Chapter 8

Functional Biomimetic Dental Restoration

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Additional information is available at the end of the chapter

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Abstract

Bioinspired functionally graded approach is an innovative material technology, which has rapidly progressed both in terms of materials processing and computational modeling in recent years. Bioinspired functionally graded structure allows the integration of dissimilar materials without formation of severe internal stress and combines diverse properties into a single material system. It is a remarkable example of nature's ability to engineer functionally graded dental prostheses. Therefore, this novel technology is designed to improve the performance of the materials in medical and dental fields. Thus, this chapter book reviews the current status of the functionally graded dental prostheses and biomimetic process inspired by the human bone, enamel and dentin-enamel junction (DEJ) structures and the linear gradation in Young's modulus of the human bone, enamel and dentin-enamel junction, as a new material design approach, to improve the performance compared to traditional dental prostheses. Notable research is highlighted regarding application of biomimetic prostheses into various fields in dentistry. The current chapter book will open a new avenue for recent researches aimed at the further development of new dental prostheses for improving their clinical durability.

Keywords: functionally graded materials, dental restorations, dental implant, dental post, dental crown

1. Introduction

The biomechanical behavior of biologic structures as well as restorative systems is influenced by several factors that interact with one another other [1, 2]. In the oral environment, several variables contribute to the long term success of restorations. Some of them are dependent on the individual, just like occlusion, load intensity and direction, temperature, moisture, wear, presence of sound tooth structure and quality of supporting tissues, whereas other factors are not controllable, such as structural integrity, microleakage, fatigue and time. Furthermore, teeth and restorative materials are characterized by intrinsic physical characteristics which are responsible for their mechanical performances during functions over time [3].

Biomaterials are essential for life and health in certain cases. They generally have a high added value for their size. Biomaterials should simultaneously satisfy many requirements and possess properties such as non-toxicity, corrosion resistance, thermal conductivity, strength, fatigue durability, biocompatibility and sometimes aesthetics. However, a single composition with a uniform structure may not satisfy all such requirements. Therefore, materials scientists increasingly aim to engineer materials that are more damage-resistant than their conventional homogeneous counterparts. This is particularly important at surfaces or at interfaces between dissimilar materials, where contact failure commonly occurs.

Learning from nature, natural biomaterials often possess the structure of functionally graded materials (FGMs) which enables them to satisfy these requirements. Many engineered materials are graded in some manner, but FGMs are often characterized by a gradient purposefully formed using compositional or microstructural design. FGMs provide the structure with which synthetic biomaterials should essentially be formed.

Bioinspired functionally graded approach is an innovative material technology, which has rapidly progressed both in terms of materials processing and computational modeling in recent years [4]. Bioinspired functionally graded structure allows the integration of dissimilar materials without formation of severe internal stresses and combines diverse materials properties into a single material system. The graded structure eliminates the sharp interface resulting from traditional core-veneer fabrication, thus, eliminating the potential for delamination between layers. Reduced stress concentration at the intersection between an interface and a free surface is another advantage of this graded transition. Likewise, the local driving force for crack growth across an interface can be increased or decreased by altering the gradients in elastic and plastic properties across the interface [5, 6].

Many applications of this innovative technology are found in medical and dental fields [7–15]. Thus, this chapter book will review the current status of the functionally graded dental prostheses and biomimetic process inspired by the human bone, enamel and dentin-enamel junction (DEJ) structures and the linear gradation in Young's modulus of the human bone, enamel and DEJ, as a new material design approach, to improve the performance compared to traditional dental prostheses.

2. Dental implant

2.1. Overview

Dental implants are an effective treatment to replace the root part of the missing natural tooth [16], in order to restore patients' appearance, speech and health [17]. They are completely placed into the jaw bone and give support to a dental prosthesis [18].

During the last 10 years, dental implants had received an increasingly growing interest and focus worldwide. They are used to treat about one million individual per year around the globe [19]. Complete restoration of dentition, rise in the mean age of population, higher number of elderly individuals in population along with increased public awareness are all causes for the increasing demand for dental implants [19].

Basically, implants should be fabricated from biomaterials congruous with the human body environmental conditions. Titanium and its alloys have been reported as the materials of choice for most dental implants because of their inertness, biocompatibility and distinguished mechanical properties [20]. However, the Young's modulus of titanium alloys is higher than that of mineralized tissues. Moreover, the dense structure of titanium for biomedical implants can result in a divergence among the titanium implant Young's modulus (110 GPa) and that of human cortical (17–20 GPa) and cancellous bones (about 4 GPa) [21, 22].

The increased stiffness of titanium implants causes stress shielding with improper loading of the underlying bone tissue [23]. Human bone is a dynamic vital tissue that undergoes continuous modifications by bone-forming and bone-eating cells in response to applied external signals. This results in a reduced mechanical loading of bone which in turn leads to bone resorption, implant loosening and ultimate failure which has been a problem for implants in the past [9]. Overloading, on the other hand, also creates high stresses in local regions of bone which can also stimulate resorption [24]. For that reason, many trials have been performed to improve the mechanical properties of different biomaterials to be compatible with those of bone tissue. Most of these efforts have directed to develop certain significant interaction features at the implant surface and bone tissue interface. Recent developments in dental implant designs, and bone tissue engineering scaffolds, have all added to manufacturing novel porous titanium structures, and these fields utilize and benefit from each other's technologies.

Other issue is configuration of implant that represents an essential factor in bone-implant interface and can promote the process of osseointegration. For promotion of dental implant stability, various implant surface adjustments have been suggested to adapt the properties of dental implants [25]. Modifying the implant surface can upgrade the interaction of implant to bone; however, there is not always a clear explanation for the mechanism of interface improvement. For example, a morphological modification, such as roughening the implant surface, can also create alterations in the chemistry of dental implant surface [26]. Sand blasting with stiff particles such as alumina, TiO_2 and ceramic has also been proposed to roughen dental implant surface [19]. Chemical modification, such as plasma spraying with different powder particles such as titanium oxide, calcium phosphate and hydroxyapatite, has been used to coat dental implants surface [27]. In spite of being very successful, there are number of disadvantages related to the previous procedures; the bulk structure is still high-density titanium, the coating materials can dissolve away over a long period of time. Furthermore, coating particles that break away from the surface spray layer could have a negative biological effect on the adjacent tissue such as peri-implantitis [27]. Thus, various alternative approaches have been employed to overcome these shortcomings of coating materials by producing porous biomaterials as an alternative for the classical solid structure. Cellular structures can create a suitable biological environment for the host tissues to grow into these porous designs [28], establishing improved early implant stability. However, this technology is an expensive which may not be affordable to many individuals seeking dental implant treatments and, therefore, methods of providing a porous structure in titanium or a titanium alloy is of strong interest to the dental implant community [29].

