Fiber-Reinforced Composites for Computer Assisted Design/Computer Assisted Manufacture of Dental Crowns

Richard C Petersen[1]*, Perng-Ru Liu[2] and Michael S Reddy[3]

[1]*Biomaterials and Restorative Sciences, School of Dentistry, University of Alabama at Birmingham, United States of America*
[2]*Restorative Sciences, School of Dentistry, University of Alabama at Birmingham, United States of America*
[3]*Office of the Dean, School of Dentistry, University of California at San Francisco, United States of America*

*Corresponding Author: Richard C Petersen, Biomaterials and Restorative Sciences, School of Dentistry, University of Alabama at Birmingham, United States of America.

Abstract

Fiber-reinforced composites can be processed by vacuum assisted resin transfer molding toward providing bulk structural material with sufficient thickness for computer assisted design/computer assisted manufacturing to fabricate dental crowns. Soaring gold prices that initiated research into substitute materials has continued since the early 1970s for many different possibilities. Fortunately, fiber-reinforced composites provide design-level advantages for high mechanical properties to include well-known excellent fracture toughness as a major problem with ceramics and oxide ceramics like alumina or zirconia that fracture into multiple pieces. On the other hand, fiber-reinforced composite crowns can withstand high loading states even without fracture or any signs of small crack propagation. Fiber-reinforced composites wear smooth into glossy wear surfaces to eliminate concerns for excessive wear on opposing teeth like ceramics. Fiber-reinforced composites have excellent adhesive bonding properties unlike ceramics or the oxide ceramics such as alumina and zirconia. Further, strong free-radical-cure bonding characteristics of fiber-reinforced composites offer major advantages for patient clinical marginal relines to generate the finest margins ever conceived. Eliminating concerns about defects at the crown margins then reduces oral exposure of sealing luting cements that can soften and dissolve by moisture hydrolysis. Blocking marginal leakage can then prevent bacterial infiltration into margin-cement gaps toward creating caries, promoting gingival recession or causing bone loss. Also, design-oriented FRCs provide numerous opportunities to incorporate additives like the efficacious broad-spectrum antimicrobial triclosan into the reline material, luting cement or bulk FRC. In addition, costs for fabricating CAD/CAM FRC crowns are considerably less than ceramics or the highly expensive oxide ceramics like zirconia.

Keywords: Fiber-Reinforced Composite; Fracture Toughness; Margins; Chipping; Wear; Adhesive Bonding; WOF: Work of Fracture;
S_{Ic}: critical strain energy release; K_{Ic}: critical stress intensity factor

Abbreviations

FRC: Fiber-Reinforced Composite; VARTM: Vacuum Assisted Resin Transfer Molding; CAD/CAM: Computer Assisted Design/Computer Assisted Manufacture; SEM: Scanning Electron Microscope; AFM: Atomic Force Microscopy; NAS: National Academy of Sciences

Introduction

Ceramic crowns have excellent esthetics, but commonly fracture catastrophically by brittle failure into multiple pieces. Preliminary mechanical tests on fiber-reinforced composite (FRC) parts fabricated by an advanced vacuum assisted resin transfer molding (VARTM)

process have demonstrated vastly improved properties for maximum flexural strength, yield strength, resilience, work of fracture (WOF), critical strain energy release (S_{Ic}), and critical stress intensity factor (K_{Ic}) over many dental ceramic computer assisted design/computer assisted manufacturing (CAD/CAM) materials [1]. FRCs are advanced engineering aerotech-level materials that have been developed for a wide diverse range of dental applications [1-25]. Subsequent CAD/CAM technology then provides the possibility of using industrial-level materials for milling crowns toward higher echelons of routine accuracy. But, ceramic crowns still fail most often due to sudden brittle fracture failure into multiple pieces with glassy-like fracture surfaces [26-46]. After ceramic brittle fracture, all crowns regardless of the material fail to a great extent because of marginal gaps that require sealing with cements that soften and dissolve by oral exposure creating micro-leakage, bacterial infiltration and secondary decay to possibly also include pulpal inflammation and periodontal disease [45-68]. Further, accelerated wear of opposing dentition is a clinical problem with ceramics [69-73]. Also, bonding of ceramics is difficult to achieve with increasing concern from more inert alumina and zirconia oxide ceramics [74-78]. Interproximal contacts must be sufficiently tight as an area and not a point or a line otherwise food wedging can occur to increase the risks for secondary decay, periodontal disease and source for painful irritation [79-88].

Numerous areas of posterior crown failure can be eliminated with FRC custom designed VARTM technology. Combined with CAD/CAM micro-precision routine operations, advanced FRC materials can be sufficiently user-friendly and design oriented to create the ideal posterior crown. Now, FRCs with CAD/CAM technology can replace the once universal standard with the gold crown after soaring prices and become a new substitute for all of the currently accepted posterior ceramic crowns. Although the 1st and 2nd molars account for only 13% of all tooth surfaces, they represent 88% of decay [89] primarily due to minor defects that help colonize bacteria [89-99] making the new FRC crown an important contribution.

Mechanical properties

Flexural testing

Mechanical Properties and Sample Thickness in Table 1 compare an early initial bulk FRC material with different commercial dental CAD/CAM materials. Testing further included a Coors® alumina oxide ceramic and tungsten carbide all tested in 3-pt bend over a 10 mm span [1]. Notice that the FRCs compare well to Fracture Toughness properties with tungsten carbide, one of the strongest bulk materials known to mankind. Also, FRC crowns could be cut to a smaller thickness than all other dental CAD/CAM crown materials or the Coors® alumina.

Thinner FRC crowns suggest a smaller amount of tooth structure needs to be removed with less pain or pulpal exposure [1]. The FRC has improved mechanical properties with significant statistical differences over all CAD/CAM Dental Materials and the industrial Coors® alumina ceramic for flexural strength ($p < 0.001$), resilience ($p < 0.05$), WOF ($p < 0.001$), S_{Ic} ($p < 0.05$), K_{Ic} ($p < 0.001$) and strain ($p < 0.001$) [1]. For a novel relevant comparison, thermoplastic PEEK polymers have been approved by the Food and Drug Administration for crowns, bridges, fixed-removal implant retained dental frameworks [100-102] and spinal fusion implants [103] with tensile strengths of only 70.3-103.5 MPa [104]. Although PEEK is reinforced with carbon fibers for temporary fixation plates [105], PEEK cannot be reinforced with fibers for long-term service [106] because of inert chemistry that prevents adequate bonding [107]. Conversely, the tensile bending failure on the lower flexural surface for the CAD/CAM FRC and all ceramics, alumina and zirconia materials manufactured under optimum industrial-level conditions exceeded PEEK in table 1 [1]. In addition, the initial FRC CAD/CAM material tested for resilience, WOF and K_{Ic} at comparable levels to one of the strongest solid material known with tungsten carbide and even greatly exceeded tungsten carbide for S_{Ic} as a measure of resistance to the unstable rapid crack propagation after critical maximum load [1]. The value for S_{Ic} in kJ/m^2 is accurately measured closely as the fracture toughness property of interest when testing for the most unusual mechanical property created with K_{Ic} in MPa*m$^{1/2}$.

