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REVIEW ARTICLE

Zirconia: Properties and casting procedures: A review article

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Abstract

Zirconia (ZrO_2) is widely used in orthopedics, in the recent past, it has also become one of the preferred among prosthetic dentists, due to its favorable properties. ZrO_2 was introduced to prosthetic dentistry about 30 years back; however, its use as in dental implants was reported only in 2004. This review article presents and briefly compares the mechanical properties of ZrO_2, various types of ZrO_2 ceramics, and the key processing techniques.

Introduction

Zirconia (ZrO_2) is an oxide ceramic; its transformation toughing capabilities was initially noted in 1970s. Clinical trials conducted to analyze the biocompatibility of ZrO_2 and its uses in dentistry reported no adverse events.[1,2]

Unalloyed ZrO_2 changes its structure from tetragonal to monoclinical on alternative treating with heat and cold. It also significantly increases in volume, which might cause a failure in procedure.[1] To maintain the tetragonal structure and increase the stability, ZrO_2 can be alloyed with metallic oxides (CaO, MgO, yttria, or CeO_2).[1,2]

In dentistry, ZrO_2 was initially used for root canals, in the 1980s. However, its use in implants has been very recent (since 2004).[1,3]

Dentists are in constant search for a metal-free tooth-colored restoration, due to the increasing interest in esthetics and growing toxic and allergic reactions to some of the metal alloys.

The recent advancements in the use of ZrO_2 both for restorative dentistry and dental implants have not failed to generate imminent interest among dentists.[2,3]

In this article, we will discuss the properties of ZrO_2 and casting procedures used in restorative dentistry.

Mechanical Properties of ZrO_2

Mechanical properties of ZrO_2 resemble stainless steel. It has monoclinic, tetragonal, and cubic patterns. At room temperature, unalloyed or pure ZrO_2 is monoclinic and remains stable up to 1170°C, transforms into tetragonal, followed by cubic phase and has melting point at 2370°C. At temperature ranging between 100°C and 1070°C, it returns to monoclinic phase.[1-4]

ZrO_2's resistance to traction can reach up to 900–1200 Mpa. It also has compression resistance of approximately 2000 Mpa. However, it is noted that surface treatments can affect the physical properties and also extended exposure to wetness can lead to detrimental effects (also termed as ZrO_2 ageing). Table 1 summarizes the mechanical properties of ZrO_2.[1-3]

Types of ZrO_2 Ceramics

Single-phase polycrystalline

Studies show that ZrO_2 stabilized with yttria (Y_2O_3), following sintering might contain up to 98% of tetragonal phase. Strength of the ZrO_2-Y_2O_3 alloy (ZYA) was directly proportional to the tetragonal phase content. Further, clinical evaluations

Table 1: Mechanical properties of ZrO_2 [3]

Properties	Parameters
Density	6.05 g/cm^3
Hardness	1200 HV
Bend strength	900–1200 Mpa
Compressive strength	2000 Mpa
Fracture toughness	7–10 Mpam$^{1/2}$
Young's modulus	210 Gpa
Thermal expansion coefficient	11×10^{-6} 1/K

Adapted from: Madfa A, Al-Sanabani FA, Al-Qudami NH, Al-Sanabani JS, AmranAG. Use of Zirconia in Dentistry. Open Biomater J 2014;5:1-9. ZrO_2: Zirconia

have demonstrated that mechanical properties of ZYA are strongly dependent on its grain size. It is also noted that below a critical average grain size (<0.3 μm) higher strengths and toughness have been recorded. This phenomenon is generally noted for polycrystalline ceramics showing a strength or toughness mechanism. Based on the sintering temperatures, the microstructure consists of equiaxed grains of tetragonal ZrO_2 of sizes ranging between 0.2 and 0.5 mm in diameter.[1,2,5]

