Aesthetic Ceramics for Dental Restorations

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Abstract: Restorations of missing teeth with aesthetic, biocompatible and reliable prostheses are in high demand in our aging societies. With more dental materials available than ever before, optimal materials selection is critical to the success of restorations. This paper reviews current aesthetic dental ceramics and their reliability. A classification of dental ceramics based on their microstructures is presented, and the mechanical properties of these materials are summarized. This classification gives dental clinicians and patients rapid access to data for current dental materials, and it can be used to find the best material match for a given restoration requirement. Finally, this review addresses failures of ceramic restorations due to the brittle nature of ceramic materials, which are a continuing challenge for mechanical and materials engineers, and for dental clinicians.

Key Words: Ceramics, Dental restorations, Reliability

1. Introduction

Dental caries, severe periodontitis, and severe tooth loss are a global burden, affecting 3.9 billion people of the global population of 7.5 billion \(^1\). For example, in Australia with 24 million people, there are over 19 million decayed teeth with 11 million additional decayed teeth each year, costing approximately AU$2 billion/year for dental care \(^2\). Dental patients demand aesthetic, biocompatible and chemically inert ceramic restorations and aging societies will drive this demand even higher \(^3\). A solution to this worldwide oral health challenge requires a global effort.

Ceramic restorations can be traced to 1792 when the processing of porcelain teeth was patented \(^4\). Ceramics have been used as main aesthetic dental restorative materials for over a century \(^5\). Particularly, over the last thirty years, computer-aided digital manufacturing of dental crowns and bridges has accelerated the development of many new materials and processing techniques \(^6\)-\(^11\). Today there is a wide range of dental ceramic or ceramic-like restorative materials available for clinical applications \(^7\), \(^12\). It is difficult for clinicians to make decisions on materials selection in restorative processes, many of which were made based on advertising claims, other than on the basis of a scientific understanding of characteristics of the materials. Due to a large number of dental ceramic products and rapidly evolving new materials, there are many classification systems. From a materials science point of view, materials should be classified according to their compositions and microstructures, because these determine the properties and functional behavior of the materials. Thus, dental ceramic and ceramic-like materials can be scientifically classified as glass ceramics, polycrystalline ceramics and resin matrix ceramics \(^12\). This paper reviews current aesthetic dental ceramics and their reliability with respect to their microstructures and mechanical properties to provide insights into rational materials selection to dental clinicians.

2. Dental ceramics

2.1 Glass ceramics

Glass ceramics are ceramic materials containing a glass phase. Mica, feldspar, leucite, lithium disilicate, and alumina glass ceramics are commonly used in dentistry.

Mica glass ceramics contain mica platelets which are internally nucleated and crystallized from the fluorine-containing base glass to form tetrasilicic fluormica (KMg\(_2\)Si\(_4\)O\(_{10}\)F\(_2\)) \(^13\). In this process, heating temperatures ranging from 1000°C to 1360 °C control mica platelet diameters of 1.1 µm to 10 µm \(^9\), \(^13\). A representative of these materials is Dicor (Dentply), in which mica platelets have a diameter of approximately 2 µm \(^11\). The mechanical properties of the material are: Vickers hardness \(H = 3.5\) GPa, Young’s modulus \(E = 68\) GPa, fracture toughness \(K_{IC} = 1.5\) MPa.m\(^{1/2}\), and flexural strength \(\sigma = 70\) MPa \(^14\), \(^15\). Due to the
low hardness and mechanical strength, mica glass ceramics are easy to machine using chairside CAD/CAM dental machines, but they are only used as inlays, onlays and veneers \(^{16}\).

**Feldspar glass ceramics** are fine-particle feldspar porcelains. Vita Mark II (Vita Zahnfabrik) is the first feldspar glass ceramic which can be manufactured for inlays, onlays, veneers, and crowns in the CAD/CAM Cerec system (Sirona). The material with a glass matrix is reinforced with 30 vol.% irregularly-shaped feldspar-based mineral crystals of 1–7 µm in size \(^{17}\). These reinforcing crystals include sanidine (K(AlSi,\(_3\)O,\(_4\)), potassium aluminum silicate), nepheline (\((Na, K)\)AlSiO\(_4\), sodium potassium aluminum silicate, and anorthoclase (\((Na, K)\)AlSiO\(_3\), sodium potassium aluminum silicate) \(^{18}\).

