Factors affecting the translucency of monolithic zirconia ceramics: A review from materials science perspective

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The use of monolithic [yttria (Y₂O₃)-stabilized tetragonal zirconia (ZrO₂) polycrystalline] (Y-TZP) ceramics to restore teeth is expanding in dentistry. However, there are still some problems about color matching and the translucency of these ceramics. The employment of Y-TZP ceramics in aesthetically critical regions is questionable due to the insufficient translucency and opacity of the restorations. The objective of this review was to assess the factors affecting the translucency of monolithic Y-TZP ceramics for a better understanding of the relevant parameters in restorations. The translucency of polycrystalline ceramics is a complex phenomenon. Apprehending the translucency regarding ceramics requires their knowledge of physical, chemical and microstructural characteristics with the light interactions among them.

Keywords: Zirconia, Y-TZP, Monolithic, Translucency, Translucent

INTRODUCTION

In dentistry, the monolithic [yttria (Y₂O₃)-stabilized tetragonal zirconia (ZrO₂) polycrystalline] (Y-TZP) ceramics have recently gained popularity, thanks to their good biocompatibility, aesthetic features, high strength and toughness, semi-translucency, radiopacity properties and lowered costs⁴⁻⁵. However, light transmission still remains a major drawback in those ceramics⁸⁻¹⁰. When restoring the anterior teeth with crowns or fixed dental prostheses, ZrO₂'s high opacity is a problem⁴⁻⁵. In conventional Y-TZP ceramics, in which dental porcelain veneered on Y-TZP core, in order to mask the opaque Y-TZP material and harmonize the optical features of restored tooth with the neighboring teeth, considerable amount of tooth preparation is required for placing a thick (approximately 1 mm) porcelain veneer portion of the restoration¹⁶⁻¹⁹. On the other hand, clinical catastrophes, such as veneer chipping and delamination are observed in zirconia-layering porcelain combinations²⁰⁻²³. Therefore, attempts have been made to develop monolithic Y-TZP ceramics without a need for layering porcelain in the last decade. The clinical advantage of these ceramics is the usage of decreased thickness compared with that of other monolithic and conventionally veneered ceramics⁵⁻⁸,¹¹,¹²,¹⁶,¹⁷,²⁶,²⁷. Another advantage is their fast and simple-fabrication employing computer assisted design and fabrication (CAD/CAM) technologies¹⁻⁲. Nevertheless, their disadvantages are mentioned as insufficient light transmittance, especially in anterior regions, wear against the opposing dentition at the posterior regions and hydrothermal aging of monolithic Y-TZP directly reacted with oral fluids²⁸⁻³².

Color and translucency of Y-TZP ceramics affect the aesthetic properties of the dental prosthesis¹⁻⁴,¹⁷,¹¹,³³. Perceived color is determined by wavelength. Translucency of fixed dental prostheses is directly related to light's spectral effect²⁰,²¹,²⁴⁻³⁵. Light, radar, X-rays, radio waves, heat are all the forms of electromagnetic radiation defined in a specific range of wavelength. A wave of magnetic and electric field components perpendicular to each other generates electromagnetic radiation. Cosmic rays (<0.0001 nm), gamma rays (0.0001–0.01 nm), X-rays (0.01–10 nm), ultraviolet (UV; 10–400 nm), visible (400–700 nm), infrared (IR) (700 nm–1 mm), microwave (1 mm–1 m) and radio waves (>1 m) take part in electromagnetic spectrum, respectively.

The translucency of a material is affected from the incident light wavelength. Normally, human eye is most sensitive to 555 nm wavelength. In translucency, when light passes through a material, it interacts with it in several ways depending upon the nature of the material and the light wavelength resulting in the combination of reflection, absorption and transmission of photons⁵⁶,⁵⁷. In internal surfaces of the Y-TZP, grain boundaries, crystallographic defects and micro-pores are light scattering centers affecting the translucency of this polycrystalline material¹⁰,¹⁷,³⁵. ZrO₂'s grain size is the most important determinant of its translucency; however, there is no direct linear proportion between the translucency and grain size of ZrO₂. Generally, in coarse-grained materials, translucency is supplied by means of a high diffusional transmission, whereas in fine-grained ones, it is given by a high in-line transmission⁵⁻³⁸. Furthermore, in grain diameters, between 0.01–0.1 μm, material might be seen from translucent to transparent.
form, and the translucency is obtained by in-line transmission. In grain diameters of 0.1–1 μm, grain boundary scattering would be observed, whereas in grain diameters of 1–10 μm diffuse transmission is seen and the material would be largely translucent4-5,38).

In Y-TZP materials, the size of crystal grains depends, to a large extent, on the size of the crystal particles present in the raw material and this is determined during the final product's formation. Furthermore, the particle size directly affects the size of grain boundaries. If the size of latter ones (scattering center) is below the size of present in the raw material and this is determined during the manufacturing process, the scattering is observed very limitedly39-41). The fact that the particle's size in the material is below a sufficient amount of visible light wavelength size also considerably declines light scattering. Thus, the aesthetic features of Y-TZP ceramics could be improved by creating a nanometric microstructure and by reducing porosity5,11,25,38-40,42).

Due to the facts mentioned above, the translucency is one of the most important determining factors of the aesthetics in dentistry. In the literature, 3 common methods of translucency measurements are mentioned, namely contrast ratio (CR), light transmittance, and translucency parameter (TP) methods4-7,17,20,22,43-46). In the CR method, measurements are taken from the reflectance of a material over a white and black background. Two measurements conducted with the white reflection backing (YW), afterwards the black backing (YB), leading to a total of 4 measurements for each specimen. The average CR is calculated as below:

$$CR = \frac{YB}{YW}$$

The CR is measured between 0 and 1, and it reaches to 1 for an opaque material. The other method is the light transmittance where measurements in ceramics could be conducted by 3 means: direct, total transmission and spectral reflectance. The direct transmission measures the light that reaches a detector, but in spectral reflectance measurements, the light transmittance measured indirectly. In the third way (total transmission), both light transmission of monolithic ZrO₂ and enables a lower and more natural shade value3-5,10,20,21,39,42).