2.2. Dental implant based on functionally graded concept

Presence of a porous surface or rough surface with macroscopic grooves and threads is one of the basic requirements of dental implants to establish a primarily mechanical stabilization between implants and bone tissues [30]. In addition, adequate support should be present mechanically between the radicular part of dental implant and its superstructure coronal part. This should be accomplished by forming a solid inner core and porous outer shell as a replacement to a completely porous structure [30]. A problematic issue is that high magnitude of stress could form at the implant shell and core junction area where the mechanical properties alter quickly [31]. Consequently, the bond between the implant covering layer and its core is weakened. Cook et al. [32] have suggested a post-sintering heat treatment in order to reduce the aforementioned problem that is related to residual accumulated stresses. This method showed an improvement in the fatigue strength of titanium alloy by about 15%. However, the concept of designing and manufacturing functionally graded structures can be useful to prevent stress concentrations between the interface layers where the elastic modulus changes suddenly [33].

Development of implants based on biocompatible FGMs for various applications in medical and dental fields has been emphasized [7–15]. FGM permits the integration of different materials without creating severe internal stresses and combines various unlike properties into a single material system (**Figure 1**). Materials in nature, such as bones and teeth, are the source to the development of FGM concept with its origin in regard to their sophisticated

Figure 1. FGM dental implant with graded material composition.

properties [34, 35]. For example, bone design which gradually changes from a dense, stiff external structure (the cortical bone) to a porous internal one (the cancellous bone) reflects the idea that functional gradation has been utilized by biological adaptation [34]. This unique bony structure demonstrates biologic revolution and enhances the material's reaction to extrinsic loads. Thereby, improved structure for a synthetic implant must exhibit alike gradation. A similar trend has been noticed in the development of functionally graded dental implants with the suggestion of placing surface layer coatings, adding porosity gradients and composite materials formed basically of metal and ceramics (e.g. hydroxyapatite), which ought to promote implant performance with regard to stress distribution and biocompatibility issues [36, 37].

Hydroxyapatite/titanium FGM, based on the criterion of minimum residual thermal stress, was optimally designed and fabricated by Chu et al. [38]. Due to the gradual increase of the thermal expansion coefficient from the substrate to the coating outer layer, the titanium component enhanced the mechanical properties of the coating and also assisted in decreasing the residual stresses in the final coating. Additionally, Khor et al. [39] produced hydroxyapatite-titanium functionally graded coatings which result in improvements related to microstructure, density, porosity, micro-hardness, and Young's modulus. Hedia and Mahmoud [7] utilize the finite element method (FEM) to optimize the hydroxyapatite/titanium functionally graded dental implant, based on the criterion of minimum von Mises' stress. Improved analysis by including this effect in another numerical investigation was later made by Hedia [8]. Yang and Xiang [12] used FEM to study the biomechanical behavior of a threaded functionally graded biomaterials dental implant/surrounding bone system under both static and harmonic occlusal forces. They found that functionally graded biomaterials dental implant effectively diminishes the stress difference at the implant-bone interfaces where maximum stresses occur. Furthermore, Wang et al. [11] investigated the thermal-mechanical performance of hydroxyapatite/titanium functionally graded dental implants with the FEM. They concluded that the functionally graded implants with different hydroxyapatite fraction perform almost equally well, while the titanium yields much higher von Mises' stress. Functionally graded coatings containing hydroxyapatite and glass also were prepared by Yamada et al. [40].The concentration of glass increased from the innermost to the outermost. The glass phase was noticed to improve adhesion of the coating to the titanium substrate.

The concept of creation of functionally graded structures in porous materials by changing the structure of the lattice has also been investigated [41]. Tolochko et al. [30] used Laser-forming techniques with continuous wave and pulsed lasers to produce dental implants from Ti powders with two different zones. They made a compact core and irregular porous shell by incorporating selective laser sintering (SLS) for the porous surface and selective laser melting (SLM) for the solid core. Microscopical examination showed that the average pore size was 100–200 μm and the porosity 40–45%. Traini et al. [42] used a laser metal sintering technique to construct Ti alloy dental implant incorporating a gradient of porosity, from the inner core to the outer surface. The functionally graded materials were proven to give better approximate to the elastic properties of the bone (**Figure 2**). Mangano et al. [43] used direct laser fabrication that has potential to produce dental implants with irregular and narrow intercommunicating crevices and shallow depressions using Ti alloy powder. However, they noticed a residue of metal

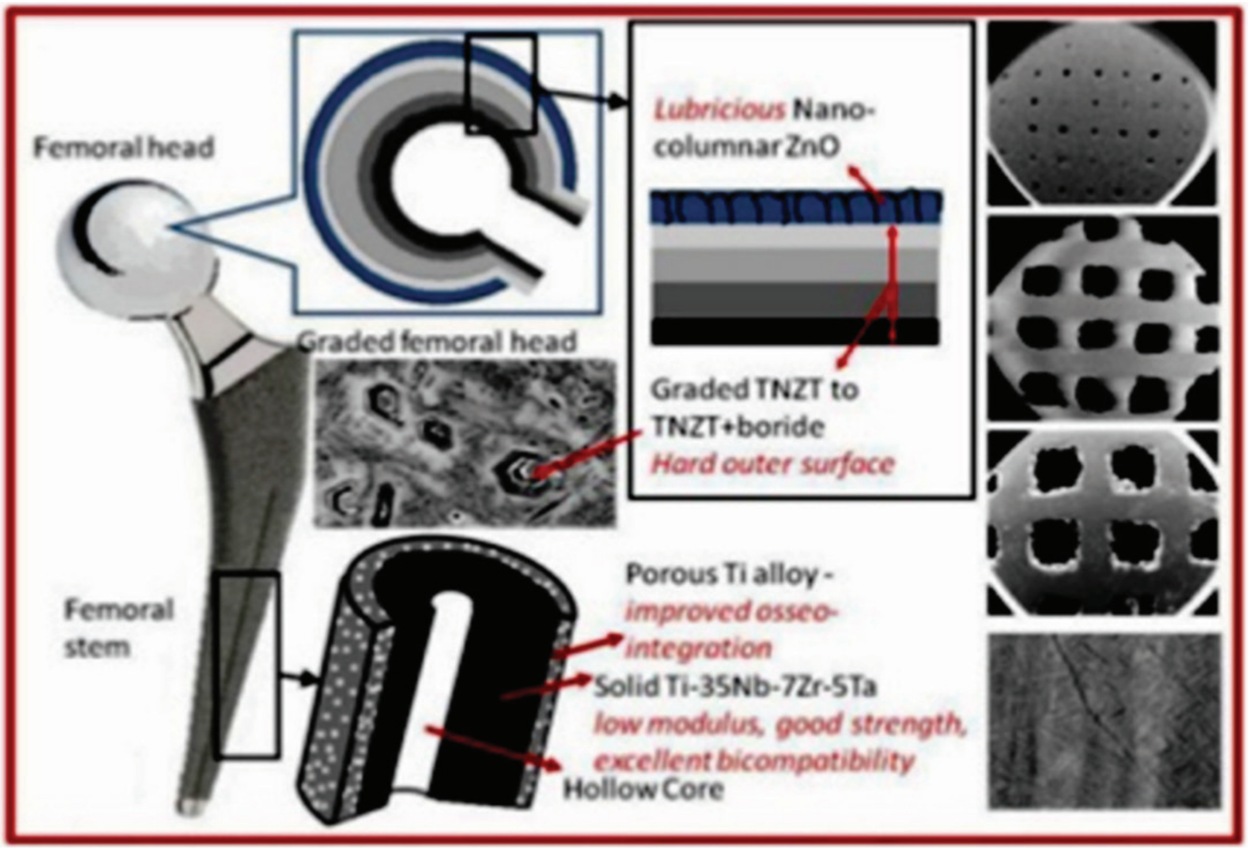

Figure 2. FGM implant with porous Ti alloy.

particles on the implant surface under stereo-scanning electron microscopy. As a result, they proposed acid etching procedure as a treatment to remove the surface adherent particles [43].