Typical mechanical properties of Vita Mark II are: Vickers hardness \(H = 6.2\) GPa, Young’s modulus \(E = 68\) GPa, fracture toughness \(K_{IC} = 0.9\) MPa.m\(^{1/2}\), and flexural strength \(\sigma = 100\) MPa \(^{19}\). Failure rates for load-bearing posterior crowns made from feldspar glass ceramics can be higher due to their lower strength. The materials are widely used as aesthetic veneers for porcelain-fused-to-metal restorations and bilayered all-ceramic structures. They are also used as light-load-bearing anterior monolithic crowns, inlays and onlays.

**Leucite glass ceramics** consist of approximately 40 vol.% leucite (K(AlSi\(_3\)O\(_4\))) crystals in a silica-based glass (K\(_2\)O–Al\(_2\)O\(_3\)–SiO\(_2\)) \(^{20}\). An example of these materials is IPS Express CAD (Ivoclar Vivadent), which contains leucite crystals of 1–3 µm in size \(^{20}\). The material is CAD/CAM machinable and can be used as inlays, onlays, veneers, and crowns. The mechanical properties of the material are: Vickers hardness \(H = 5.6\) GPa, Young’s modulus \(E = 70\) GPa, fracture toughness \(K_{IC} = 1.3\) MPa.m\(^{1/2}\), flexural strength \(\sigma = 134\) MPa \(^{20}\). Compared to feldspar glass ceramics, leucite glass ceramics have much higher resistance to high-cycle high-load fatigue impacts, indicating their suitability as a better choice for restorations under teeth clenching and grinding conditions \(^{22}\).

**Alumina glass ceramics** are generated in glass infiltration or slip casting processes. One of these materials is In-Ceram Celay Alumina (Vita Zahnfabrik). The material is made in dry-pressing and partial sintering to obtain preform alumina blanks with 30% porosity of pore sizes of 1–5 µm \(^{21}\). The blanks are infiltrated with lanthanum-aluminosilicate glass (La\(_2\)O\(_3\)–Al\(_2\)O\(_3\)–SiO\(_2\)) for 6 h at 1170°C and then cooled to room temperature. Excess glass is removed from the infiltrated materials by sand blasting. The material microstructure consists of fairly uniform, roughly round alumina particles of 1–3 µm diameters and glass matrix filling in interconnected pores \(^{24}\). The material properties are: Vickers hardness \(H = 11.8\) GPa, Young’s modulus \(E = 254\) GPa, indentation toughness \(K_{IC} = 2.5\) MPa.m\(^{1/2}\), and flexural strength \(\sigma = 500\) MPa \(^{24}\). Although alumina glass ceramics have improved mechanical properties, they lack aesthetics. They are generally used as core materials in veneer-core bilayered all-ceramic structures.

**Lithium disilicate glass ceramics**, such as IPS e.max Press (Ivoclar Vivident), are made of 70% highly interlocked lithium disilicate (Li\(_2\)SiO\(_3\)) crystals of 5 µm in length and 0.8 µm in diameter, and 30% glass matrix (SiO\(_2\)–Li\(_2\)O–K\(_2\)O–ZnO–P\(_2\)O\(_5\)–Al\(_2\)O\(_3\)–La\(_2\)O\(_3\)) \(^{29}\). There are two reinforcing mechanisms for lithium glass ceramics to achieve high flexural strength of over 400 MPa. First, lithium disilicate crystals and glassy matrix have different thermal expansions which result in tangential compressive stresses around the crystalline phase that provide crack deflection and increased strength \(^{23}\). Secondly, lithium disilicate crystals have interlocked and layered crystal structures, which contribute to the strengthening of the material \(^{26}\). These mechanisms make lithium disilicate glass ceramics much stronger than mica, feldspar and leucite glass ceramics. The mechanical properties of IPS e.max Press are: Vickers hardness \(H = 5.5\) GPa, Young’s modulus \(E = 91\) GPa, fracture toughness \(K_{IC} = 2.5–3\) MPa.m\(^{1/2}\), and flexural strength \(\sigma = 440\) MPa \(^{25,26}\). Unlike high-strength alumina glass ceramics, lithium disilicate glass ceramics are aesthetically attractive and match natural teeth well. They are used as inlays, onlays, veneers, crowns and bridges. Particularly, they can be used in monolithic all-ceramic structures to replace veneer-core bilayer structures in load-bearing posterior restorations, where fractures often occur at weak veneer-core interfaces \(^{27,29}\).

