inside the articulating surfaces of the arthritic hip [3].

In 1923 Dr. Marius N. Smith-Petersen, of Boston was the first to perform a mold arthroplasty on a patient. After removing a shard of glass from a workman's back that had been embedded in his back for more than a year, he observed a synovial-like reactive membrane had formed around it; he utilized this membrane to repair the workman's back. The initial concept consisted of a hollow hemisphere of glass in the form of a ball that could be inserted over the femoral head of the hip joint. The goal was to encourage cartilage regeneration on both sides of the molded glass part to achieve the desired results. Smith-Peterson wanted to remove the glass after the restoration of the cartilage. Although glass offered a fresh, smooth surface for movement, and although it was biocompatible, it could not sustain the rigors of walking and rapidly disintegrated [6-7].

Bakelite and Vitallium (the latter of which is an alloy consisting of chromium, cobalt, and molybdenum) were considered new materials at the time, and they were later shown to be biologically inert and to have great mechanical resistance.

In 1938, P.W. Wiles, a Londoner, performed the first total hip arthroplasty implant. The prosthesis was divided into two stainless steel metal parts congruent with each other; an acetabular part was fixed with a screwed plate, and the femoral part was composed of a sphere that was fixed with a nail-washer system.

In 1939, A.T. Moore and H. Bohlman created the itallium endoprosthesis, which consisted of a solid sphere linked to a short-flanged stem [7].

Later, in 1951, Dr. Waldius invented an acrylic hinge and fabricated it out of cobalt chrome (Co-Cr) in 1958. This prosthesis, along with numerous other hinged designs such as Dr. Shiers' in the United Kingdom and the Guepar prosthesis from France, was in use until the early 1970s [5]. From 1960-1970, the total hip arthroplasty (THA) device, developed by Sir John Charnley, represented a significant advancement in the hip implant effectiveness. The THA device was composed of two parts: a metal femoral prosthesis and acetabular ingredients consisting of ultra-high-molecular-weight polyethylene (UHMWPE) bonded to the bone using poly (methyl methacrylate), or PMMA [3]-[4], [8]. The basic concept of this system has not changed much over the years; however, it remains applicable to all current THA replacements. Following the success of the hip joint, the same material combinations and geometrical designs have been used for complete knee arthroplasty (TKA) [1].

Additionally, in the 1970s, Maurice Muller proposed a second-generation prosthesis that modified the stem so that it could "self-lock" and stabilize against the cortical femoral. Cement was placed with this model on the anterior and posterior sides of the cortical, while the stem was in direct contact with the medial and lateral cortices. However, despite technical advancement, the long-term outcome was not satisfying, particularly in the case of cement blockage and the issue of polyethylene wear debris.

In the same period, Mittelmeier [55] proposed a ceramic-ceramic system (COC) with a quadrilateral shank with different depressions to facilitate blocking. However, the problem they were unable to solve was at the level of the bone-ceramic acetabular interface. Nevertheless, the COC is still one of the best systems available today regarding friction coefficient and debris formation.

Between 1970 and 1980, Shikata presented a form of alumina femoral heads with a high molecular weight polyethylene component when the investigation of artificial joints in alumina (Al_2O_3) was just underway (COP). In recent years, the materials used in alumina have been extensively researched to produce high-tech goods with low porosity, great fracture resistance, and density, among other characteristics [7].

Even though the initial results of using alumina in the orthopedics field were promising, a high rate of fractures in vivo was discovered in the various applications. As a result, the mineral zirconia (ZrO_2) has been investigated, as it exhibits a higher rate of resistance to breakage and higher mechanical strength than alumina. The high mechanical capacity of zirconia is associated with a stress-induced phase transition from its tetragonal metastable to its stable monoclinic phase at room temperature, which is caused by its tetragonal metastable phase to its stable monoclinic phase at room temperature, respectively [9]-[10]. In 1988, the previously studied metal-metal combined systems were revalued, introducing metals with a high content of carbides in the Metasul prosthesis of Sulzer Orthopedics with a shallow wear rate, thus opening the doors to the prostheses of coating like the one introduced in 1991 from Wagner: a cemented prosthesis characterized by two metal components each coated with titanium, with Metasul joint [12].

In the 1990s, new surgical procedures and bearing surfaces were developed, resulting in significant advancements [13].

In the nineties, using zirconia in femoral heads was relatively common, especially in combination with polyethylene (COP) bearings, because of its excellent mechanical strength and high tensile strength. However, tetragonal zirconia is very unstable after the hydrothermal impacts of in vivo degradation. Furthermore, it converts with a high conversion rate in its monoclinic phase, indicating that it is highly unstable [14]-[15].

In the early 2000s, because of this problem, two attractive ceramic-on-ceramic zirconia alternatives for bearings were proposed: the first was obtained by oxidizing zirconium oxide (OxiniumTM of Smith and Nephew Orthopedics), and the second was a mixture of alumina and zirconia, known as ZTA, which was found to be suitable not only for orthopedic bearings but also, in this instance, for COP and COC applications [2]. Furthermore, because of the weight distribution, zirconium ceramic compounds (ZTA) have better mechanical capabilities than either ordinary alumina or zirconium ceramics. Zirconium ceramic compounds (ZTA) comprise 80% polycrystals of tetragonal zirconia and 20% alumina, respectively [16]-[17].

In 2003, CeramTec proposed a new category of ZTA femoral heads (BIOLOX®delta) with a new volume distribution of components: 82% alumina matrix, 17% yttrium stabilized zirconia, two minor additives to increase material hardness, 0.5% strontium oxide and 0.5% chromium oxide, and two minor additives to increase material hardness. Furthermore, adding a small amount of yttrium oxide to zirconia (1.3% moles) was intended to stabilize the tetragonal polymorph, which was previously unstable[15]-[18]. To date, the materials in ZTA have a resistance and a toughness that makes the comparison with other materials difficult for the same purpose of use. The biomaterials BIOLOX®delta and AZ209 from KYOCERA Medical are now in the hip arthroplasty market. CeramTec Medical Products (Plochingen, Germany) manufactures BioLox®delta, while KYOCERA Medical (Osaka, Japan) manufactures AZ209.

In recent years, total joint replacements have established themselves as a widely accessible surgical technique with a value in lifestyle restoration that is unmatched in medical practice. After many decades of progressively increasing surgical procedures and prosthetic designs, there are great hopes for the long-term durability and performance of total joint arthroplasty and replacement [20]. On the other hand, the result of complete joint replacements is dependent on the patient's features, the surgical method, and the implant design. Patient-related issues, such as demographic shifts, may be exacerbated by technological advancements in total joint replacements, which tend to outweigh them. In addition, variations in surgical trends and orthopedic practice may arise due to changes in the incidence, severity, and joint specificity of arthritis caused by changes in the population's age distribution [21].

2. Microstructural Properties

In the 1970s, alumina was proposed as a bearing surface material for orthopedic implants, while partly stabilized ZrO_2 was developed during the mid-to-late 1980s [11]. Finally, in the middle of the 1970s, new ceramic-based materials were investigated; one of them was characterized by the inclusion of zirconium oxide in various percentages in an alumina matrix, resulting in the production of a contemporary high-purity ceramic material [22].

