Australian Journal of Basic and Applied Sciences, 8(19) Special 2014, Pages: 252-257

AENSI Journals

Australian Journal of Basic and Applied Sciences

ISSN:1991-8178

Journal home page: www.ajbasweb.com

Review on the Translucency of Zirconia (Y-TZP) Ceramics for Dental Crown Applications

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ARTICLE INFO

Article history:
Received 15 April 2014
Received in revised form 22 May 2014
Accepted 25 October 2014
Available online 10 November 2014

Keywords:
yttria-stabilized tetragonal zirconia; dental crown; translucency; particle size; sintering temperature; slip casting

ABSTRACT

Background: Zirconia-based dental ceramic is widely used for crown restoration because of its superior mechanical properties and favorable biocompatibility. However, yttria-stabilized tetragonal zirconia (Y-TZP), which is used in most dental crown restorations, has low translucency. **Objective:** Core translucency or opacity, one of the primary factors that control dental aesthetics, is a very important consideration in the selection of materials used for ceramic restoration. Researchers have made considerable progress in producing translucent Y-TZP, which is similar in appearance to natural teeth. **Results:** This paper discusses several parameters that affect the translucency of zirconia, including the particle size of the zirconia powder, the fabrication method used, the sintering temperature, the presence of additives, and the rheological properties of the slurries (slip casting). **Conclusion:** Controlling of these parameters allows the fabrication of zirconia with enhanced sintered density and few pores, thus improving its translucency to match the natural appearance of human teeth.

To Cite This Article: K.Y. Theng, A. Muchtar , Norziha Yahaya, Ghazali M.J., Review on the Translucency of Zirconia (Y-TZP) Ceramics for Dental Crown Applications. ***Aust. J. Basic & Appl. Sci.,*** *8(19): 252-257, 2014*

INTRODUCTION

A dental crown is a tooth-shaped cap placed over a tooth to restore its shape, size, and strength and improve its appearance. It prevents a weak tooth from fracturing or holds together parts of a broken tooth. Dental crowns are ideally made from materials with superior optical characteristics (i.e., resembling real teeth) and bio-inertness or biocompatibility to prevent rejection of the implanted crown by the body. These crowns further feature suitable mechanical properties to replace the function of the enamel without hampering the opposing tooth.

Since the introduction of ceramic dental restoration, increased demands for new materials and processing technologies for all-ceramic restoration with significantly improved mechanical properties have been observed (Chang, Y.Y., 2011). Besides mechanical strength, the aesthetic aspect of all-ceramic restoration plays an important role in matching color to the natural appearance of the tooth. Core translucency or opacity is one of the primary factors that influence dental aesthetics. Thus, this factor is a very important consideration when selecting the material to use for ceramic restorations.

An all-ceramic crown can be divided into two parts, namely, the inner core and the outer veneer. The inner core is made of ceramic with excellent mechanical properties. The ceramic for outer veneers is selected for its superior aesthetic. Incompatibility and cohesive failure between these two types of ceramic can cause veneer ceramic chipping. Fabrication of full-contour ceramic restoration is the solution to this problem.

Among a variety of ceramic materials currently available, yttria-stabilized tetragonal zirconia (Y-TZP) exhibits excellent biocompatibility and superior mechanical properties, both of which are attributed to its transformation toughening capability. Zirconia exists in several forms as a polycrystalline ceramic with no glassy phase (Ramesh, S., 1999). For example, zirconia exists as a monoclinic phase at room temperature and transforms into a tetragonal or cubic phase when sintered. Y-TZP is used in several applications, such as fixed prostheses and dental implants. Despite its high mechanical strength, however, zirconia restorations exhibit poor translucency and, thus, fails to satisfy the requirements of aesthetic dental restoration.

This study reviews the different parameters that affect the translucency of Y-TZP ceramics. These parameters include the particle size of the Y-TZP powder, the fabrication method used, the sintering

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Australian Journal of Basic and Applied Sciences, 8(19) Special 2014, Pages: 252-257

temperature, the presence of additives, and the rheological properties of the slurries, all of which can significantly affect the appearance of dental ceramics.