Murr et al. [44] used electron beam melting to produce Ti-6Al-4V open cellular foams with different cell wall structures (solid and hollow). The elastic moduli were decreased with increased porosity as widely known for porous metals of all types. On the other hand, the micro indentation hardness of the hollow cell wall structure was higher than that of the solid cell wall. Long term stability and mechanical properties of two types of porous dental implants were investigated under both dynamic and static circumstances [23]. Implants were coated by porous layers made from ammonium hydrogen-carbonate (NH_4) HCO_3 as space holder particles. Then testing these coated implant samples was performed in fatigue and finite element analysis was used to predict their fatigue behavior. It was determined that the melting process of the electron beam has the potential to process Ti-6Al-4V implants with wide range of pore geometry [45]. The compressive properties of porous implants varied with pore structure and can resemble those of human bone [46]. To improve the surface wear resistance of the titanium structures, Laoui et al. applied laser gas nitriding using a CW Nd:YAG laser, and consequently, the coating layer withstand more cycles without fracture [46].

Nomura et al. [47] recommended the vacuum infiltration technique with sintering to generate porous titanium/hydroxyapatite composites. The elastic modulus was rated utilizing the porosity percentage and then tailored to be in the scale of bone tissue (given by 24–34% porosity).

Porosity can be specified by adjusting and controlling the applied temperature and pressure in a hot-pressing stage. Likewise, Hanks' buffered salt solution was applied to reduce the elastic modulus of the sintered porous titanium/hydroxyapatite composites. The bone implant contact and removal torque of dental implants with a porous layer produced by laser sintering were measured and compared with sandblasted-acid etched implant (i.e., those with a rough, but not porous, surface) [48]. It was decided that resultant porous dental implants fabricated by the sintering process are better in terms of biocompatibility and biomechanical properties.

Basically, adequate combination of both mechanical properties and biocompatibility constitute important factors in the application of any biomaterial within the medical or dental field. Surface characteristics govern the material biocompatibility, while its mechanical strength is determined by the average mechanical strength of the materials. According to Chenglin et al. [49] and Lim et al. [50], the combinations of hydroxyapatite and Ti-6Al-4V can results in an excellent functionally graded material. Although the surface layer is essentially hydroxyapatite, the resultant functionally graded material exhibits excellent properties with regards to biocompatibility and bone-bonding ability or dental-bonding ability. Superior mechanical strength in the functionally graded material is accomplished by Ti-6Al-4V phase. Yokoyama et al. [51] analyzed the biocompatibility and mechanical properties of hydroxyapatite/titanium functionally graded implant synthesized by spark sintering technique and found that much enhancement was accomplished by this technique. Miyao et al. [52] manufactured titanium/hydroxyapatite functionally graded material utilizing spark plasma sintering method, and both biocompatibility and mechanical properties as an implant were investigated. They reported that the titanium/hydroxyapatite functionally graded material implants made by the spark plasma sintering method showed strength, excellent biocompatibility, and controllability for graded bioreaction. Watari et al. [53] fabricated the hydroxyapatite/titanium functionally graded dental implant and tested its biocompatibility in Wistar strain rat. They noticed that hydroxyapatite/titanium functionally graded dental implant had better biocompatibility than titanium implant. Foppiano et al. [54] evaluated in vitro the biocompatibility of functionally graded bioactive coating of novel glasses utilizing mouse osteoblast-like cells. Their results exhibited that functionally graded bioactive coating performed at least as well as tissue culture polystyrene and Ti-6Al-4V alloy in the performed biocompatibility tests. Also, functionally graded bioactive coating may influence gene expression favorably promoting osseointegration. Animal implantation tests have exhibited that the coexistence of the hydroxyapatite component in both titanium/hydroxyapatite implants and bone accelerates new bone formation from earlier stage without inflammation [55]. Hedia [9] introduced the optimal design of functionally graded material dental implant in the form of thin layer of cancellous bone around the implant. When compared with conventional titanium implants, stresses concentration in the cortical bone, cancellous bone, and implant were shown to be reduced with the optimal design of collagen/hydroxyapatite functionally graded material implant. In terms of biocompatibility and controllability, collagen/hydroxyapatite functionally graded material was excellent. Hedia claimed that the use of functionally graded material concept in dental implant materials achieve full integration of the implant with living bone, thus increasing the life span of implant. The computational results showed that the use of a functionally graded implant effectively reduces the stress difference at the implant-bone interfaces where the maximum stresses occurred.

2.3. Biomimetic process and biological interaction

Different biomimetic strategies were established to manufacture new materials, which are thought to promote the levels of biological and mechanical performance of biomaterials [56, 57].

A number of researchers utilized bovine and human sera in vitro to investigate protein adsorption on biomaterials [58, 59]. The observed reactions on the biomaterials surface which is in contact with these protein-containing solutions have also been studied using Dulbecco's Modified Eagle's minimum essential medium supplemented with 10% Nu-Serum [60], which includes growth factors, hormones and vitamins within their composition. Immersion in cell-containing solutions is a step further regarding *in vitro* method to mimic the real condition of biomaterials immersed into body fluids.

Most dental implant materials aim to support cell attachment by conferring a suitable an area for cell adhesion [61]. Mangano et al. seeded human dental pulp stem cells on direct laser metal sintered titanium scaffolds and acid etched surfaces. They observed that gene expression and protein secretion were faster on laser sintered scaffolds [62]. Cheng et al. proposed using a template from human trabecular bone to produce porous Ti-6Al-4V materials using particularly laser sintering method as additive manufacturing technology. Different porosities (low, medium and high) ranging from 15–70% with interconnected structure were manufactured to produce structures that simulated the human body trabecular bone. After certain surface treatment with calcium phosphate particles and acid etching, the trabecular bone structure revealed micro and nanoscale porosities which were able to boost osteoblast cell differentiation. Therefore, well-suited devices for dental and orthopedic implants can be produced using the potential of this trabecular structure [18].

Incorporation of a modified sponge replication method and anodization process represents another trial to promote the mechanical and biological properties of porous titanium structures as well. Titanium scaffolds with elongated pores were produced by coating a stretched polymeric sponge template with TiH_2. The anodization of the titanium can produce a nanoporous surface that can stimulate osteoblast cell proliferation and enhance attachment on implant surfaces [23]. Pore geometry has probably a potential strong effect on cell attachment and matrix formation [63]. However, different pore geometries within a single material and manufacturing process are rarely investigated by researchers. Recently, Markhoff et al. [64] evaluated the viability and proliferation of human osteoblast cells in porous Ti-6Al-4V using various scaffold designs and cultivation methods. They applied additive manufacturing technology to produce different pore geometries (cubic, diagonal, pyramidal), using both static and dynamic culture techniques which interestingly showed no significant differences in their results, however, the pyramidal pore design with a 400–620 μm pore size and 75% porosity showed the best results in regard to cell activity and its migration.