In the TP method, the calculations are directly made from the light reaching the detector and passing the ceramic and scattering are measured20). Transmittance (T) is calculated as follows:

$$T = \frac{L_{specimen}}{L_{source}} \times 100\%$$

where the subscripts B and W refer to colour coordinates $L^*$, $a^*$, and $b^*$ of the specimen luminance and L source is the source of luminance20).

The CR and light transmittance methods have the possibility of being either luminous or spectral146). In the TP method, the calculations are directly made from the color difference for the specimens on the white and black backgrounds. Differences in perceived color ($\Delta E^*$) can be determined by the CIELAB coordinates46). For TP, color parameters are achieved through CIE-Lab (Commission Internationale de l’Eclairage $L^*$, $a^*$, $b^*$) formulation7). Color difference ($\Delta E^*_{ab}$) and TP are calculated with the formulation indicated below:

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

$$\text{TP value} = [(L^*_{B} - L^*_{W})^2 + (a^*_{B} - a^*_{W})^2 + (b^*_{B} - b^*_{W})^2]^{1/2}$$

where the subscripts B and W refer to colour coordinates over a black and white background, respectively7,21).

There is an increase in the number of studies investigating the translucency features of monolithic Y-TZP ceramics. There are many physical and chemical factors affecting the quality and translucency of the finally sintered monolithic Y-TZP ceramics: starting from blank fabrication12,47,48, dopants39,49,50), phase type49), yttria content12,24,51), porosity5-6,45), impurity8), defects9), birefringence36-40, oxygen vacancies36), grain size32, grain boundary31,49,50), sintering temperature5,32,42, sintering process23,53,54), reflexion and refractive index36) of the material and light scattering39,54,55). Some authors conducted theoretical investigations using scattering models, such as, Rayleigh-Gans-Debye (RGD), Rayleigh and Mie, the grain size and birefringence's effects on the in-line transmission of non-absorbing dense ceramics36,41) where the factors affecting the translucency of Y-TZP ceramics were evaluated.

THE PARAMETERS AFFECTING THE Y-TZP CERAMIC’S TRANSLUCENCY

**Blank fabrication**

In the manufacturing process of monolithic ZrO₂ blanks, ZrO₂ powders are ground to decrease the particle size and mixed with the binder to eliminate the closed porosity and further improve the density and compaction of the green body48,56). This specific process leads to improved light transmission of monolithic ZrO₂ and enables a lower and more natural shade value3-5,10,20,21,39,42).

In such a production method, some process parameters like chemical purity of the powder, type of pressing, granule characteristics, and pre-sintering treatment have a crucial impact on the determination of final properties48,56). The chemical composition of 3Y-TZP powders was examined and an amorphous phase forming a continuous layer at grain boundaries and multiple junctions were observed in the material possessing the largest amount of impurities, along with a greater grain size12,13). It was concluded that yttrium transport yields larger amounts of impurities, which affect the stability of 3Y-TZP12). As a result, cubic phase transformation occurs leading to an enrichment of cubic grains in yttrium, which leaves neighboring tetragonal grains depleted, less stable, and more sensitive to transformation.

Powder granulometry and uniaxial or isotropic compaction modes are also decisive for the final microstructure. When blanks are uniaxial, pressed coarse pseudo-grain structures are liable to occur. Isostatic pressing yields more intense and homogeneous compaction. The milling process of the Y-TZP is a significant step for final restoration and there are two types of milling, namely soft miling from partially sintered, green state Y-TZP and hard milling of fully sintered Y-TZP. Soft milling is mostly preferred in cases of hot isostatic pressed ZrO₂ implants21,24,38,57-59).

**Microstructure**

In ceramics containing glass and crystal matrix, the translucency can be improved by increasing the glassy phase portion. In high-density-single-phase ceramics and ZrO₂, strength and other properties are closely
related to porosity in the microstructure of a ceramic material\textsuperscript{13-15}. Hence, for improved translucency of Y-TZP ceramics, lower porosity is necessitated\textsuperscript{5}. Y-TZP ceramics’ grain size, porosity and density are directly determined by the applied heating method and final sintering temperature\textsuperscript{2,4,5,50}. Almazdi et al.\textsuperscript{50} made a publication on the average pore size of the microwave-sintered specimens being smaller than that of the conventionally sintered ones. Presenda et al.\textsuperscript{53} pointed out finer grain microstructure (final grain size<250 nm) with microwave sintering. However, no correlation between light scattering and pores for materials with a submicron-sized grain and submicron-sized grain and high density (>99\%) was detected\textsuperscript{2,57}.

**Grain size**

The correlation between particle size and light wavelength size is one of the most important factors affecting light scattering\textsuperscript{60}. In a material having similar grain size with light wavelength, light scattering becomes very large\textsuperscript{43}. According to general knowledge, in materials containing a matrix and particles, the refractive indices of matrix and particles, and the chemical structure of particles are directly affects light scattering. Materials containing particles in sizes less than about 0.1 \(\mu\)m appear less opaque due to less reflection and absorption when exposed to visible light wavelength than those containing large particles\textsuperscript{60}. Materials with particles larger than 10 \(\mu\)m have surface reflection, absorption and refraction, while the number of particles per unit volume is small and the opacity may be reduced by less reflection\textsuperscript{43}. However, due to the polycrystalline structure of zirconia, its unique light scattering property depending on the size of the grains results in different characteristics which are difficult to explain with classical physics information.

