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A REVIEW ON THE BIOMEDICAL APPLICATIONS OF ALUMINA

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Abstract: This review presents the composition, structure, mechanical characteristics, and applications of alumina (aluminum oxide) in biomedical. Alumina used for implant manufacturing is either single-crystal sapphires or high density and quality polycrystalline. The major sources of highly-purity alumina are organic corundum and bauxite. Like any other brittle component, polycrystalline alumina's mechanical characteristics are largely dependent on grain size and porosity distribution. It was shown that, due to slowed subcritical crack production, the fatigue intensity of alumina could be increased above the crucial pressure due to the presence of liquid. Due to its high inertness, that results in outstanding biocompatibility and tissue nonsensitization, alumina has significant benefits over other products in biomedical uses. Just like in artificially joints and teeth, the higher compressive strength than tensile strength allows it more efficient for compressive loadings. There were some attempts for coating alumina on steel substrates in order to benefit of its outstanding biocompatibility and to resist metal oxidation.

Keywords: *Alumina, dental, implant, joint, knee.*

1. Introduction

Since 1970, aluminum oxide (commonly known as alumina) has been utilized as a material for the production of prosthesis and a devices component for surgical purposes. In an in vivo environment, it is an inert component that has good corrosion resistant. It induces limited reaction to the tissue and remains stable for plenty of years. It is present in emery, topaz, and emerald in nature as corundum, and also in ruby and priceless gemstones of sapphire. [1]. Industrially, it is isolated from ores including such cryolite and bauxite by the Bayer method. Alumina most important use is in aluminum metal manufacturing. Alumina is popularly seen as an abrasive because of its hardness and because of its elevated melting temperature as a refractory component., other than applications in prosthesis and surgical devices[2].

Industrially, using the Bayer process, alumina is isolated out of bauxite. In three stages, the Bayer mechanism can then be taken into account [3]:

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1. Extraction: minerals containing bauxite aluminum are purposefully isolated out of the insoluble components by dissolving them in a sodium hydroxide solution.

$$Al\,(OH)_3 + Na^+ + OH^- \rightarrow Al\,(OH)_4^- + Na^+ \qquad (1)$$

2. Accumulation: There is accumulation of crystalline aluminum trihydroxide. With the exception of controlled chemistries, that is the opposite of the isolation step.

$$Al\,(OH)_4 + Na^+ \rightarrow Al\,(OH)_3 + Na^+ + OH^- \qquad (2)$$

3. Calcination: To form alumina, aluminum trihydroxide is calcined. Water is pushed away in order to shape alumina,. This method determines the final product's properties.

$$2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O \qquad (3)$$

Depending on the product in which it will be used, the alumina produced through the Bayer method is re-crystallized. Depending on the heat-treatment conditions, alumina occurs in many crystal phases: α, δ, γ, η, θ, ρ, and χ. Nevertheless, α-alumina is quite thermally stable and thus seen as a biomaterial with a rhomboedral form a = 4.658Å and c = 13.191Å) as shown in **Figure 1**). The arrangement of O^- atoms including two-third octahedral locations inhabited by Al^{3+} ions might be seen as a tight-packed hexagonal set of O^- atoms [4]. Therefore, in a twisted octaedron, each Al^{+3} ion is bound to six O^- atoms. Each of these octaedrons has one hand on the top and one on the bottom layers. The effect is induced by Al^{+3} ion repulsion in the interaction of the heads of octahedra. These close packaging of the oxygen and aluminum atoms in this context enables to achieve better thermally and mechanically properties[5].

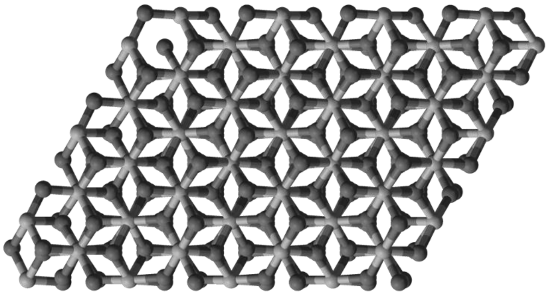

Figure 1. Structure of Alumina (Light and dark spheres refer to Aluminum and Oxygen molecules)[6].