Translucency of Zirconia:

Translucency or light transmittance is the fraction of incident light that passes through a medium. It is the key criterion necessary for dental ceramic to achieve a superior aesthetic appearance. Translucency is an important consideration in the selection of dental materials and closely associated with the chemical composition and microstructure of dental ceramics. The translucency of a dental material also depends on its light-scattering property. When light strikes the surface of an object, light is distributed by scattering centers, such as pores and grain boundaries. However, when the scattering center is smaller than the wavelength of the incident light, light scattering is inhibited, resulting in translucency (or even transparency) of the material. Thus, controlling the scattering centers of a material is the key to developing a translucent material.

In dental research, ceramic translucency is expressed as a contrast ratio. The optimum translucency of a ceramic should be within the range of translucency of the natural tooth. If the ceramic material is too translucent, the ceramic cannot mask the discoloration of the underlying tooth structure or restoration. The translucency of anterior teeth is an important consideration and desirable property for aesthetic reasons.

Parameters Affecting the Translucency of Zirconia:

Particle size of Y-TZP powder:

The particle size of Y-TZP powder is the first parameter to consider when developing translucent zirconia. Researchers have developed translucent zirconia using nano-sized powders to create high densification during sintering and form nanocrystals. Nano-sized powder is used because of its large surface area, which provides a substantial sintering driving force. This characteristic helps decrease the activation energy and sintering temperature of the specimen. At lower sintering temperatures and shorter diffusion distances, the specimen is easily sintered with high relative density, simultaneously minimizing pore formation in the microstructure of the ceramic.

The use of nano-sized powders also promotes the formation of smaller crystals. The volume fraction and mean size of sample crystals affect light transmittance. Grain sizes smaller than the wavelength of visible light (380 nm to 780 nm) inhibit light scattering in the material, thereby improving the translucency of the material. (Apetz, R., 2003) showed that polycrystalline alumina with a small crystal size exhibits greater translucency than alumina with a large crystal size.

Sintering temperature:

The sintering temperature influences the light transmittance properties of Y-TZP by changing its microstructure and crystalline phases (Denry, I., J.R. Kelly, 2008). During sintering, pores in the granular material are eliminated by atomic diffusion driven by capillary forces. The rise in sintering temperature results in solid-state diffusion, and particles are sintered together. This process produces zirconia ceramics with higher relative densities. The density of a ceramic material is a key factor that affects its translucency because this property controls the number and size of pores in the microstructure. At high relative densities, the porosity of the ceramic microstructure is minimized and less light is scattered (Jiang, L., 2011). Reported that transmittance exceeds 17% when the density of a Y-TZP specimen is theoretically higher than 98.5% at temperatures ranging from 1450°C to 1500°C.

In addition to porosity control, formation of homogeneous zirconia microcrystals in the tetragonal phase can also achieve good light transmittance. The tetragonal phase reduces light scattering at the interface between adjacent crystals. (Djurado, E., 2000) reported that tetragonal zirconia has a smaller crystal size (~13 nm) than monoclinic zirconia (~22 nm). Smaller crystal sizes minimize the light-scattering properties of the ceramic. Controlling the sintering temperature is thus important in forming tetragonal-phase zirconia. Transformation from the monoclinic phase to the tetragonal phase of zirconia occurs when the sintering temperature reaches 1170°C. Addition of 3 mol% yttria to zirconia powder also stabilizes tetragonal-phase zirconia at room temperature.

