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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 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 costs¹⁻⁸. However, light transmission still remains a major drawback in those ceramics⁹⁻¹⁵. When restoring the anterior teeth with crowns or fixed dental prostheses, ZrO₂'s high opacity is a problem^{4,5}. 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 combinations²⁰⁻²⁵. 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 ceramics^{5-8,11,22,26,27}. Another advantage is their fast and simple-fabrication employing computer assisted design and fabrication (CAD/CAM) technologies^{4,28}. 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 fluids²⁹⁻³².

Color and translucency of Y-TZP ceramics affect the aesthetic properties of the dental prostheses^{1-7,11,33}. Perceived color is determined by wavelength. Translucency of fixed dental prostheses is directly related to light's spectral effect^{20,25,34,35}. 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 photons^{36,37}. In internal surfaces of the Y-TZP, grain boundaries, crystallographic defects and micro-pores are light scattering centers affecting the translucency of this polycrystalline material^{10,17,35}. 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 diffusion transmission, whereas in fine-grained ones, it is given by a high in-line transmission^{9,38}. 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 translucent^{4-5,38}.

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 the light wavelength being scattered, 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 porosity^{5,11,25,38-40,42}.

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) methods^{4-7,17,20,22,43-46}. 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 reference backing (YW), afterwards the black backing (YB), leading to a total of 4 measurements for each specimen. The average CR is calculated as below:

$$\text{CR} = \text{YB}/\text{YW}^5$$

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 methods, the light transmittance measured indirectly. In the third way (total transmission), both the light reaching the detector and passing the ceramic and scattering are measured². Transmittance (T) is calculated as follows:

$T = (\text{L}_{\text{specimen}}/\text{L}_{\text{source}}) \times 100\%$, where L specimen is the specimen luminance and L source is the source of luminance².

The CR and light transmittance methods have the possibility of being either luminous or spectral⁴³. 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 (ΔE) can be determined by the CIELAB coordinates⁴⁵. For TP, color parameters are achieved through CIE-Lab (Commission Internationale de l'Éclairage L^* , a^* , b^*) formulation⁷. Color difference (ΔE^*_{ab}) and TP are calculated with the formulation indicated below:

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

TP value = $[(LB^* - LW^*)^2 + (aB^* - aW^*)^2 + (bB^* - bW^*)^2]^{1/2}$, where the subscripts B and W refer to colour coordinates over a black and white background, respectively^{5,7,21}.

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 fabrication^{12,47,48}, dopants^{30,49,50}, phase type⁴⁹, yttria content^{12,24,51}, porosity^{5-6,45}, impurity⁸, defects⁵, birefringence^{36,40}, oxygen vacancies³⁰, grain size³², grain boundary^{31,49,50}, sintering temperature^{2,5,42}, sintering process^{52,53}, reflexion and refractive index³⁶ of the material and light scattering^{39,54,55}. 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 ceramics^{39,41} 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 body^{48,56}. This specific process leads to improved light transmission of monolithic ZrO₂ and enables a lower and more natural shade value^{3-5,10,20,21,39,42}.

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 properties^{48,56}. 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 size^{12,13}. 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 isostatic 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 milling 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 implants^{5,21,24,38,57-59}.

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^{3,5}. Hence, for improved translucency of Y-TZP ceramics, lower porosity is necessitated². Y-TZP ceramics' grain size, porosity and density are directly determined by the applied heating method and final sintering temperature^{2,5,45,58}. Almazdi *et al.*⁵⁹ 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.*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^{2,57}.

Grain size

The correlation between particle size and light wavelength size is one of the most important factors affecting light scattering⁶⁰. In a material having similar grain size with light wavelength, light scattering becomes very large⁶¹. 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 μm appear less opaque due to less reflection and absorption when exposed to visible light wavelength than those containing large particles⁶⁰. Materials with particles larger than 10 μm have surface reflection, absorption and refraction, while the number of particles per unit volume is small and the opacity may be reduced by less reflection⁶¹. 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^{2,5}. In contrast to that, Denry and Kelly¹² 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 microstructure¹.

The employment of La_2O_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^{54,62}. Presenda *et al.*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 grains⁵⁴.