Various studies have reported a reverse transformation from monoclinic to tetragonal phase with annealing at 900°C for an hour or with short heat treatments (900–1000°C) for 1 min. This leads to reduction in strength through relaxation of compressive stresses on the surface. Hence, during the process of fabrication, firing of veneering porcelain might assist the reverse transformation.[1,2] Temperature ranges between 1350 and 1550°C are used for soft machining of presently available ZYA. Due to the wide temperature range, studies have shown that there might be instances where cubic phases are seen, which is not desirable for biomedical applications, as it makes ZYA more unstable.[1,2]

Dispersion toughened

Dispersion-toughened ZrO_2 combinations include ZrO_2-toughened Al_2O_3 (ZTA) or ZrO_2-toughened mullite appears to be the least widely published and commercially important. ZTA can be processed either by soft machining or casting. Post the glass infiltration of porous ceramic composite initial sintering happens at 1100°C for 2 h. It is noted that the amount of porosity of ZTA is higher as compared with ZYA.[1,2]

One of the examples of a dispersion-toughened ceramic dental material is In-Ceram®. It contains Al_2O_3 and ZrO_2 in the volume ratio of 70:30%, with an interpenetrating composite of 30% glass and 70% polycrystalline ceramic. Due to its better consistent processing as compared to slip-cast ceramic, In-Ceram® is assumed to show better mechanical properties for machining. It is noted that in some of the latest forms of ZTA better mechanical properties are exhibited by following fine and uniform dispersion of ZrO_2 in alumina matrix.[1,2,6]

Partially stabilized

Significant amount of research is conducted on magnesia partially stabilized ZrO_2 (PSZ), it is one of the commercially important and microstructurally complex. However, not much of success is noted due to its porosity, which can be attributed to the large grain size (30–60 μm). Intragranular precipitates in these ceramics contain tetragonal phases along with cubic stabilized matrix. Stabilization involves dopant addition of various minerals (CaO, MgO, La_2O3, and Y_2O_3) in concentrations less than necessary for complete cubic ZrO_2 stabilization. Complete stabilization is purposefully not achieved in PSZ. Precipitates are nucleated following sintering or solution annealing in the cubic solid solution single-phase field at temperatures more than 1850°C and grown at lower temperatures at about 1100°C within the two-phase tetragonal solid solution plus cubic solid solution phase field; a process termed "aging." One of the examples of commercially available PSZ is Denzir-M® (Mg-PSZ ceramic). Commercial materials of Mg-PSZ contain about 8–10 mol% of magnesium oxide in the composition.[1,2,7]

Factors which have led to reduced success of Mg-PSZ include:

Temperature control: In addition to a high sintering temperature, necessity to maintain the cooling cycle with a preferred temperature of 1100°C as precipitation of the transformable tetragonal phase occurs during this stage and is critical in fracture toughness.[7]

Purity: Difficulty in procuring precursor of Mg-PSZ which if free of SiO2 leads to the formation of magnesium silicates, thereby affecting the stability of the material.[1]

Clinical Usage of ZrO_2: An Overview

Attributable to its stability and other properties, ZrO_2-based fixed partial dentures have much broader usage spectrum as compared to other ceramics. Furthermore, due to its high fracture resistance, ZrO_2 is finding its use also as dental implant abutment.[1,2]

Computer aided design/computer aided manufacturing (CAD/CAM) ZrO_2 dental materials can be produced using two primary casting techniques, soft machining and hard machining.[1,2,8]

Soft machining

Direct ceramic machining of presintered ZYA has become increasingly popular in dentistry. After scan of die pattern, CAD is used to design an expanded restoration. Later using computer-assisted machining, a presintered ceramic blank is grinded. The restoration is then sintered at high temperature. Several variations of this process exist depending on how the large sintering shrinkage of ZYA is compensated for and how the scanning is performed. Both contact scanners and non-contact scanners are available and the latter are characterized by a higher density of data points and a greater digitizing speed as compared to the former.[1,2,8]

