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Improving Sustainability of Technical Ceramics Production: Synergistic Approach

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Abstract

Sustainable development is a concept focused on preserving current resources for them to be available to future generations as well, while at the same time fulfilling current human needs and facilitating adequate levels of development. Nowadays, there are many possible applications of sustainability principles, such as in the fields of the economy, agriculture, environment, energy, transport, architecture, and production. Sustainable production of materials and goods aims at improving the processes which are less damaging to the environment, which conserve natural resources and use low levels of energy, possibly derived from sustainable sources. One of the intensive energy- and resource-consuming industries is the conventional production of technical ceramics. Although non-toxic, ceramic waste is generated during the machining of the green bodies and is typically landfilled. To improve the sustainability of technical ceramics production, methods of recycling ceramic waste need to be developed and applied.

Keywords: sustainability, technical ceramics, alumina, aluminum oxide, waste, recycling

JEL classification: Q30

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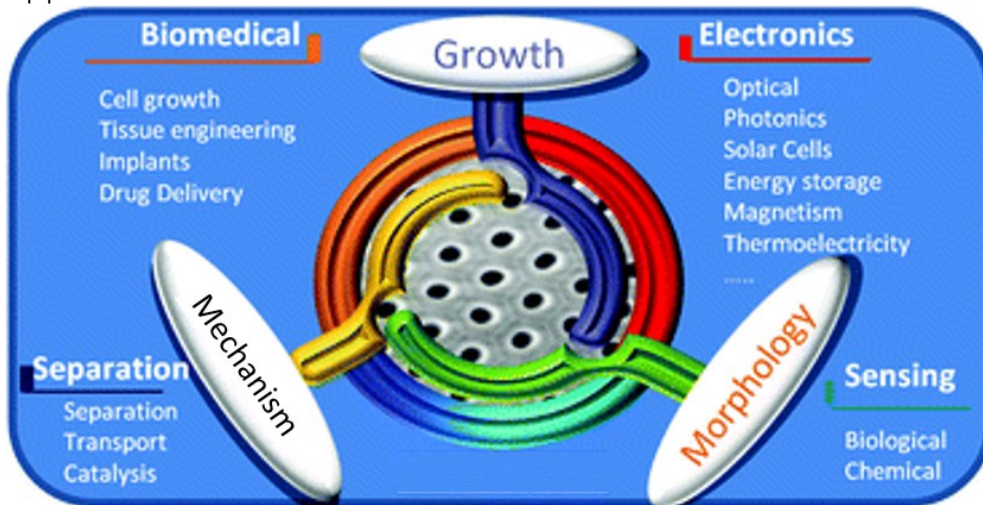
Introduction

Technical or engineering ceramics are inorganic materials with a combination of properties that make them an optimal selection for many applications where most other materials cannot be applied. The most well-known applications of technical ceramics are electronics and electrics, aerospace and aeronautics, chemical engineering, and medicine and dentistry, Ruys (2018), Figure 1. All advanced technical ceramics applications require high-purity materials due to their high property requirements.

Some of the most extraordinary properties of technical ceramics include high wear resistance due to high hardness, excellent thermal conductivity while being an electric insulator. Materials that withstand the highest temperatures, at which metals may not be used, are ceramics. Alumina or aluminum oxide, Al_2O_3 , is one of the most widely used technical ceramics, due to its favorable combination of physical (such as hardness, strength, toughness) and thermal properties (thermal conductivity, dimensional stability), corrosion resistance to most aggressive media, and reasonable price (Piconi et al., 2014).

Most technical ceramic applications require the production of highly controlled ceramic powders, with uniform particle size, and often nanosized to minimize the porosity of the final product. Appropriate selection of the processing additives is the next difficult process stage since the type and optimal amounts of additives strongly influence the final ceramic properties. Finally, an energy-intensive and carefully controlled production process, called firing or sintering is needed to harden the ceramic product.