In 1974, Alumina Al_2O_3 (corundum particles that have been chemically refined and crushed) was first commercialized as Biolox. The ISO-6474 standard, first published in 1980, was created to increase the Alumina (Al_2O_3) quality used in hip joints while lowering the hazard of breakage. Alumina (Al_2O_3) quality is influenced by several parameters, including purity, particle size, and density [5]. With the development of ceramic-on-ceramic joints, the issue of polyethylene wearing dust is no longer a concern. Since its inception more than 40 years ago, three generations of ceramic Biolox have been produced (the first being Bioloxs, followed by Bioloxs forte, and finally Bioloxs delta), each being superior to the preceding in terms of density, grain size, and purity [5].

In the 1990s, the introduction of Bioloxs forte (CeramTec AG; Phlochingen, Germany) improved the performance of alumina hip joints. Biolox Forte is composed of nearly 98 % pure alumina (Al_2O_3) with a trace of magnesium oxide (MgO) to prevent the growth of alumina grains during sintering. Another advantage of Biolox Forte produced using the hot isostatic technique is its microstructure, which is more uniform and dense, and its mechanical characteristics, which have been significantly upgraded as a result of manufacturing process advancements leading to improved product characteristics [8]-[23].

In 1995, Biolox Forte became commercially accessible; this material was created utilizing a better raw material with the same grain size and a reduced number of contaminants sintered in the open air throughout the manufacturing process [5]-[18]. However, although the alumina bearings have been improved, they have still been confined to a small number of hip component designs [8].

In 2000, the ceramic Biolox® Delta (CeramTec GmbH, Germany) was first marketed. It was created to minimize the incidence of head element and liner cracks during joint replacement, which was also quite small at the time of development [15]. This was a mixture of alumina and zirconia known as ZTA, in this case, suitable not only as orthopedic bearings but also for both ceramic-on-polyethylene (COP) and ceramic-on-ceramic (COC) implants (Figure 1). In zirconium ceramic compounds (ZTA), tetragonal zirconia polycrystals account for 80% wt distribution, while alumina accounts for 20% wt distribution. Therefore, the mechanical characteristics of ZTA are superior to those of standard alumina and zirconia [7].

Fig. 1 Total knee replacement system with a femoral and tibial component of Biolox® ceramic composite, ball heads, and inserts of BIOLOX®delta [19]

In 2003, a new type of ZTA femoral head (BIOLOX®delta) was proposed by CeramTec. It is an alumina (Al_2O_3) ceramic composite that has been made mostly of nano-sized, Yttria-stabilized tetragonal zirconia and strontium oxide [16]. It is believed that the transition of this zirconia phase into an alumina ceramic matrix helps prevent possible fracture growth (Figure 2) [25]. In addition, increasing the mechanical qualities of the ceramic composite boosts its dependability while also allowing for more design flexibility. According to the authors, using large-diameter femoral head parts should potentially lower the risk of dislocation while simultaneously enhancing stem mobility and minimizing the danger of impingement between the rim of the liner and/or cup and the neck of the stem [26]. BIOLOX delta is the fourth generation of alumina ceramic. This generation has shown enhanced material density and grain size five times smaller than the third generation articulation [27].

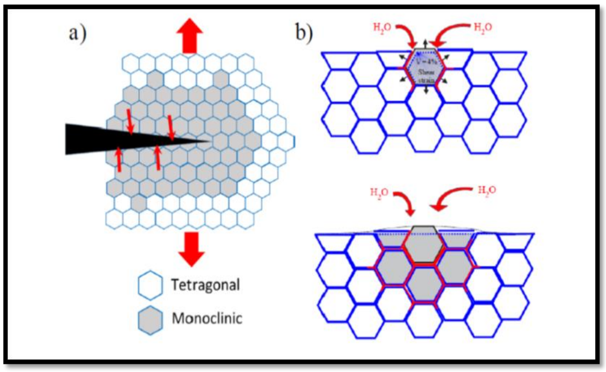


Fig. 2 Schematic illustration of (a) phase transformation toughening and (b) aging. In (b): Nucleation on a particular grain at the surface, leading to micro-cracking and stresses to the neighbors (top); growth of the transformed zone, leading to extensive micro-cracking and surface roughening (bottom). The red path represents water penetration due to micro-cracking around the transformed grains [11]

3. Manufacturing and Materials of Prosthesis

The manufacturing process of a ceramic composite includes numerous steps. The first step is the creation of the powder of the ceramic composite using different processes (Figure 3) like mechanical mixing [28]-[29], sol-gel technology [30], hydrothermal oxidation [31], co-precipitation combined [32], plasma technique [33], etc. The powders are then green formed, which may be done in a variety of ways, including die pressing [34], wet pressing [35], uniaxial pressing [36], and cold isostatic pressing [37], to produce green compacted samples. Then, the green compacted particles are densified by sintering them [38]. The abbreviations used to define the different sintering technologies are listed in Table 1 [39].

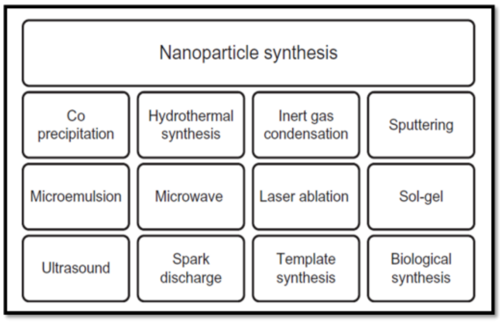


Fig. 3 Nanoparticle synthesis techniques [40]

The homogenous spread of ZrO_2 inside the ceramic matrix is critical for increasing the toughening effect of microcrack nucleation in ceramic materials. Through homogeneous powder synthesis processes, it is possible to regulate the uniform dispersion of zirconia particles in the alumina matrix (Figure 4). Several methods for powder processing have been investigated to generate homogeneous powder mixtures, and the precipitate and sol-gel techniques are the most straightforward and commercially available for creating ZrO_2 doped nanoparticles, respectively [30].

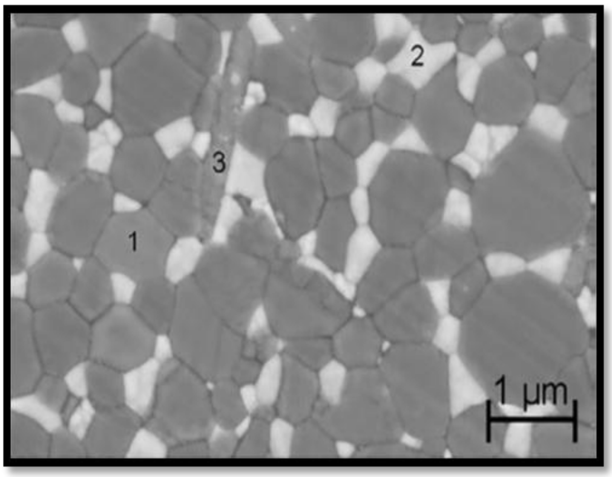
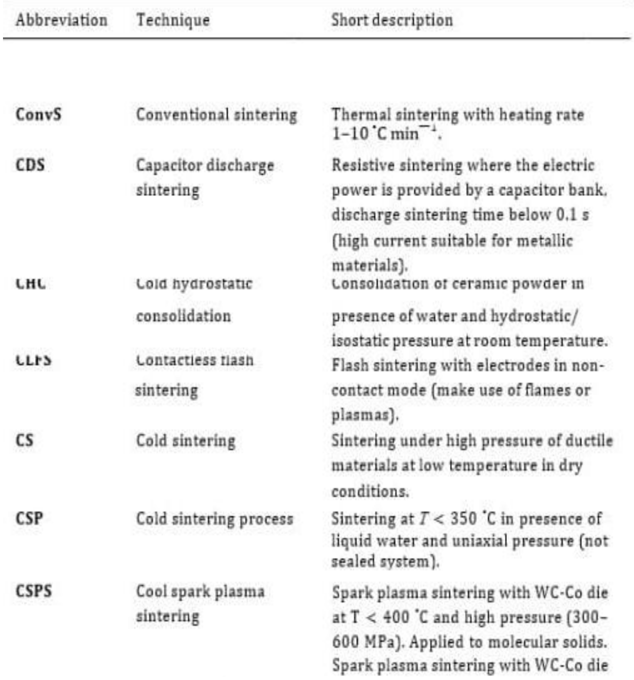