Crucial steps in the discovery of novel implant materials and structures include many in vitro studies. However, various inherent limitations are present in relation to the use of different cell culture methods to estimate the long-term service of an implant. Such limitations involve the lack of a three-dimensional environment that properly simulate both chemical and mechanical bone properties, the absence of exerted mechanical loads at the bone-implant interface after implantation procedure, the lack of proteins intricate matrix and different types

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of bone cells that are present at the bone-implant interface in vivo and the difficulty of preserving the culture for long time periods. Despite the researchers' efforts to improve the different in vitro studies using 3D environments and bioreactors, the in vivo studies represent the source to the current information regarding long-term implant stability.

Designing titanium dental implants with intertwined pores and irregular crevices using a laser sintering process was performed by Mangano et al *in vivo* studies [65] which showed 95% success rate on clinical observation after 1 year postoperatively. On the other hand, histological evaluations made by Shibli et al. who measured human bone tissue response to three types of dental implants: direct laser fabrication, sand-blasted acid-etched and machined commercially pure titanium under unloaded circumstances. Their results revealed that eight weeks post implant insertion, the bone-implant contact produced by the direct laser and sandblasted acid-etched processes was not significantly different but was higher than that of the machined implant, and there were no significant differences between the three types. These findings are explained and attributed to the surface roughness that was produced in both laser and sandblasting techniques, which improved the osseointegration process [66]. Another study using male Sprague-Dawley rats indicated that the biological fixation was affected by the percentage of titanium implants porosity (25, 11, 3%). Examinations after sixteen weeks showed that calcium ions concentration increased proportionally with increased percentage of porosity [67]. Laoui et al. inserted a Ti implant into a dog's lower jaw and their result showed a clear bone growth into the porous structure within the porous surface layer with no observed inflammation at the interface [46]. Tolochko et al. [30] inserted a prototype porous dental implant into the lower jaw of a cadaver which demonstrated a firm integration of the implant into the alveolar ridge of the lower jaw with a maximum gap width of 200–300 μm at the bone-implant interface. Another trial was made to decrease the required healing time for the dental implant and bone by covering a titanium dental implant with a layer of TiO_2 nanotubes, which was tested in a rat femur. Various diameter sizes of these nanotubes were used (30, 50, 70, and 100 nm), with the highest removal torque and osseointegration rate seen in the 30 nm implants after two weeks while the 70 nm implants exhibited the highest value after six weeks for both tests [23].

3. Dental restorations

The dental restorations categorize as dental post and crown.

3.1. Dental post

3.1.1. Overview

The primary role of teeth in the oral cavity is to serve as a mechanical device for mastication. Restoration of endodontically treated tooth presents a great challenge in everyday practice of dental clinicians. Despite the numerous developments in materials and techniques, patients' demand for improved aesthetics, function and longevity of such restoration drives researchers and practitioners to make further developments. This challenge is even greater in cases where there is massive tooth damage due to caries or trauma. This is explained by less fracture resistance of damaged tooth due to reduction in the number of cross-linked collagen fibers and loss of moisture within the tooth [68]. In such cases, there is often a need to compensate for the lack of tooth substance by additional restoration, which is achieved by placing a post in the root canal and core build up [69].

The main role of a post is to provide retention of the core of an endodontically treated tooth. When an occlusal force is applied coronally, the force is transferred to dentine through the core and post system. In such cases, stress tends to be concentrated at the coronal and apical regions (**Figure 3**). Stress concentrations at the coronal region of the root are likely to be due to the increased flexure of the compromised root structure, while stress concentrations at the apical region (**Figure 4**) are generally due to the root canal taper and post characteristics [70]. The regions of high stress concentration were also observed at the apical termination of the post [71]. In such cases, stress concentration which occurred at the apical end, could initiate a root fracture. This phenomenon is dependent on post geometry, material choice of the post and the adhesion between post and dentine. Considerable controversy exists with regards to the ideal choice of material and design of post and core.

Furthermore, as enamel and dentine reveal slightly mismatch coefficient of thermal expansion, thermal loads may even generate stresses in intact sound tooth [72].This problem is increased if the tooth is restored with various restorative materials. The effect of thermal stimuli may be further amplified during mastication as functional load could create tensile stresses on the buccal side of the teeth and compressive stresses on the lingual side.

Endodontically treated teeth are at higher risk of biomechanical failure than vital teeth [73]. The placement of a dental post creates an unnatural restored structure since it fills the root canal space with a material that has a defined stiffness unlike the pulp. Hence it is difficult to recreate the original stress distribution within the tooth in order to avoid fractures. Therefore, post systems must be carefully selected to reduce the incidence of root fractures and to preserve the root if failure occurs. Generally, there are significant mismatch between material properties of these types of posts, e.g. stiffness, and surrounding dental tissues resulting in the poor stress distribution and root fracture.

A widely discussed issue in the literature up to date is the most appropriate material for posts construction [74]. Flexible material that has a flexible dentine-like quality with a low Young's modulus, such as fiber-reinforced composite posts is the most highly recommended material for reducing the risk of root fracture [75, 76]. However, de-bonding of the post and movement of the core can occur due to stress concentrations focused at the post-dentine interface, which consequently results in microleakage [77]. On the other hand, rigid posts require minimal tooth preparation due to their smaller diameters but this may lead to root fracture [78, 79]. For the previous reasons, dental practitioners are left with two options: either continuing to use posts with a high modulus, which could lead to an irreparable failure or choosing low modulus posts that can result in a reparable failure [74].

3.1.2. Dental post based on functionally graded concept

Needless to say, dental post should be high modulus of elasticity at coronal part which is approximately similar to the crown/s and bridge abutment/s and it gradually reduced towards