Figure 1
Applications of Aluminium Oxide Ceramics

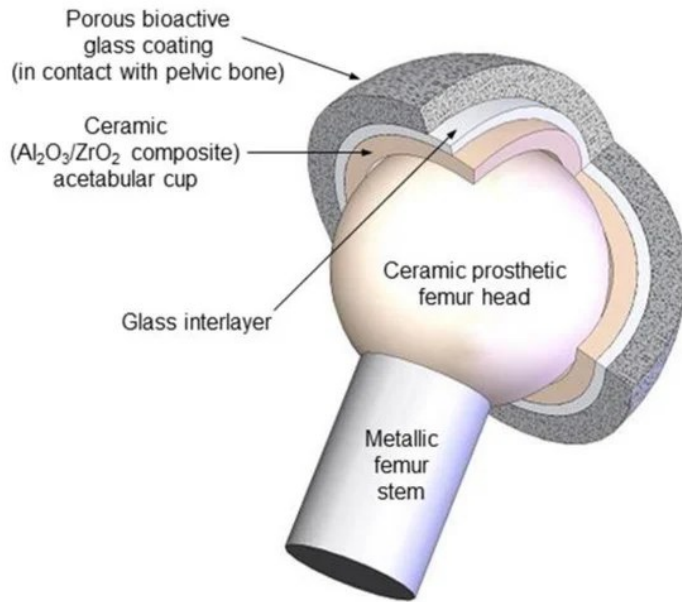


Source: Ruiz-Clavijo (2021)

The first applications of alumina ceramic in medicine were done in the 1960s. Since then, many improvements in the production of parts acting as substitutes for human teeth and bones were done. Due to high chemical resistance, i.e., inertness, ceramics are considered a safe and biocompatible material. Due to high wear resistance, ceramics are favorable materials selection for load-bearing prostheses, such as hip prosthesis, Figure 2 and dental implants, Figure 3.

Figure 2

Aluminum Oxide / Zirconium Oxide Composite Ceramic Implants for Femoral Prosthetics







Source: Baino (2019)

Ceramic parts are typically formed from ceramic powder either by pressing the powder in a mold or by mixing the powder with water and casting, which is a process known as slip-casting. Novel production techniques, such as 3-d printing, are being developed to produce highly complex geometry parts which would be otherwise impossible to obtain by pressing or casting. The current research trend in ceramics is focused on the development of new materials and processes, but also on improving the properties of already known ceramic materials.

Figure 3

Aluminum Oxide and Zirconium Oxide for Dental Crowns and Dental Bridges

<p>Crown</p> 	<ul style="list-style-type: none"> • Zirconia • Alumina • Lithium disilicate • Composite resins 	<p>Onlays & Inlays</p> 	<ul style="list-style-type: none"> • Zirconia • Alumina • Lithium disilicate • Unfilled resins • Composite resins • Amalgam
<p>Bridge</p> 	<ul style="list-style-type: none"> • Gold alloys • Stainless steel • Ni-Cr alloys • Co-Cr alloys 	<p>Veneer/Dental facet</p> 	<ul style="list-style-type: none"> • Lithium disilicate • Leucite • Composite resins

Source: Branco (2020)

Slip casting is a reasonably simple and cost-effective technique, environmentally friendly and versatile, as products of different sizes and shapes may be produced.

Most ceramic powders have a low affinity towards water, i.e., are hydrophobic, and different additives must be used to prevent sedimentation. These additives are called dispersants, and the mixture of water and ceramic powder is typically called suspension, slurry, or colloidal solution. To optimize the suspension and the subsequent casting, rheological, i.e., flow properties must be optimized, Baino (2019). The parameters that must be optimized are, first, related to the flow properties of the suspension, for it to be as low in viscosity as possible while maximizing the solid load, i.e., the ceramic content. Second, suspension compositions may be optimized for the highest density of the ceramic part before and after sintering, for highest hardness, for highest impact strength, or other properties.

After the suspension is cast into a mold, it needs to dry, after which a brittle and soft body is produced, the so-called green body. The green bodies are then machined (drilled, milled, or similar) to add final geometry details or to correct the surface shaping. These material removal processes inevitably produce a waste ceramic powder. This waste is usually disposed of in regulated landfills, as is legally prescribed. Ceramic powder generated after machining of the green bodies is classified as "Absolute Non-hazardous" to the environment, according to the European List Of Waste, Eurostat (2010). Different county legislations allow either wet or dry landfilling, or both, Dentoni (2014). Nevertheless, the landfilling taxes must be paid, so additional costs arise when the waste ceramic powder is not recycled. If the waste ceramic powder would be used for producing new ceramic components, it would both eliminate the landfill costs, as well as lower the costs of buying new, unused ceramic powder.