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 transmission⁵⁴. 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-TZPs is about 1 μm ⁶³. If the great majority of the sizes of tetragonal grains are above 1 μm , then the simultaneous *t*→*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-TZP⁶⁰. Moreover, reducing the grain size of 3Y-TZP ceramics is the most convenient way to enhance its translucency. Zhang⁶⁰ 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 (TIT), at a slightly less translucency level, TIT=2% at 555 nm wavelength, the grain size of 3Y-TZP could be approximately 120 nm⁴⁰. 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 translucency⁶⁴. In terms of high-density nano-crystalline ZrO_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 ZrO₂ crystal structure becomes more compact whereas porosity, defect, and flaws decrease⁵.

Porosity plays a significant role in the translucency of ZrO₂ material. Pores larger than 50 nm result in considerable scattering, thus reducing light transmission ("pore scattering")^{5,64}. 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^{52,65}. 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 crystals⁶⁰. 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 ceramics³⁶. Dopant is an oxide and acts as a grain boundary-engineering tool which has a control over the composition of the grain boundaries of ZrO₂^{30,62,65}. Various oxides, such as Al₂O₃, Sc₂O₃, Nd₂O₃, and La₂O₃, MgO and GeO₂, 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 ZrO₂ grain boundaries in Y-TZP ceramics and dopant segregation is a decisive parameter in ensuring hydrothermal stability and high-translucency^{30,36,62}. Moreover, the study of Zhang *et al.*⁶² revealed that the cation dopant radius is another key factor for controlling segregation. They reported that a large trivalent dopant such as La³⁺ originating from La₂O₃, which is oversized compared to Zr⁴⁺, displayed a distinctive segregation at ZrO₂ grain boundary. In the same study, introducing 0.2 mol% La₂O₃ to 0.1 wt% Al₂O₃-doped 3Y-TZP yielded 42% higher translucency than conventional 0.25 wt% Al₂O₃-doped 3Y-TZP. However, reducing Al₂O₃ 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 ZrO₂ at room temperature^{5,10}. These are usually CaO, MgO, Y₂O₃ or CeO₂. Their amounts should be controlled in terms of transformability, phase stability and mechanical properties¹¹. In general, ZrO₂ is stabilized with 3 moles of Y₂O₃. *T*↔*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 propagation¹⁰⁻¹².

In addition to the mechanical strength and phase stability of 3Y-TZP, its extreme opacity is one of the most important disadvantages. Hence, monolithic ZrO₂ ceramics with 5 to 8% of yttria have emerged as having less opacity⁶⁰. However, such a strategy sacrifices the flexural strength⁶⁶ and fracture toughness because of the partial loss of the transformation toughening effect of tetragonal ZrO₂^{20,60}.

Phase type and percentage (cubic, monoclinic, tetragonal)

The phase type and percentage also affect the translucency of the monolithic Y-TZP ceramics³¹. The monoclinic phase itself may act as a flaw or defect in ZrO₂ microstructure. These porosities or imperfections may reduce the translucency by enhancing scattering of incident light⁶⁷. The higher Y₂O₃ content tended to raise the amount of cubic phase present in ZrO₂. A combination of fine grain size and cubic ZrO₂ 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^{5,42}. Kim *et al.*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 translucency¹. However, increasing the sintering temperature to obtain more translucent ceramics by increasing the grain size is not desirable¹². 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^{1,3,45,49}.

One of the ways to improve the color and translucency features of monolithic ZrO₂ is to increase the sintering temperature and time. Ebeid *et al.*⁴⁵ stated that changing the sintering parameters of monolithic ZrO₂ 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 time⁶⁸.

CS, MS and spark plasma sintering (SPS)

The heat transfer mechanisms of the Y-TZP ceramics sintered conventionally are conduction, convection and radiation⁵³. 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 contingent on the dielectric properties of the material⁵⁹.