Material	Sample Thickness (mm)	Flexural Strength (MPa)	Modulus (GPa)	Yield Strength (MPa)	Resilience (kJ/m²)	WOF (kJ/m²)	S_{Ic} (kJ/m²)
1. FRC BisGMA/ Styrene Vinyl-Ester Resin and E-Glass	0.49 (±0.19)	575.7 (±129.1)	24.6 (±15.8)	441.3 (±74.5)	5.57 (±2.38)	18.77 (±11.63)	1.313 (±1.028)
2. Vita Mark II CAD/CAM Ceramic	0.74 (±0.01)	103.8 (±17.0)	46.6 (±4.3)	103.8 (±17.0)	0.1 3 (±0.04)	0.1 3 (±0.04)	0.022 (±0.008)
3. 3M Paradigm® CAD/CAM MZ100 polymer	0.94 (±0.10)	156.4 (±16.8)	12.2 (±2.0)	129.7 (±14.3)	1.44 (±0.69)	1.44 (±0.69)	0.063 (±0.036)
4. ProCAD CAD/ CAM Leucite Ceramic	1.16 (±0.20)	129.5 (±32.4)	26.2 (±5.8)	129.5 (±32.4)	0.37 (±0.14)	0.37 (±0.14)	0.023 (±0.002)
5. Spinel Ceramic InCeram CAD/ CAM	1.02 (±0.18)	339.5 (±16.1)	65.5 (±22.5)	339.5 (±16.1)	1.08 (±0.37)	1.08 (±0.37)	0.035 (±0.024)
6. Alumina InCe-ram CAD/CAM	0.86 (±0.19)	314.0 (±124.9)	63.8 (±25.3)	314.0 (±124.9)	1.08 (±0.85)	1.08 (±0.85)	0.059 (±0.014)
7. Zirconia InCe-ram CAD/CAM	1.06 (±0.29)	248.5 (±102.7)	39.0 (±21.6)	246.8 (±102.9)	1.03 (±0.66)	1.03 (±0.66)	0.046 (±0.034)
8. Alumina Coors AL300 Industrial Alumina	0.82 (±0.30)	231.8 (±71.7)	79.6 (±31.2)	231.8 (±71.6)	0.68 (±0.64)	0.68 (±0.64)	0.066 (±0.051)
9. Tungsten Carbide Cermet metal/ceramic	0.37 (±0.01)	2278.7 (±40.8)	253.9 (±16.2)	1583.1 (±45.9)	5.84 (±0.18)	13.46 (±0.56)	0.279 (±0.005)
*3M Corp Z100 Dental Polymer Composite	2.05 (±0.13)	117.6 (±5.45)	19.5 (±1.3)	95.4 (±14.6)	4.48 (±0.41)	4.48 (±0.41)	0.036 (±0.023)
*Amalgam Kerr, Inc. Tytin®	2.11 (±0.11)	86.0 (±10.6)	43.6 (±6.1)	62.6 (±13.5)	1.40 (±0.28)	1.40 (±0.28)	0.013 (±0.012)

***Table 1:** Mechanical Properties and Sample Thickness [1] (±standard deviations in parentheses).*

*The last two samples were a dental composite and amalgam direct filling for comparisons but tested in an ideal 4pt bend over a 40 mm span [1]. Table 1 CAD/CAM materials were precision cut as unnotched samples to the smallest minimum thickness without breakage and before 3-point testing [1]. The smaller-than-normal samples were prepared primarily because dental CAD/CAM materials supplied as small blanks often do not exceed dimensions over 15.0 mm. By providing accurate test results, engineering design-level mechanical tests can be compared at a later time by the same exact precise methods with any new material invented.

Edge chip testing and chip toughness

Edge chipping: Fracture toughness properties related to edge chip testing are complex in nature requiring close attention to technique and specific parameters requiring excessive sample tests for a single comparison between only a few different materials [108-110]. Large amounts of data need to be compiled exactly to compare a single material with several others. Nevertheless, edge tests require low-cost equipment and test methods are relatively simple. An indentation near the edge of a brittle material can be applied with increasing load until a small thin chip starts to peel away [111]. The indentation load develops a defect area below the material surface [111]. With increasing load the cracks grow more toward the edge boundary until the edge is reached and a chip separates from the sample [111]. From a practical standpoint, a concentrated contact near the edge of a brittle ceramic material can lead to chipping during micro-impact CAD/CAM crown fabrication. For an example, figure 1 scanning electron microscopy (SEM) compared identical crowns with (A) a tougher smoother defect-free FRC crown margin and (B) multiple chip defects for a ProCAD ceramic crown margin [1]. The size of the largest ProCAD chip in figure B is approximately 356 um x 766 um while small chipping is seen along the entire edges of the margins. Conversely, FRC fibers block crack propagation and chipping [2] with high S_{Ic} (Table 1), resulting in margins with smooth sharply defined edge lines. From edge chip tests found in literature comparing monolithic yttrium-stabilized zirconia (TZP) to weaker identical CAD/CAM ceramic materials [108,109], the FRC generated fracture toughness increases in much greater excess than the zirconia TZP.
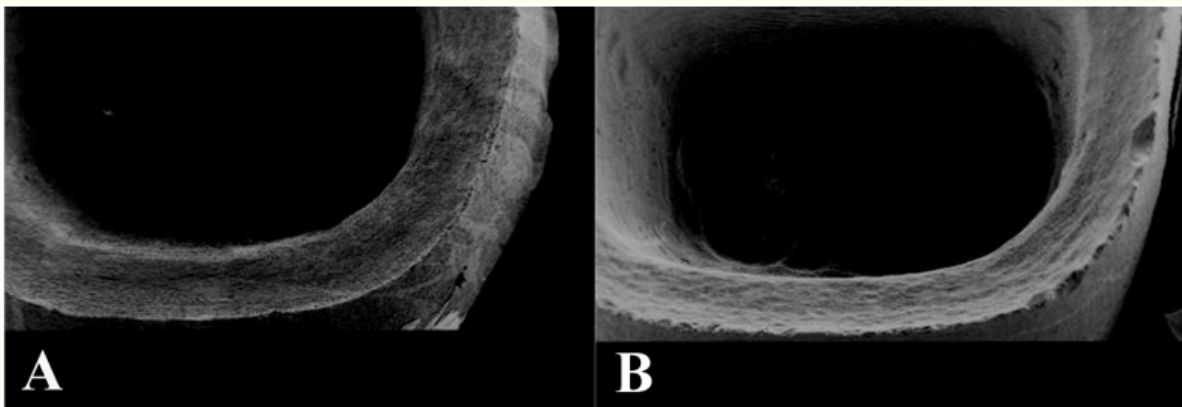

Figure 1: *(A) SEM FRC no edge chips (B) SEM ProCAD ceramic with multiple edge chips.*

Chip Toughness by Izod Impact energy toughness: Izod Impact is a comparative standardized test method to determine fracture toughness in kJ/m^2 units during a high-strain rate [6,8] in contrast to static low-strain rate fracture toughness methods that determine specific properties with absolute values also in kJ/m^2 units for resilience, WOF and S_{Ic} or similarly with bulk methods according to the National Academy of Sciences (NAS) for K_{Ic}, but in units of $MPa*m^{1/2}$ [10]. Modified Izod Impact testing was performed by cantilever fixturing according to ASTM standard D 256-00 without a sample machined notch necessary to concentrate impact stress to then provide fracture toughness for full bulk sample energy values [6,8]. Energy testing for high-strain rate toughness full breakage was accomplished with a Tinnius Olsen Plastic Tester [6,8]. All samples broke through completely, producing 2 separate pieces with fractured free ends. Further, ASTM standards are available that can use identical high strain-rate Izod pendulum testing to measure dynamic toughness for both Polymer Chip Impact Strength D 4508-98 on unnotched samples and a ceramic criterion for Chip Resistance C 368 [25]. Izod pendulum testing according to ASTM Standard for Advanced Ceramics D 256 is then a measure of the fracture energy, with particular appreciation of resistance to crack propagation in tough ductile fiber-reinforced materials [25] and especially relevant to CAD/CAM high micro-impact milling chipping defects.