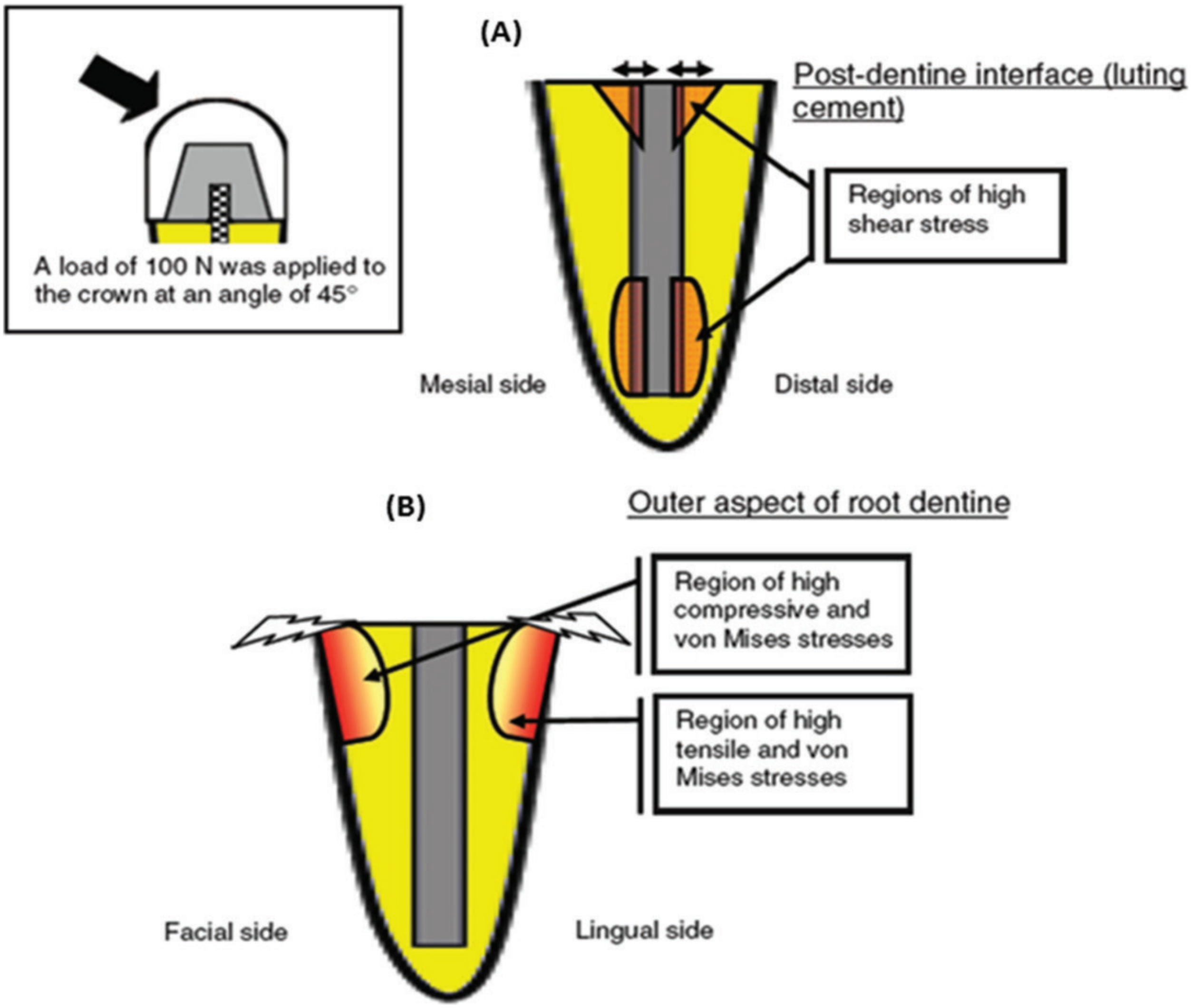

Figure 3. Schematic diagram obtained from FEM analysis showing the typical distribution of (A) shear and (B) tensile, compressive and von Mises stresses in a post and core restored teeth..

the apical part of the tooth (**Figure 5**). Ramakrishna et al. [80] suggested that ideal dental post should be stiff at the coronal region, i.e. in the region of the core, so that the core is not stressed excessively when occlusal force is applied to the crown and its stiffness should be reduced apically. The high stiffness eradicates the stress from the core and the gradual reduction of stiffness along the post would dissipate the stress from the post to the dentine uniformly. The gradual dissipation of stress would also help to eliminate local stress concentration areas and reduce the interfacial shear stress growth.

The problem of materials' properties mismatch can possibly be solved by compositional gradient of multilayer materials achieved in FGMs. Drake et al. The power distribution law was utilized to prove that significant stress and plastic strain reduction can be accomplished through increasing the ceramic materials thickness gradient and tailoring the exponent to create a compositional change gradient close to the parts showing high modulus and little plasticity [81].

Figure 4. Stress concentration due to commercial dental post.

Matsuo et al. [82] fabricated functionally graded dental post (FGDP) using laser lithography, one of the photo-curing type computer-aided design/computer-aided manufacturing (CAD/CAM). The elastic modulus of the post could be changed longitudinally at its apical end by decreasing the filler content of ceramic powders from 64 to 0% in polymer matrix. They used FEM and showed that stress was reduced further by 30% in functionally graded dental post compared with the uniform one. Fujihara et al. [83] fabricated functionally graded dental post and analyzed the stress distribution by FEA. They showed that the peak tensile and shear stresses for a functionally graded dental post were less than that of stainless steel post. They suggested that the modulus of elasticity of post material should be as close as possible to the modulus of elasticity of dentine and crown at the apical part and the coronal part respectively, in order to minimize the chance of interfacial debonding. Lately, Abu Kasim et al. [84] patented three types of multilayered composite materials that were produced using powders of zirconia (ZrO_2), alumina (Al_2O_3), hydroxyapatite (HA), and titanium (Ti) to develop newly designed functionally graded dental post. The stress distribution of a newly constructed functionally

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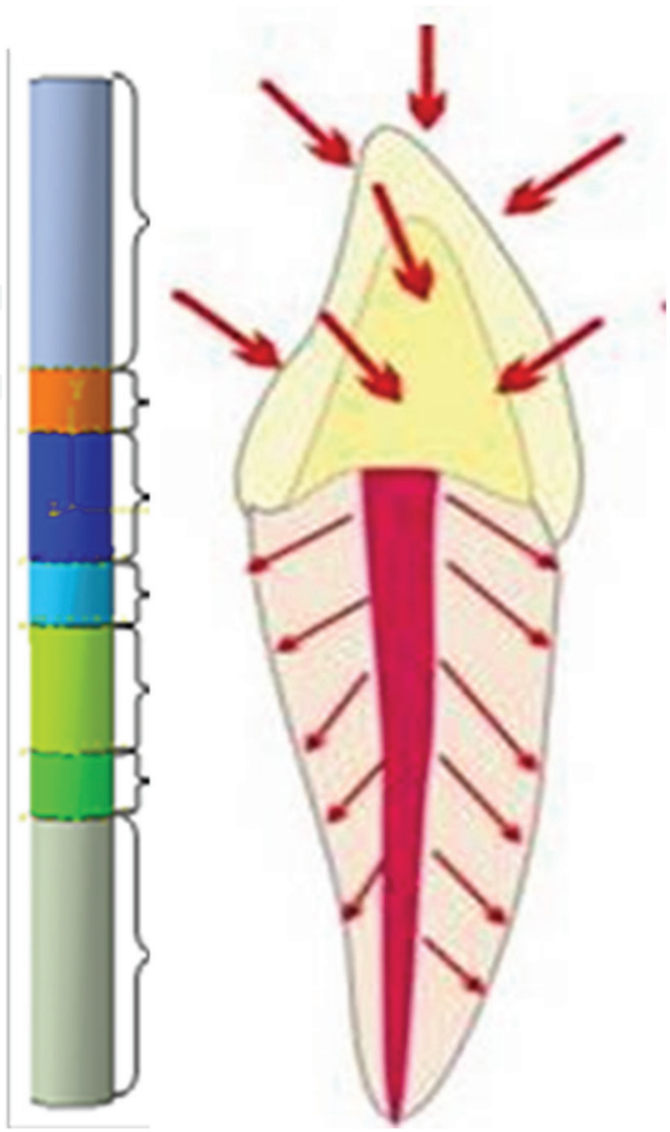

