

Methods of Strengthening Ceramics

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Abstract:**Aim**

To know about the various methods of strengthening ceramics.

Objective

To provide information on ceramic dental materials and various techniques to strengthen ceramics.

Background

Ceramics are defined as solids with a mixture of metallic or semi-metallic and non-metallic elements that are quite hard, non-conducting and corrosion-resistant. Today's ceramic restoration application, despite its popularity gained through esthetical advantages and superior hygienically features, has a fragile structure due to its low tensile strength quality. In the long run, it can lose its endurance against shear and draw strengths that occur while chewing. Technical flaws like micro cracks and porosity which appears during production causes mechanical failure in porcelain restoration. This article reviews the concepts and mechanisms of strengthening ceramics.

Reason

To review about the various methods of strengthening ceramics for improving the results.

Keywords: ceramics, tempering, stress, transformation

INTRODUCTION

In dentistry, ceramics represents one of the four major classes of materials used for the reconstruction of decayed, damaged or missing teeth. The other three classes being metals, polymers and composites. The word Ceramic is derived from the Greek word "keramos", which literally means 'burnt stuff', but which has come to mean more specifically a material produced by burning or firing [1]. A ceramic is an earthly material usually of silicate nature and may be defined as a combination of one or more metals with a non-metallic element usually oxygen. The American Ceramic Society has defined ceramics as inorganic, non-metallic materials, which are typically crystalline in nature, and are compounds formed between metallic and non-metallic elements such as aluminium & oxygen, calcium & oxygen, silicon & nitrogen [2]. The term porcelain is referred to a specific compositional range of ceramic materials made by mixing kaolin, quartz and feldspar in proper proportioning and fired at high temperature [3,4]. Porcelain is essentially a white, translucent ceramic that is fired to a glazed state. [5]

In dentistry, ceramics are widely used for making artificial denture teeth, crowns, bridges, ceramic posts, abutments, and implants and veneers over metal substructures [6]. Ceramic material used in dentistry is a glassy matrix that is produced via sintering and it contains leucite crystals; it can be identified as a sort of ceramic that is not totally transformed into glass phase. Ceramics are characterized by their refractory nature, hardness, chemical inertness, biocompatibility and susceptibility to brittle fracture [7,8]. Crystal structure of ceramic material contains ionic and covalent type of strong bonds that gain stability and determination. However, because of those bonds, ceramic has a fragile structure. Ceramic has a high rigidity and pressure strength and low flexion performance [9]. The pressure strength of dental ceramics is between 350-550 MPa and the draw strength value is 20-60 MPa. That is

why ceramic structure should be supported either by metal or substructures more durable which decrease effects of tension strength occurring on surface or should be strengthened structurally.[10,11]

CLASSIFICATION OF CERAMICS

Composition;

Pure alumina, pure zirconia, silica glass, leucite-based glass ceramics, lithia-based glass ceramics.

Processing methods;

Sintering, partial sintering and glass infiltration, heat pressing, slip casting, CAD/CAM and copy milling.

Core;

In-ceram spinell

In-ceram alumina

In-ceram zirconia

Firing temperature;

High fusing (1,300°C), medium fusing (1,101-1,300°C), low fusing (850-1,000°C), ultra low fusing (below 850°C).

Substructure material;

Feldspathic porcelain, cast metal, swaged metal, glass ceramics, CAD/CAM, sintered ceramic core.

Microstructure;

Amorphous glass, crystalline porcelain, crystal containing glass, partially crystallized porcelain and apatite ceramic.

Translucency;

Opaque, translucent, transparent.

Indications;

Anterior and posterior crowns, veneers, posts and cores, FPDs, stain ceramic, glaze ceramic, metal ceramic, inlays, onlays and implants.[12]

COMPOSITION OF CERAMIC

Feldspar - it is the lowest fusing component, which melts first and flows during firing, initiating these components into a solid mass.

Silica (Quartz)- Strengthens the fired porcelain restoration, remains unchanged at the temperature normally used in firing porcelain and thus contribute stability to the mass during heating by providing framework for the other ingredients.

Kaolin- binder, increases moldability of the unfired porcelain, imparts opacity to the finished porcelain product. Glass modifiers, e.g. K, Na, or Ca oxides or basic oxides- they interrupt the integrity of silica network and acts as flux.

Colour pigments or frits, e.g. Fe/Ni oxide, Cu oxide, MgO, TiO₂, and Co oxide- to provide appropriate shade to the restoration.

Zr/Ce/Sn oxides and Uranium oxide.[13]

PROPERTIES

Dental ceramics exhibit excellent biocompatibility with the oral soft tissues and are also chemically inert in oral cavity. They possess excellent aesthetics. Ceramics are good thermal insulators and their coefficient of thermal expansion is almost close to the natural tooth [14,15]. Dental ceramics possesses very good resistance to the compressive stresses, however, they are very poor under tensile and shear stresses. This imparts brittle nature to the ceramics [16,17,18] and tend to fracture under tensile stresses. Structural defects lead to the failure in dental ceramic prostheses. Defects may arise in the form of micro-cracks of sub-millimeter scale; during fabrication of ceramic prostheses and also from application of masticatory forces in the oral cavity [19]. Fatigue strength plays an important role in the durability and longevity of dental ceramic restorations.