Impact fracture toughness improvements for FRCs produce a larger irregular ductile fracture surface area indicative of higher debonding energy and fiber fracture compared with a brittle smooth cleavage surface with non-FRC controls [6,8,25]. Scanning electron microscopy (SEM) illustrated weak, smooth, brittle cleavage in non-FRC control material [6,8,25]. In contrast, SEM highlighted increased toughness ductility for FRCs with fiber/polymer debonding and fiber breakage regarding energy dissipation [6,8,25]. Also, fiber pull-out was observed sporadically as another form of energy consumption. Energy adsorption mechanisms with fiber reinforcement are obviously outstanding when compared to non-FRC controls. Energy consumption is the chief mechanism to restrict crack propagation as a measure of toughness. The more dominating fiber reinforcement in effect acts as an accentuated barrier to crack propagation by deflecting energy laterally.

The fracture toughness impact test outcome demonstrated vastly superior chip toughness values for FRCs over corresponding commercial non-FRC controls, $p < 0.001$ [6,8,25]. The magnitude of improvement for chip toughness when adding fibers to non-FRC controls was so exceptional that material advancement toward dental filling materials was necessarily acknowledged. Impressive results from Izod energy-toughness measurements predict a strong reduction in marginal chipping when fibers are added to non-FRC controls. As a result, testing by ASTM standard D 4508-98 has been offered as a means to make relative comparisons for the purpose of evaluating chip toughness. Assessment is especially relevant for areas under stress with high rates of strain. High strain rates are thus considered necessary to promote crack propagation and associated directly with chipping energy dissipation mechanisms, for example during high micro-impact CAD/CAM milling. Izod pendulum testing provides a direct measurement of energy and toughness in the standard kJ/m^2 units for simple fracture toughness analysis. The extent of fracture toughness increases as a measure of chip resistance is outstanding when adding fibers to conventional non-FRC controls.

Fibers block crack propagation during chipping: Atomic force microscopy (AFM) chip toughness images show the top particulate-filled-type matrix surface layer of a discontinuous FRC that can compact at extremely high packing forces (Figure 2A). Further, a chip in a top surface layer is shown blocked by underlying fibers beneath (Figure 2B). The compaction tool surface for a top cover with the samples in figure 2 was machined non-polished from ultra high molecular weight polyethylene during related polymerization shrinkage tests. The material composite fiber has a surface area a couple orders of magnitude larger than a particle of similar diameter. Subsequent fibers beneath the surface then act as major barriers to crack propagation during an impact chipping episode in addition to adding high fracture toughness properties and virtually stop crack propagation near the material surface.
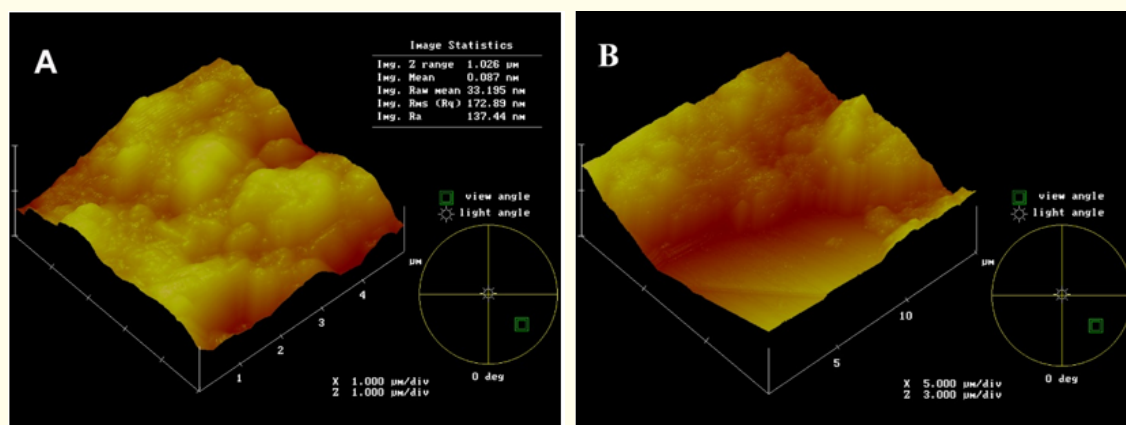

Figure 2: AFM for FRC with top particulate-filled matrix compressed flat by a non-polished machined tooled cover into a cavity mold squeezes the matrix toward the surface with removal at the margin borderline escape vents. No subsequent cutting, finishing or polish: (A) Without surface chip. (B) With surface chip exposing fiber underneath.

National Academy of Sciences (NAS) recommendations: The issues of low ceramic or oxide ceramic edge chip toughness or chip resistance bring up another important matter of concern regarding bulk material fracture toughness testing. Common dental K_{Ic} fracture toughness testing using notched man-made defects is considered exceptionally unpredictable and criticized to a major proportional extent by the NAS to end such non-bulk material testing practices that create new theory in misguided attempts to provide an unrealistic measure of rapid crack propagation with a K_{Ic} value [1,10]. Although non-bulk K_{Ic} methods with artificial man-made flaws are highly unreliable according to the NAS, bulk test methods for S_{Ic} testing in table 1 are highly accurate for close repeatable results [10]. Most importantly, dental fracture toughness testing with man-made/machined defects will not be considered valid results by the NAS. So, literature journal test results using non-bulk K_{Ic} fracture toughness methods on current oxide ceramic zirconia should also be rejected as recommended by the NAS. In accordance with the NAS recommendations, all fracture toughness results in table 1 were performed using bulk fracture methods without artificial defects introduced to simulate a natural crack.