α-alumina is high density (3.97 specific gravity), non-porous, and almost not active. It is exceptionally tough and scratch-resistant. (nine on the scale of Mohs, tight to the diamond). In vivo conditions, it has excellent resistivity to corrosion.[7] Resistance to fatigue and crack, rely on the alumina surface porosity and purity, and these affect the final properties. In contrast, alumina is extremely wet table on the ground, resulting in low friction coefficient. This outstanding wetting properties are attributed to an outside alumina layer in which it adsorbs water and biological molecules from a molecular movie. Alumina's weak resistance and wear coefficient exists Only if the roughness is a little below than 0.02µm, i.e. the size of the grain is less than 4µm with a very small size range. If the roughness of the surface reaches 0.02µm, broad grains will be out and contribute to very fast load-bearing surfaces wear. **Table 1**mentions some of the 99.5% purity alumina mechanical properties[8].

The porosity of alumina could be adjusted by the manner it is treated. Two main chemical methods are used in alumina production:

1. The conventional method of ceramic powder: this procedure requires the following procedure: powder extraction, shape formation and the densification,

normally witha finishing of the final phase. The ceramics developed by the current approach are very compact, having a porosity of almost zero percent.

2. Solution/gelation or "sol/gel": The method is mainly used to manufacture porous alumina or alumina that is used for coatings applications up to forty percent porosity. There are four key steps associated: starting from dispersion followed by gelation, then drying, and finally firing.

Table 1. Mechanical properties of Alumina (99.5% purity)

Mechanical Property	Value (99.5% Alumina)
Density	3.96 (g / cm3)
Flexeural strength	344 M Pa
Elastical module	310.0 G Pa
Share module	125 G Pa
Module (Bulk)	170 G Pa
Poissons ratio	0.22
Compressive	2200 M Pa
Hardness	1000 kg/mm2
Fractured toughness	3.51 M Pa. m1/2

The environmental effects of aluminum-based ceramics are usually marginal, but this is not valid for methods of processing. All of these processes can affect the environment significantly. For the conventional ceramic powder process a more significant environmental impact comes from the process of forming in which various binders, solvent and other harmful agents were utilized. Strong acids, binders, solvents, and plasticisers are used for the sol/gel process. Organic compounds with Various concentrations could be released as a product of combustion, like plasticizers and binders, depending on the firing circumstances, resulting in sever environmental effects.

2. Biomaterial Applications of Alumina

In an in vivo setting, alumina is not active and immune to corrosion[9]. This induces limited tissue reaction and holds stable for several years. It resists bioresorbable; therefore, the body identifies and tries to distinguish it as impurities, through the developed of a fibrous capsule across the implant. Moreover, as an aluminum product is inserted, biomolecules and proteins adsorb on the substrate in jiffy, thereby shielding the implant from the immunity response of the skin. In practice, it is possible to adjust the surface between tissues and alumina, avoiding the creation of a fibrous envelope across the implant. Alumina is biocompatible, though, implant-wearing alumina particles may induce a significant foreign-body reaction[10].

Mohanty [11] reviewed the applications of Alumina-ceramic alloys in biomedical applications. In this review, Mohanty classified alumina ceramic into biodegradable, bioinert, and bioactive; depending on the response of the body.

The uses of porous alumina have been reviewed, analyzed, and discussed by Xifre-Perez et al. [12]. This analysis comprises biocompatibility, surface morphology, in-depth nanostructuring, surface processing and coatings.

In the current paper, a review was made on the different applications of alumina in different biomedical fields, including dental application, joint replacement, and bone spacers.

3. Nanoporous Alumina

Planar and cylindrical nano-porous alumina sheets with diameters ranging from 5 to 130nm can be generated using a diluted solution of either oxalic acid or sulfuric acid with anodizing voltages of approximately 8 to 100 volts. The pores ' size is calculated by the width of the resultant surface of alumina and can range from nanometers to plenty of hundreds of microns. To achieve high uniformity of the pore, a two-step anodization system is used. In a sulfuric acid or oxalic bath, the aluminum surface is first anodized[13].

Upon absorbing a few microns of aluminum, the anodization is halted and the transparent alumina coating is extracted through out etching. The etchant, a combination of chromical acid and phosphoric acid, destroys alumina even quicker than aluminum, which is highly selective. The remaining aluminum is dimpled with the dimples acting as a standard surface of seed from which by the second step of anodization an exceedingly uniform porous layer can be produced. The exact size of the pore and the pore shape is calculated by regulating the anodizing voltage in this second anodization.

The diameter of the pore increases at about 1.28nm per volt with anodization voltage. Fixed anodizing voltages resulting in straight pores, whereas step-by-step anodizing voltage changes could be used to add smaller diameter branch channels, allowing the manufacture of a tree-like nanoscale structure. Such nanoporous could be utilized either as orthopedic implant coatings to osseointegration enhancement or as protein separation membranes (Figure 2).