METHODS OF STRENGTHENING CERAMICS

The major drawbacks of ceramics are brittleness, low fracture toughness and low tensile strength. Methods used to overcome the deficiencies of ceramics fall into two categories including methods of strengthening brittle materials and methods of designing components to minimize stress concentration and tensile stress [20].

The approaches in strengthening ceramics are as follows;

1. Shot peening
2. Strengthen with a metal substructure
3. Dispersion strengthening of glasses
4. Enamelling of high strength crystalline ceramics
5. Controlled crystallization of glasses
6. Production of prestressed surface layers in dental porcelain via ion exchange, thermal tempering.
7. Optimum Restoration Design
8. Crack tip blunting
9. Transformation Saturation
10. Minimizing the number of firing cycles

SHOT PEENING

Shot peening is a type of surface treatment used to strengthen ceramics. It is a cold working process that

shoots balls (shot) of steel, ceramics or glass beads at the workpiece to mechanically prestress the material surface beyond its yielding point[21]. The localized plastic deformation induces residual stresses into the surface region of the material. The surface residual stresses are compressive. The induced compressive residual stresses inhibit crack growth under both static and cyclic loading, increasing the material hardness, fatigue life and resistance to stress corrosion cracking.

STRENGTHEN WITH A METAL SUBSTRUCTURE

The restoration system which involves strengthening the ceramic material with metal was firstly invented by Weinstein in 1962. Metal ceramic systems were developed to reinforce the ceramics[22]. They are:

1. Noble metal alloy systems (high gold, low gold, gold free).
2. Base metal alloy systems (NiCr,Ti)

In order to strengthen dental ceramic and to improve its strength against tension, shear and pressure forces, generally a metal substructure is used. In a ceramic that sub-structurally improved by metal, micro fractures spread if only this strong substructure gets deformed. The perimeter of thermal dilatation of substructure material should be higher than porcelain's. During cooling process, metal substructure shrinks more and more and it supports porcelain with pressure generated [23]. Earlier methods employed to enhance bonding with precious metals were coating with tin oxide. Platinum copings were electroplated with a layer of tin oxide to which aluminous porcelain was attached.

Twin foil technique involves laying down of two platinum foils in close opposition to each other foil provides a matrix for the bonding of the porcelain which is removed after baking. The outer foil forms an inner skin to the crown. It is tin plated and oxidized to achieve a strong chemical bond with the aluminous core porcelain[24].

Noble metal foils are adapted, swaged and brazed on to dies and then bonded to feldspathic porcelain [25]. The advantages here include reduction of metal and labour cost, a porcelain butt fit, avoidance of metal collar, less stresses at the porcelain metal interface, reduction of internal micro cracks and subsurface porosity, so lesser sites of crack propagation.

DISPERSION STRENGTHENING OF GLASSES

Dental ceramics that contains glass phase can be strengthened by dispersion strengthening i.e. dispersing ceramic crystals of high strength and elasticity such as leucite, lithium disilicate, alumina, magnesia-alumina, spinel, zirconia in the glass matrix. When crystal materials are added in the glassy phase, a strong glass-crystal composition is obtained, thus durability and fracture resistance increases. Crystal particles prevent micro fractures to push on forward and it provides a strong structure[26].

Limiting factors while choosing reinforcing crystals are fusion temperature, coefficient of thermal expansion, bonding properties with dental porcelain, mechanical strength and resistance to thermal shock during rapid firing cycles.

Quartz (10-15%) undergoes changes during heating and has a high coefficient of thermal expansion and the strengthening effect of quartz is poor.

Alumina reinforcement: When alumina crystals are dispersed in a glass matrix and heated and cooled, different stress patterns are observed due to the differences in thermal expansion between glass and alumina[27].

ENAMELLING OF HIGH STRENGTH CRYSTALLINE CERAMICS

During firing some form of crystallization takes place in ceramics (sintered or high alumina), resulting in an interlocking crystalline system which is better able to withstand high stresses than feldspathic porcelain. High alumina cores with aluminous porcelain veneers have been used in combination. These laminates are much stronger than regular porcelain, similar to metal ceramic systems. The bonding at the interface is chemical in nature and an ionic bond ensures no porosity as the wetting of the porcelain enamel on high alumina is good[28].

CONTROLLED CRYSTALLIZATION OF GLASSES

Under normal conditions, when a glass is heated up to a determined degree and then get cooled down, it does not crystallize. In this method, ceramic structure is heated up to first softening temperature, made to crystallize by adding a nucleating agent like titanium dioxide, lithia, zinc oxide, silica or metal phosphates[29]. Though the glass is amber in colour and glassy it becomes translucent and tooth like after crystallization or ceramming for 1 hour at 600°C. Here high thermal shock resistance and improved strength property has been observed.