Maximum crown loading tests

First-round occlusal load test studies on pre-damaged FRC crowns compared to monolithic mechanical-thermocycled zircon crowns and monolithic zirconia yttrium stabilized crowns in the literature produced higher average maximum loads at 5118N from approximate 1.09±0.32 mm thick FRC crowns without fracture or even visible deep cracks. By comparison, approximate 1.2 mm thick zircon crowns and approximate 3.2 mm thick zirconia TZP crowns produced maximum loads at 1622N, or 1957N and 4516N respectively that fractured catastrophically into multiple pieces [46,47]. The maximum bite force ever recorded in the Guinness Book of World Records is still only 4337N for 2 seconds [26]. Further, when considering an impossible off-axis worst-case-scenario FRC loading, after maximum loading an intact FRC crown was then subjected to a 2nd transverse or sideways loading at a cusp (Figure 3A). Nevertheless, the fracture was still at approximately 89% of the maximum occlusal load for that crown and did not occur completely through the cusp or delaminate between plys. Instead, the fracture traveled in irregular jagged fashion indicative of crack deflections for extremely good energy adsorption fracture toughness. In fact, fracture toughness energy adsorption before yield for resilience was only approximately 8% less for the transverse loading through the cusp compared to the top occlusal force on that same crown. Because the final average load for all top occlusal crowns was stopped at only about 6.5% lower past maximum force, WOF, S_{Ic} and K_{Ic} energy adsorption comparisons were not made with the exceptional transverse loading to complete failure on the crown cusp shown in Figure 2A. Higher magnification in another software program revealed a highly chemically-resistant crystalline pure-silica appearing material without a single woven ply visible along the fracture surface. Conversely, from laboratory mechanical testing, ceramics and alumina or zirconia oxide ceramics all break to expose glass-like appearing fracture surfaces similar to zirconia crowns in journal literature that fracture into multiple pieces [46,47]. In addition, the new milled advanced VARTM FRC materials tested for maximum crown loading can provide the highest levels for white esthetics (Figure 3B).
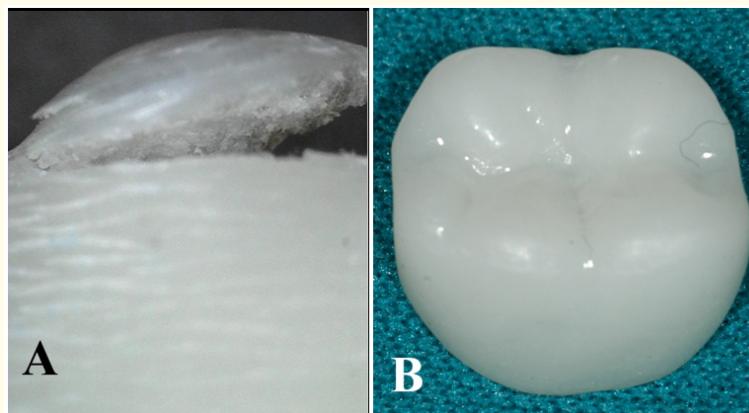

Figure 3: (A) Photo of an FRC cusp that fractured by directed transverse load on the molar cusp (no polish or glaze) (B) Photo FRC CAD/CAM milled crown and glazed by glosscoat to the most esthetic white finish.

Brittle ceramic fatigue crack growth

In terms of FRC crown longevity with an average maximum test load at 5118N, normal maximum biting forces are referenced in a range from 200-540N, 400-800N and 600-1200N [27,63,112,113] that are sufficiently low so that FRC crowns would appear permanently safe during long clinical service. In fact, most CAD/CAM crowns materials should be acceptable when first placed in the mouth. However, of ultimate significance ceramics and oxide ceramics like alumina and zirconia fail over time due to fatigue from extremely small defects when smaller stresses break molecular bonds to release energy so fast that cracks continue to grow. By crack propagation, small ceramic or oxide ceramic defects have been calculated to coalesce and extend up to around 20-100 micrometers or more as critical sizes that cause fracture. As such, fracture occurs at much weaker loads than the ideal maximum loads reported in literature of unstressed brittle materials. Consequently, small defects in brittle materials can grow to critical sizes and suddenly release accelerated energy at mach-level speeds to produce sudden catastrophic failure that fractures ceramics, alumina, and zirconia into multiple pieces. Although brittle materials fail at yield to produce resilience energy adsorption results equal to WOF, FRCs have high levels of energy adsorption after yield during WOF and continue to strain even well beyond critical load to remain fully intact after the initial maximum load crack propagation. FRCs are extremely fracture-resistant and ideally tough enough to easily block crack propagation by high energy adsorption from fibers that are some of the strongest materials known [2]. Notice from table 1, FRCs show superior fracture toughness at each level to provide property values orders of magnitude higher than all other CAD/CAM materials and compare even with one property for S_{Ic} 4.7X higher than the massively strong tungsten carbide. S_{Ic} is the mechanical property value of most interest for the K_{Ic} value in catastrophic brittle materials to measure rapid energy release during fracture crack propagation to failure. Subsequent fracture toughness is then the biggest problem with ceramic crowns and also oxide ceramics like alumina and zirconia crowns due to fatigue crack growth that creates sudden brittle destructive material failures into multiple fracture pieces.

As examples for the potential of ceramic fracture by catastrophic brittle failure, advanced zirconia oxide ceramics and a lithium disilicate have demonstrated relative concern for patient use in long-term cyclic fatigue environments. Although strengths were projected for a lithium disilicate ceramic at 400 MPa, a translucent zirconia at 550 - 650 MPa and a porcelain fused to zirconia at 1400 MPa, photos show crowns from those same materials fractured at the margins during initial seating on laboratory stone die models (Figure 4). Low ceramic or oxide ceramic edge chip toughness can accentuate failure in the relatively important margin crown areas where edges with less bulk concentrate stresses considerably [108-111].
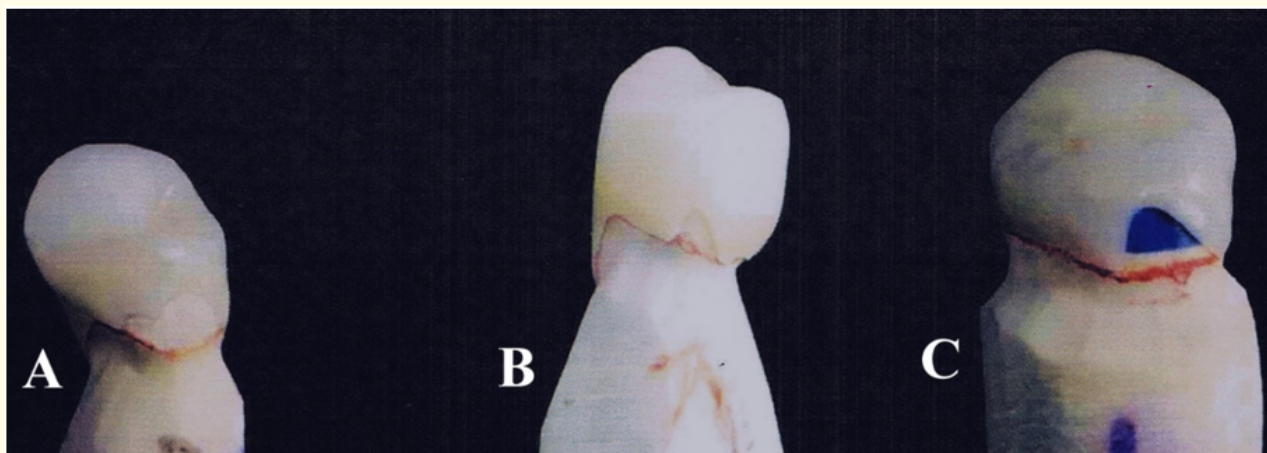

Figure 4: *Crowns fractured on the margins without loading after seating on the stone patient dies.*
(A) Lithium disilicate (B) Translucent zirconia (C) Porcelain fused to zirconia.