When sintering is shortened, the grain size of the material is declined, and therefore, the light transmittance of Y-TZP ceramics is increased\textsuperscript{2,40}. In contrast to that, Derny and Kelly\textsuperscript{12} stated that the number of grain boundaries affects the translucency and this depends on the average grain size. Increased number of grain boundaries is a result of decreased grain size, and therefore, a decrease in translucency is observed. As the sintering temperature rises, the grain size of Y-TZP also increases. However, at the temperatures exceeding 1.600°C, grain growth is accompanied with hollow holes in the zirconia microstructure\textsuperscript{10}.

The employment of La\textsubscript{2}O\textsubscript{3} as co-doping oxide enhances the possibility to achieve a finer microstructure. Furthermore, the optical transmission because of smaller porosity, a narrow grain boundary width and high in-line transmission is also improved\textsuperscript{49,62}. Presenda et al.\textsuperscript{53} reported that the mean grain sizes of the Y-TZP materials sintered by the help of conventional sintering (CS) methods substantially differ from those sintered by microwave sintering (MS) methods. They stated that the great difference in mean grain size of the LAVA material, when the results of MS and CS are compared at the same temperature, might be due to obtaining the material as a pre-sintered block. In terms of pre-sintered materials, particles have already formed necks among each other. When the dwelling time is raised, those particles transform together into larger particles. Although the sintering temperature is the same for CS and MS, first the grain boundaries are heated and therefore, active mass diffusion among the grains is quite rapid in CS. On the other hand, due to the volumetric heating in MS, the cores of grains are heated first, which creates a temperature gradient leading to a heat flow from inside of the material towards the grain boundary. This is attributed to the slower rate of mass diffusion of particles at the grain boundaries in MS, which, as a result, yields smaller grains\textsuperscript{54}.

**Grain boundary effect**

In general, the grain boundary light scattering effect is minimized by increasing the grain size and this gradual increase enables the light beam to pass through the material and therefore it encounters less with the grain boundaries. Thus, translucency of coarse-grained ceramics is dependent on the diffuse-transmission mechanism, and fewer interactions of light/grains with boundaries in thinner ceramics result in more light transmission\textsuperscript{54}. On the other hand, as the size of the grains in the microstructure grows, the strength of ceramics is reduced relatively. The grain-size threshold for spontaneous phase transformation from tetragonal (\(t\)) to monoclinic (\(m\)) in 3Y-TZP’s is about 1 \(\mu\)m\textsuperscript{60}. If the great majority of the sizes of tetragonal grains are above 1 \(\mu\)m, then the simultaneous \(t\rightarrow m\) transformation from the sintering temperature may reduce the strength of 3Y-TZP upon cooling. From this point, the approach of grain coarsening is not an efficient method for producing translucent 3Y-TZP\textsuperscript{60}. Moreover, reducing the grain size of 3Y-TZP ceramics is the most convenient way to enhance its translucency. Zhang\textsuperscript{60} reported that the average grain size of 3Y-TZP should be approximately 82 nm (for a thickness of 1.3 mm), 77 nm (for a thickness of 1.5 mm), and 70 nm (for a thickness of 2 mm) for attaining a satisfactory level of translucency in dental ceramics. Besides, in-line transmission according to Rayleigh scattering model (\(T_{IT}T\)), at a slightly less translucency level, \(TIT=2\%\) at 555 nm wavelength, the grain size of 3Y-TZP could be approximately 120 nm\textsuperscript{40}. However, the mean grain size is nearly half the size of the current fine 3Y-TZP (Lava Plus) whose grain size is 250 nm on average.

**Porosity, impurities and defects**

The fabrication of high-quality nano-crystalline Y-TZP ceramics with little to no porosity and imperfections is challenging. Compared to the grain boundary, the presence of pores in the material and the amount of these pores are more important for translucency\textsuperscript{64}. In terms of high-density nano-crystalline ZrO\textsubscript{2}, it is unlikely that pore diameter would be greater than the grain size and the usage of <50-nm grain zirconia declines the light scattering problem. Employing 40-nm powder instead of 90-nm amplifies the sintering density and reduces pores.
and scattering. Sintering temperature also has a primary role in determining the sintering density. With raising temperature, the $\text{ZrO}_2$ crystal structure becomes more compact whereas porosity, defect, and flaws decrease\textsuperscript{9}.

Porosity plays a significant role in the translucency of $\text{ZrO}_2$ material. Pores larger than 50 nm result in considerable scattering, thus reducing light transmission ("pore scattering")\textsuperscript{5,60}. The impurities affect the optical features of the material and lead to changes and variations in color. These changes may increase the difficulty of obtaining desired colors and achieving satisfactory color control, stability, and translucency.

**Oxygen vacancies**

Sintering conditions have a significant effect on the oxygen vacancies. When the Y-TZP is under controlled firing or sintering is done in an environment with reduced reactions, oxygen vacancies occur\textsuperscript{22,65}. The amount of these oxygen vacancies affects light scattering as they serve as scattering centers. On the other hand, after post sintering in an oxidizing environment, heat treatment could put some oxygen back into Y-TZP crystals\textsuperscript{60}. However, this process also creates porosity due to the combination of vacancies to produce larger ones at high temperatures. Therefore, the main consideration is to control the heat treatment to pull down the oxygen vacancies in the material.