ION EXCHANGE (CHEMICAL TEMPERING)

In general, ceramic restorations fail because of larger and deeper micro fractures caused by tensile strength. Ion exchange method is to generate at low temperature a compressive layer on ceramic's surface in order to micro fractures becomes larger. This compressive layer on surface is created by exchange of some ions with bigger ions of glass matrix. Dental ceramic material is plunged into melted potassium nitrate salt tank cooler than glass transition temperature and Na⁺ ions found on dental ceramic's surface change place with K⁺ ions of salt tank. By way of compressing on silicate system, Potassium ions which are bigger than sodium ions, generate a compression power [30,31]. This surface compression gives an increase in strength on the surface of porcelain.

THERMAL TEMPERING

Rapid cooling or quenching of a surface of an object while it is still hot creates residual surface compressive stresses on the surface of the ceramics. As the core is hot and soft and still in its molten state it tends to shrink and tries to pull the outer surface which is rigid now. On solidification, residual tensile stresses are created on the inner core and residual compressive stresses on the outer surface [32]. Hot glass phase ceramics are quenched in silicone oil or other special liquids [33].

OPTIMUM RESTORATION DESIGN

Before designing a ceramic restoration which will cope with every negative condition, ceramic's weakness against low tensile strength, its fragility and sensitivity to micro fractures should be considered. In this design, ceramic should be protected from high tension. Avoid sharp edges and apparent thicknesses from restorations [34,35]. Best way to decrease the tensile strength on bridges is to design connector zones that have intense stress with an appropriate thickness and shape [36]

Minimizing stress concentrators and stress raisers: Stress raisers are discontinuities in ceramic restoration that can cause stress concentration. The design of the ceramic should avoid these stress concentrators. Abrupt changes in contour including any grooves, pits, notches can alter the stress flow lines. The internal angles in tooth preparation should not be sharp but rounded.

CRACK TIP BLUNTING

Porcelains are solid materials that have a very small work of fracture[37,38,39]. They will tolerate cracks much deeper than 0.025 mm but when the crack propagates its tip radius remains the same throughout the length and very little force is required to propagate the stress. Once porcelain is under tension, the crack propagates and a complete fracture occurs suddenly. Crack tip blunting is a reinforcing mechanism. The principle is somewhat perplexing in that hollow spaces are actually used to strengthen ceramics. As the crack progresses it is dissipated into the void space. The stress is usually increased at the narrow tip of the crack which is reduced at the voids and this prevents crack propagation[40].

TRANSFORMATION SATURATION

Transformation saturation is a phenomenon, based on a phase transformation principal caused by tension strength. In transformation saturation method mostly leucite and zirconium is used to strengthen the ceramic. In this method, changes of temperature in ceramic material play an important role. During thermal changes, volumes of leucite and zirconium found in glassy phase increases in glassy matrix and it creates pressure stresses inside the structure. This pressure stresses both prevent micro fractures to push on and does decrease tension stresses situated at microfracture's peak [41].

Pure zirconia can exhibit a polymorphic phase transformation.

1. Monoclinic (P2₁/c)- from room temperature to heating to 1,170°C
2. Tetragonal (p4₂/nmc)- 1,170°C to 2,370°C
3. Cubic (fm3/m)- above 2,370°C till the melting point.

On cooling from 950°C there is an increase in volume leading to a catastrophic failure. Pure zirconia is alloyed with stabilizing oxides, such as CaO, MgO, Y₂O₃ or CeO₂ which allows the tetragonal structure to remain stable at room temperature, thus efficiently arresting the crack propagation and leading to high toughness [42,43].

MINIMIZING THE NUMBER OF FIRING CYCLES

The purpose of porcelain firing procedure is to densely sinter the particles of powder together and produce a relatively smooth, glassy layer on the surface. Several chemical reactions occur over time at porcelain firing temperature: of particular importance is increase in concentration of crystalline leucite. Changes in the leucite content caused by multiple firing can alter the coefficient of thermal contraction of some porcelain products and produce stresses during cooling, sufficient to cause crack propagation in the porcelain [44].

OTHER METHODS TO IMPROVE STRENGTHENING ARE:

- Good condensation techniques (powder condensation), programmed firing schedules, high pressure compaction, vacuum fired porcelain and better condensation in the wet stage which are all very essential to minimize shrinkage and avoid excessive air bubbles.
- If the surface is undisturbed, the strength of the glazed surface specimen is found to be higher.
- Thermal stresses occurring during improper cooling can cause cracks and weaken the porcelain. Water (saliva) can act as a network modifier and weaken the structure[45].

CONCLUSION

It is apparent that ceramics as a material group would continue to play a vital role in dentistry owing to their natural aesthetics and sovereign biocompatibility with no known adverse reactions. However, there will always remain a compromise between aesthetics and biomechanical strength. In order to achieve adequate mechanical and optical properties in the final porcelain restoration, the amount of glassy phase and crystalline phase should be optimised. Good translucency requires a higher content of the glassy phase and good strength requires a higher content of the crystalline phase. Hence, the two material phases need to be balanced. Even though the material is high abrasion resistant, fracture toughness and resistance to the tensile stresses are inherent disadvantages. To prevent these clinical problems we must strengthen porcelain material using appropriate methods. If dental ceramics have strength structure, dental ceramics will become more indispensable material than amalgam and composite for all-round restorations.

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