The high strength of lithium disilicate glass ceramics make them very difficult to machine. Currently, only pre-crystallized **lithium metasilicate glass ceramic** blocks, such as IPS e.max CAD (Ivoclar Vivadent), can be directly milled using chairside or laboratory dental CAD/CAM systems, followed by sintering at high temperatures to achieve crystallization for high strength. IPS e.max CAD contains approximately 40% lithium metasilicate crystals embedded in a glassy phase with grain sizes of 0.5–1 µm \(^{30,33}\). The material properties are: the Vickers hardness \(H = 5.4 ± 0.1\) GPa, the Young’s modulus \(E = 97.48\) GPa, fracture toughness \(K_{IC} = 1\) MPa.m\(^{1/2}\), and the biaxial strength \(\sigma_b = 130\) MPa \(^{30–32}\).

## 2.2 Polycrystalline ceramics

Polycrystalline ceramics as restorative materials include alumina, zirconia, zirconia-toughened alumina and alumina-toughened zirconia \(^{33}\). Among them, zirconia is most popular. It has been used for dental implants, abutments, and cores in veneer-core bilayer restorations, and more recently for monolithic crowns and bridges \(^{13–30}\).

**Zirconia** has a unique polymeric character with monoclinic, tetragonal and cubic structures at different...
temperatures and pressures. Tetragonal and cubic zirconia polymorphs are metastable and require dopants to stabilize these phases. Thus, zirconia is often doped with many other oxides to control phase transformations to form stabilized zirconia alloys. Among these, yttrium-stabilized tetragonal zirconia polycrystal (Y-TZP) is the most important in dentistry. The toughening mechanism in zirconia due to the tetragonal-to-monoclinic phase transformation results in a high damage tolerance and enhanced fracture toughness for the material, making it the strongest and most fracture resistant ceramic.

Zirconia has low-strength, porous pre-sintered and high-strength, densely sintered states. An example of pre-sintered Y-TZP is IPS e.max Zir CAD (Ivoclar Vivadent), which is machinable and suitable for rapid generation of cores, crowns and bridges using chairside or laboratory-based CAD/CAM systems. The material contains nearly 50 vol.% of isolated or interconnected pores and Y-TZP crystals of approximately 300-nm in size. The material properties are: the Vickers hardness \( H = 1.11 \) GPa, the Young’s modulus \( E = 29.34 \) GPa, fracture toughness \( K_{IC} = 0.8 \) MPa.m\(^{1/2}\), and flexural strength \( \sigma = 50–90 \) MPa.

Sintered Y-TZP is produced at temperatures between 1200°C and 1600°C to obtain a range of microstructures. Most sintered zirconia material for dental restorations have less than 1 vol.% porosities and zirconia crystals of 300 nm or less in size. For IPS e.max Zir CAD sintered at 1200°C, the material properties are: the Vickers hardness \( H = 13.15 \) GPa, the Young’s modulus \( E = 168.19 \) GPa, fracture toughness \( K_{IC} = 5.5 \) MPa.m\(^{1/2}\), and flexural strength \( \sigma = 900 \) MPa.

2.3 Resin-matrix ceramics

Resin-matrix ceramics are composed of organic matrices and predominantly ceramic phases. These materials were developed to mimic natural teeth’s properties. They are easier to machine due to their compatibility with composite resins, as opposed to brittle glass-matrix ceramics or polycrystalline ceramics.