Hard machining

Two known systems of hard machining available for ZrO_2 dental restorations are Denzir® (Cadesthetics AB) and DC-Zirkon® (DCS Dental AG). ZYA blocks are prepared by presintering at temperatures <1500°C to arrive at a minimum density of 95%

of the theoretical density. Following which blocks are processed under high pressure in an inert gas atmosphere into hot isostatic pressing at temperatures ranging between 1400 and 1500°C. This leads to a very high density (>99% of the theoretical density). Later using milling systems, these ZYA blocks can be machined. Due to the high hardness and low machinability properties of fully sintered ZYA, special focus needs to be provided to ensure that the milling system is vigorous. A study report noted that as compared to fully sintered alumina with lower material removal rates, ZYA is significantly harder to machine.[1,2]

Clinical studies

Table 2 summarizes key characteristics from major clinical trials studying ZrO_2 prosthesis in dentistry.[1]

Conclusion

Use of ZrO_2 across various fields of prosthetic dentistry is growing by the day and similar is the scenario on the research front. We see considerable amount of focus in the market on ZrO_2-based materials. This review focused on understanding the

Table 2: Summary of clinical trials on ZrO2 prosthesis[1]

Investigator	Patients	Prostheses	Initiated	Observ. Time (mean)
I. Sailer	45	57 multiunit, posterior	1998	53 mos.
C. Hammerle¨		3-unit, 4-unit		
Univ. Zurich¨		One 5-unit		
Cercon (Dentsply)				
P. Pospiech	36	18 single unit, posterior	2000	42 mos.
Saarland Univ.		38 multiunit, posterior		
Lava (3 M ESPE)				
S. Rinke		89 single unit, posterior	2000	
Private Pract.				
Cercon (Dentsply)				
M. Kern	68	36 3-unit, posterior	2000	62 mos.
S. Wolfart				
C-A Univ. Kiel		45 3-unit, posterior inlay retained		47 mos. (10 Fx)
e.MaxPress (Ivoclar)				
A. Huls		62 3-unit and 4-unit, posterior	2000	
Univ. Gottingen				
Cercon (Dentsply)				
P. Vultvon	18	2 3-unit	2001	36 mos.
Steyern Malmo¨		12 4-unit (1 or 2 pontics)		
Univ. DC-Zircon		6 5-unit (1 or 2 pontics)		
A. Raigrodski	16	20 3-unit, posterior	2002	26 mos.
U. Washington				
Lava (3 M ESPE)				
M. Kern	58	65 3-unit, posterior	2002	31 mos.
S. Wolfart				
C-A Univ. Kiel				
In-Ceram Zr (Vita)				
M. Kern	51	24 3-unit, posterior	2003	27 mos.
S. Wolfart				
C-A Univ. Kiel		37 3-unit, posterior		31 mos.
Cercon (Dentsply)		Cantilever		

Contd...

Table 2: *Continued*

Investigator	Patients	Prostheses	Initiated	Observ. Time (mean)
E. Durm	42	42 3-unit, posterior	2003	
W. Mormann¨				
U. Zurich¨				
Vita YZ (CEREC)				
J. Sorensen	48	38 3-unit, posterior	2003	30 mos.
Pacific Dent. Inst.		14 4-unit, posterior		
Lava (3 M ESPE)				
F. Beuer	36	38 single unit	2004	12 mos.
LMU Munchen¨		22 3-unit, posterior		
e.max ZirCad (Ivoclar Vivadent)		1 4-unit posterior		
R. Zajia, K. Chong, K. May, Univ. Mich. DC-Zircon	19	20 3-unit posterior FPDs on natural abutments	2004	12 mos.
F. Beuer		21 3-unit, posterior	2005	12 mos.
L-M Univ. Munchen¨				
Cercon (Dentsply)				
C. Larsson	18	25 2-unit to 5-unit implant supported	2005	12 mos.
Malmo¨ Univ.				
DC-Zircon and In-Ceram Zr (Vita)				

Adapted from: Denry I, Kelly JR. State of the art of zirconia for dental applications. Dent Mater 2008;24:299-307. ZrO_2: Zirconia

mechanical properties, casting procedures, and also a quick view into the latest research happening on ZrO_2.

Clinical long-term studies are necessary to further validate, however, from the data available from current and past research, it can be inferred that ZrO_2 has good endurance and resistance properties. Further studies on the use of ZrO_2 in both prosthetic and implant dentistry among various patient groups are crucial.

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