**Dopants**

Translucency of the Y-TZP ceramics is associated with the dopants employed in the chemical composition of the ceramics\textsuperscript{30}. Dopant is an oxide and acts as a grain boundary-engineering tool that has a control over the composition of the grain boundaries of $\text{ZrO}_2$\textsuperscript{30,62,65}. Various oxides, such as $\text{Al}_2\text{O}_3$, $\text{Sc}_2\text{O}_3$, $\text{Nd}_2\text{O}_3$, and $\text{La}_2\text{O}_3$, $\text{MgO}$ and $\text{GeO}_2$, may be utilized for doping Y-TZP ceramics. In general, Y-TZP ceramics contain 0.25 wt% of alumina as a dopant. In new generation ceramics, especially monolithic Y-TZP, lower amounts of alumina are used to obtain a more translucent material. Dopant oxides are able to segregate at $\text{ZrO}_2$ grain boundaries in Y-TZP ceramics and dopant segregation is a decisive parameter in ensuring hydrothermal stability and high-translucency\textsuperscript{30,10,62}. Moreover, the study of Zhang et al.\textsuperscript{42} revealed that the cation dopant radius is another key factor for controlling segregation. They reported that a large trivalent dopant such as La\textsuperscript{3+} originating from $\text{La}_2\text{O}_3$, which is oversized compared to Zr\textsuperscript{4+}, displayed a distinctive segregation at $\text{ZrO}_2$ grain boundary. In the same study, introducing 0.2 mol% $\text{La}_2\text{O}_3$ to 0.1 wt% $\text{Al}_2\text{O}_3$-doped 3Y-TZP yielded 42% higher translucency than conventional 0.25 wt% $\text{Al}_2\text{O}_3$-doped 3Y-TZP. However, reducing $\text{Al}_2\text{O}_3$ content is crucial due to the risk of degradation of mechanical properties and hydrothermal stability as well. Monolithic Y-TZP ceramics are in close contact with the oral environment so hydrothermal stability is of greater concern and the amount of dopant is important as well because of the secondary phase precipitation which would possess a deteriorating impact on the translucency of Y-TZP ceramics by scattering light.

**Yttria content (3% or 5–8%)**

Various oxides are employed to stabilize the tetragonal phase of $\text{ZrO}_2$ at room temperature\textsuperscript{5,49}. These are usually $\text{CaO}$, $\text{MgO}$, $\text{Y}_2\text{O}_3$ or $\text{CeO}_2$. Their amounts should be controlled in terms of transformability, phase stability and mechanical properties\textsuperscript{11}. In general, $\text{ZrO}_2$ is stabilized with 3 moles of $\text{Y}_2\text{O}_3$. $T\leftrightarrow m$ transformation influences the mechanical properties of this material. Thanks to the fine particle size microstructure and phase transformation mechanism of the 3Y-TZP, the closure of the cracks starts during the volume expansion (4–5 %) and thus prevents the crack propagation\textsuperscript{10–12}.

In addition to the mechanical strength and phase stability of 3Y-TZP, its extreme opacity is one of the most important disadvantages. Hence, monolithic $\text{ZrO}_2$ ceramics with 5 to 8% of yttria have emerged as having less opacity\textsuperscript{60}. However, such a strategy sacrifices the flexural strength\textsuperscript{60} and fracture toughness because of the partial loss of the transformation toughening effect of tetragonal $\text{ZrO}_2$\textsuperscript{20,60}.

**Phase type and percentage (cubic, monoclinic, tetragonal)**

The phase type and percentage also affect the translucency of the monolithic Y-TZP ceramics\textsuperscript{31}. The monoclinic phase itself may act as a flaw or defect in $\text{ZrO}_2$ microstructure. These porosities or imperfections may reduce the translucency by enhancing scattering of incident light\textsuperscript{45}. The higher $\text{Y}_2\text{O}_3$ content tended to raise the amount of cubic phase present in $\text{ZrO}_2$. A combination of fine grain size and cubic $\text{ZrO}_2$ with an isotropic refractive index, which helps to avoid scattering from grain boundaries, yields improved translucency. Tetragonal phase has a large birefringence. To achieve enhanced translucency with high tetragonal phase percentage, the grain size should be reduced in order not to compromise the strength of the material.

**Sintering temperature**

The translucency of the material varies depending on the sintering, consequently, on crystal content in ceramics\textsuperscript{5,42}. Kim et al.\textsuperscript{2} concluded that shorter sintering times should be considered in order to obtain more translucent Y-TZP ceramics. Increasing holding (dwell) time during sintering leads to grain growth in the Y-TZP ceramics, affecting translucency\textsuperscript{11}. However, increasing the sintering temperature to obtain more translucent ceramics by increasing the grain size is not desirable\textsuperscript{13}. This would lead to metastability and LTD of Y-TZP; hence, higher sintering temperatures were found to result in migration of Y to grain boundaries, and uneven distribution of the Y-stabilizing ions causing cubic phases being not desirable\textsuperscript{13,45,49}.

One of the ways to improve the color and translucency features of monolithic $\text{ZrO}_2$ is to increase the sintering temperature and time. Ebeid et al.\textsuperscript{55} stated that changing the sintering parameters of monolithic $\text{ZrO}_2$ in the specified operating range had no negative effect on phase transformation, surface roughness and biaxial
flexural strength. However, the tribological properties of the material may be affected from the sintering time that the fast and speed-sintered monolithic Y-TZP materials have greater volume loss than those of normally sintered counterparts that would affect the translucency by time.\(^{(69)}\)

**CS, MS and spark plasma sintering (SPS)**

The heat transfer mechanisms of the Y-TZP ceramics sintered conventionally are conduction, convection and radiation.\(^{(68)}\) In CS, the heat is applied onto the external surface of the Y-TZP ceramic. It reaches the core thanks to thermal conduction during the sintering process and produce high temperature gradients and stresses within the material. Thus, grain coarsening occurs in the microstructure, which leads to deterioration of the final mechanical features of the material. However, MS enables rapid and even heating of the material both internally and externally. Moreover, some limitations to this sintering method exist. For instance, many ceramics are unable to absorb microwaves well at room temperature and therefore, in microwave furnaces, silicon carbide susceptors (materials that absorb electromagnetic energy and convert it to heat) are required to be used in order to externally heat the material by thermal conduction. In general, microwave systems use a frequency of 2.45 GHz. Increasing the frequency of microwave radiation can decrease the sintering temperature. The energy is transferred to Y-TZP ceramics as the electromagnetic area interacts with a molecular dipole and the effect of this field is stated as approximately \(2.2^{(68)}\). However, various phases such as monoclinic, cubic and tetragonal may possess different refractive indices that would affect the translucency to a relative degree.