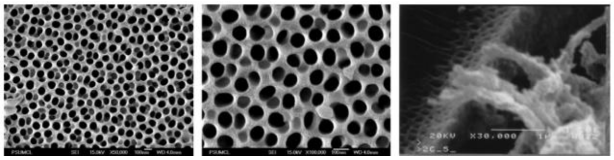

Figure 2. Nano porous alumina. The left and center is fabricated using the anodization process while the right architecture is Osteoblast interaction with the nano porous[1].

4. Alumina as Joint Replacements

It was first discovered in the seventeenth of last century that it was possible to exploit the characteristics of alumina ceramics to supply improved the applications of orthopedic of the implants for. From then on, owing to its outstanding resistance to wear and the capability to create clean and polished surfaces, alumina has often been used for worn surfaces for joint replacement protheses[14]. Alumina is typically used in the manufacture of femoral heads for hip substitution implants and knee replacement implants wear plates. About three million femoral heads of alumina have been inserted to date. Full hip replacement and knee replacement implants are shown in Figure 3 and Figure 4[15]. For hip substitution, the alumina femoral head for the opposite articulating layer is used together with a plastic femoral tip and an acetabular cup constructed of extremely-high molecular weight of polyethylene (EHMWPE) or alumina. [16]. Two factors depend on the success of such joint substitution:

1. The wear behavior and frictional of the materials, and
2. The quality of implant anchorage to the natural tissue.

Researches have shown that alumina wear levels on EHMWPE are approximately twenty times smaller than on the ultra-high-molecular-weight polyethylene (UHMWPE) for iron, culminating in lower debris production. Wear debris leads to complex and difficult conditions like osteolysis, leading to long-term implant failure[17]. A pair of ceramic bearings in alumina–alumina is preferable to alumina–EHMWPE or metal, culminating in good resistance of wear and preventing the response of inflammatory from the particles of the polyethylene. In contrast, tests have also shown that ceramic debris from EHMWPE is less toxic. Alumina head fracture rates range from 0 percent for ceramics produced after 1990 to 13.4 percent for pre-1990 ceramics. When low-density alumina with a very rough microstructure was utilized, the large fracturing levels of alumina heads prior to 1994 were triggered[18].

Material scientists have significantly improved alumina processing techniques over the years, leading to increased mechanical strength. Today's generation is alumina pressed heavy, laser labeled and checked for evidence. Since 1994, this material is on the market. Femoral head fracture rate is 0.004 percent[19]. Alumina is used in complete knee replacements for parts that come into contact with bone, and in slipping sections a mixture of alumina and EHMWPE is used. Issues caused by polyethylene contamination in these devices are far more serious than in hip implants (Figure 3and Figure 4).

In orthopedic uses, alumina is not the best product. The alumina-grade modulus of the Young is 370–410GPa. This is greater than cancellous bone (0.055–0.55GPa) or corticalbone (6–26GPa) (Young's module often relies on the person's age and bone tissue position in the body). Therefore, the mechanical characteristics of alumina and bone are not paired[20]. The implant of alumina will shield around the bone from any other mechanically loading, and the implant will carry the entire load. Such mechanical protection can contribute to compressive stress on the bone, resulting in the bone being resorbed and weakened, resulting in implant failure[21].

Figure 3. Total hip replacement[22].

Figure 4. Knee replacement[23].

5. Bone Spacers Applications of Alumina

The porosity alumina of more than thirty percent might be utilized as bone spacers to cover missing bone parts due to traumatic injury or cancer. Bonse spacers are placed onto tissues using metal pins [24]. The dynamic elastic design of the implant enables bone cells to penetrate into the implant, eventually resulting in a new structure of tissue. Usually the pore width exceeds 100μm. [25] This will not only allow the bone to expand, it will also facilitate vascularization. Porous alumina is extracted either by sol/gel or by a hydrothermal exchange system to expose the porous structure of corals nanocrystals [26-28].

6. Alumina as Dental Applications

High density alumina was used practically for teeth replacement of the dental applications (**Figure 5**). As polycrystalline alumina could be fractured during inserting the implant into the root of the dental, single crystal alumina is used for dental implants. The bending strength of single crystal alumina (12,500 kg/cm^2) is higher than that of polycrystalline alumina (3,400 kg/cm^2). Implants are typically constructed by cylindrical single crystal alumina core allaround in which polycrystalline alumina is fused. Alumina dental implants have several disadvantages. They have a high elasticity implant module. In result, the use of alumina implants is increasing and substitutes like those of dental porcelain are now being substituted[29].

