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Review Article

The science and application of IPS e.Max dental ceramic

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Abstract The aim of this paper is to report the state of current literature and recommendations for the lithium disilicate glass-ceramic IPS e.Max. The materials science, mechanical and optical properties were reviewed. Additionally an assessment was conducted of current implementation recommendations and clinical outcomes. This paper provides a brief historical overview, summary of the findings the findings of current literature, and clinical recommendation for the use of IPS e.Max CAD in dental applications.

Introduction

Over the last few decades the field of dental ceramics has evolved rapidly, both in material properties and manufacturing techniques. Among these advancements is the introduction of glass-ceramics, which are both highly esthetic and possess exceptional mechanical properties. One such material is the IPS e.Max line (Ivoclar Vivadent, Schaan, Liechtenstein), which comes in two forms, a block that can be milled in a CAD/CAM system (IPS™ e.Max CAD) and an ingot used for pressable crown fabrication following the lost wax technique (IPS™ e.Max Press). Due to the recent nature of these materials research into the material science, mechanical and optical properties, and clinical applications is still ongoing. By focusing on reviewing literature related IPS™ e.Max CAD, this paper aims to provide a background on the material, a brief review of current literature related to the materials science and mechanical properties of the material, a review of the optical and esthetic properties of the material, and an overview of clinical findings, recommendations, and applications.

Background and material history

Lithium disilicate ($2SiO_2$—Li_2O) dental ceramics were first introduced in 1988 for use as a heat-pressed core material marketed as IPS™ Empress 2 (Ivoclar Vivadent, Liechtenstein) [1]. Empress 2 was classified as a glass ceramic, a subgroup of particle-filled glasses, and contained

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approximately 70% crystalline lithium disilicate filler [1—3]. The use of a pressure casting procedure resulted in a material that possessed less defects and more uniform crystal distribution [4]. Reformulation and refinement of the production process of Empress 2, led to the production of a new ceramic line. The new ceramic formulation was released in 2005 under the brand of IPS™ e.Max Press [5]. Ultimately the introduction of the e.Max line would lead to the discontinuation of the Empress 2 line in 2009 [6].

With the advent of digital dentistry and advances in computer-aided design and computer-aided manufacturing methods, IPS™ e.Max CAD was introduced in 2006 as a lithium disilicate glass-ceramic, specifically prepared for CAD/CAM use [4,7]. The material comes prepared in a "blue state," where it is composed primarily of lithium metasilicate (Li_2SiO_3), which is easier to mill and results in lower bur wear [4,7]. After the milling process is completed, the material is heat treated and glazed in one step, forming the final lithium disilicate restoration [4,6,7]. Due to its esthetic nature, impressive strength, and ease of use, IPS™ e.Max CAD has seen increasing use over the several years.

Microstructure properties and phase transformation

The fact IPS™ e.Max CAD is milled and delivered in different states, makes the microstructure properties and phase transformation an area of particular interest. Due to the unique and dynamic nature of the material, there has been significant interest in understanding the microstructure of both the partially crystallized and fully crystallized microstructure of the material. Additional interest has been taken in phase transformation process. Due to the relationship between microstructure and mechanical and optical properties, ongoing characterization of these states has been the subject of intense study.

As mentioned briefly before, e.Max CAD is purchased and milled in a partially crystallized, "blue state." [4,7] According to the manufacturer, various formulations of glass (namely SiO_2, Li_2O, P_2O_5, ZrO_2, ZnO, K_2O, and Al_2O_3 plus additional colorant ions) are combined using glass technology via a pressure-casting procedure [4]. The partially crystalized blocks used for milling in IPS™ e.Max CAD are composed 40% lithium metasilicate crystals (Li_2SiO_3), 0.2—1.0 μm in size and platelet shaped, set in a glassy phase along with lithium disilicate nuclei [4]. A study that analyzed the various phases present in the material through various firing temperatures confirmed the presence and persistence of a glassy phase through X-ray diffraction (XRD) [8]. The partially crystalized state is more easily milled and results in less bur wear and high edge stability [4,7,9].