Fig. 4 Microstructure of Biolox Delta showing (1) alumina grains, (2) yttria-stabilized
zirconia grains, (3) platelet-shaped crystal of strontium aluminate [8]

The low-temperature autoclave aging performance of zirconia toughened alumina (ZTA) composites manufactured by a conventional powder mixing procedure was investigated in [42]; a high-purity alumina powder with content greater than 99.9% (Condea HPA 0.5, Ceralox Division, Tucson, AZ) was mixed with varied proportions of yttria-stabilized zirconia powder (3Y-TZP, Tosoh TZ-3YS, Tosoh Corporation, Tokyo, Japan). For two hours, samples were sintered in the air at 1873 K. The effect of the alumina matrix on the results of local SEM and AFM measurements was investigated. Although alumina restricts the pace of transformation in grains, the restricting influence of the matrix after a grain has been started in the transformation process may be stronger than the driving force for the transformation, resulting in partly changed grains. Observations were made of transformations occurring in both agglomerates and isolated zirconia grains. According to this hypothesis, the microstructural environment seems to be more significant for aging sensitivity than grain size, according to this hypothesis [43].

Table 1 List the abbreviations used to identify the different sintering techniques. A short description of the technologies is also provided [42]



Abbreviation	Technique	Short description
ConvS	Conventional sintering	Thermal sintering with heating rate 1–10 °C min^{-1}.
CDS	Capacitor discharge sintering	Resistive sintering where the electric power is provided by a capacitor bank, discharge sintering time below 0.1 s (high current suitable for metallic materials).
CHC	Cold hydrostatic consolidation	Consolidation of ceramic powder in presence of water and hydrostatic/ isostatic pressure at room temperature.
CLFS	Contactless flash sintering	Flash sintering with electrodes in non-contact mode (make use of flames or plasmas).
CS	Cold sintering	Sintering under high pressure of ductile materials at low temperature in dry conditions.
CSP	Cold sintering process	Sintering at $T < 350$ °C in presence of liquid water and uniaxial pressure (not sealed system).
CSPS	Cool spark plasma sintering	Spark plasma sintering with WC-Co die at $T < 400$ °C and high pressure (300–600 MPa). Applied to molecular solids. Spark plasma sintering with WC-Co die

The wet chemical technique (sol-gel) resulted in an Al_2O_3/ZrO_2 composite gel precursor powder containing 5–15 mol % ZrO_2 [38]. The DTA/TG, XRD, and FTIR spectroscopies of the washed gel containing pseudo boehmite and amorphous ZrO_2 were used to analyze the gel's composition. The DTA/TG results show that pseudo boehmite decomposes in three stages, while amorphous zirconia decomposes in a single step, according to the results. The development of Al_2O_3 in the calcined powder phase follows the series of pseudo boehmite →bayerite → boehmite $\rightarrow \gamma\text{-}Al_2O_3 \rightarrow \theta\text{-}Al_2O_3 \rightarrow \alpha\text{-}Al_2O_3$, while that of ZrO_2 follows amorphous $ZrO_2 \rightarrow t\text{-}ZrO_2 \rightarrow (t + m)ZrO_2$ [38].

The effects of adding MgO to the alumina powder and the effects of hot isotactic pressing (HIPing) on sintered $\alpha\text{-}Al_2O_3$ ceramics for use in Total Hip Arthroplasty (THA) were examined in [44]. Pressureless sintering in the air at temperatures ranging from 1280 to 1460°C for 2 hrs was carried out at various temperatures to establish the sinterability of these powders and the lowest temperature necessary to achieve closed porosity. The HIP cycles were carried out at temperatures of 1300 and 1325°C with applied pressures of 150 MPa for a total of 30 min. Magnesium oxide (MgO) was used as a sintering aid, helping to manage particle size and promote the achievement of full density. The resultant ceramic material can potentially increase both the duration and the stability of ceramic prostheses, resulting in a considerable improvement in the quality of life for a large number of patients while also avoiding the high expense of surgical procedures [44].

Yttria Stabilized Zirconia (3YTZP)–carbon nanotube (CNT) composites were synthesized by growing CNTs directly on zirconia particles and densifying them by the Spark Plasma Sintering (SPS) method [45]. Scanning electron microscopy (SEM) investigation of the 3YTZP-CNT powders revealed a uniform distribution of carbon nanotubes without the development of agglomerates, in contrast to the previously observed mixing of carbon nanotubes in ceramic compositions. The samples were sintered to about 100% of their theoretical density and ground thoroughly to get a microstructure with finer grain size. CNT retention in sintered nanocomposites was demonstrated using high-resolution transmission electron microscopy (HRTEM) and Raman spectroscopy at temperatures of up to 1600°C. The strength of samples containing 4% carbon nanotubes sintered at 1600°C rises from 260 MPa for samples containing no carbon nanotubes to 312 MPa for samples containing carbon nanotubes sintered at the same temperature. When sintered at the same temperature without carbon nanotubes, the indentation fracture toughness increases proportionately [45].

The effect of silicon carbide (SiC) particle additions on the density of alumina–mullite–zirconia composites and their microstructure, mechanical characteristics, and thermal shock behavior were determined in [46]. Using Dolapix dispersant, alumina, zircon, and silicon carbide particles were utilized to generate high concentrations (51 vol. % loading) and stable aqueous solutions, which were then tested for stability (0.5 wt. %). In all combinations, the mass ratio of alumina to zircon was around 85/15. Each slip was blended for 20 minutes in a planetary mill and then solidified using the slip casting process with a plaster mold. After 24 hours of healing at room temperature, the cast pieces were dried in an oven set at 110 ° C. The sintering process was done in two steps, the first step occurring at 1600°C and the second at 1500°C, with respective holding times of 2 and 5 hrs [46].

Yttria–ceria doped tetragonal zirconia (Y, Ce–TZP)/alumina (Al_2O_3) composite were investigated in [47]. It was manufactured using cold isostatic pressing at 350 MPa and burning at 1500^oC up to 1650^oC in the air at different temperatures. Y, Ce–TZP/Al_2O_3 composite powders were made in two ways: (1) by employing the sol-gel process and in situ synthesis of the composite, and (2) by mechanical mixing of the powders as they were received. According to the results obtained using the first preparation method, the physical properties of the composites were improved due to the high degree of homogeneity achieved through the sol-gel technique. In addition, the Vickers hardness and bending strength obtained using the first preparation method were higher than those obtained using the second method [47].