**Light scattering**

The translucency of dental porcelain depends largely upon light scattering\(^{(40)}\). One of the most important factors affecting light scattering is the inner pores. The amount of light reflected, absorbed and transmitted depends on the chemical composition of the Y-TZP ceramics, the crystal structure in the material, and the size of the incident wavelength according to the size of the particles.\(^{(2)}\) The outer surfaces of the material also play an important role in the light scattering of Y-TZP ceramics, in which the rough surfaces affect translucency negatively.\(^{(55,72)}\).

**Reflexion and refractive index**

In ceramics, to achieve an improved translucency, the refractive index adjustment of various phases present in the microstructure can be done by compositional alterations. In dental ceramics consisting of glassy matrix and crystals, for less scattering of light but more transparency, the crystal content in the matrix must be low or the refractive index of the crystal content should be close to that of the matrix.\(^{(7)}\) However, Y-TZP ceramics are polycrystalline materials without any matrix. The refractive index for \(\text{ZrO}_2\) is stated as approximately 2.2.\(^{(2)}\) However, various phases such as monoclinic, cubic and tetragonal may possess different refractive indices that would affect the translucency to a relative degree.

**Birefringence (double refraction)**

It means that the refraction index is anisotropic in different crystallographic directions, as found in non-symmetric crystal structures, typically non-cubic or strained.\(^{(40)}\) Tetragonal \(\text{ZrO}_2\) has a large birefringence. Such a consequence causes the discontinuity of the refractive index at the grain boundaries if the adjacent grains do not possess the same crystallographic orientation. This situation causes both reflection and refraction at grain boundaries, resulting in diversions in the incident beam and thus reductions in light transmittance.\(^{(69)}\)

In the literature, the birefringence for monoclinic \(\text{ZrO}_2\) is about 0.070, but there is no known reliable data for tetragonal lattices due to the weak transparency of single crystals.\(^{(69)}\) \(\text{ZrO}_2\) has higher birefringence than \(\text{Al}_2\text{O}_3\), accordingly the grain sizes necessary to obtain transparency have to be much smaller. Klimke \textit{et al.}\(^{(40)}\) calculated the expected in-line transmission by RGD approximation for dense tetragonal \(\text{ZrO}_2\) ceramics with a thickness of 0.5 mm at 640 nm wavelength depending on grain size and average birefringence. They reported that for an in-line transmission >50% the microstructure has to consist of particles <58 nm assuming a birefringence of 0.02, <25 nm for birefringence of <0.03 and 3 nm for a birefringence of 0.09.

**Flexural strength, fracture toughness and Weibull modulus**

It has been inhibited that monolithic Y-TZP ceramics with lower flexural strength are generally more translucent than those with higher flexural strength.\(^{(41,66,74)}\) On the
other hand, higher sintering temperatures of dental ZrO₂ lower the flexural strength⁴.

Fracture toughness is the material’s resistance to speed crack propagation and is not generally affected by flaws on the surface or dependent upon the initial crack size. The evaluation of fracture toughness is more valuable than the comparison of the strength of ceramic materials⁶⁻⁷⁻⁸⁻⁹. Weibull modulus is utilized to describe variability in measured material strength of brittle materials⁷⁴⁻⁷⁶. If the flaws or defects are homogeneously distributed in a Y-TZP material, the Weibull modulus will be high. If the flaws are clustered inconsistently, Weibull modulus will be low. A material’s low Weibull modulus will exhibit low reliability and its strength will be broadly distributed. Therefore, it may be assumed that a material with low Weibull modulus would have lower translucency than that of a material with high Weibull modulus depending on the phase composition and distribution.

Low temperature degradation (LTD) or hydrothermal aging

It is the spontaneous transformation of the tetragonal to monoclinic ZrO₂ phase in the presence of water (hydrothermal aging)⁴⁹⁻⁵⁰. The chemistry of grain boundaries is of great importance for the aging behavior of Y-TZP ceramics⁷⁷. The presence of micro-pores at pseudo-grain boundaries may decrease endurance to LTD by facilitating diffusion of water species⁷⁸. With the release of micron or nano-sized ZrO₂ particles, the surface of the restoration roughens and this could cause enhanced wear rates and loss of mechanical properties⁶²⁻⁷⁹.

The filling of oxygen vacancies by “water-derived species” (probably in the form of OH⁻) at the grain boundary is thought to initiate the hydrothermal aging of Y-TZP ceramics⁶⁰. Ce-stabilized ZrO₂ (Ce-TZP) is far more resistant to hydrothermal aging than 3Y-TZP⁷⁸. The translucency of polycrystalline ceramics is a complex phenomenon. Understanding of translucency of monolithic Y-TZP ceramics needs the knowledge of physical, chemical and microstructural characteristics of these ceramics with the light interactions of the pores, grains and grain sizes and grain boundaries. The most important determinants of translucency of Y-TZP ceramics are pores, grain size, incident light wavelength, and all the other co-factors affect more or less its amount to a relative extent. Recent studies tried to eliminate the anisotropic structure of these ceramics using nano-sized Y-TZP with different percentage of yttria using different dopants in order to increase translucency. However, these changes in the microstructure would sacrifice the whole strength of the material. The translucency and the strength of the monolithic Y-TZP materials should be balanced in order to be used in anterior and posterior region restorations in dentistry.

CONCLUSIONS

The translucency of polycrystalline ceramics is a complex phenomenon. Understanding of translucency of monolithic Y-TZP ceramics needs the knowledge of physical, chemical and microstructural characteristics of these ceramics with the light interactions of the pores, grains and grain sizes and grain boundaries. The most important determinants of translucency of Y-TZP ceramics are pores, grain size, incident light wavelength, and all the other co-factors affect more or less its amount to a relative extent. Recent studies tried to eliminate the anisotropic structure of these ceramics using nano-sized Y-TZP with different percentage of yttria using different dopants in order to increase translucency. However, these changes in the microstructure would sacrifice the whole strength of the material. The translucency and the strength of the monolithic Y-TZP materials should be balanced in order to be used in anterior and posterior region restorations in dentistry.