Examples of these new ceramic composites include resin nano ceramic and polymer infiltrated ceramic networks. These material can be used as veneers, inlays/onlays, monolithic anterior and posterior crowns.

Lava Ultimate (3M ESPE) is the first resin nano ceramic. It is a CAD/CAM machinable, and aesthetic material. The material contains 80 wt.% (or 54 vol.%) ceramic phase including discrete silica nanoparticles of 20-nm diameter, zirconia nanoparticles of 4–11-nm diameter, and zirconia-silica nanoclusters, and organic filler particles. The combination of these ceramic nanoparticles reduces the interstitial spacing of resin filler particles, leading to higher volume nanoceramic content. As a new material, the published mechanical properties of resin nano ceramic show a large inconsistency depending on testing methods. The reported material properties are: the Vickers hardness \( H = 1.05–1.15 \) GPa, the Young’s modulus \( E = 12.22–14.8 \) GPa, fracture toughness \( K_{IC} = 0.91–2.02 \) MPa.m\(^{1/2}\), and flexural strength \( \sigma = 200 \) MPa.

Vita Enamic (Vita Zahnfabrik) is a polymer infiltrated ceramic network. It is manufactured by infiltrating a porous ceramic network with a monomer mixture and followed curing for polymerization. This hybrid ceramic is comprised of 86 wt.% (or 75 vol.%) structure-sintered, dual network ceramic matrix filled with 14 wt.% organic polymer phase. The composition of the ceramic phase is a fine-structure feldspar ceramic enriched with alumina, leucite and zirconia. The organic polymer network is composed of urethane dimethacrylate and triethylene glycol dimethacrylate.

Like human teeth, dental restorations must withstand chewing, which is a cyclic loading process with approximately 1400 cycles/day at different loading conditions in very complex chemical environments, depending on individual dietary habits. Oral forces are difficult to measure and vary dramatically from individual to individual. The published maximum bite forces can be as high as 500–700 N. In addition to human mastication, many people have the behavior of bruxism, i.e., they grind or clench their teeth at night, during which high forces as high as 800 N can be unconsciously and repeatedly applied. The high grinding/clenching forces in bruxism can be severe enough to damage teeth.

Clinical failure analyses reveal that fracture is fatal to ceramic restorations. Figure 1 demonstrates a clinical fatigue fracture of a glass ceramic crown, which was in urgent need of repair or replacement.
replacement. A number of fatigue-induced failure characteristics have been described in the literature. For instance, a longitudinal fracture was found from margin of a Dicor crown. A connector fracture was observed in a 4-unit porcelain-veneered fixed denture prosthesis are observed, respectively. In laboratory-based failure analyses of porcelain-veneered zirconia prostheses, veneer chipping was found. A partial cone crack was also discovered in a crown veneer loaded with a sphere indenter at 300 N after \(6 \times 10^4\) cycles. Fracture can also be seen at a connector of a 3-unit fixed denture prosthesis after \(7.8 \times 10^4\) cycles with a sphere indenter at 700 N.

In addition to fatigue-induced clinical failures, ceramic restorations also fail due to wear-induced fracture and chipping. Human teeth and restorations not only undergo mechanical fatigue and environmental degradation processes but also suffer from oral wear during chewing, grinding and clenching processes. In particular, occlusal wear can cause severe material losses in both human teeth and restorations but also induce surface cracks that lead to fractures in teeth and restorations. For example, cracks originating from wear facets on the occlusal surface were observed in a clinically fractured porcelain-veneered zirconia molar crown. Many factors control wear in dental restorations. Particularly, the microstructures and mechanical properties of applied materials affect the wear behavior of restorative materials. Oral environments such as food hardness, saliva properties, chewing behavior and masticatory loads also influence the wear of human teeth and restorations. Further, manufacturing techniques and surface modification processes of restorations determine the surface quality, which in turn conditions the wear performance of ceramic restorations in the oral environment.

A laboratory wear study found wear-induced surface cracks on highly polished lithium disilicate surfaces at applied loads of 5 N and 25 N, as shown in Figure 2. These microcracks can propagate, leading to fractured crowns.