Once milling has been completed the restoration is subjected to a second round of heat treating. The manufacturer considers the material fully crystallized after being tempered at 850 °C for 20—25 min under a vaccum [4,7]. Various studies have been conducted to attempt to elucidate crystalline phase transformation process for lithium disilicate ceramics [8—11]. During the phase transformation process, it has been shown through XRD analysis that in addition to lithium metasilicate, lithium orthophosphate (Li_3PO_4) and cristoballite (SiO_2) forms [8,12]. Results from differential scanning calorimetry suggest that bulk crystallization is the primary method for transformation with nucleation and crystallization occurring as two distinct events [8,10]. The previous study showed that at low temperatures (below 590 °C) lithium disilicate precipitation was not seen, while at temperatures between 590 °C and 780 °C spherical precipitations of lithium orthophosphate and lithium disilicate were formed [8]. Another study determined that by increasing the pressure of when firing, it was possible to achieve crystal transformation without residual lithium metasilicate at 800 °C (with a 2 min hold) when utilizing plasma spark sintering [10]. The method was introduced to overcome perceived shortcomings in crystal evolution and attempt to improve the properties of the evolved crystalline phase. Initial studies have demonstrated the impact firing time, schedule, and methodology can have on both microstructural and macrostructural material properties [8].

Once the restoration has been heat treated the restoration has undergone crystalline phase transformation and is now a predominantly lithium disilicate glass-ceramic. Manufacturer literature states that fully crystallized IPS™ e.Max CAD produces a microstructure of 70% fine grain lithium disilicate crystals, embedded in a similar glassy matrix [4]. The microstructure has been characterized as highly-interlaced lithium disilicate crystals 5 μm long with a diameter of 0.8 μm [12]. It has also been noted that there is a level of uniform porosity in the fired samples [6,8]. Factors related to crystalline structure such as size, volume fraction, and distribution are known to play a significant role in both the mechanical and chemical properties of a ceramic material, however, despite many studies, the exact relationship between microstructure and mechanical properties has yet to be determined [6,8,12,13]. Understanding the role microstructure, micromechanical, and phase transformation properties of IPS™ e.Max CAD plays in the macrostructural properties of fracture toughness, compressive strength, and even optical properties, material characterization will certainly continue to be an area of intense study.

Mechanical properties

IPS™ e.Max CAD has seen increasing use since its introduction due to its exceptional mechanical properties.

Studies have ranged from understanding the evolution of the material, to comparing material performance to existing all-ceramic and CAD/CAM products on the market. The following section will present the current understanding of the mechanical properties of the partially crystalized starting material, changes during the firing process and information available related to the mechanical properties of the final, tempered material.

Characterization of the material in its partially crystallized "blue state" has been performed to determine the initial properties of the material. In this partially crystallized, form the material exhibits moderate flexural strength of 130 MPa and fracture toughness at 0.9—1.25 MP A $m^{1/2}$ [4,6,7,12]. Manufacturer literature also reports a Vickers hardness of 5400 MPa in the partially crystallized state [4].

After tempering the mechanical properties of the material change dramatically. Manufacturer literature states that the restoration experiences 0.2% linear shrinkage [4]. This shrinkage has been noted as a possible cause of gaps at the margins of restorations and compromise internal fit, though this shrinkage does not result in discrepancies significantly different than other CAD/CAM materials [14,15]. The fully crystalized form of IPS™ e.Max CAD (obtained by following manufacturer specifications firing at 770 °C for 5 min, then 850 °C for 10 min) [4] has been shown to possess a recorded flexural strength of 262—360 MPa and a fracture toughness of 2.0—2.5 MPa [4,6—8,15]. IPS™ e.Max CAD has been shown to have flexural strength above other leucite reinforced dental ceramics [2,7,15,16]. One study on the evolution of mechanical properties at different temperatures throughout the heating process showed that the macromechanical physical properties could be significantly altered depending on the heating schedule [8]. Another study concluded that compared IPS™ e.Max CAD to other available CAD/CAM ceramics concluded that mechanical properties are dependent on structural composition of material not their chemical formulation [15].