According to [48], pulsed electric current sintering was used to create dense Al_2O_3-15 weight percent (ZrO_2-3% molY_2O_3) nanocomposites with a 3 wt.% self-lubricating component (CaF_2, BaF_2, MoS_2, WS_2, h-BN, or graphite). In addition to mechanical and tribological parameters, the microstructure of the materials was investigated. Only BaF_2, which partially melted during the consolidation process, retained its composition of self-lubricating materials. Based on the results of Vickers indentation, the hardness of the Al_2O_3/ZrO_2 matrix was 20.35 GPa, and Young’s modulus of the matrix was 320 GPa. A reduction in the hardness of the composite was seen with all solid lubricant additions [48].

The effects of graphene and carbon nanotubes (CNFs) addition on the mechanical and electrical characteristics of thick alumina-toughened zirconia composites were generated in [49] utilizing a mixture of an aqueous colloidal powder process and spark plasma technology (SPS). As a consequence of adding CNFs and GO to ZTA composites, hardness and fracture toughness values were reduced. However, fracture toughness was marginally increased in the ZACNF and ZAGO composites sintered at 1500ºC. In addition, the incorporation of graphene into the zirconia/alumina matrix significantly improved electrical conductivity [49].

The influence of MgO doping on the characteristics of low zirconium concentration materials was investigated in [50]. Ce-TZP/Al_2O_3 material was used for joint replacement. The nanocomposite powders were made of MgO/Ce-TZP gel and nano α-Al_2O_3 (Ce-TZP, CeO_2 stabilized tetragonal ZrO_2, whose contents were 5, 10, 15, 20, and 25 vol. %, respectively) by heating a mixture of MgO/Ce-TZP gel and nano α-Al_2O_3 at 700 °C for 30 minutes. Once formed into bulk pellets, the MgO/Ce-TZP/Al_2O_3 nanocomposites were sintered at 1600 °C for 2 hrs in the air [50].

Pressureless sintering (PLS), hot isostatic pressing (HIP), and sintering + hot isostatic pressing (sinter + HIP) techniques were used to create alumina ceramic composites with additions of 0.1 weight percent of several forms of carbon nanotubes (CNTs) to the alumina ceramic matrix [51]. While the hardness of the composites remained almost unchanged, the relative density of the composites increased to more than 94 %, with a broad range of grain sizes and fracture toughness values [51].

Alumina-Y-TZP composites were made using alumina Al_2O_3 powder and 3 mol % yttrium titanates [52]. Y-TZP (Kyoritsu, Japan) has a mean particle size of roughly 200 nm and a specific surface area (SSA) of 13 m^2/g, comparable to Y-TZP. First, the alumina-zirconia samples of varying Y-TZP inclusion (0, 5, 10, 15, and 20% vol. %) were fabricated using the alumina ball milling process. Then a cold isostatic pressing (CIP) method was used to compress the powders into discs with a diameter of 20 mm, and rectangular bars with a size of 5 mm in width, 5 mm in height, and 15 mm in length were produced. A rapidly heated furnace (ModuTemp, Australia) was then utilized to sinter the samples in the air, using a two-step sintering process developed by the researchers. Initial heating to T1 temperatures ranging from 1400°C to 1550°C was carried out at a rate of 20°C/min with a dwell time of 1 minute, followed by fast cooling to T2 temperatures ranging from 1350°C to 1400°C at a rate of 50°C/min with a 12-hour dwell period [52].

Composites made of yttria-stabilized zirconia (3Y-TZP) with additions of 1.5 and 10% wt multi-walled carbon nanotubes (MWCNTs) were studied in [53]. The samples were created using spark plasma sintering (SPS) and common sintering at a temperature of 1500°C. They discovered that during high-temperature sintering, MWCNTs maintain their structure and are distributed along the ZrO_2 grain boundaries, forming an interconnected network. In this study, it was discovered that adding 1 wt. % MWCNTs to a composite increased the relative composite density from 98.3 to 99.0% [53]-[54].

In a previous article, the excellent stability of these materials under acceleration aging circumstances, which corresponded to 5–10 times the needed lifecycle of the implants, was proven. Compared to pure alumina, the composite has a major contribution in strength and hardness due to the low zirconia concentration of the material. According to the published data, the average strength of the material is 1380 MPa, which seems to be more than twice the strength of pure alumina. The fracture toughness has increased to around 6 MPa $m^{½}$, which represents an increase of approximately 50%. Compared to pure alumina, there is a minor drop in the hardness of the material. Therefore, it was decided to add a small amount of chromium oxide (Cr_2O_3) to the mix to counteract the hardness drop induced by the inclusion of zirconia. Finally, adding strontium oxide (SrO) to the material during the sintering process leads to creating strontium aluminate ($SrAl_{12}$–$xCrxO_{19}$) platelets. Because of their large size, these flat, elongated crystals act as a barrier to the progression of fractures by dispersing crack energy (Figure 5).

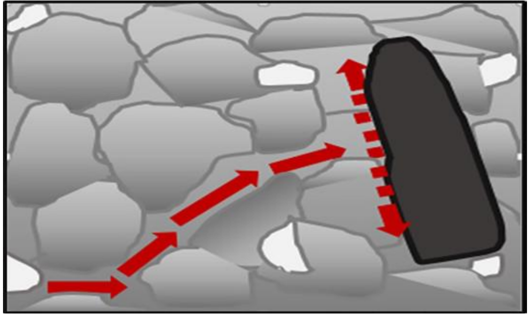


Fig. 5 Influence of platelets on inhibiting crack growth [8]

4. Conclusion

The studies and prior research publications included in the literature review are primarily concerned with three areas: In the first step, the composite BIOLOX Delta (which is composed of 82 wt. % Al_2O_3 and 17 wt. % Yttria) is prepared. Stabilized ZrO_2, 0.5 wt. % strontium oxide, and 0.5 wt. % chromium oxide are used in this formulation. Because of the alumina matrix's stabilizing effect, the Yttria concentration in the ZrO_2 grains is 1.3 mol.%, which is less than the level generally required for monolithic Y-TZP. The second field involves reinforcing the BIOLOX Delta with various quantities of additives (MgO, CaF_2, MWCNT, CNFS, GO, CaO), with the most common preparation methods being sol-gel and ball mill. These publications enabled the identification of the BIOLOX Delta as a bioceramic material for medical applications, with particular attention paid to its tribological qualities (wear and friction).

In ZTA material, the strong hardness and stability of Al_2O_3 are coupled with the toughening action of ZrO_2 to produce a material with outstanding properties. According to ISO 6474-2 for medical applications of ZTA composites, the Al_2O_3 amount should be 60–90 wt.%, and the ZrO_2 percentage should be 10–30 wt.% (by weight). Because ZrO_2 has a greater density than Al_2O_3 (6.09 g/cm^3 vs. 3.99 g/cm^3), the proportion of Al_2O_3 in the total volume is considerably larger.

The most commonly used ZTA material, BIOLOX® Delta, from Ceram Tec Company in Germany, has 80 vol % alumina, 17 vol % zirconia, and 3 vol % strontium aluminate platelets, according to the manufacturer. However, individual zirconia grains are usually isolated from one another at such a low concentration of zirconia. As a result, the hydrothermal aging is thus restricted to individual zirconia grains due to this limitation. In addition, the alumina matrix surrounding the alumina crystals effectively retards further propagation.