4. Conclusions

This paper presents an overview of aesthetic ceramics for restorations based on a classification from a materials science point of view. Understanding of microstructures and mechanical properties of dental ceramics is crucial for materials selection in restorative design. Today, with more dental materials with improved microstructures and mechanical properties than ever before, fatigue- and wear-induced fracture is still a major concern in ceramic restorations because ceramics are much weaker than metals and they are brittle. Reducing fracture rates in ceramic restorations is a key challenge in restorative dentistry.

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References

1) Marcenes, W., Kassebaum, N. J., Bernabe, E., Flaxman, A., Naghavi, M., Lopez, A. and Murray, C. J. L.: Global burden of oral conditions in 1990-2010: A systematic analysis, Journal of Dental Research, 92, 592-597, (2013).
2) Tooth decay – Australia’s most prevalent health condition,
Australian Dental Association, (2012).

3) Rekow, E. D., Silva, N. R. F. A., Coelho, P. G., Zhang, Y., Guess, P. and Thompson, V. P.: Performance of dental ceramics: Challenges for improvements, Journal of Dental Research, 90, 937-952, (2011).

4) Anusavice, K.: Philips’ science of dental ceramics, 11th Edition, 655-719, Saunders, (2003).

5) Kelly, J. R., Nishimura, I. and Campbell, S. D.: Ceramics in dentistry: historical roots and current perspectives, Journal of Prosthetic Dentistry, 75(1), 18-32, (1996).

6) Yin, L. and Stoll, R.: Ceramics in restorative dentistry, In: Low, I. M., (Ed.): Advances in Ceramic Matrix Composites, 624-655, Woodhead Publishing, (2014).

7) Denny, I. and Kelly, J. R.: Emerging ceramic-based materials for dentistry, Journal of Dental Research, 93, 1235-1242, (2014).

8) Yin, L., Song, X. F., Song, Y. L., Huang, T. and Li, J.: An overview of in vitro abrasive finishing and CAD/CAM of bioceramics in restorative dentistry, International Journal of Machine Tools and Manufacture, 46, 1013-1026, (2006).

9) Ben, S.: Reliability and properties of core materials for all-ceramic dental restorations, Japanese Dental Science Review, 44, 3-21, (2008).

10) Miyazaka, T., Hotta, Y., Kuniim, J. Kuriyama, S. and Tamaki, Y.: A review of dental CAD/CAM: current status and future perspectives from 20 years of experience, Dental Materials Journal, 28(1), 44-56, (2009).

11) Mörmann, W. H.: The evolution of the CEREC system, Journal of American Dental Association, 137, 7s-13s, (2006).

12) Graci, S., Thompson, V. P., Ferencz, J. L., Silva, N. R. F. A. and Bonfante, E. A.: A new classification system for all-ceramic and ceramic-like restorative materials, International Journal of Prosthodontics, 28, 227-235, (2015).

13) Dong, X., Yin, L., Jahannir, S., Ives, L. K. and Rekow, E. D.: Abrasive machining of glass-ceramics with a dental handpiece, Machining Science and Technology, 4 (2), 209-233, (2000).

14) Quinn, J. B., Su, L., Flanders, L. and Lloyd, I.: "Edge toughness" and material properties related to the machining of dental ceramics, Machining Science and Technology, 4(1), 291-304, (2000).

15) Jahannir, S. and Dong, X.: Wear mechanism of a dental glass-ceramic, Wear, 181-183, 821-825, (1995).

16) Montazerian, M., Alizadeh, P. and Yekta, B. E.: Pressureless sintering and mechanical properties of mica-ceramic/ Y-PSZ composites, Journal of European Ceramic Society, 28, 2687-2692, (2008).

17) Peterson, I. M., Pajares, A., Lawn, B. R., Thompson, V. P. and Rekow, E. D.: Mechanical characterization of dental ceramics by hertzian contacts, Journal of Dental Research, 77(4), 589-602, (1998).