Figure 2 shows the spectral integral transmittance values of specimens prepared from zirconia powders (size, 40 and 90 nm) at four sintering temperatures. The data show that, regardless of the particle size, determining a suitable sintering temperature is crucial to achieve good light transmittance because the specimens can only yield high light transmittance (up to 18%) at a sintering temperature of 1500 °C. The fabrication method used in this study involves uniaxial pressing of the nano-sized zirconium dioxide powder, followed by cold isostatic pressing (CIP). Slip casting is more efficient than uniaxial pressing for producing translucent ceramics because the slip-cast green body exhibits packing with higher homogeneity and achieves high-density sintering. (Golestani-fard, F., 2011) investigated the effects of uniaxial pressing and slip casting on the microstructure of the resulting alumina and revealed that slip-cast alumina exhibits a higher relative density (97.8%) than uniaxial-pressed alumina (96.3%).

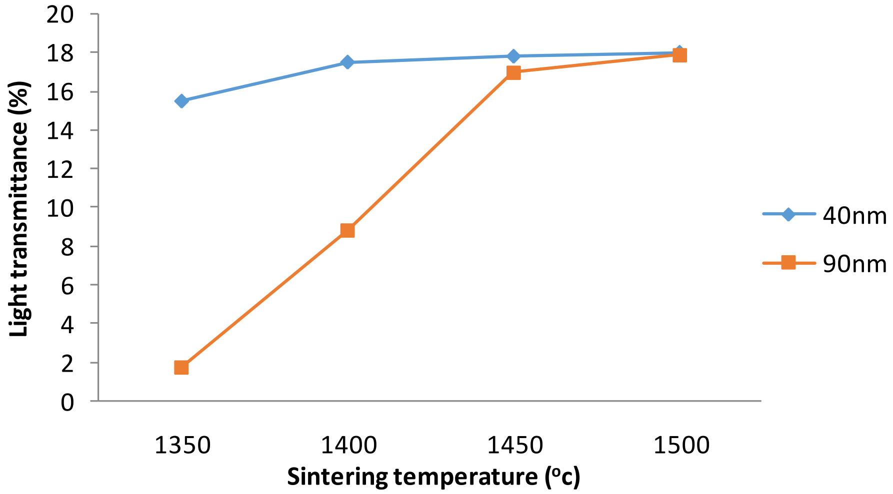

Fig. 2: Statistics of transmittance of specimen prepared from 40 nm and 90 nm zirconia powder at different sintering temperatures (Jiang, L., 2011).

Fabrication method:

Different methods, such as slip casting, uniaxial pressing, CIP, hot isostatic pressing (HIP), and spark plasma sintering (SPS), are used to fabricate Y-TZP ceramics. Slip casting is a common wet-forming method in ceramic processing. Researchers have proven that slip-cast ceramics exhibit more homogenous densities than ceramics formed by uniaxial pressing (Amat, N.F., 2013). A green body with uniform density is an important factor that affects the translucency of ceramics. Sintered green bodies exhibit improved light transmittance because the scattering medium, including the pores left after firing, are kept to a minimum.

Slip casting as a forming method, however, is hindered by the aging process of yttria slurries. Studies indicate that the aging process of a yttria binary suspension increases the viscosity of the slurry. When the slurry exhibits high viscosity, agglomeration occurs and spreads to the pores during sintering of the specimen. Dispersants are thus added to the solution to produce a dispersed yttria slurry and solve the aging phenomenon. Polyethyleneimine (PEI), a polyelectrolyte dispersant agent, is often used as a dispersant agent to control the degree of dispersion and improve the rheology of the concentrated aqueous nano-sized zirconia slurry. According to (Amat, N.F., 2013) the optimal amount of PEI that must be added to an yttria-stabilized zirconia mixture to obtain a well-dispersed slurry is 0.5 wt%. In their study, sintered density values of up to 98.8% of the theoretical density were obtained using suitable colloidal processing.