Color and optical properties

In restorative dentistry, color and optical properties play a major role in patient satisfaction and restorative success. As mechanical properties of available ceramics improved, attention on optical properties such as color and tooth structure moved to the forefront. IPS™ e.Max CAD addresses these needs by coming available in several shades and translucencies. This section will discuss the color and translucency properties of the material.

IPS™ e.Max CAD is available in the standard A through D shades and also includes a line of bleach shades [4,7]. Like most dental ceramics, the color of the material is determined by colorant ions dispersed in the matrix. For IPS™ e.Max CAD the primary ions consist of V^{+4}/V^{+3} (blue/yellow), Ce^{+4} (yellow), and Mn^{+3} (brown) [17]. All color formulations are delivered in the aforementioned "blue state," during the firing stage, the coloring ions, namely Vanadium, change their oxidation states resulting in the noticeable shift in color [4]. Additional refinement of the final color of a delivered restoration can be performed by adding stain and glaze to the surface of the restoration before the tempering process.

Besides coming in a wide variety of colors IPS™ e.Max CAD is also available in three levels of translucency, medium opacity (MO), high translucency (HT), and low translucency (LT) [4]. This variation is accomplished via differences in the microstructure of the material. Both formulations have identical crystal content but differ in crystal sizes, with HT ceramic exhibiting crystals of 1.5 $\times$ 0.8 mm dispersed in a glassy matrix, whereas LT ceramic exhibits smaller crystals (0.8 $\times$ 0.2 mm) in a higher density matrix [12]. By producing a material where the refractive index of the lithium disilicate crystalline phase and the glassy phase possess a similar index of refraction, it is possible to produce the highly translucent formulation of the material [18]. The interface between the glassy and crystalline phases of the material are responsible for the light scattering properties noted in the material. Therefore, increasing the percent crystallinity of the material will improve mechanical properties by compromise translucency and color of the material [18]. As research into the microstructure properties of the material continues, additional insight into the optical properties of the material could be gained and implemented to further tailor the visual outcomes of IPS™ e.Max CAD restorations.

Clinical performance and indications

Since the release of IPS™ e.Max CAD a little over a decade ago, many studies have focused on determining the clinical recommendations and limitations of the material. As a result of this relatively limited timeframe, there is a distinct lack of literature discussing long-term survival and outcomes for the material. The manufacturer and other groups have released recommendations and clinical guidelines to consider when utilizing the material. The following section will discuss indications, implementations considerations, and literature regarding failure and fatigue testing.

Since its release, IPS™ e.Max CAD has seen an increase in its implementation and expansion of its indications. Initially, IPS™ e.Max CAD was recommended for use as an esthetic framework, an inlay and onlay material, as an anterior veneering matrial [4]. In 2016 the manufacturer released an updated list of indications that suggested IPS™ e.Max CAD could be implemented as a veneering material, for inlays and onlays, partial and full crowns, three-unit fixed partial dentures (FPD) in the anterior, premolar and posterior region. Some studies have corroborated these recommendations by suggesting e.Max can be used for monolithic crowns, veneers, and fixed partial dentures, not just as a framework [19]. A study in 2013 found that monolithic posterior three unit FPDs in the posterior mouth were susceptible to high load (1900 N) failure at the connectors but could be recommended for posterior. The same study showed that bi-layered FPDs on the other hand were susceptible to low-load (699 N) failure and should be avoided [13]. A fatigue testing study suggested the threshold for bulk fracture in a monolithic lithium disilicate crown could be reached in forces as low as 1,100 to 1,200 N [20]. One point of interest is that the 2016 manufacturer indications recommend the use of IPS™ e.Max CAD for minimally invasive crowns (1 mm material thickness). Several studies on properties at 1 mm suggest a possible risk of complications when utilizing such a thin restoration. One study suggested that an increase in material thickness from 1.6 mm to 1.8 mm could lead to an increase in predicted failure loads from 1,400 N to over 2,000 N [2]. A fatigue study found that cyclical loading of monolithic veneers were highly susceptible to early failure rates, thus further calling into question the recommendation for using IPS™ e.Max CAD for thin, full-coverage restorations.