In reality, when the fracture comes into contact with one of these crystals, it requires more energy to get around it; if this energy is unavailable, the fracture will not continue to spread. The final result is a mixture of approximately 75% Al_2O_3, 25% ZrO_2, and less than 1% Cr_2O_3 and SrO, with the remainder primarily composed of alumina.

References

[1] RAHAMAN N, YAO A, BAL B, GARINO J, & RIES M. Ceramics for Prosthetic Hip and Knee Joint Replacement. *Journal of the American Ceramic Society*, 2007, 90(7): 1965-1988. doi: 10.1111/j.1551-2916.2007.01725.x.

[2] MEROLA M, and AFFATATO S. Materials for hip prostheses: A review of wear and loading considerations. *Materials (Basel)*, 2019, 12(3): 495, doi: 10.3390/ma12030495.

[3] KNIGHT S R, AUJLA R, and BISWAS S P. 100 Years of Operative History Er Ci Us E on Er Al. *Orthopedic Reviews*, 2011, 3: 2–4, doi: 10.4081/or.2011.16.

[4] PAPAS P V, CUSHNER F D, and SCUDERI G R. The History of Total Knee Arthroplasty. *Techniques in Orthopaedics*, 2018, 33(1): 2-6, doi: 10.1097/BTO.0000000000000286.

[5] AFFATATO S, MODENA E, TONI A, and TADDEI P. Retrieval analysis of three generations of Biolox s femoral heads : Spectroscopic and SEM characterisation. *Journal of the Mechanical Behavior of Biomedical Materials*, 2012, 13: 118-128, doi: 10.1016/j.jmbbm.2012.04.003.

[6] HERNIGOU P. Smith-Petersen and early development of hip arthroplasty. International Orthopaedics, 2014, 38(1): 193-198, doi: 10.1007/s00264-013-2080-5.

[7] CINIGLIO M. Analysis of the effects of low-temperature degradation on mechanical properties of BIOLOX ® delta femoral heads through fractographic study and Raman spectroscopic analysis. Master's Degree Thesis.

[8] GOPAL V, and MANIVASAGAM G. *Zirconia-alumina composite for orthopedic implant application*. Elsevier Inc., 2019.

[9] PEZZOTTI G, YAMADA K, SAKAKURA S, and PITTO R P. Raman spectroscopic analysis of advanced ceramic composite for hip prosthesis. *Journal of American Ceramic Society*, 2008, 91(4): 1199-1206, doi: 10.1111/j.1551-2916.2007.01507.x.

[10] PICONI C, and MACCAURO G. Zirconia as a ceramic biomaterial. *Biomaterials*, 1999, 20(1): 1-25, doi: 10.1016/S0142-9612(98)00010-6.

[11] PALMERO P, MONTANARO L, REVERON H, & CHEVALIER J. Surface Coating of Oxide Powders: A New Synthesis Method to Process Biomedical Grade Nano-Composites. *Materials*. 2014, 7(7): 5012-5037, doi: 10.3390/ma7075012.

[12] ANDEOL Q, VISTE A, DESMARCHELIER R, LERAT J L, and FESSY M H. Metasul vs. Cerasul bearings: a prospective, randomized study at a mean eighteen years. *International Orthopaedics*, 44(12): 2545-2551, 2020, doi: 10.1007/s00264-020-04855-9.

[13] CROWNINSHIELD R D, ROSENBERG A G, and SPORER S M. Changing demographics of patients with total joint replacement. *Clinical Orthopaedics and Related Research*, 2006, 443(443): 266-272, doi: 10.1097/01.blo.0000188066.01833.4f.

[14] NISHIHARA H, HARO ADANEZ M, and ATT W. Current status of zirconia implants in dentistry: preclinical tests. *Journal of Prosthodontic Research*, 2019, 63(1): 1-14, doi: 10.1016/j.jpor.2018.07.006.

[15] ROY M E, NOEL O F, and WHITESIDE L A. Phase Transformation and Roughening in Artificially Aged and Retrieved Zirconia-Toughened Alumina Femoral Heads. *Journal of Arthroplasty*, 2019, 34(4): 772-780, doi: 10.1016/j.arth.2018.12.025.

[16] TATEIWA T. et al. Burst strength of BIOLOX®delta femoral heads and its dependence on low-temperature environmental degradation. *Materials (Basel)*, 2020, 13(2): 350, doi: 10.3390/ma13020350.

[17] BIAMINO S, FINO P, PAVESE M, and BADINI C. Alumina-zirconia-yttria nanocomposites prepared by solution combustion synthesis. *Ceramics International*, 2006, 32(5): 509-513, doi: 10.1016/j.ceramint.2005.04.004.

[18] KUNTZ M, and KRÜGER R. The effect of microstructure and chromia content on the properties of zirconia toughened alumina. *Ceramics International*, 2020, 44(2): 2011-2020, doi: 10.1016/j.ceramint.2017.10.146.

[19] MEIER E, GELSE K, TRIEB K, et al. First clinical study of a novel complete metal-free ceramic total knee replacement system. *Journal of Orthopaedic Surgery and Research*, 2016, 11(1): 21, doi: 10.1186/s13018-016-0352-7.

[20] POITOUT D G. *Biomechanics and biomaterials in orthopedics*, second edition, Springer, London, 2016, doi: 10.1007/978-1-84882-664-9.

[21] ETHGEN O, BRUYERÈ O, RICHY F, et al. Health-Related Quality of Life in Total Hip and Total Knee Arthroplasty: A Qualitative and Systematic Review of the Literature. *Journal of Bone and Joint Surgery* - Series A, 2004, 86(5): 963-974, doi: 10.2106/00004623-200405000-00012.

[22] AFFATATO S, RUGGIERO A, DE MATTIA J S, and TADDEI P. Does metal transfer affect the tribological behaviour of femoral heads? Roughness and phase transformation analyses on retrieved zirconia and Biolox® Delta composites. *Composites Part B: Engineering*, 2016, 92: 290-298, doi: f,10.1016/j.compositesb.2016.02.020.

[23] HORNAK J. Synthesis, properties and selected technical applications of magnesium oxide nanoparticles: A review. *International Journal of Molecular* Sciences, 2021, 22(23): 12752, doi: 10.3390/ijms222312752.

[24] NEVELOS J E, INGHAM E, DOYLE C, et al. The influence of acetabular cup angle on the wear of 'BIOLOX Forte' alumina ceramic bearing couples in a hip joint simulator. *Journal of Materials Science: Materials in Medicine*, 2001, 12(2): 141-144, doi: 10.1023/A:1008970027306.

[25] LOPES A C O, COELHO P G, WITEK L, et al., Nanomechanical and microstructural characterization of a zirconia-toughened alumina composite after aging. *Ceramics International*, 2019, 45(7): 8840–8846, doi: 10.1016/j.ceramint.2019.01.211.

[26] MASSIN P, LOPES R, MASSON B, and MAINARD D. Does Biolox® Delta ceramic reduce the rate of component fractures in total hip replacement? *Orthopaedics & Traumatology: Surgery & Research*, 2014, 100(6): S317-S321, doi: 10.1016/j.otsr.2014.05.010.