18) Yin, L., Song, X. F., Qu, S. F., Han, Y. G. and Wang, H.: Surface integrity and removal mechanism in simulated dental finishing of a feldspathic porcelain, Journal of Biomedical Materials Research Part B – Applied Materials, 79B(2), 365-378, (2006).

19) Deng, Y., Lawn, B. R. and Lloyd, I. K.: Characterization of damage modes in dental ceramic bilayer structures, Journal of Biomedical Materials Research A, 63, 137-145, (2002).

20) Höland, W., Rheinberger, V., Apel, E. and van’t Hoen, C.: Principles and phenomena of bioengineering with glass-ceramics for dental restoration, Journal of European Ceramic Society, 27, 1521-1526, (2007).

21) Bindl, A., Lüthy, H. and Mörmann, W. H.: Strength and fracture pattern of monolithic CAD/CAM-generated posterior crowns, Dental Materials, 22 (1), 29-36, (2006).

22) Yin, L., Lymer, R., Billau, N., Peng, Z. and Stoll, R.: Damage morphology produced in low-cycle high-load indentations of feldspar porcelain and leucite glass ceramic, Journal of Materials Science, 48, 7902-7912, (2013).

23) Yin, L., Ives, L. K., Jahannir, S., Rekow, E. D. and Romberg, E.: Abrasive machining of glass-infiltrated alumina with diamond burs, Machining Science and Technology, 5(1), 43-61, (2001).

24) Jung, Y. G., Peterson, I. M., Kim, D. K. and Lawn, B. R.: Lifetime-limiting strength degradation form contact fatigue in dental ceramics, Journal of Dental Research, 79, 722-731, (1998).

25) Denny, I. and Holloway, J. A.: Ceramics for dental applications: a review, Materials, 3, 351-368, (2010).

26) Höland, W., Apel, E., van’t Hoen, C. and Rheinberger, V.: Studies of crystal phase formation in high-strength lithium disilicate glass ceramics, Journal of Non-Crystalline Solids, 352, 404-4050, (2006).

27) Guess, P. C., Zavenali, R. A., Silva, N. R. F. A., Bonfante, E. A., Coelho, P. G. and Thompson, V. P.: Monolithic CAD/ CAM lithium disilicate versus veneered Y-TZP crowns: Comparison of failure modes and reliability after fatigue, International Journal of Prosthodontics, 23, 434-442, (2010).

28) Guazzatoa, M., Proosb, K., Quacha, L. and Swain, M.V.: Strength, reliability and mode of fracture of bilayered porcelain/zirconia (Y-TZP) dental ceramics, Biomaterials, 25, 5045-5052, (2004).

29) Swain, M.V.: Unstable cracking (chipping) of veneering porcelain on all-ceramic dental crowns and fixed partial dentures, Acta Biomaterialia, 5, 1668-1677, (2009).

30) Bühler-Zemp, P. and Völkel, T.: IPS e.max press scientific documentation, Ivoclar Vivadent, 1-24, (2005).

31) El-Meliegy, E. and van Noort, R.: Glasses and glass ceramics for medical applications, Springer, 209-218, (2012).