As another green-body fabrication method for Y-TZP, the starting powder can be directly consolidated by CIP or uniaxial pressing followed by CIP. Slip-casted green bodies may further be subjected to CIP to improve their relative density and packing uniformity. (Mouzon, J., 2008) showed that application of CIP to green bodies produced by slip casting and uniaxial pressing results in zirconia with the same density. Whereas slip cast and pressed samples share similar densities after CIP and pre-sintering, the homogeneity of the final microstructure obtained after HIP varies. Figure 3 shows that slip-cast yttria exhibits enhanced translucency throughout the sample, whereas pressed and HIP yttria samples exhibit high translucency only at the edges of the material–rest of the sample is barely translucent. This unusual phenomenon cannot occur in Y-TZP ceramics. (Huo, D., 2012) showed that addition of sodium polyacrylic acid (PAA-Na) as a dispersant to yttria ceramics also improves their translucency, as shown in Figure 3. (Khor, K.A., Y.W. Gu, 1998) reported that HIP zirconia shows reduced numbers of pores and enhanced density. Thus, Y-TZP presumably exhibits superior aesthetic quality after HIP. Further research must be conducted to confirm this hypothesis.

The enhanced microstructural homogeneity obtained by slip casting is confirmed by the results shown in Figure 4. Figure 4 shows that many macro-sized defects (indicated by black arrows) are present in the pressed yttria ceramic sample. These defects are formed by hard agglomerates, which create different densities throughout the sample during pressing. These defects do not appear in the slip casting sample because mixing can be improved by the presence of a liquid. Figure 5 shows that addition of a dispersant and slip casting results in samples with significantly smaller grain sizes than those obtained via HIP. Therefore, slip casting is superior to uniaxial pressing as the first consolidation stage prior to CIP in preparing homogeneous optical ceramics.

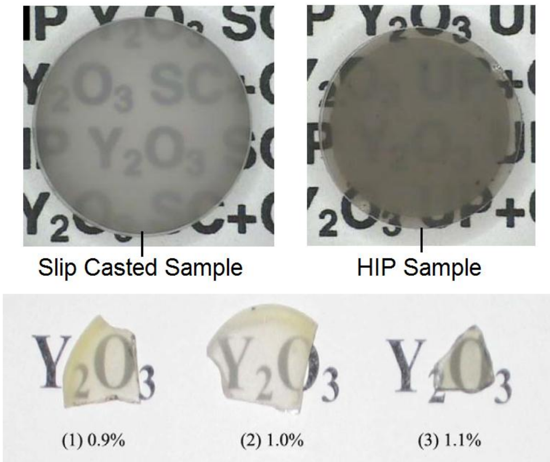

Fig. 3: Comparison of translucency between a sample of slip-casted yttria and yttria after HIP (Mouzon, J., 2008), and slip-casted Yttria with different amount of sodium polyacrylic acid (PAA-Na) as dispersant (Huo, D., 2012).

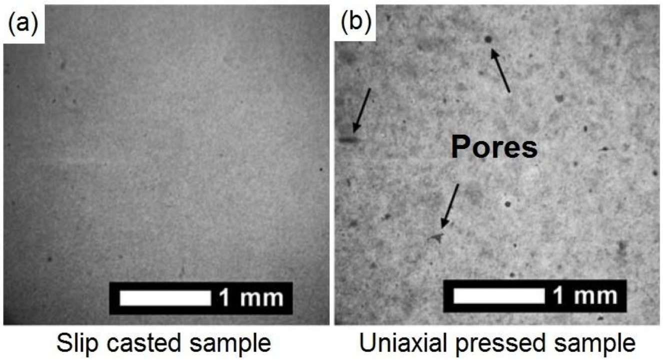

Fig. 4: Optical micrographs showing the transmission of (a) a slip-casted yttria pellet and (b) a pressed yttria pellet (Mouzon, J., 2008).