REFERENCES

1) Stawarczyk B, Özcan M, Hallmann L, Ender A, Mohl A, Hammerle CHF. The effect of zirconia sintering temperature on flexural strength, grain size, and contrast ratio. Clin Oral Investig 2013; 17: 269-274.
2) Kim MJ, Ahn JS, Kim JH, Kim HY, Kim WC. Effect of the sintering conditions of dental zirconia ceramics on the grain size and translucency. J Adv Prosthodont 2013; 5: 161-166.
3) Kurtulmuş Yılmaz S, Ulusoy M. Comparison of the translucency of shaded zirconia all-ceramic systems. J Adv Prosthodont 2014; 6: 415-422.
4) Vichi A, Carabba M, Paravina R, Ferrari M. Translucency of ceramic materials for CEREC CAD/CAM system. J Esthet Restor Dent 2014; 26: 224-231.
5) Vichi A, Sedda M, Fabian Fonzar R, Carabba M, Ferrari M. Comparison of contrast ratio, translucency parameter, and flexural strength of traditional and “augmented translucency” zirconia for CEREC CAD/CAM system. J Esthet Restor Dent 2016; 28: 32-39.
6) Kanchanavasit W, Triwatana P, Suputtamongkol K, Thananakit A, Chatchaiganan M. Contrast ratio of zirconia-based dental ceramics. J Prosthodont 2014; 23: 456-461.
7) Kim H, Kim S, Lee J, Han J, Yeo I, Ha S. Effect of the amount of thickness reduction on color and translucency of dental monolithic. J Adv Prosthodont 2016; 8: 37-42.
8) Ghodsi S, Jafarian Z. A review on translucence zirconia. Eur J Prosthodont Restor Dent 2018; 26: 62-74.
9) Zhang Y, Lawn BR. Evaluating dental zirconia. Dent Mater J 2019; 35: 15-23.
10) Sulaiman TA, Abdulmajeed AA, Donovan TE, Vallittu PK, Närhi TO, Lassila LV. The effect of staining and vacuum sintering on optical and mechanical properties of partially and fully stabilized monolithic zirconia. Dent Mater J 2015; 34: 605-610.
11) Sulaiman TA, Abdulmajeed AA, Donovan TE, Ritter AV, Vallittu PK, Närhi TO, et al. Optical properties and light irradiance of monolithic zirconia at variable thicknesses. Dent Mater J 2015; 31: 1180-1187.
12) Denny I, Kelly JR. Emerging ceramic based materials for dentistry. J Dent Res 2014; 93: 1235-1242.
13) Ueda K, Göth JP, Erdelt K, Stimmelmayer M, Kappert H, Beuer F. Light transmittance by a multi-coloured zirconia material. Dent Mater J 2015; 34: 310-314.
14) Sulaiman TA, Abdulmajeed AA, Donovan TE, Ritter AV, Lassila LV, Vallittu PK, et al. Degree of conversion of dual-polymerizing cements light polymerized through monolithic zirconia of different thicknesses and types. J Prosthodont 2015; 114: 103-108.
15) Sravanthi Y, Ramani YV, Rathod AM, Ram SM, Turakhia H. The comparative evaluation of the translucency of crowns fabricated with three different all-ceramic materials: an in vitro study. J Clin Diagn Res 2015; 9: 30-34.
16) Ritter RG. Use of high translucency zirconia in aesthetic zone. Dent Today 2013; 32: 118-119.
17) Shiraiishi T, Watanabe I. Thickness dependence of light transmittance, translucency and opalescence of a ceria-stabilized zirconia/alumina nanocomposite for dental applications. Dent Mater 2016; 32: 660-667.
18) Kumagai N, Hirayama H, Finkelman MD, Ishikawa-Nagai S. The effect of translucency of Y-TZP based all-ceramic crowns fabricated with difference substructure designs. J Dent 2013; 41: 87-92.
19) Guess PC, Kulis A, Witkowski S, Wolkowitz M, Zhang Y, Strub J. Shear bond strengths between different zirconia cores and veneering ceramics and their susceptibility to thermocycling. Dent Mater J 2008; 24: 1556-1567.
20) Tong H, Tanaka CB, Kaizer MR, Zhang Y. Characterization of three commercial Y-TZP ceramics produced for their high-translucency, high-strength and high-surface area. Ceram Int 2016; 42: 1077-1085.
21) Matsuzaki F, Sekine H, Homma S, Takanashi T, Furuya K, Yajima Y, et al. Translucency and flexural strength of monolithic translucent zirconia and porcelain-layered zirconia. Dent Mater J 2015; 34: 910-917.
22) Tuncel I, Turlp I, Üşümez A. Evaluation of translucency of monolithic zirconia framework and zirconia materials. J Adv Prosthodont 2016; 8: 181-186.
23) Luo XP, Zhang L. Effect of veneering techniques on color and translucency of Y-TZP. J Prosthodont 2010; 19: 465-470.
24) Harada K, Raigrodski AJ, Chung KH, Flinn BD, Dogan S, Mandel LA. A comparative evaluation of the translucency of zirconias and lithium disilicate for monolithic restorations. J Prosthet Dent 2016; 116: 257-263.
25) Harianawala H, Kheur MG, Apte SK, Kale BB, Sethi TS, Kheur SM. Comparative analysis of transmittance for different types of commercially available zirconia and lithium disilicate materials. J Adv Prosthodont 2014; 6: 456-461.
26) Dikicier S, Ayyıldız S, Ozen J, Sipahi C. Effect of varying core thicknesses and artificial aging on the color difference of different all ceramic materials. Acta Odontol Scand 2014; 72: 629-639.
27) Nordahl N, Vult von Steyern P, Larsson C. Fracture strength of ceramic monolithic crown systems of different thickness. J Oral Sci 2015; 57: 255-261.