Figure 5. Ceramic dental implants[30].

Like any brittle material, polycrystalline alumina's thermodynamic properties are entirely dependent on droplet size and propagation and porosity. For instance, high-purity alumina's compressive strength could be represented as " σ=K.d^{-n}", in which "K" and "n" are constants parameters function on the temperature, and "d" is the volume of the plant. This association with pure alumina is shown in Figure 6[31].

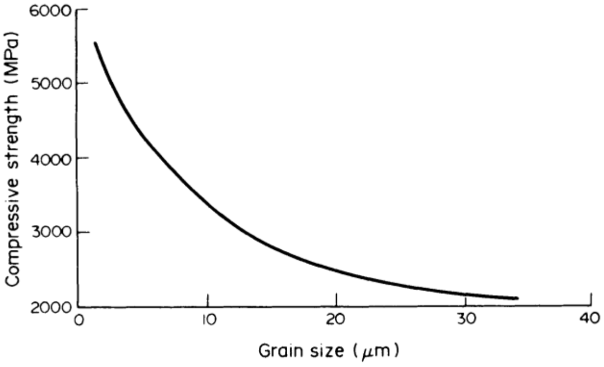

Figure 6. Connection of size of grain and compressive strength for alumina[32].

The correlation for high density alumina between porosity and grain size is shown in Figure 7. The grains have been much smaller once the porosity is below 2 percent, which decreases the intensity as mentioned above. Through incorporating 0.1% MgO, the width of grains can be reduced to 2μm or less.

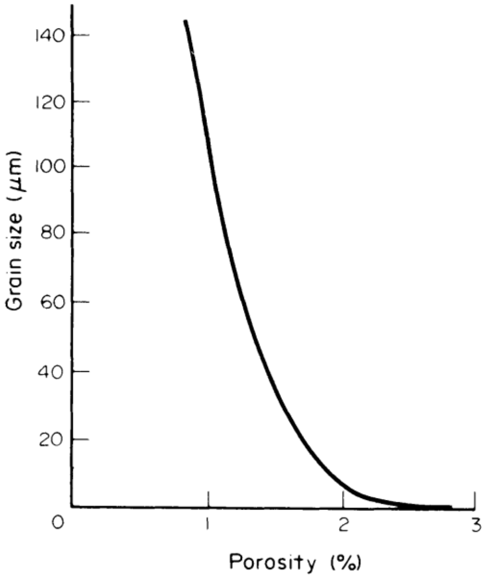

Figure 7. Connection of porosity and grain size[33].

7. Other Applications of Alumina

Alumina was used for ENT applicants and maxillofacial surgery in addition to joint institution, spacers for bones, and implants. For neurochirurgical operations such as cranioplasty, alumina implants were also used. In keratoprostheses (corneal replacement) alumina was also used. Porous alumina was also used over long periods of time to control the delivery of vaccines, drugs, and hormones.

8. Alumina Matrix Composites

Composites of the alumina matrix compose of alumina, which constitutes 82 percent of the total product weight. Zirconium oxide (known as zirconia) nanoparticles are applied to the alumina matrix, making up twenty percent of the volume. In the tetragonal phase, these particles are stabilized since they provide good mechanical characteristics. The composites are strengthened in various forms:

1. Formation of elongated strontium oxide crystals in the matrix in situ, which deflects any subcritical cracks;
2. Adding small particles of zirconia homogeneously dispersed in the matrix, and then creating a toughening conversion;
3. Building a solid alumina solution with chromium oxide, leading to increased durability.

The USFDA has licensed composites of alumina matrix for utilization in implant ball-head as a constitution for EHMWPE. In 2001, the very first clinical trials were carried out, with over 65,000 ball heads inserted globally since then.

9. Conclusion

In an in vivo setting, alumina is very inactive and immune to corrosion. Alumina causes minimal tissue reaction and stabilizes for plenty years of application. While some implants are individual crystals, plenty of the alumina are polycrystalline. Because of its outstanding resistance to corrosion, good tear resistance, biocompatibility, and strong compressive strength, it is commonly used in loadbearing applications. In addition, alumina has the most appropriate tribological properties in orthopedic implants for articulating surfaces. High elasticity modulus, low toughness, cyclic failure, smooth crack growth, and tensile strength sensitivity are part of the concerns for strong load-bearing applicants, however. Recently, alumina matrix ceramics investment may extend the implant lifespan for the current 15 years. The employment of alumina is expected to continue to expand in the near future in dental, orthopedic, and maxillo-facial applications.

Conflicts of interest

There are no conflicts to declare.

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