The "Transforming our world: the 2030 Agenda for Sustainable Development" was adopted in 2015 by the United Nations, for it to be implemented up to 2030. The Agenda aims at achieving a more balanced development through the improvement of different aspects of human life on Earth. The Agenda is comprised of 17 Sustainable Development Goals (SDGs), and the 169 Targets connected to the Goals. SDGs comprise a wide area of challenges in sustainable development and different interconnected economic, social, and environmental problems, Transforming our world: the 2030 Agenda for Sustainable Development (2015). The goals that are most strongly connected to the more sustainable production of ceramic materials are Number 12: Responsible Consumption and Production, and Number 13: Climate Action,

Figure 4. Climate Action goals are focused on the reduction of the carbon footprint of all the necessary processes. In the case of technical ceramics production, the intensive energy processes involve the production of aluminum oxide from the bauxite ore and the sintering of the ceramic.

Figure 4

Sustainable Development Goals related to Ceramic Materials production



Source: United Nations (2015)

Goal 12 Targets that are most closely related to the technical ceramics production are:

- 12.2 "By 2030, achieve the sustainable management and efficient use of natural resources" by reducing the amounts of bauxite ore extraction.
- 12.4 "By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle by agreed international frameworks, and significantly reduce their release to air, water and soil to minimize their adverse impacts on human health and the environment" by reducing and optimizing the amounts of additives used in the processing of the green bodies, and by replacing conventional ceramic additives, that are typically synthetic organic compounds, with greener additives, for example, citric acid, Sever (2018).
- 12.5 "By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse", which in the production of alumina technical ceramics is oriented towards the recycling of waste powder that is left over after machining by using it as a replacement instead of new alumina powder, Vukšić (2021).
- 12.6 "Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle", which is closely related to ceramics produced for electric and electronic components, since its ever-increasing worldwide demands, Vukšić (2019).

Methodology

Green bodies of alumina ceramics were produced by the slip casting process. Aqueous suspensions were prepared by adding primary (new) and secondary (waste) alumina powder to the distilled water. Primary high-purity alumina powder was produced by Alcan Chemicals, USA, had an average particle size of 300 nm to 400 nm, and its composition is presented in Table 1.

Table 1

Composition of new Alumina Powder

MgO	0.066 wt%
Fe₂O₃	0.015 wt%
SiO₂	0.02 wt%
Na₂O	0.05 wt%
CaO	0.015 wt%
Al₂O₃	Rest

Secondary alumina powder was obtained from the production of technical ceramics in the American-Croatian company Applied Ceramics, i.e., from the facility in Sisak, Croatia after the machining of green bodies. The first study involved the preparation of different ratios of waste to new ceramic powders, namely: 15, 20, 45, and 60 dwb% waste alumina powder, where dwb% is the abbreviation for dry weight basis, i.e., the mass fractions of waste alumina powders was calculated based on total amounts of both ceramic powders (new and waste) before adding distilled water. To all samples of distilled water, a commercially available dispersant called Tiron from Sigma-Aldrich Chemie GmbH, Germany was added in different amounts from 0.03 to 0.2 wt%. After the powder mixture was added to the distilled water, the obtained suspensions were homogenized in the planetary ball mill PM 100 by Retsch

GmbH, Germany, using the rotational speed of 300 rpm for 60 min. The homogenization was assisted by the addition of eight high-purity alumina balls, each 10 mm in diameter. The cup of the ball mill was also made from high-purity alumina, in order not to add impurities to the prepared suspensions.

After analyzing the influence of the dispersant Tiron amount on the apparent viscosity of prepared suspension with different amounts of waste powder, the most favorable suspension composition was used for further research. The selection criteria were the highest amount of added waste alumina powder while keeping the apparent viscosity below 25 mPa s. The selected suspension was cast in several gypsum molds of 21 mm × 21 mm × 21 mm and green bodies were prepared, and then sintered in an electric furnace, i.e., conventionally, at 1550 °C. The applied heating rate was 5 °C min⁻¹, and the holding time was 2 h. After cooling, the density of the sintered ceramics was determined using Archimedes' method in distilled water. The calculation of the relative density was done based on the theoretical density of alumina ceramics 3.987 g cm⁻³. Scanning electron microscopy was used for the study of the microstructure by Tescan Vega3 microscope, Brno, Czech Republic.