Similar fracture toughness problems with CAD/CAM ceramics can be encountered following normal clinical patient service (Figure 5). Fracture of a lithium disilicate crown can occur in spite of good bulk ceramic at the margin (Figure 5A). An alternate problem is presented with fracture of porcelain fused to an underlying zirconia coping (Figure 5B).
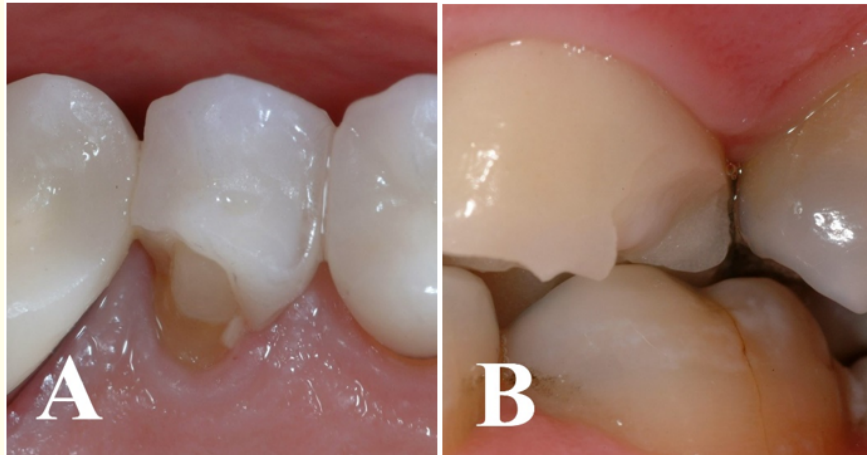

Figure 5: *Clinical photos of different fractured CAD/CAM crowns. (A) Lithium disilicate (B) Porcelain fused to zirconia.*

Other clinical concerns

Margins: Margins are a major problem for all crowns and have been questioned in the literature extensively. Marginal defective spaces with cement exposure create cement softening and degradation that produce micro-leakage, bacterial penetration and secondary caries to also possibly include pulpal inflammation and periodontal disease [45-68]. With declining laboratory technician skills, acceptable marginal gaps have greatly increased from 1990 and earlier at less than 39 um [53,56,58,60] up to 120 um commonly referenced after about 2010 [45,64-66,68,75]. One exceptional SEM restorative study in 1976 from extracted human teeth after 3 weeks showed that bacteria grow immediately into margin gaps for amalgam and gold as small as 5 - 30 um [54]. So, even margins that appear acceptable by the highest clinical standards may not be good enough.

Fortunately, following CAD/CAM FRC crown milling relatively acceptable margins can now be relined clinically to the patient's tooth and then polished back to a perfect fit [1]. The reline material can include a margin bead incorporated with highly crystalline insoluble short quartz fiber that can be designed to improve bonding to the FRC crown. In addition, the reline can also increase crown retentive fit to the tooth. The FRC is a free-radical cure thermoset that maintains acceptable levels of exposed reactive surface groups and the FRC reline material is similarly a well-studied free-radical ambient-cure thermoset adhesive. So, the FRC crown can have margins activated precisely by acid etching to expose additional free-radical sites to improve bonding. Also, the FRC reline bonding material can have efficacious broad-spectrum triclosan antimicrobial mixed in to better protect the susceptible margins from secondary decay [16-18]. Even the entire FRC crown is being planned to have triclosan incorporated during VARTM into the bulk material. In terms of FDA approval, adhesive/bonding formulations are already sold with triclosan [114-117].

Wear

Accelerated wear of opposing dentition is a major problem with some ceramics [69-73]. For brakes FRCs are well-known to wear less than metal into glossy smooth surfaces from reconsolidated wear-film debris that includes crystalline nanoparticulate [118-127].

Similarly, Dental FRC fillings have been tested to wear less than enamel into some of the smoothest glossy surfaces known to exist and even polish outside the margins of the dental restoration fillings [2-4] to project the elimination of possible occlusal crown wear on opposing dentition.

Bonding

Secondary bonding of ceramics is difficult with increasing problems from more inert alumina and zirconia oxide ceramics [74-78]. Sandblasting of internal zirconia crown surfaces is needed to achieve adhesive mechanical retention, but defects reduce strength [128]. On the other hand, thermoset FRCs form high-strength covalent adhesive bonds [129-131]. In addition to improving crown retention, another consideration for adhesively bonding FRC crowns to tooth structure includes improvements over low ceramic fracture resistance by increasing the underlying support that reduces the tensile strength in the ceramic [26].

Stress transfer for biological healing responses

The FRC modulus of 24.6 GPa, table 1, is closer to the modulus of natural bone at about 14 GPa [100] and considerably less stiff than most ceramics, alumina or zirconia in a range from around 26.2 GPa to 79.6 GPa from table 1 [1] and also metals [100,103]. Lower stiffness is thought to benefit clinical crown responses with lower modulus for bone implant healing reactions due to better physiologic stress-transfer loading [103]. Also, lower bone-like modulus is thought to benefit bone implant-retained prosthetic frameworks due to better stress-transfer energy adsorption [100] to improve implant survival rate, greatly influence less bone loss, less peri-implantitis and increase patient quality of life [101] with light-weight comfort commonly expressed by patients [102].

Regarding CAD/CAM material mechanical properties, by Wolff's Law biomaterial modulus (approximately stiffness) is important to stimulate bone growth and prevent resorption [132]. Remodeling of bone takes place in response to mechanical stimulation so that the new hard bone tissue is better adapted to the load [132]. Thus, osteogenic and osteoclastic bone responses are related to normal activities on the bone *in vivo* [132]. So, if more physiologic clinically relevant load is applied more osteogenic activity occurs and if less load is applied more osteoclastic activity occurs [132]. Consequently, a stiff metal can carry so much of the load and transfer extra stress in a nonuniform way to certain areas of the bone so that other areas of the bone are shielded or under-stressed and reabsorb according to Wolff's Law [132]. With much higher modulus materials highly nonuniform stress transfer is of serious concern in terms of bone resorption through stress shielding [132] in addition to commonly expressed questions of patient comfort [102].

FRCs compared to metals and ceramics

Metal comparisons

VARTM FRCs developed with CAD/CAM technology for crowns and bridges are a completely new innovation in Dental Materials [1]. Increasing unstable gold prices since 1971 combining going off the gold standard initiated extensive research into substitute materials to reduce noble metal content particularly for gold crowns and porcelain-fused-to-gold white esthetic materials. Base metal alloys with nickel practically eliminated noble metals completely, but are considered to be more technique sensitive and hard to cast for laboratory technicians that have difficulty in obtaining acceptable fittings due to high solidification shrinkage.

Ceramic comparisons

Ceramics are superior to many other materials based on basic properties to contain heat for energy purposes, esthetics that resist staining or bleaching, inertness for high chemical resistance to maintain surface smoothness and resistance to biologic interaction that includes bacterial colonization. However, because ceramic fracture toughness is low, cyclic fatigue produces crack propagation to a critical size that continues on to catastrophic fracture into multiple pieces at lower-than-normal mechanical properties for maximum strength [24-46]. Also, CAD/CAM does not produce margins with earlier acceptable gold limits for defects of less than 39 um [53,56,58,60], whereas FRCs can be relined for a perfectly acceptable marginal fit [1].