Figure 5. Uniform stress distribution due to functionally graded dental post [15].

graded dental post that is comprised of multiple layer design of ZrO_2-Ti-HA was studied in Ref. [85]. The results were evaluated in comparison to those of posts constructed from a single homogeneous material such as titanium and zirconia. In terms of stress distribution, it was concluded that the new multilayered dental post showed better results and advantages in comparison to homogenous posts with a better stress distribution at the post-dentine interface of functionally graded dental post (FGDP). Therefore, it is important to ascertain the thermal behavior of FGDP in order predict their performance in the oral environment. Madfa et al. [86] examined thermal stress in endodontically treated teeth restored with FGDP under cold and hot conditions using finite element analysis. They found that the magnitude of thermal stresses at the post and surrounding structures interface were greater in the zirconia and titanium posts especially at the middle third of the posts. In this study, thermal analysis showed that thermal stress level is closely related to the amount of temperature gradient. The peak stress by thermal stimuli for the zirconia and titanium posts are approximately three times higher than FGSP. This is due to that the FGDP possibly improved the heat flow into dentine because of the gradual change in thermal conductivity. Madfa [15] also investigated the shear stress distribution of a newly designed functionally graded dental post which consisted of multilayer design of ZrO_2-Ti-HA and was compared to posts fabricated from homogeneous material such as titanium and zirconia. They reported that shear stress of FGDP at posts and surrounding structures was lower than titanium and zirconia posts when tooth loaded obliquely. It was observed that the peak shear stress for the FGSP reduced approximately three times of those for titanium and zirconia posts. Moreover, Madfa [15] analyzed the strain distribution pattern in the natural tooth and endodontically treated teeth restored within either FGDP or titanium and zirconia posts. Strain mainly occurred at the coronal third of the root and gradually diminished towards the apical third. This strain may result from the increased displacement of the alveolar bone in the cervical region, relieving the apical third from any undue strain. The same authors found that FGDP and natural tooth models distributed strain uniformly in the tooth structure, the strain found to concentrate at the coronal third of the root, where the cemento-enamel junction (CEJ) creates a physiological discontinuity of the mechanical properties of natural tissue.

Furthermore, Madfa et al. [87] compared the fracture resistance and failure modes of endodontically treated bovine teeth restored with FGDP prototype, prefabricated titanium and cast posts. Their results found that there was no significant difference in the mean fracture resistance (N) for endodontically treated teeth restored with FGDP, titanium and cast posts. Surprisingly, the failure mode evaluation results exhibited significant differences between the groups. Most typically, fracture of the sample in all groups occurred initially at the crown margin on the palatal side where loading was applied. The fracture line then progressed towards the buccal surface of the root, above, below or at the simulated bone level. If the fracture terminates above or at the simulated bone level, this fracture mode was considered to be

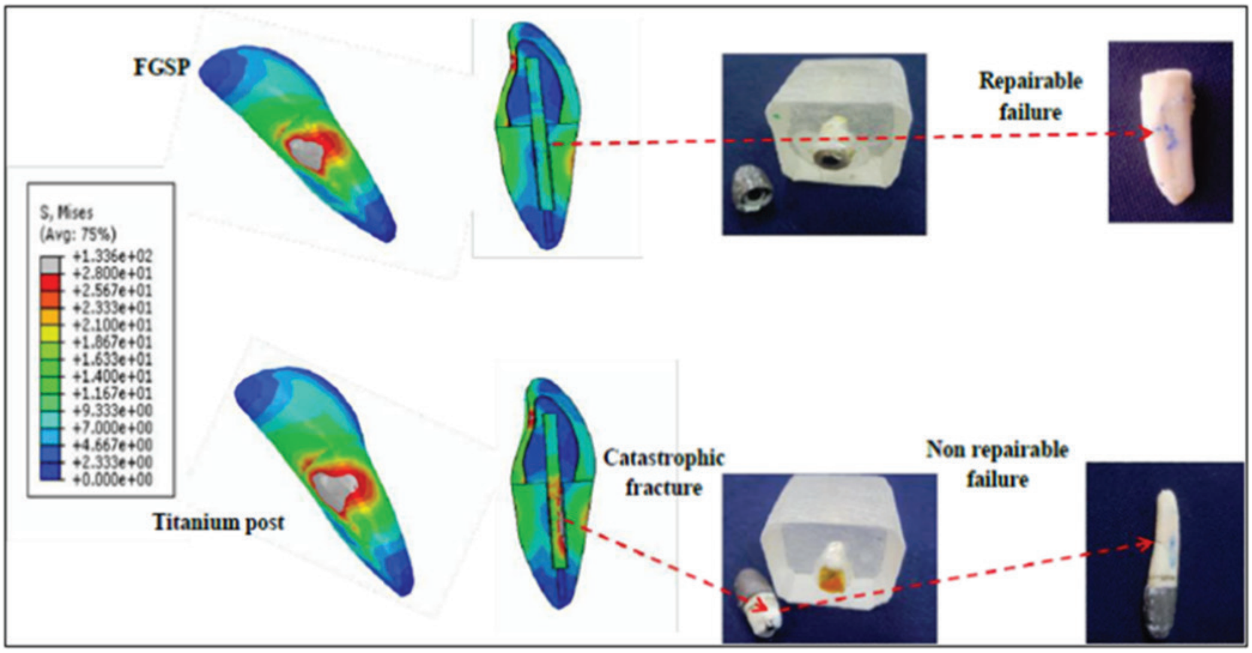

Figure 6. Relationship between failure mode and the finite element analysis [15].

repairable. The FGDP and the endodontically treated teeth without post showed more repairable failures compared to titanium and cast posts. The stress were concentrated at middle and apical thirds for endodontically treated teeth restored with titanium and cast posts compared to FGSPs and endodontically treated teeth without posts [15] as shown in **Figure 6**.

3.2. Dental crown

3.2.1. Overview

Ceramic dental restorations are designed to restore both function and esthetics of the compromised teeth. However, these materials showed somewhat poor flexural strength, particularly when exposed to fatigue loading in wet environments [88–90]. Consequently, this can result in severe discomfort to patients and can reduce the durability for ceramic prostheses due to their flexural fracture [91–93]. Furthermore, in metal-ceramic restorations, there are mismatches in the mechanical properties between the veneering porcelain and underlying metal core. The Young's modulus of the veneering porcelain is 60–80 GPa, while that of the metal core is in the range of 80–230 GPa [94]. Moreover, there are mismatches in the thermal properties between the veneering porcelain and metal core, where thermal expansion coefficient for metal core is usually higher than that of veneering porcelain (**Figure 7**). These significant mismatches between both materials properties result in stresses concentration at the metal-ceramic interfaces which may cause interface cracking and consequently lead to restoration failure [95, 96].