Sintering takes place through 2 main heat-activated processes, namely densification and grain growth. Densification mechanisms depend on atomic diffusion in polycrystalline ceramics and viscous flow in glassy materials. MS favors the use of a lower temperature range during the process, which prevents prolonged-heating resulting in larger grains and coarsening of grains. It produces a final product with higher density and more uniform and small grain size in the microstructure. Consequently, translucency is increased in comparison to those obtained from conventional firing of Y-TZP ceramics^{2,53,59,69}. MS method is a faster method than CS and homogenizes microstructure by increasing productivity^{2,70}.

SPS is an effective method of sintering the Y-TZP material at relatively low temperatures that limits grain growth and contributes to full densification of the ceramic powders^{52,71,72}. In this method, the high temperature levels as 3–10 thousands °C creates melting and evaporation of powder particle surfaces. As a result of the formation of the necks, the material can be sintered in a short time such as 5–20 min with uniaxial pressing⁷¹. Field-Assisted Sintering Technology-Spark Plasma Sintering (FAST-SPS) sintering of Y-TZP ceramics may result in reduced pore and smaller grain sizes⁷².

Light scattering

The translucency of dental porcelain depends largely upon light scattering⁶¹. 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 particles². 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^{55,73}.

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 matrix⁴⁷. However, Y-TZP ceramics are polycrystalline materials without any matrix. The refractive index for ZrO₂ is stated as approximately 2.2³⁶. 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 strained⁴⁰. Tetragonal ZrO₂ 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 transmittance⁶⁰.

In the literature, the birefringence for monoclinic ZrO₂ is about 0.070, but there is no known reliable data for tetragonal lattices due to the weak transparency of single crystals⁴⁰. ZrO₂ has higher birefringence than Al₂O₃, accordingly the grain sizes necessary to obtain transparency have to be much smaller. Klimke *et al.*⁴⁰ calculated the expected in-line transmission by RGD approximation for dense tetragonal ZrO₂ 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^{31,66,74}. On the

other hand, higher sintering temperatures of dental ZrO₂ lower the flexural strength¹.

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 materials^{12,69}.

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 properties^{62,79}.

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 ceramics⁶². Ce-stabilized ZrO₂ (Ce-TZP) is far more resistant to hydrothermal aging than 3Y-TZP⁷⁸.

Wavelength (visible wavelength 500–555 nm or different wavelengths)

Visible wavelength is between 300–700 nm in the light spectrum. In the daylight, the visible wavelength is approximately 555 nm. The size of the grains compared with the wavelength of incident light is the most important determinant of the translucency of the Y-TZP ceramics. If the grain and wavelength of incident light are in a similar range, the amount of light scattering increases with grain size and lowers the translucency (light transmittance)⁵⁴. If grain size is much larger than the wavelength of the incident light, the amount of light scattering becomes inversely proportional to the grain size, and independent of the wavelength of incident light^{2,80}.

Theoretical investigations (scattering models) and quantum-mechanical perspective

Several researchers tried to predict the desirable grain size of 3Y-TZP ceramics for achieving a good translucency and transparency employing light

scattering models^{40,54,81}. From quantum-mechanical point of view, electromagnetic radiation is composed of groups or packets of energy called photons. The energy of a photon is defined by the following relationship:

$E=hc/\lambda$, where h is a universal constant called Planck's constant, with a value of 6.63×10^{-34} J-s, ν is frequency which is defined in terms of hertz (Hz), c is the electromagnetic constant, and λ is the wavelength. Photon energy is proportional to the frequency of the radiation, or inversely proportional to the wavelength.

When defining the optical properties of a material from the quantum-mechanical perspective, the main matter is the interaction between the microstructure and photons. In other circumstances, a wave treatment is more suitable at one time or another.

For non-absorbing dense ceramics (corundum), Apetz and van Bruggen⁵⁴ proposed a theoretical model, which explains the grain size and birefringence effects on the in-line transmission using RGD scattering model. It has been widely accepted for guessing the transparency in birefringent Al₂O₃. On the other hand, with the larger birefringence the validity of the RGD approximation worsens as in tetragonal ZrO₂. Rayleigh scattering model explains in-line transmittance of 3Y-TZP with grain sizes smaller than 80 nm. For grain sizes considerably larger than 80 nm, Mie scattering model, the grain-size independent model, required to be used⁶⁰.

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.

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