[27] DAVIS E T, et al. Mid-term outcomes of the R3^{TM} delta ceramic acetabular system in total hip arthroplasty. *Journal of Orthopaedic Surgery and Research*, 2021, 16(1): 1-17, doi: 10.1186/s13018-020-02192-6.

[28] SHERIF EL-ESKANDARANY M, et al. Mechanical milling: A superior nanotechnological tool for fabrication of nanocrystalline and nanocomposite materials. *Nanomaterials*, 2021, 11(10): 2484, doi: 10.3390/nano11102484.

[29] ROJAC T, and KOSEC M. Mechanochemical synthesis of complex ceramic oxides. *High-Energy Ball* Milling, 2010: 113–148, doi: 10.1533/9781845699444.2.113.

[30] CATAURO M, and CIPRIOTI S V. *Sol-Gel Synthesis and Characterization of Hybrid Materials for Biomedical Applications*. Springer Singapore, 2019.

[31] TAYLOR N J. *Liquid-Feed Flame Spray Pyrolysis Synthesis of Oxide Nanopowders for the Processing of Ceramic Composites*. Ph.D. Thesis, University of Michigan, 2015.

[32] YILDIZ Ö, and SOYDAN A M. Synthesis of zirconia toughened alumina nanopowders as soft spherical granules by combining co-precipitation with spray drying. *Ceramics International*, 2019, 45(14): 17521-17528, doi: 10.1016/j.ceramint.2019.05.314.

[33] GRABIS J, STEINS I, RASMANE D, KRUMINA A, and BERZINS M. Particulate Nanocomposites Produced By Plasma Technique. *Proceedings of the Estonian Academy of Sciences, Engineering*, 2006, 12(4): 349-357.

[34] GONZALO-JUAN I, and RIEDEL R. Ceramic synthesis from condensed phases. *ChemTexts*, 2016, 2(2): 1-21, doi: 10.1007/s40828-016-0024-6.

[35] RAMING T P. *The synthesis of Nano-nano dual phase ceramic composites*. Ph.D. Thesis, University of Twente, 2000.

[36] MESHALKIN V P, and BELYAKOV A V. Methods

used for the compaction and molding of ceramic matrix composites reinforced with carbon nanotubes. *Processes*, 2020, 8(8): 1004, doi: 10.3390/PR8081004.

[37] ARMENTANI E, BOCCHINI G F, CRICRÌ G, and ESPOSITO R. Metal powder compacting dies: Optimised design by analytical or numerical methods. *Powder Metallurgy*, 2003, 46(4): 349-360, doi: 10.1179/003258903225008607.

[38] SARKAR D, MOHAPATRA D, RAY S, et al. Synthesis and characterization of sol-gel derived ZrO 2 doped Al 2 O 3 nanopowder. *Ceramics International*, 2006, 33: 1275-1282; doi: 10.1016/j.ceramint.2006.05.002.

[39] SERGENT J E. *Ceramic materials*. Chapter 4, In BARLOW F D., & ELSHABINI A. (Eds.). *Ceramic Interconnect Technology Handbook* (1st ed.). CRC Press, 2007. https://doi.org/10.1201/97813152212812007.

[40] RANE A V, KANNY K, ABITHA V K, and THOMAS S. *Methods for Synthesis of Nanoparticles and Fabrication of Nanocomposites*. Elsevier Ltd., 2018.

[41] DAUVERGNE C, and FANTOZZI G. Microstructural Investigation of the Aging Behavior of (3Y-TZP)–Al 2 O 3 Composites. J*ournal of the American Ceramic Society*, 2005, 88(5), 1273-1280, doi: 10.1111/j.1551-2916.2005.00221.x.

[42] DEVILLE, S., CHEVALIER, J., FANTOZZI, G., BARTOLOME, J., et al. (2003) Low-Temperature Ageing of Zirconia-Toughened Alumina Ceramics and Its Implication in Biomaterial Implants. *Journal of the European Ceramic Society*, 23: 2975-2982. doi: 10.1016/S0955-2219(03)00313-3.

[43] BIESUZ M, GRASSO S, and SGLAVO V M. What's new in ceramics sintering? A short report on the latest trends and future prospects. *Current Opinion in Solid State & Materials Science*, 2020, 24(5): 100868, doi: 10.1016/j.cossms.2020.100868.

[44] BOCANEGRA-BERNAL M H, DOMÍNGUEZ-RIOS C, GARCIA-REYES A, et al. Hot isostatic pressing (HIP) of α-Al2O3 submicron ceramics pressureless sintered at different temperatures: Improvement in mechanical properties for use in total hip arthroplasty (THA). *International Journal of Refractory Metals and Hard Materials*, 2009, 27(5): 900-906, doi: 10.1016/j.ijrmhm.2009.05.004.

[45] DATYE A, et al. Synthesis, microstructure and mechanical properties of Yttria Stabilized Zirconia (3YTZP) - Multi-Walled Nanotube (MWNTs) nanocomposite by direct in-situ growth of MWNTs on Zirconia particles. *Composites Science and Technology*, 2010, 70(14): 2086-2092, doi: 10.1016/j.compscitech.2010.08.005.

[46] MAJIDIAN H, EBADZADEH T, and SALAHI E. Effect of SiC additions on microstructure, mechanical properties and thermal shock behaviour of alumina-mullite-zirconia composites. *Materials Science and Engineering: A*, 2011, 530(1): 585-590, doi: 10.1016/j.msea.2011.10.027.

[47] NAGA S M, ABDELBARY E M, AWAAD M, et al. Effect of the preparation route on the mechanical properties of Yttria-Ceria doped Tetragonal Zirconia/Alumina composites. *Ceramics International*, 2013, 39(2): 1835-1840, doi: 10.1016/j.ceramint.2012.08.031.

[48] ERKIN CURA M, et al. Microstructure and tribological properties of pulsed electric current sintered alumina-zirconia nanocomposites with different solid lubricants. *Ceramics International*, 2013, 39(2): 2093-2105, doi: 10.1016/j.ceramint.2012.08.065.

[49] RINCÓN A, MORENO R, CHINELATTO A S A, et al. Effect of graphene and CNFs addition on the mechanical and electrical properties of dense alumina-toughened zirconia composites. *Ceramics International*, 2016, 42(1): 1105-1113, doi: 10.1016/j.ceramint.2015.09.037.

[50] ZHANG Y, et al. Effect of MgO doping on properties of low zirconium content Ce-TZP/Al2O3 as a joint replacement material. *Ceramics International*, 2017, 43(2): 2807-2814, doi: 10.1016/j.ceramint.2016.11.122.

[51] BOCANEGRA-BERNAL M H, DOMINGUEZ-RIOS C, ECHEBERRIA J, et al. Effect of low-content of carbon nanotubes on the fracture toughness and hardness of carbon nanotube reinforced alumina prepared by sinter, HIP and sinter + HIP routes. *Materials Research Express* , 2017, 4(8), doi: 10.1088/2053-1591/aa7f22.

[52] SIVANESAN S, LOONG T H, NAMASIVAYAM S, and FOULADI M H. Two-Stage Sintering of Alumina-Y-TZP (Al 2 O 3 / Y-TZP) Composites. *Key Engineering Materials*, 2019, 814: 12-18, doi: 10.4028/www.scientific.net/KEM.814.12.