28) Baldissara P, Lukacej A, Ciocca L, Valandro FL, Scotti R. Translucency of zirconia copings made with different CAD/CAM systems. J Prosthodont 2010; 104: 6-12.
29) Kim HK, Kim SH. Effect of hydrothermal aging on the optical properties of precolored dental monolithic zirconia ceramics. J Prosthodont 2018; 121: 676-682.
30) Ramdourova A, Kocjan A, Swain MV, Kosmac T. The combined effect of alumina and silica co-doping on the ageing resistance of 3Y-TZP bioceramics. Acta Biomater 2015; 11: 477-487.
31) McLaren EA, Lawson N, Choi J, Kang J, Trujillo C. New high-translucent cubic-phase-containing zirconia: Clinical and laboratory considerations and the effect of air abrasion on strength. Compend Contin Educ Dent 2017; 38: e1-9.
32) Stawarczyk B, Frevert K, Ender A, Roos M, Sener B, Wimmer T. Comparison of four monolithic zirconia materials with conventional ones: Contrast ratio, grain size, four-point flexural strength and two-body wear. J Mech Behav Biomed Mater 2016; 59: 128-138.
33) Contrepois M, Soenen A, Bartala M, Laviole O. Marginal adaptation of ceramic crowns: A systematic review. J Prosthodont 2013; 110: 447-454.
34) Wang F, Takahashi H, Iwasaki N. Translucency of dental ceramics with different thicknesses. J Prosthodont 2013; 110: 14-20.
35) Pecho OE, Ghinea R, Ionescu AM, Cardona JC, Paravina RD, Pe´rez MM. Color and translucency of zirconia ceramics, human dentine and bovine dentine. J Dent 2012; 40: 34-40.
36) Shahmiri R, Standard OC, Hart JN, Sorrell CC. Optical properties of zirconia ceramics for esthetic dental restorations: A systematic review. J Prosthodont 2018; 119: 36-46.
37) Tabatabaian F. Color aspect of monolithic zirconia restorations: A review of the literature. J Prosthodont 2019; 28: 276-287.
38) Hallmann L, Mehr A, Ulmer P, Reussner E, Stadler J, Zenobi R, et al. The influence of grain size on low-temperature degradation of dental zirconia. J Biomed Mater Res 2012; 100: 447-456.
39) Yamashita I, Tsukuma K. Light scattering by residual pores in transparent zirconia ceramics. J Ceram Soc Jpn 2011; 119: 133-135.
40) Klimmek J, Trunc M, Krell A. Transparent tetragonal yttria-stabilized zirconia ceramics: Influence of scattering caused by birefringence. J Am Ceram Soc 2011; 94: 1850-1858.
41) Alghazzawi TF. The effect of extended aging on the optical properties of different zirconia materials. J Prosthodont Res 2017; 61: 305-314.
42) Jiang L, Liao Y, Wan Q, Li W. Effects of sintering temperature and particle size on the translucency of zirconium dioxide dental ceramic. J Mater Sci Mater Med 2011; 22: 2429-2435.
43) Alghazzawi TF, Janowski GM. Correlation of flexural strength of coupons versus strength of crowns fabricated with different zirconia materials with and without aging. J Am Dent Assoc 2015; 146: 904-912.
44) Shiraiishi T, Wood DJ, Shinozaki N, Van Noort R. Optical properties of base dentin ceramics for all-ceramic restorations.
Dent Mater 2011; 27: 165-172.
45) Eheid K, Wille S, Hamdy A, Salah T, El-Etreby A, Kern M. Effect of changes in sintering parameters on monolithic translucent zirconia. Dent Mater 2014; 30: 419-424.
46) Spink LS, Rungruanganut P, Megremis S, Kelly JR. Comparison of an absolute and surrogate measure of relative translucency in dental ceramics. Dent Mater 2013; 29: 702-707.
47) Ilie N, Stawarzczuk B. Quantification of the amount of blue light passing through monolithic zirconia with respect to thickness and polymerization conditions. J Prosthet Dent 2015; 113: 114-121.
48) Saridag S, Tak O, Almacic G. Basic properties and types of zirconia: An overview. World J Stomatol 2013; 2: 40-47.
49) Zhang F, Inokoshi M, Batuk M, Hadermann J, Naert I, Van Meerbeck B, et al. Strength, toughness and aging stability of highly-translucent Y-TZP ceramics for dental restorations. Dent Mater J 2016; 32: e327-737.
50) Nakamura T, Nakano Y, Usami H, Wakabayashi K, Ohnishi H, Sekino T, et al. Translucency and low-temperature degradation of silica-doped zirconia: A pilot study. Dent Mater J 2016; 35: 571-577.
51) Heffernan MJ, Aquilino SA, Diaz-Arnold AM, Haselton DR, Stanford CM, Vargas MA. Relative translucency of six all-ceramic systems. Part I: core materials. J Prosthet Dent 2002; 88: 4-9.
52) Zhang H, Kim BN, Morita K, Yoshida H, Lim JH, Hiraga K. Optical properties and microstructure of nanocrystalline cubic zirconia prepared by high-pressure spark plasma sintering. J Am Ceram Soc 2011; 94: 2981-2986.
53) Presenda A, Salvador MD, Peñaranda-Fonte FL, Moreno R, Borrell A. Effect of microwave sintering on microstructure and mechanical properties in Y-TZP materials used for dental applications. Ceram Int 2015; 41: 7125-7132.
54) Aperz T, Van Bruggen MPB. Transparent alumina: a light-scattering model. J Am Ceram Soc 2003; 86: 480-486.