32) Alao, A. R. and Yin, L.: Nano-mechanical behaviour
of lithium metasilicate glass-ceramic, Journal of the Mechanical Behavior of Biomedical Materials, 49, 162-174, (2015).
33) Deryn, I. and Kelly, J. R.: State of the art of zirconia for dental application, Dental Materials, 24, 299-307, (2008).
34) Chevalier, J., Gremillard, L., Virkar, A.V. and Clarke, D. R.: The tetragonal-monoclinic transformation in zirconia: lessons learned and future trends, Journal of American Ceramic Society, 92, 1901-1920, (2009).
35) Alao, A. R., Stoll, R., Song, X. F., Miyazaki, T., Hotta Y, Shibata, Y. and Yin, L.: Surface quality of yttria-stabilized tetragonal zirconia polycrystal in CAD/CAM milling, sintering, polishing and sandblasting processes, Journal of the Mechanical Behavior of Biomedical Materials, 65, 102-116, (2017).
36) Alao, A. R. and Yin, L.: Nano-scale mechanical properties and behavior of pre-sintered zirconia, Journal of the Mechanical Behavior of Biomedical Materials, 36, 21-31, (2014).
37) Alao, A. R. and Yin, L.: Assessment of elasticity, plasticity and resistance to machining-induced damage of porous pre-sintered zirconia using nanoindentation techniques, Journal of Materials Science & Technology, 32, 401-410, (2016).
38) Ritzberger, C., Apel, E., Höland, W., Peschke, A. and Rheinberger, V. M.: Properties and clinical application of three types of dental glass-ceramics and ceramics for CAD-CAM technologies, Materials, 3, 3700-3713, (2010).
39) Alao, A. R. and Yin, L.: Nanoindentation characterization of the elasticity, plasticity and machinability of zirconia, Materials Sciences & Engineering A, 628, 181-187, (2015).
40) Alao, A. R. and Yin, L.: Loading rate effect on the mechanical behavior of zirconia in nanoindentation, Materials Sciences & Engineering A, 619, 247-255, (2014).
41) Chen, C., Trindade, F. Z., de Jager, N., Kleverlaan, C. J. and Feilzer, A. J.: The fracture resistance of a CAD/CAM Resin Nano Ceramic (RNC) and a CAD ceramic at different thicknesses, Dental Materials, 30, 954-962, (2014).
42) Backer, A. D., Münchow, E. A., Eckert, G. J., Haras, A. T., Platt, J. A. and M. C. Bottino, : Effects of simulated gastric juice on CAD/CAM resin composites—morphological and mechanical evaluations, Journal of Prosthodontics, in press, (2015). DOI: 10.1111/jopr.12420.
43) Albero, A., Pascual, A., Camps, I. and Grau-Benitez, M.: Comparative characterization of a novel cad-cam polymer-infiltrated-ceramic-network, Journal of Clinical and Experimental Dentistry, 7, e495-e500, (2015).
44) Lava™ Ultimate CAD/CAM Restorative Technical Product Profile, 3M ESPE, (2011).
45) Quinn, G. D., Giuseppetti, A. A. and Hoffman, K. H.: Chipping fracture resistance of dental CAD/CAM restorative materials: Part I – Procedures and results, Dental Materials, 30, e99-e111, (2014).
46) Ruse, N. D. and Sadoun, M. J.: Resin-composite blocks for dental CAD/CAM applications, Journal of Dental Research, 93, 1232-1234, (2014).
47) VITA ENAMIC : Technical and scientific documentation, VITA Zahnfabrik, (2015).
48) Della Bona, A., Corazza, P. H. and Zhang, Y.: Characterization of a polymer-infiltrated ceramic-network material, Dental Materials, 30, 564-569, (2014).
49) Homaei, E., Farhangoost, K., Tsoi, J. K. H., Matinlinna, J. P. and Pow, E. H. N.: Static and fatigue mechanical behavior of three dental CAD/CAM ceramics, Journal of the Mechanical Behavior of Biomedical Materials, 59, 304-313, (2016).
50) Kelly, J. R.: Ceramics in restorative and prosthodontic dentistry, Annual Review of Materials Science, 27, 443-467, (1997).
51) Fasbinder, D. J., Dennison, J. B., Heys, D. R. and Lampe, K.: The clinical performance of CAD/CAM-generated composite inlays, Journal of American Dental Association 136, 1714-1723, (2005).
52) Rebow, E. D. and Thompson, V. P.: Engineering long term clinical success of advanced ceramic prostheses, Journal of Materials Science: Materials in Medicine, 18, 47-56, (2007).
53) Zhang, Y., Sailer, I. and Lawn, B. R.: Fatigue of dental ceramics, Journal of Dentistry, 41 (12), 1135-1147, (2013).
54) DeLong, R.: Intra-oral restorative materials wear: rethinking the current approaches: How to measure wear, Dental Materials, 22(8), 702-711, (2006).
55) Peng, Z., Rahman, M. I. A., Zhang, Y. and Yin, L.: Wear behavior of pressable lithium disilicate glass ceramic, Journal of Biomedical Materials Research Part B – Applied Materials, 104(5), 968-978, (2016).

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