In spite of the continuous improvement in dental prostheses such as using a strong zirconia or alumina core to support the esthetic porcelain veneer, ceramic prostheses are still susceptible to failure at a rate of about 1–3% each year [97]. Also, ceramics prostheses have a dense, high purity crystalline structure at the cementation surface that cannot be adhesively bonded to tooth dentin support [98]. Although some authors recommended particles abrasion as surface roughening treatment to improve the bond of ceramic-resin-based cements utilizing mechanical interlocking, particles abrasion further causes surface defects or microcracks which could result in deterioration of flexural strength of ceramic prostheses on the long-term service [99–105]. Furthermore, the white opaque appearance of the zirconia cores

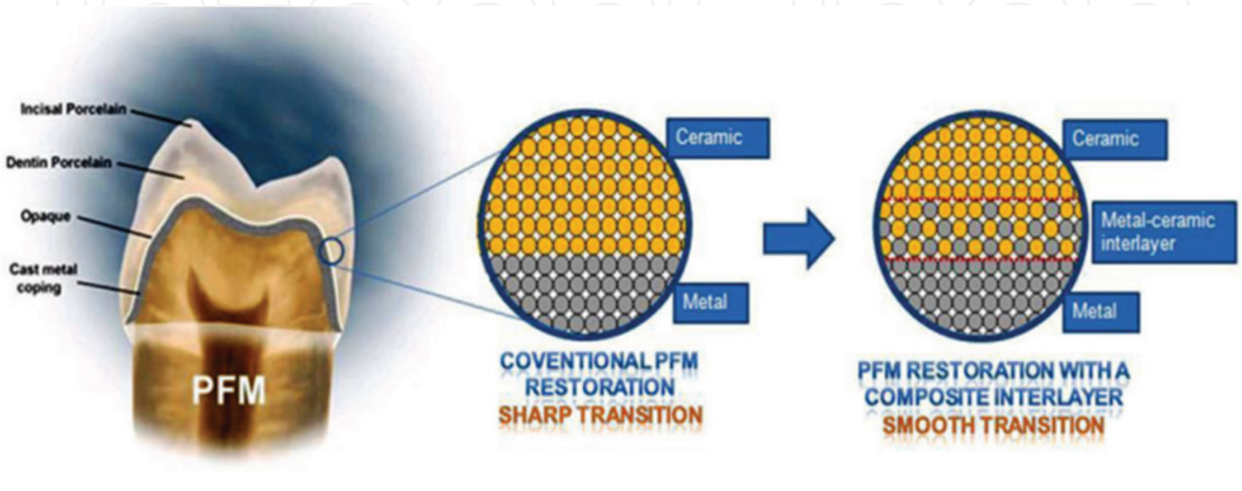

Figure 7. Schematic of the conventional sharp restoration and the new graded approach.

necessitates placing a thick layer of porcelain veneer with stepwise change in translucency to cover zirconia core thereby achieving better esthetic results [106]. In addition, dental crowns generate over $2 billion in revenues each year, with 20% of crowns being all ceramic units. Aging populations will drive the demand for all types of dental restorations even higher [107]. Moreover, occlusal contacts induce deformation and cracking of dental crowns leading to structure failure [108].

For the above reasons, it is highly advisable to develop ceramic prostheses that are more resistant to cracking under occlusal contact in recent decade for long term service and success [109, 110]. Composite ceramics have been designed in an effort to improve strength and toughness while enhancing functionality. For many years, simple laminate materials have been developed, where a number of materials with different properties are bonded into a layered structure [111]. Even though these composites combine varying properties, the abrupt interfaces between the two materials often reserve residual stresses [10, 112] and perhaps delaminate under load [113].

3.2.2. Dental crown based on functionally graded concept

Natural teeth are composed of layered structures, dentin and enamel, that are bonded by a functionally graded dentin-enamel junction (DEJ) layer that is about 10–100 micrometers thick [114, 115]. The DEJ acts as a bridge between the hard brittle enamel (E~70 GPa) and the softer durable dentin layer (E~20 GPa), allowing a smooth Young modulus transition between the two structures [115] as shown in **Figure 8**. He and Swain [35] investigated the nanoindentation mechanical behavior of the inner and outer regions of human enamel. They reported that inner enamel has lower stiffness and hardness but higher creep and stress redistribution abilities than their outer counterpart. They attributed this observation to the gradual compositional change throughout

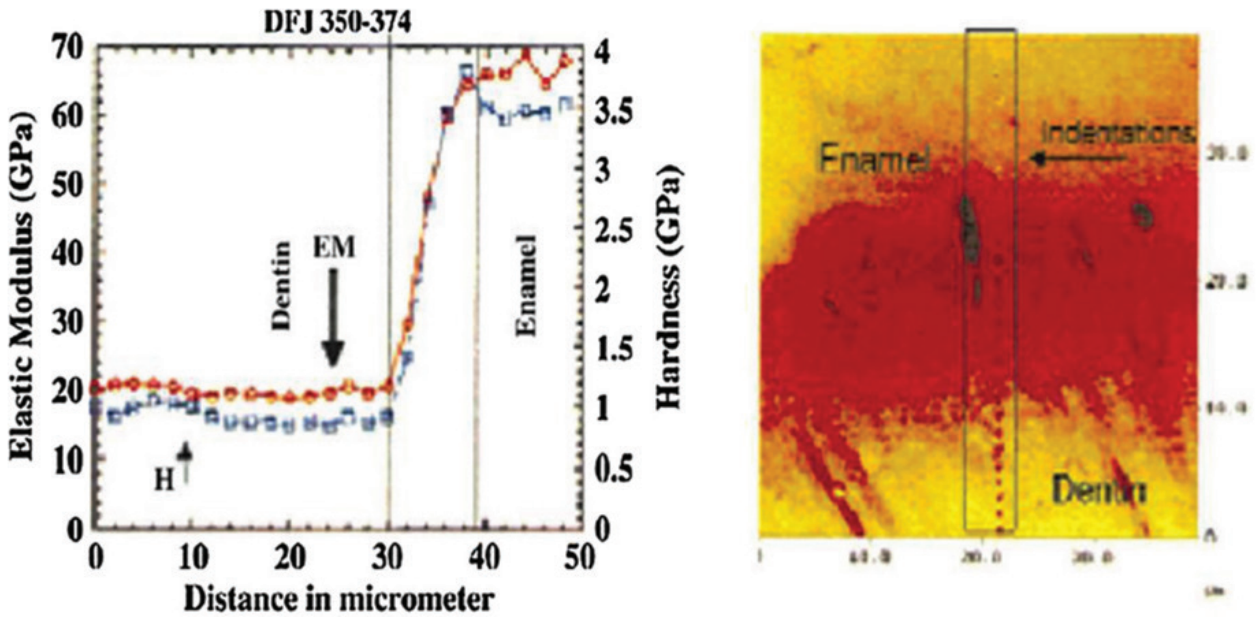

Figure 8. Elastic modulus distribution in natural DEJ [10].

the enamel from the outer region near the occlusal surface to the inner region near DEJ. They suggested that enamel can be regarded as a functionally graded natural bio-composite.

Inspired by the microstructure and mechanical properties of natural teeth, synthetic functionally graded materials were proposed to mimic the DEJ. Recently, functionally graded dental prostheses inspired by the DEJ structures and the linear gradation in Young's modulus of the DEJ have been recommended, as an alternative technique, aiming to enhance the overall performance of metal-ceramic and all-ceramic dental restorative systems. This technique permits the production of a material with very different characteristics within the same material at various interfaces [4].