FRC comparisons

FRCs are extremely design oriented with fibers that have some of the strongest, stiffest, most ductile and crystalline chemically resistant properties known. FRCs are highly fracture resistant with high energy adsorption during large deflections. Conversely, ceramics and other advanced oxide ceramics most commonly fail by brittle fracture failure. VARTM FRC polymers cure from a low-viscosity resin state so that multiple additives can be incorporated to optimize mechanical and unique specialty physical properties. Triclosan antimicrobial is a particularly useful additive that can be blended through a VARTM FRC process.

High-tech ceramics are assessed according to the ease by which the material can be shaped with cutting or abrasive tools consistent with grindability and susceptibility to edge chipping surface damage relative to fracture toughness, edge toughness and brittleness [133]. Machining of FRCs is much easier in contrast to ceramics and particularly advanced oxide ceramics when costs related to milling grinding might be 80% or more of the overall expenses [134]. Regardless, work to reduce ceramic costs by higher milling rates has generated more surface flaws that reduce material strengths [134]. Further, machinability of ceramics is associated with chips and grinding striations not seen with FRCs that mill much smoother seen on SEM (Figure 1A and 1B). Costs analyses show defect-free FRC machining [1] with shortened milling times, easier adjustments and lower polishing times allow one-visit patient appointments to insert a crown and lower bur costs. Outlays for less aggressive FRC milling equipment greatly reduce buying expenses. Zirconia requires much longer production times for both machining and sintering with minimum two-visit patient appointments to place a crown while costs for milling equipment, furnace and machining tools are much greater. Further, probable milling defects are expected in all ceramics as possible crack propagation initiators for potential fracture failure [128]. Fixed-removable frameworks for implant retained dentures can provide important retention for commonly loosely fitting lower dentures. Originally, zirconia CAD/CAM milling blocks were fully sintered and difficult-to-machine, time consuming and costly for burs [128]. But now zirconia is pre-sintered, milled and sintered with high percent shrinkage [128]. Fortunately, because clinical handpiece grinding adjustments with FRCs are many times easier than with dental ceramics, alumina, zirconia or metals, any crown, bridge, coping or framework adjustment needed requires much less time or bur cost for FRCs.

The current acceptable FRC CAD/CAM crown margins can now be adhesively relined with an FRC bonding material and then polished back to the most perfect fit ever conceived without inaccuracies from impression, stone model, wax crown, investment or melted gold dimensional changes with a metal cast crown. On the contrary, margins for all current crowns have some gaps that need to be sealed with luting cements. Subsequent larger marginal gaps between the tooth and crown prevent proper sealing to permit oral fluid micro-leakage into the cements that in turn start to dissolve so that bacterial infiltration can eventually occur. As reline FRC material packs parallel along a bond plane; excess resin is squeezed out of the fiber network leaving high concentrations of crystalline chemically-resistant fibers packed onto the margins that are easily polished back after curing to a smooth insoluble marginal finish line [4]. In effect, by relining the crown margins, the marginal gaps will reduce in magnitude potentially down under the micrometer level to seal margins perfect with gaps in possibly nanometer dimensions well below sizes for bacteria prone to creating secondary decay, gingivitis or periodontal disease [48,49,51,52,54,56,57]. When low viscosity luting cements are developed, high-tech insoluble chemically-resistant alumina nano fibers as some of the strongest and stiffest materials can be used without increasing film thickness between the tooth and the crown to reduce microcracking, moisture penetration and increase bond strength.

By FRC design-engineering principles, the crown and bridge luting cement can be vented at the FRC crown surface to reduce possibilities of increasing cement film thickness between the tooth and inside of the crown. Subsequent FRC filling materials are well designed with extremely high mechanical properties with wear characteristics for some of the smoothest materials known to mankind for the purpose of then filling in the miniature crown vents on the occlusal surface. FRCs have demonstrated excellent well-known wear less than metal and into glossy smooth surfaces for brakes [2]. Subsequent dental FRC fillings have then been tested to wear less than enamel into the smoothest mankind surfaces known to exist and even polish the enamel surrounding the filling [2,3]. FRC fillings with fibers above 1.0 mm wear down by fiber smoothing to generate the smallest highest-crystalline nano-particles possibly known for polishing while the

plasticized surface polymer consolidates all nanoparticulate into the smoothest glossiest and most wear-resistant surface [2,3] to entirely eliminate the problem of crown wear on opposing dentition.

FRCs are model materials to incorporate triclosan antimicrobial [82-84]. The broad-spectrum efficacious antimicrobial triclosan acts both as a hydrophobic wetting agent to reduce resin viscosity during the mixing or infusion stages for fiber-resin impregnation and as a toughening agent by bond entanglements to toughen the cured polymer matrix with greater flexural and adhesive bond strength [82-84]. The odd alarmist triclosan controversy over bacterial resistance has been unjustifiable without any bacterial resistance reported in over 40 years resulting in recommendations for triclosan use wherever a health benefit is possible [83, 84]. Triclosan can be incorporated easily into a reline material intended to eliminate marginal gaps and improve the internal fit or into a luting cement using proprietary bonding steps. Still, VARTM FRC bulk infusion of triclosan for CAD/CAM parts entails some difficulty in processing technology that will require more development.

Of important note, ceramics, alumina and zirconia are not known anywhere for use as structural materials except in extremely specific applications that normally require thermal protection. However, FRCs are developed to be used everywhere imaginable except where higher thermal environments may be a concern or also where extremely immense impact is a consideration. FRCs are one of the most important and versatile structural material developments in the world today key to many diverse applications due to high design oriented properties. Uses of FRCs include fabrication for various types of aerotech structures, aircraft, marine manufacturing, commercial/military cars and trucks, ballistic material, pipelines, water resistant surface protection and repairs. On the other hand, ceramics, alumina or zirconia are not sufficiently structural for such important use because of fatigue crack growth with sudden brittle catastrophic failure.

Conclusions

FRCs are well known for exceptional strengths and particularly fracture toughness where superior high-strength fibers dominate most properties. FRCs can be processed by VARTM for CAD/CAM milling to produce clinical patient crowns in one appointment. Further, FRCs have excellent adhesive bonding characteristics that allow margin relines directly on the patient's prepared tooth for defect-free margins and possibly one of the best crowns ever conceived in Dentistry. On the other hand, ceramics, alumina or zirconias are prone to brittle fracture failure. Also, ceramics and ceramic oxides do not bond well so that problems extend into adhesive retention with the final luting cement. FRCs wear smooth into glossy surfaces to eliminate problems of ceramic excessive wear on opposing teeth. FRCs are considered the original engineering design material so that multiple additives can be incorporated into the crowns or marginal reline, for example like the efficacious triclosan antimicrobial. The history of FRCs in multiple diverse applications suggest that the new CAD/CAM material will excel even over past gold crowns as a new measure for standards of excellence.

Acknowledgement

Conflicts of Interest

Authors declare no conflicts of interest.

Bibliography

1. Richard C Petersen and Perng-Ru Liu. "3D-Woven Fiber-Reinforced Composite for CAD/CAM Dental Application". *Society for Advanced Materials and Process Engineering, Sampe Journal 2016, Symposium: Long Beach, CA* (2016).