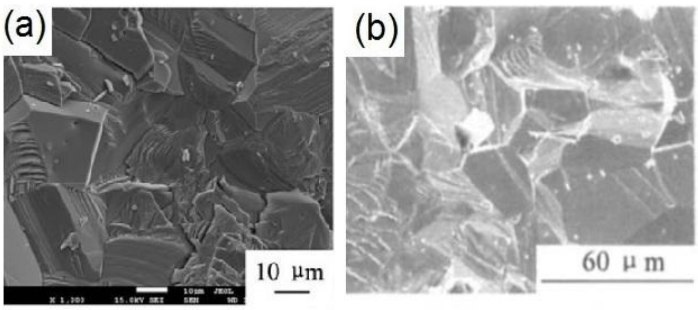

Fig. 5: SEM fracture surfaces of (a) slip casted yttria with 1.0% of PAA-Na as dispersant (Huo, D., 2012) and (b) HIP yttria (Khor, K.A., Y.W. Gu, 1998).

Spark plasma sintering (SPS) is another fabrication technique that can be used to produce fully dense bulk oxide ceramics with a nanocrystalline microstructure. It is an electric current-assisted consolidation technique adopted with uniaxial powder compaction. In SPS, the electric current provides high heating and cooling rates, as well as good temperature homogeneity. The pressure applied during uniaxial powder compaction aids densification by increasing the surface-energy driving force. This combination of high heating rate and uniaxial pressure can effectively eliminate defects in the green body during sintering.

(Aman, Y., 2009) studied the influence of green-state processes on the sintering behavior and optical properties of spark plasma-sintered alumina and reported that colloidal processing before SPS can produce a sample with homogeneous, green, compact, and small pore sizes. This phenomenon can facilitate densification by grain sliding and rearrangement and thus lead to higher sintered densities by SPS. Therefore, further research can be conducted on the combination of both colloidal processing and SPS to fabricate translucent zirconia.

Influence of Different Additives:

Additives are used in most cases to fabricate translucent Y-TZP. Additives such as cobalt, praseodymium, calcium, or copper are often used as sintering aids to improve the properties of zirconia ceramics (López-Honorato, E., 2012). However, not all elements added to Y-TZP can improve densification. For example, the addition of CuO reduces the sintering temperature of yttria zirconia because of the formation of liquid at about 1100 °C (Raigrodski, A.J., 2012). At concentrations above 1 wt%, CuO induces the formation of large pores in the microstructure, which is not desirable in the production of translucent zirconia.

Researchers found that adding NiO stabilizes the cubic and tetragonal phases of Y-TZP. Tetragonal-phase Y-TZP must be stabilized to prevent Y-TZP from transforming into a monoclinic phase, which exhibits poor mechanical properties. Y-TZP green bodies with NiO also densify faster at temperatures above 1100 °C. However, at temperatures above 1300 °C, NiO inhibits the full densification of Y-TZP, preventing the acquisition of superior translucency. Therefore, NiO is not a desirable additive for Y-TZP.

(Chen, C.G., C.M. Zhou, 2008) studied the effect of nano-sized alumina Al2O3 additive on Y-TZP ceramics. A minute addition of alumina (0.25 wt%) was shown to stabilize the tetragonal phase of zirconia and increase the densification of the sintered bodies. Data shows that at 1300 ºC, the shrinkage of the sintered specimen for alumina-added Y-TZP is slightly larger than that of Y-TZP without any additive. Lower temperature is ideal to achieve maximum shrinkage for the alumina-added Y-TZP. Fewer pores acting as light scattering center form at higher densification rates, thus improving translucency.

Conclusion:

Y-TZP exhibits potential in dental crown applications owing to its high mechanical properties and superior biocompatibility. Y-TZP can also be aesthetically improved using nano-sized powders, high sintering temperature, dispersants, and suitable additives. These techniques allow the fabrication of zirconia with enhanced sintered density and few pores, thus improving its translucency to match the natural appearance of human teeth. Y-TZP becomes suitable for ceramic dental restoration when all of the desired properties (natural appearance, superior mechanical properties, and bio-inertness) for dental crown application are fulfilled.

ACKNOWLEDGEMENT

The authors acknowledge the sponsorship granted by the Universiti Kebangsaan Malaysia (UKM) under the FRGS/1/2013/SG06/UKM/01/1 and GUP-2012-060.

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