[53] LEONOV A A, ABDULMENOVA E V, and KALASHNIKOV M P. Structure, Phase Composition, and Mechanical Properties of Composites Based on ZrO2 and Multi-Walled Carbon Nanotubes. *Inorganic Materials: Applied Research*, 2021, 12(2): 482-490, doi: 10.1134/S2075113321020313.

[54] BAIG N, KAMMAKAKAM I, FALATH W, and KAMMAKAKAM I. Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges. *Material Advances*, 2021, 2(6): 1821-1871, doi: 10.139/d0ma00807a.

[55] MITTELMEIER H. Zementlose Verankerung von Endoprothesen nach dem Tragrippenprinzip. *Z Orthop*, 1974, 112: 27–33.

参考文:

[1] RAHAMAN N, YAO A, BAL B, GARINO J, 和 RIES M. 用于假体髋关节和膝关节置换的陶瓷。美国陶瓷学会杂志，2007，90(7)：1965-1988。土井: 10.1111/j.1551-2916.2007.01725.x。

[2] MEROLA M 和 AFFATATO S. 髋关节假体材料：磨损和负载考虑因素综述。材料（巴塞尔），2019，12（3）：495，土井：10.3390/ma12030495。

[3] KNIGHT S R、AUJLA R 和 BISWAS S P. 100年的手术历史呃词我们艾尔艾尔。骨科评论，2011，3：2-4，土井：10.4081/or.2011.16。

[4] PAPAS P V、CUSHNER F D 和 SCUDERI G R。全膝关节置换术的历史。骨科技术, 2018, 33(1): 2-6, 土井: 10.1097/BTO.0000000000000286。

[5] AFFATATO S、MODENA E、TONI A 和 TADDEI P. 三代Biolox股骨头的检索分析：光谱和扫描电镜表征。生物医学材料力学行为学报, 2012, 13: 118-128, 土井: 10.1016/j.jmbbm.2012.04.003.

[6] HERNIGOU P. 史密斯-彼得森和髋关节置换术的早期发展。国际骨科，2014, 38(1): 193-198, 土井: 10.1007/s00264-013-2080-5。

[7] CINIGLIO M. 通过断层研究和拉曼光谱分析低温降解

对BIOLOX ®三角洲股骨头机械性能的影响。硕士学位论文。

[8] GOPAL V 和 MANIVASAGAM G. 用于骨科植入物应用的氧化锆-氧化铝复合材料。爱思唯尔公司，2019。

[9] PEZZOTTI G、YAMADA K、SAKAKURA S 和 PITTO R P. 用于髋关节假体的先进陶瓷复合材料的拉曼光谱分析。美国陶瓷学会杂志, 2008, 91(4): 1199-1206, 土井: 10.1111/j.1551-2916.2007.01507.x.

[10] PICONI C 和 MACCAURO G. 氧化锆作为陶瓷生物材料。生物材料, 1999, 20(1): 1-25, 土井: 10.1016/S0142-9612(98)00010-6。

[11] PALMERO P、MONTANARO L、REVERON H 和 CHEVALIER J. 氧化物粉末的表面涂层：一种加工生物医学级纳米复合材料的新合成方法。材料。2014, 7(7): 5012-5037, 土井: 10.3390/ma7075012.

[12] ANDEOL Q、VISTE A、DESMARCHELIER R、LERAT J L 和 FESSY M H. 美苏尔与塞拉苏尔轴承：平均18年的前瞻性随机研究。国际骨科，44(12): 2545-2551, 2020, 土井: 10.1007/s00264-020-04855-9。

[13] CROWNINSHIELD R D、ROSENBERG A G 和 SPORER S M. 改变全关节置换患者的人口统计数据。临床骨科及相关研究, 2006, 443(443): 266-272, 土井: 10.1097/01.blo.0000188066.01833.4f。

[14] NISHIHARA H、HARO ADANEZ M 和 ATT W. 牙科氧化锆植入物的现状：临床前试验。口腔修复研究杂志, 2019, 63(1): 1-14, 土井: 10.1016/j.jpor.2018.07.006.

[15] ROY M E、NOEL OF F 和 WHITESIDE L A. 人工老化和回收氧化锆增韧氧化铝股骨头的相变和粗糙化。关节成形术杂志, 2019, 34(4): 772-780, 土井: 10.1016/j.arth.2018.12.025。

[16] TATEIWA T.等人。BIOLOX®delta股骨头的爆破强度及其对低温环境退化的依赖性。材料 (巴塞尔), 2020, 13(2): 350, 土井: 10.3390/ma13020350。

[17] BIAMINO S、FINO P、PAVESE M 和 BADINI C. 溶液燃烧合成制备的氧化铝-氧化锆-氧化钇纳米复合材料。国际陶瓷，2006，32(5)：509-513，土井：10.1016/j.ceramint.2005.04.004。

[18] KUNTZ M 和 KRÜGER R. 微观结构和氧化铬含量对氧化锆增韧氧化铝性能的影响。陶瓷国际, 2020, 44(2): 2011-2020, 土井: 10.1016/j.ceramint.2017.10.146.

[19] MEIER E，GELSE K，TRIEB K，等。新型全无金属陶瓷全膝关节置换系统的首次临床研究。骨科外科与研究杂志，2016, 11(1): 21, 土井: 10.1186/s13018-016-0352-7.

[20] POITOUT D G. 骨科中的生物力学和生物材料，第二版，施普林格，伦敦，2016年，土井：10.1007/978-1-84882-664-9。

[21] ETHGEN O、BRUYERÈ O、RICHY F 等。全髋关节和全膝关节置换术中与健康相关的生活质量：文献的定性和系统评价。骨与关节外科杂志 - A 系列，2004, 86(5): 963-974, 土井: 10.2106/00004623-200405000-00012。

[22] AFFATATO S、RUGGIERO A、DE MATTIA J S 和 TADDEI P. 金属转移会影响股骨头的摩擦学行为吗？回收氧化锆和Biolox® 三角洲复合材料的粗糙度和相变分析。复合材料乙部分：工程，2016，92：290-298，土井：f,10.1016/j.compositesb.2016.02.020。

[23] HORNAK J. 氧化镁纳米粒子的合成、性质和选定的技术应用：综述。国际分子科学杂志，2021，22(23): 12752, 土井: 10.3390/ijms222312752。

[24] NEVELOS J E、INGHAM E、DOYLE C 等。髋关节模拟器中髋臼杯角度对“BIOLOX强”氧化铝陶瓷轴承对磨损的影响。材料科学杂志：医学材料，2001，12(2): 141-144, 土井: 10.1023/A:1008970027306。

[25] LOPES A CO、COELHO P G、WITEK L 等. 氧化锆增韧氧化铝复合材料老化后的纳米力学和微观结构表征。国际陶瓷，2019，45(7): 8840–8846，土井：10.1016/j.ceramint.2019.01.211.

[26] MASSIN P、LOPES R、MASSON B 和 MAINARD D. Biolox®三角洲陶瓷是否会降低全髋关节置换术中组件骨折的发生率？骨科与创伤学：外科与研究，2014，100(6)：S317-S321，土井：10.1016/j.otsr.2014.05.010。

[27] DAVIS E T, 等。R3TM三角洲陶瓷髋臼系统在全髋关节置换术中的中期结果。骨科手术与研究杂志，2021，16(1)：1-17，土井：10.1186/s13018-020-02192-6。

[28] SHERIF EL-ESKANDARANY M 等。机械铣削：用于制造纳米晶体和纳米复合材料的卓越纳米技术工具。纳米材料，2021, 11(10): 2484, 土井: 10.3390/nano11102484.