2. Richard C Petersen., *et al*. "Fiber-Reinforced Composites: A Breakthrough in Practical Clinical Applications with Advanced Wear Resistance for Dental Materials". *EC Dental Science* 17.5 (2018): 430-458.

3. Richard C Petersen. "EC Dental Science Editor's Column-2017. Important Dental Fiber-Reinforced Composite Molding Compound Breakthroughs". *EC Dental Science* ECO.01 (2017): 52-58.

4. Richard C Petersen. "Advancing Discontinuous Fiber-Reinforced Composites above Critical ength for Replacing Current Dental Composites and Amalgam". *Journal of Nature and Science* (JNSCI), 3.2 (2017): e321.

5. Richard C Petersen and Perng-Ru Liu. "Mechanical Properties Comparing Composite Fiber Length to Amalgam". *Journal of Composites* (2016): 3823952.

6. Petersen RC. "Discontinuous Fiber-reinforced Composites above Critical Length". *Journal of Dental Research* 84.4 (2005): 365-370.

7. Petersen, R.C. "United States Patent approved Chopped Fiber Reinforced Dental Material (High Purity Quartz) Assigned United States application number 09259317 (2001).

8. Petersen RC and Wenski EG. "Mechanical Testing of a Photocured Chopped Fiber-Reinforced Composite". Society for Advanced Materials and Process Engineering, SAMPE 2002 Affordable Materials Technology-Platform to Global Value and Performance (2002): 380-394.

9. Petersen RC., *et al*. "Stress-transfer Micromechanics for Fiber Length in a Photocure Vinyl Ester Composite". *Polymer Composites* 27.2 (2006): 153-169.

10. Petersen Richard C. "Accurate Critical Stress Intensity Factor Griffith Crack Theory Measurements by Numerical Techniques". *Sampe* (2013): 737-752.

11. Petersen RC., *et al*. "Fracture Toughness Micromechanics by Energy Methods with a Photocure Fiber-Reinforced Composite". *Polymer Composites* 28.3 (2007): 311-324.

12. Petersen RC., *et al*. "Micromechanics for Fiber Volume Percent with a Photocure Vinyl Ester Composite". *Polymer Composites* 28.3 (2007): 294-310.

13. Richard C Petersen. "Carbon Fiber Biocompatibility for Implants". *Fibers* 4.1 (2016): 1.

14. Richard C Petersen. "Titanium Implant Osseointegration Problems with Alternate Solutions Using Epoxy/Carbon-Fiber-Reinforced Composite". *Metals* 4.4 (2014): 549-569.

15. Richard C. Petersen "Bisphenyl-Polymer/Carbon-Fiber-Reinforced Composite Compared to Titanium Alloy Bone Implant". *International Journal of Polymer Science*. Polymeric Biomaterials for Tissue Engineering Applications annual focus/special issue Invited Paper located (2011).

16. Petersen RC. "Computational Conformational Antimicrobial Analysis Developing Mechanomolecular Theory for Polymers Biomaterials in Materials Science and Engineering". *International Journal of Computational Materials Science and Engineering* 3.1 (2014): 48.

17. Richard C. Petersen "Triclosan Computational Conformational Chemistry Analysis for Antimicrobial Properties in Polymers". *Journal of Nature and Science* 1.3 (2015): e54.

18. Richard C Petersen. "Triclosan Antimicrobial Polymers". *AIMS Molecular Science* 3.1 (2016): 88-103.

19. Petersen RC. "In: Micromechanics/Electron Interactions for Advanced Biomedical Research". Saarbrücken, Germany: LAP LAMBERT Academic Publishing Gmbh & Co. KG. Chapters 1-8, 12, 23-26 (2011): 1-126, 168-178, 395-451.

20. Petersen RC. Chapter 11 "Wear of fiber-reinforced composite". In: Micromechanics/Electron Interactions for Advanced Biomedical Research. Saarbrücken, Germany: LAP LAMBERT Academic Publishing Gmbh & Co. KG. ISBN 163-167 (2011).

21. Petersen RC. In: Micromechanics/Electron Interactions for Advanced Biomedical Research. Saarbrücken, Germany: LAP LAMBERT Academic Publishing Gmbh & Co. KG. Chapters 11, 13, 23 (2011): 163-165, 179-187, 395-415.

22. Petersen RC. "Appendix D Hydrophobic low-viscosity styrene-free vinyl ester resin systems". In: Micromechanics/Electron Interactions for Advanced Biomedical Research. Saarbrücken, Germany: LAP LAMBERT Academic Publishing Gmbh & Co. KG. (2011): 499-504.

23. Petersen RC and Lautenschlager EP. "Improved Posterior Composite Interproximal Contact Design". 27th Annual Meeting of the American Association for Dental Research, Minneapolis, Minnesota (1998).

24. Petersen RC. "Interproximal Contact Measurement with High Viscosity Experimental Condensable Dental Composites". 77th General Session of the International/American Association for Dental Research; Vancouver, British Columbia, Canada (1999).

25. Petersen RC and Dusevich VM. "Scanning electron microscopy chip toughness evaluation for fiber-reinforced composites" Micromechanics/Electron Interactions for Advanced Biomedical Research. Saarbrücken, Germany: LAP LAMBERT Academic Publishing Gmbh & Co. KG. In: Chapter 12 (2011).

26. Anusavice KJ., *et al*. "In: Phillips' Science of Dental Materials 11th edition". St. Louis: Elsevier Saunders. Chapter 21 Dental Ceramics (2003): 655-719.

27. Attia A and Kern M. "Fracture strength of all-ceramic crowns luted using two bonding methods". *Journal of Prosthetic Dentistry* 91.3 (2004): 247-252.

28. Peterson IM., *et al*. "Mechanical Characterization of Dental Ceramics by Hertzian Contacts". *Journal of Dental Research* 77.4 (1998): 589-602.

29. Lawn BR., *et al*. "Making Ceramics Ductile". *Science* 263.5150 (1994): 1114-1116.

30. Rekow ED., *et al*. "Performance of Dental Ceramics: Challenges for Improvements". *Journal of Dental Research* 90.8 (2011): 937-952.

31. Lin L., *et al*. "An overview of In Vitro Abrasive Finishing & CAD/CAM of Bioceramics in Restorative Dentistry". *International Journal of Machine Tools and Manufacture* 46.9 (2006): 1013-1026.

32. Rekow D and Thompson VP. "Near-Surface Damage-A Persistent Problem in Crowns Obtained by Computer-Aided Design and Manufacturing". *Proceedings of the Institution of Mechanical Engineers* 219.4 (2005): 233-243.

33. Sindel J., *et al*. "Evaluation of Subsurface Damage in CAD/CAM Machined Dental Ceramics". *Journal of Materials Science: Materials in Medicine* 9.5 (1998): 291-295.

34. Li K and Liao W. "Surface/Subsurface Damage and the Fracture Strength of Ground Ceramics". *Journal of Materials Processing Technology* 57.3-4 (1996): 207-220.

35. Jalalian E., *et al*. "The Effect of Preparation Design on the Fracture Resistance of Zirconia Crown Copings (Computer Associated Design/Computer Associated Machine, CAD/CAM System)". *Journal of Dentistry* 8.3 (2011): 123-129.