Due to the relatively recent introduction of IPS™ e.Max CAD there are few clinical studies that exist that look restoration longevity. One study over a 45 month period showed only 0.91% clinical failure for monolithic single unit IPS™ e.Max crowns and 1.83% failure for layered single unit crowns, with a combined failure rate of 1.15% [21]. Although the failure rate was between the two types was statistically significant and corroborated *in vitro* studies, the authors cautioned drawing conclusions due to the short time frame of the study and low failure rate [21]. Another two-year study did not find any indication of crown-fracture, marginal adaptation or caries [9]. One six-year study showed 87.6% of monolithic single unit crowns remained clinically acceptable and a 70.1% without any complications whatsoever [22]. Initial studies suggest good short to medium term survivability for single unit crowns made from IPS™ e.Max CAD. Finally, one study looked at collected literature to determine projected survival rates of various all ceramic restorations. For IPS™ e.Max CAD they concluded that inlays and onlays would have significantly long expected lifetimes (10% at 124 years and 30 years respectively) but a significantly shorter estimated lifetime (10% failure in 30 years) when compared to crowns with a zirconia substructure [23]. Unfortunately there is a lack of literature that provides a more comprehensive look at short term studies, and a lack of complete data and inconsistent reporting introduces further difficulties [7]. There is a lack of clinical studies that assess the survival of monolithic IPS™ e.Max CAD restorations in multiple unit FPD applications.

For single anterior teeth most all ceramic systems have been clinically proven to have acceptable longevity and wear characteristics in clinical trials. For single-unit crowns esthetics can be a primary consideration [2]. The translucency properties of IPS™ e.Max CAD in both the HT and LT formulation, make it possible to place margins that blend with adjacent dentition, effectively masking the edges of the restoration [4,24]. Edge discoloration is another concern when it comes to margin placement. One study found a 3 of 23 (alfa score of 87.0%) IPS™ e.Max CAD crowns cemented with dual-cure self-etching cement (Multilink Automix [MA], Ivoclar Vivadent) exhibited localized marginal staining after two years [9]. Unfortunately, much like clinical failure rates of posterior restorations, there is little clinical evidence of failure for anterior restorations due to fracture or undesirable esthetic complications.

Conclusion

Since its introduction, IPS™ e.Max CAD has seen growing popularity due to the combination of its excellent mechanical properties and acceptable aesthetics. Recent studies have primarily looked at understand microstructure properties and crystallization kinetics and their impact on macrostructural mechanics. Initial studies in this field have indicated that deviations in protocol of the tempering procedure can produce substantial changes in microstructural properties. Additional evidence has shown that changes in microstructure in the material can have a wide variety on not only physical properties but also optical properties, such as translucency and color.

Clinical studies of IPS™ e.Max CAD have been limited in scope, partially due to the limited time the material has been available on the market. Several studies have shown promising short-term and medium-term survivability for single unit crowns and initial results for implementation for inlays and onlays is also promising. Some *in vitro* studies have produced results that call into question the use of the material in layered posterior multi-unit FPDs and veneers that could experience heavy occlusal forces, however there is a lack of clinical data to determine the significance of these results. To date there is insufficient long-term survival data available.

IPS™ e.Max CAD provides a unique opportunity to researchers and clinicians alike. The initial results of the material appear promising, and current literature suggests there is a great amount yet to be learned about the material. With its growing clinical presence, this material will certainly continue to be a point of interest in the fields of restorative dentistry and materials science.

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