[29] ROJAC T 和 KOSEC M. 复杂陶瓷氧化物的机械化学合成。高能球磨，2010：113-148，土井：10.1533/9781845699444.2.113。

[30] CATAURO M 和 CIPRIOTI S V. 用于生物医学应用的混合材料的溶胶-凝胶合成和表征。施普林格新加坡，2019。

[31] TAYLOR N J. 用于陶瓷复合材料加工的氧化物纳米粉末的液体进料火焰喷雾热解合成。博士论文，密歇根大学，2015。

[32] YILDIZ Ö 和 SOYDAN A M. 通过将共沉淀与喷雾干燥相结合，合成氧化锆增韧氧化铝纳米粉末作为软球形颗粒。国际陶瓷，2019, 45(14): 17521-17528, 土井: 10.1016/j.ceramint.2019.05.314.

[33] GRABIS J、STEINS I、RASMANE D、KRUMINA A 和 BERZINS M. 等离子技术生产的微粒纳米复合材料。爱沙尼亚科学院学报, 工程, 2006, 12(4): 349-357.

[34] GONZALO-JUAN I 和 RIEDEL R. 凝聚相的陶瓷合

成。化学文摘, 2016, 2(2): 1-21, 土井: 10.1007/s40828-016-0024-6。

[35] RAMING T P. 纳米纳米双相陶瓷复合材料的合成。博士论文，特温特大学，2000。

[36] MESHALKIN V P 和 BELYAKOV A V. 用碳纳米管增强的陶瓷基复合材料的压实和成型方法。进程，2020，8(8)：1004，土井：10.3390/PR8081004。

[37] ARMENTANI E、BOCCHINI G F、CRICRÌ G 和 ESPOSITO R. 金属粉末压制模具：通过分析或数值方法优化设计。粉末冶金，2003，46(4): 349-360，土井: 10.1179/003258903225008607。

[38] SARKAR D、MOHAPATRA D、RAY S 等。溶胶-凝胶衍生的氧化锆2掺杂的铝2O3纳米粉末的合成和表征。国际陶瓷，2006，33：1275-1282；土井：10.1016/j.ceramint.2006.05.002。

[39] SERGENT J E. 陶瓷材料。第4章，在 BARLOW F D. 和 ELSHABINI A.（编辑）中。陶瓷互连技术手册（第1版）。CRC 出版社，2007。https://doi.org/10.1201/97813152212812007。

[40] RANE A V、KANNY K、ABITHA V K 和 THOMAS S. 纳米粒子的合成方法和纳米复合材料的制造。爱思唯尔有限公司，2018。

[41] DAUVERGNE C 和 FANTOZZI G. (3是-TZP)- 铝2O3复合材料老化行为的微观结构研究。美国陶瓷学会杂志，2005，88(5)，1273-1280，土井：10.1111/j.1551-2916.2005.00221.x.

[42] DEVILLE，S.，CHEVALIER，J.，FANTOZZI，G.，BARTOLOME，J.，等。(2003) 氧化锆增韧氧化铝陶瓷的低温老化及其在生物材料植入物中的意义。欧洲陶瓷学会杂志，23：2975-2982。土井: 10.1016/S0955-2219(03)00313-3。

[43] BIESUZ M、GRASSO S 和 SGLAVO V M. 陶瓷烧结有什么新进展？关于最新趋势和未来前景的简短报告。固态与材料科学的当前观点, 2020, 24(5): 100868, 土井: 10.1016/j.cossms.2020.100868.

[44] BOCANEGRA-BERNAL M H，DOMÍNGUEZ-RIOS C，GARCIA-REYES A，等。在不同温度下无压烧结的α-氧化铝亚微米陶瓷的热等静压(时髦的)：改善用于全髋关节置换术(THA)的机械性能。国际难熔金属和硬质材料杂志，2009，27(5): 900-906，土井：10.1016/j.ijrmhm.2009.05.004。

[45] DATYE A 等。氧化钇稳定氧化锆(3YTZP)-多壁纳米管(多壁碳纳米管)纳米复合材料的合成、微观结构和机械性能，方法是在氧化锆颗粒上直接原位生长MWNT。复合材料科学与技术，2010，70(14): 2086-2092，土井: 10.1016/j.compscitech.2010.08.005.

[46] MAJIDIAN H、EBADZADEH T 和 SALAHI E. 添加SiC 对氧化铝-莫来石-氧化锆复合材料的微观结构、机械性能和热冲击行为的影响。材料科学与工程：一个，2011, 530(1): 585-590, 土井: 10.1016/j.msea.2011.10.027。

[47] NAGA S M，ABDELBARY E M，AWAAD M，等。制备路线对氧化钇-氧化铈掺杂四方氧化锆/氧化铝复合材料力学性能的影响。国际陶瓷，2013，39(2)：1835-1840，土井：10.1016/j.ceramint.2012.08.031。

[48] ERKIN CURA M 等。脉冲电流烧结氧化铝-氧化锆纳米复合材料与不同固体润滑剂的微观结构和摩擦学性能。国际陶瓷，2013，39(2)：2093-2105，土井：10.1016/j.ceramint.2012.08.065。

[49] RINCÓN A、MORENO R、CHINELATTO A S A 等。添加石墨烯和CNFs对致密氧化铝增韧氧化锆复合材料的机械和电学性能的影响。陶瓷国际, 2016, 42(1): 1105-1113, 土井: 10.1016/j.ceramint.2015.09.037。

[50] ZHANG Y，等。氧化镁掺杂对低锆含量铈-TZP/氧化铝作为关节置换材料性能的影响。国际陶瓷，2017，43(2): 2807-2814, 土井: 10.1016/j.ceramint.2016.11.122。

[51] BOCANEGRA-BERNAL M H、DOMINGUEZ-RIOS C、ECHEBERRIA J 等。低含量碳纳米管对烧结法、时髦的法和烧结+时髦的法制备的碳纳米管增强氧化铝断裂韧性和硬度的影响[J].材料研究快报，2017，4(8)，土井: 10.1088/2053-1591/aa7f22.

[52] SIVANESAN S、LOONG T H、NAMASIVAYAM S 和 FOULADI M H. 氧化铝-是-TZP (铝 2 O 3 /是-TZP) 复合材料的两阶段烧结。关键工程材料，2019，814: 12-18，土井: 10.4028/www.scientific.net/KEM.814.12.

[53] LEONOV A A，ABDULMENOVA E V，和 KALASHNIKOV M P. 基于氧化锆 和多壁碳纳米管的复合材料的结构、相组成和机械性能。无机材料：应用研究，2021，12（2）：482-490，土井：10.1134/S2075113321020313。

[54] BAIG N、KAMMAKAKAM I、FALATH W 和 KAMMAKAKAM I. 纳米材料：合成方法、性质、最新进展和挑战的综述。材料进展，2021，2(6): 1821-1871，土井: 10.139/d0ma00807a

[55] MITTELMEIER H. 根据支撑肋原理对内置假体进行无水泥锚固。Z骨科，1974，112：27-33.