55) Kim HK, Kim SH, Lee JB, Ha SR. Effects of surface treatments on the translucency, opalescence, and surface texture of dental monolithic zirconia ceramics. J Ceram Process Res 2016; 115: 773-779.
56) Jiang L, Wang CY, Zheng SN, Xue J, Zhou JL, Li W. Effect of Fe2O3 on optical properties of zirconia dental ceramic. Chin J Dent 2016; 115: 773-779.
57) Chaim R, Levin M, Shlayer A, Estournès C. Sintering and densification of nanocrystalline ceramic oxide powders: A review. Advances Appl Ceram 2008; 107: 159-169.
58) Zhang Y, Lawn BR. Novel zirconia materials in dentistry. J Dent Res 2015; 113: 114-121.
59) Almazdi AA, Khajah HM, Monaco EA Jr, Kim H. Applying microwave technology to sintering dental zirconia. J Prosthet Dent 2012; 108: 304-309.
60) Zhang Y. Making yttria-stabilized tetragonal zirconia translucent. Dent Mater 2014; 30: 1195-1203.
61) Subaşi MG, Alp G, Johnston WM, Yilmaz B. Effect of thickness on optical properties of monolithic CAD-CAM ceramics. J Dent 2018; 71: 38-42.
62) Zhang F, Vanmeensel K, Batuk M, Hadernmann J, Inokoshi M, Van Meerbeck B, et al. Highly-translucent, strong and aging-resistant 3Y-TZP ceramics for dental restoration by grain boundary segregation. Acta Biomater 2015; 16: 215-222.
63) Bravo-Leon A, Morikawa Y, Kawahara M, Mayo MJ. Fracture toughness of nanocrystalline tetragonal zirconia with low yttria content. Acta Mater 2002; 50: 4555-4562.
64) De Souza RA, Pietrowski MJ, Anselmi-Tamburini U, Kim S, Munir ZA, Martin M. Oxygen diffusion in nanocrystalline yttria-stabilized zirconia: the effect of grain boundaries. Phys Chem Chem Phys 2008; 10: 2067-2072.
65) Zhang S, Sha H, Castro RHR, Fallar R. Atomic modeling of La3+ doping segregation effect on nanocrystalline yttria-stabilized zirconia. Phys Chem Chem Phys 2018; 20: 13215-13223.
66) Carabba M, Keeling AD, Aziz A, Vichi A, Fabian Fonzar R, Wood D, et al. Translucent zirconia in the ceramic scenario for monolithic restorations: A flexural strength and translucency comparison test. J Dent 2017; 60: 70-76.
67) Fathy SM, El-Fallal AA, El-Negy SA, El Bedawy AB. Translucency of monolithic and core zirconia after hydrothermal aging. Acta Biomater Odontol Scand 2015; 23: 86-92.
68) Kaizer MR, Gierthmuhlen PC, Dos Santos MB, Cava SS, Zhang Y. Speed sintering translucent zirconia for chairside one-visit dental restorations: Optical, mechanical, and wear characteristics. Ceram Int 2017; 43: 10999-11005.
69) Marinis A, Aquilino SA, Lund PS, Gratton DG, Stanford CM, Diaz-Arnold AM, et al. Fracture toughness of yttria-stabilized zirconia sintered in conventional and microwave ovens. J Prosthet Dent 2013; 109: 165-171.
70) Kim HK, Kim SH. Comparison of the optical properties of pre-colored dental monolithic zirconia ceramics sintered in a conventional furnace versus a microwave oven. J Adv Prosthodont 2017; 9: 394-401.
71) Ahsanzadeh-Vaqqani M, Razavi RS. Spark plasma sintering of zirconia-doped yttria ceramic and evaluation of the microstructure and optical properties. Ceram Int 2016; 42: 18931-18936.
72) Becker MJ, Shomrat N, Tsur Y. Recent advances in mechanism research and methods for electric-field-assisted sintering of ceramics. Adv Mater 2018; 30: e1706369.
73) Akar GC, Pekkan G, Çalış E, Esıktaşçuoğlu G, Özcan M. Effects of surface-finishing protocols on the roughness, color change, and translucency of different ceramic systems. J Prosthet Dent 2014; 112: 314-321.
74) Zadeh PN, Lümkemann N, Sener B, Eichberger M, Stawarzczuk B. Flexural strength, fracture toughness, and translucency of cubic/tetragonal zirconia materials. J Prosthet Dent 2018; 120: 948-954.
75) Afferrante L, Ciavarella M, Valenza E. Is Weibull’s modulus really a material constant? Example case with interacting collinear cracks. Int J Solids and Struct 2006; 43: 5147-5157.
76) Pereira GK, Silvestri T, Camargo R, Rippe MP, Amaral M, Kleverlaan CJ, et al. Mechanical behavior of a Y-TZP ceramic for monolithic restorations: effect of grinding and low-temperature aging. Mater Sci Eng C Mater Biol Appl 2016; 63: 70-77.
77) Grogić-Valdez AA, Rainforth WM, Zeng P, Ross IM. Decoloration of hydrothermal degradation of 3Y-TZP by alumina and lanthaun co-doping. Acta Biomater 2013; 9: 6226-6235.
78) Swain MV. Impact of oral fluids on dental ceramics: what is the clinical relevance? Dent Mater 2014; 30: 33-42.
79) Camposilvan E, Leone R, Gremillard L, Sorrentino R, Zarone F, Ferrari M, et al. Aging resistance, mechanical properties and translucency of different yttria-stabilized zirconia ceramics for monolithic dental crown applications. Dent Mater 2018; 34: 879-890.
80) Casolco SR, Xu J, Garay JE. Transparent/translucent polycrystalline nanostructured yttria stabilized zirconia with varying colors. Scr Mater 2008; 58: 516-519.
81) Pecho OE, Ghinea R, Ionescu AM, Cardona JC, Della Bona A, Mdel MP. Optical behavior of dental zirconia and dentin analyzed by Kubelka-Munk theory. Dent Mater 2015; 31: 60-67.