Francis et al. [115] introduced a procedure to create a DEJ-like interface and enamel coating involved depositing slurries of oxide or glass powder by a draw-down blade method, drying at then higher temperature heating. They used alumina-glass or alumina-polymer composite to mimic the dentin and a calcium phosphate-based coating to mimic the enamel. Bonding between the two materials was accomplished by a eutectic melt in the $CaO-Al_2O_3-SiO_2$ system. The interpenetration in this DEJ-like interface originates from a solidified melt phase penetrating into the dentin. Huang et al. [10] added a FGM layer forming an enamel-like dental ceramic layer. FE simulations of the structure showed that the addition of FGM adhesive layer could significantly reduce the stress concentrations in the sub-surface of ceramic. This increases the resistance of the structure to radial cracking. This suggests the possibility of building synthetic bio-inspired functionally graded dental multilayers that have comparable or better durability than those of natural teeth. Consequently, also showed similar reductions in stress concentrations in simulations using a bio-inspired functionally graded material layer have been shown also by Niu et al. [14]. Their experimental study demonstrated the processing of such functionally graded multi-layers and the increased critical loads in dental multilayer structures with FGM structures.

Rahbar and Soboyejo [13] used computational and experimental effort to develop crack-resistant multilayered crowns that are inspired by the functionally graded DEJ structure. The calculated stress distributions revealed that the highest stress was concentrated at the ceramic outer layer of crown which then was reduced significantly toward the DEJ with the use of bioinspired functionally graded architecture. In addition, promotion of improvements in the critical crack size was reported because of these bioinspired functionally graded layers. Du et al. [116] also found that the bioinspired functionally graded layers were also shown to promote improvements in the critical crack size. Suresh [117] established that controlled gradients in mechanical properties offer unprecedented opportunities for the design of surfaces with resistance to contact deformation and damage that cannot be realized in conventional homogeneous materials.

Graded dental crowns have been shown to display improved features relative to conventional ones, namely higher resistance to contact and sliding [118, 119]; higher adhesion of porcelain to the substructure (metal or ceramic) [120–122]; improved esthetical properties and improved behavior under fatigue conditions [122]. FGM design can address another important point related to diminishing the thermal residual stresses which persist at the metal-ceramic interface after firing of porcelain throughout its cooling cycles. Such stresses are additionally exaggerated due to the presence of a prominent mismatch between the metal and porcelain thermal expansion behavior. Basing on the remnant thermal residual stress level in the crown and along with those originating from occlusal functional loads, a disastrous restoration failure can follow. It was revealed that FGMs reduce dramatically the remnants of thermal stresses raised at the metals and ceramics interface in other fields of applications [123]. Some studies demonstrated that when the contact surface of alumina or silicon nitride was infiltrated with aluminosilicate or oxynitride glass, respectively, they noticed that the graded glass/ceramic surfaces produced in this manner offered much better resistance to contact damage with and without a sliding action than either constituent ceramic or glass [124, 125].

A number of the studies investigated the effects of increasing elasticity as a function of depth from the surface on the resistance to contact damage. They established that mass fracture and failure of veneer may be considerably diminished by specific gradual inclination of the modulus of elasticity through the veneer material thickness. These graded layers show a noticeable increased resistance to fatigue sliding-contact and flexural damage regarding veneered and monolithic core ceramics. This is due to the reduction of the tensile stresses intensity as a result of this gradient and, at the same time, transfers these stresses from the surface layer toward the interior, away from the source of failure-inducing surface defects [126–133] as shown in **Figure 9**.

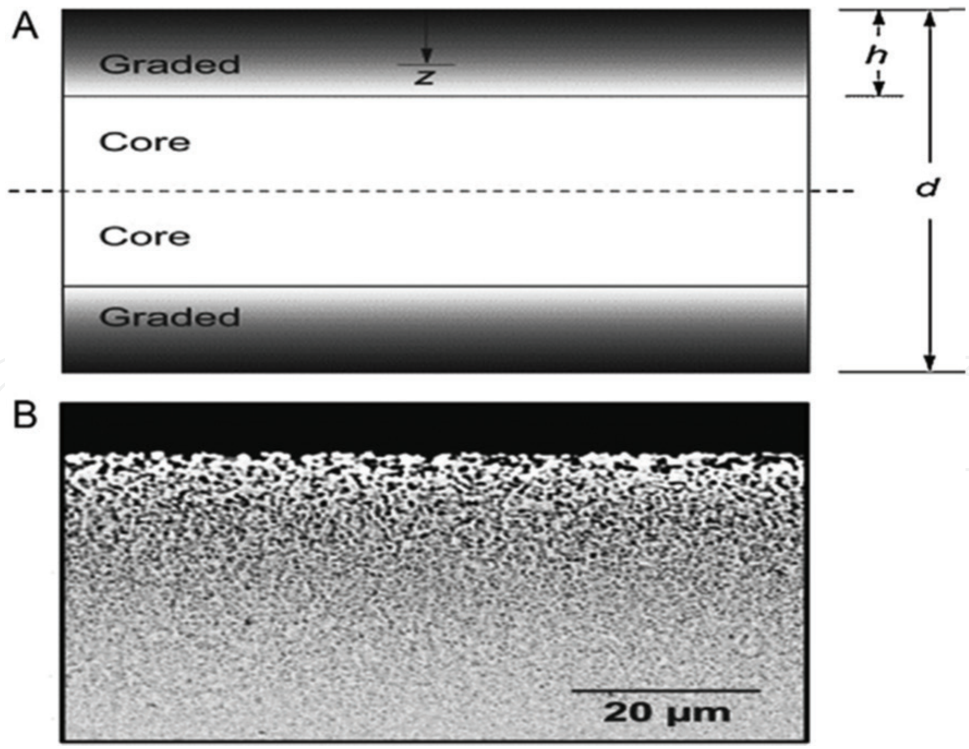

Figure 9. Morphology of the graded zone. (A) Schematic of graded structure, (B) Section view of graded zone of glass-infiltrated yttria stabilized zirconia [126].

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4. Conclusions and future perspectives

The development and selection of biocompatible, long-lasting, direct-filling tooth restoratives and indirectly prosthetic materials capable of withstand the aggressive environment of the oral cavity, have been a challenge for practitioners of dentistry since the beginning of dental practice. In order to replace the mechanical function of tooth from a restorative perspective, it is not only important to study its localized tissue properties but also its bulk structural behavior. Therefore, this chapter highlights functionally graded dental implant and restorations inspired from nature. The bioinspired functionally graded structure can be seen as the precursor to recent studies. This is a remarkable example of nature's ability to engineer functionally graded dental prostheses. These dental prostheses mimic the biological and mechanical behavior of natural bone and tooth. These prostheses could potentially lead to superior long-term clinical performance for dental prostheses.

Work in this area is promising and provides a basis for exciting improvements in dental implant and restorations for patients. However, the body of research to date has still not clearly identified the optimal graduation for the most effective biomechanical and biological properties and their behaviors. Therefore, further studies are necessary to evaluate the potential of advanced manufacturing methods to optimize the graduation structure of dental prostheses. The present chapter opens a new avenue for recent researches aimed at further development of new direct filling tooth restoratives and indirect prosthetic materials for improving their clinical durability.

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