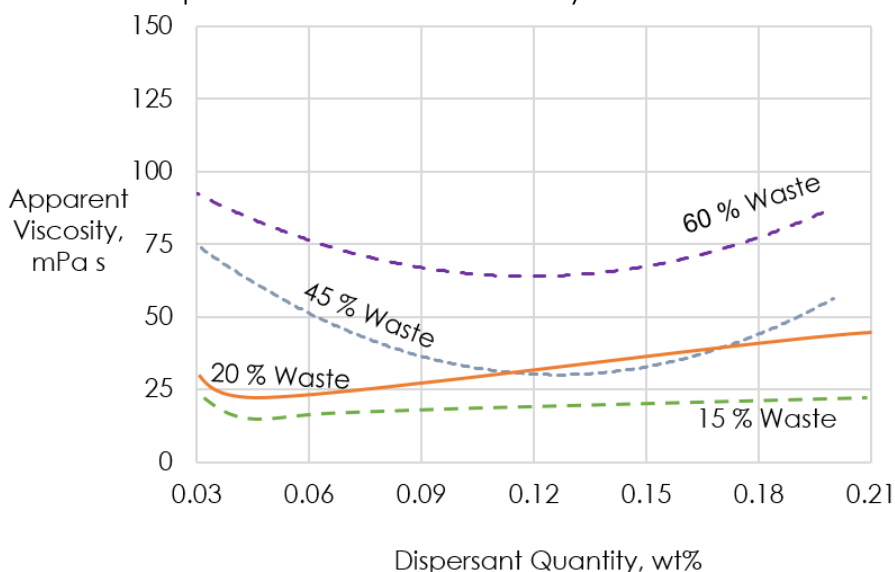
Results

The analysis of the influence of the amount of dispersant Tiron on the apparent viscosity for each suspension, i.e. with different amounts of waste powder, is shown in Figure 5. The apparent viscosity shown in Figure 5 was measured at a shear rate of 51.44 s⁻¹, as the closest to the shear rate of 50 s⁻¹, corresponding to the theoretical shear rate in gravitational casting.

For the suspension with 60 dwb% of waste (secondary) alumina powder, the viscosity was too high for it to be adequate for the slip casting technique. The suspension with 45 dwb% waste powder would require a high amount of dispersant for achieving the optimal viscosity. Both suspensions, with 15 and 20 dwb%, were found to need a minimal amount of dispersant for achieving the lowest viscosity.

Figure 5

Influence of Dispersant Amount on Viscosity for different Amounts of Waste Powder

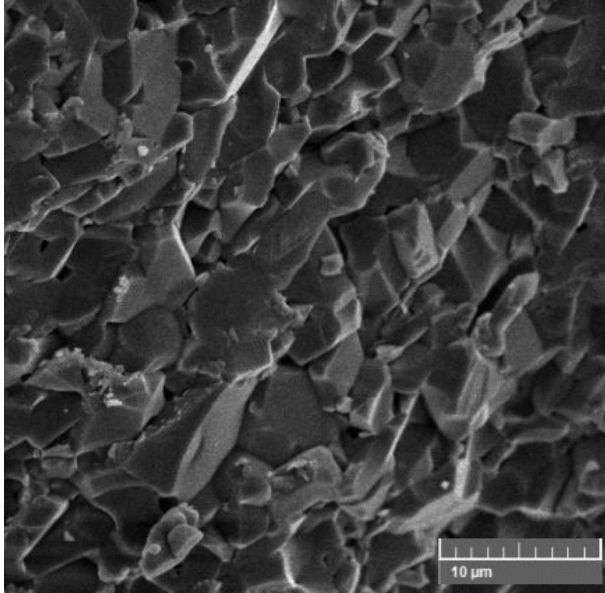


Based on the theoretical density of aluminum oxide, the relative density of the sintered samples was calculated to be 97.2 %, which is not a fully satisfactory value for pure slip cast alumina ceramics, Anand (2014).

Scanning electron microscopy showed that the bonding between the alumina particles was satisfactory, Figure 6. The analyzed micrographs of samples showed similar morphologies through the sample: the grain size was in the range between 1 to 10 μm , with irregularly shaped alumina grains, having sharp edges and being randomly orientated.

Figure 6

Scanning Electron Microscopy Image of Sintered Alumina (3300 Times Magnification)



Conclusion

The recycling options for waste alumina powder, obtained by machining the green bodies were studied. Suspensions with 45 and 60 dry weight base percent of waste alumina powder were found to be too viscous for slip casting technique. The most appropriate amount of added waste alumina powder was found to be 20 dwb%, for it required a very low amount of dispersant while adding a significant amount of waste into new material. The achieved relative density was high, considering that ceramic waste powder was used. Higher values may be achieved for pure alumina ceramics. Scanning electron microscopy confirmed a good bonding of alumina particles without abnormal grain growth.

This study shows that it is possible to recycle waste alumina powder by mixing it with a larger part of new alumina powder to produce technical ceramics by slip casting. The effect of other additives should be studied, as well as the interaction between additives. Typically, besides dispersants, additives that improve green body strength are used too, as well as additives that lower the risk of abnormal grain growth of ceramics during sintering.

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