36. Zhang Y., *et al*. "Fatigue of Dental Ceramics". *Journal of Dentistry* 41.12 (2013): 1135-1147.

37. Andreiuolo RF., *et al*. "Dual-Scan Techique for the Customization of Zirconia Computer-Aided Design/Computer-Aided Manufacturing Frameworks". *European Journal of Dentistry* 7.5 (2013): 115-118.

38. Silva NRFA., *et al*. "Modified Y-TZP Core Design Improves All-Ceramic Crown Reliability". *Journal of Dental Research* 90.1 (2011): 104-108.

39. Kokubo Y., *et al*. "Clinical Evaluation of Procera AllCeram Crowns in Japanese Patients: Results After 5 Years". *Journal of Oral Rehabilitation* 36.11 (2009): 786-791.

40. Donovan Terence E. "Factors Essential for Successful All-Ceramic Restorations". *Journal of the American Dental Association* 139.4 (2008): 14S-18S.

41. Kim JH., *et al*. "Damage Maps for Layered Ceramics under Simulated Mastication". *Journal of Dental Research* 87.7 (2008): 671-675.

42. McClaren EA and White SN. "Survival of In-Ceram Crowns in a Private Practice: A Prospective Clinical Trial". *Journal of Prosthetic Dentistry* 83.2 (2000): 216-222.

43. Gokce S., *et al*. "A Comparative In Vitro Study of the Load at Fracture of All-Ceramic Crowns with Various Thicknesses of In-Ceram Core". *Journal of Contemporary Dental Practice* 9.4 (2008): 17-25.

44. Leevalioj C., *et al*. "In Vitro Study of Fracture-Incidence and Compressive Fracture Load of All Ceramic Crowns Cemented with Resin Modified Glass Ionomer and Other Luting Agents". *Journal of Prosthetic Dentistry* 80.6 (1998): 699-707.

45. Contrepois M., *et al*. "Marginal adaptation of ceramic crowns: A systematic review". *Journal of Prosthetic Dentistry* 110.6 (2013): 447-454.

46. Rohr N., *et al*. "Correlations between fracture load of zirconia implant supported single crowns and mechanical properties of restorative material and cement". *Dental Materials Journal* 37.2 (2018): 222-228.

47. Okutan M., *et al*. "Fracture load and marginal fit of shrinkage-free ZrSiO4 all-ceramic crowns after chewing simulation". *Journal of Oral Rehabilitation* 33.11 (2006): 827-832.

48. Riccitiello F., *et al*. "In vitro evaluation of the marginal fit and internal adaptation of Zirconia and Lithium Di-silicate single crowns: Micro-CT comparison between different manufacturing procedures". *The Open Dentistry Journal* 12 (2018): 160-172.

49. Bergenholtz G., *et al*. "Bacterial leakage around dental restorations: its effect on the dental pulp". *Journal of Oral Pathology* 11.6 (1982): 439-450.

50. Tinschert J., *et al*. "Marginal fit of alumina and zirconia-based fixed partial dentures produced by a CAD/CAM system". *Operative Dentistry* 26.4 (2001): 367-374.

51. Paloma F and Peden J. "Periodontal considerations of restorative procedures". *Journal of Prosthetic Dentistry* 36.4 (1976): 387-394.

52. Felton DA., *et al*. "Effect of in vivo crown margin discrepancies on periodontal health". *Journal of Prosthetic Dentistry* 65.3 (1991): 357-364.

53.   Christensen GJ. "Marginal fit of gold inlay castings". *Journal of Prosthetic Dentistry* 16.2 (1966): 297-305.

54.   Saltzberg DS., *et al*. "Scanning electron microscope study of the junction between restorations and gingival cavosurface margins". *Journal of Prosthetic Dentistry* 36.5 (1976): 517-522.

55.   Grasso JE., *et al*. "The quality of restorative dental care". *Journal of Prosthetic Dentistry* 42.5 (1979): 571-578.

56.   Hunter AJ and Hunter AR. "Gingival margins for crowns: A review and discussion. Part II: Discrepancies and configurations". *Journal of Prosthetic Dentistry* 64.6 (1990): 636-642.

57.   Gardner FM. "Margins of complete crowns-Literature review". *Journal of Prosthetic Dentistry* 48.4 (1982): 396-114.

58.   Dedmon HW. "The relationship between open margins and margin designs on full cast crowns made by commercial dental laboratories". *Journal of Prosthetic Dentistry* 53.4 (1985): 463-466.

59.   Wanserski DJ., *et al*. "An analysis of margin adaptation of all-porcelain facial margin ceramonmetal crowns". *Journal of Prosthetic Dentistry* 56.3 (1986): 289-292.

60.   Hung SH., *et al*. "Marginal fit of porcelain-fused-to-metal and two types of ceramic crown". *Journal of Prosthetic Dentistry* 63.1 (1990): 26-31.

61.   Jacobs MS and Windeler AS. "An investigation of dental luting cement solubility as a function of the marginal gap". *Journal of Prosthetic Dentistry* 65.3 (1991): 436-408.

62.   Tao J and Han D. "The effect of finish line curvature on marginal fit of all-ceramic crowns". *Quintessence International* 40.9 (2009): 745-752.

63.   Baig MR., *et al*. "Evaluation of the marginal fit of a zirconia ceramic computer-aided machined (CAD) crown system". *Journal of Prosthetic Dentistry* 104.4 (2010): 216-227.

64.   Beuer F., *et al*. "Marginal and internal fits of fixed dental prostheses zirconia retainers". *Dental Materials* 25.1 (2009): 94-102.

65.   Grenade C., *et al*. "Fit of single tooth zirconia copings: comparison between various manufacturing processes". *Journal of Prosthetic Dentistry* 105.4 (2011): 249-255.

66.   Vojdani M., *et al*. "Comparison the marginal and internal fit of metal copings cast from wax patterns fabricated by CAD/CAM and conventional wax up techniques". *Journal of dentistry, Shiraz University of Medical Sciences* 14.3 (2013): 118-129.

67.   Ashtiani RE., *et al*. "Microleakage of four dental cements in metal ceramic restorations with open margins". *Iranian Red Crescent Medical Journal* 17.11 (2015): e19611.

68.   Ha S.-J and Cho J.-H. "Comparison of the fit accuracy of zirconia-based prostheses generated by two CAD/CAM systems". *The Journal of Advanced Prosthodontics* 8.6 (2016): 439-448.

69.   Rashid H., *et al*. "Advancements in all-ceramics for dental restorations and their effect on the wear of opposing dentition". *European Journal of Dentistry* 10.4 (2016): 583-588.

70.   Rupawala A., *et al*. "A study on the wear of enamel caused by monolithic zirconia and the subsequent phase transformation compared to two other ceramic systems". *The Journal of Indian Prosthodontic Society* 17.1 (2017): 8-14.

71. Mulay G., *et al*. "An evaluation of wear of human enamel opposed by ceramics of different surface finishes". *The Journal of Indian Prosthodontic Society* 15.2 (2015): 111-118.

72. Hmaidouch R., *et al*. "Tooth wear against ceramic crowns in posterior region: a systematic literature review". *International Journal of Oral Science* 5.4 (2013): 183-190.

73. Derand P., *et al*. "Wear of low-fusing dental porcelains". *The Journal of Prosthetic Dentistry* 81.4 (1999): 460-463.

74. Luthra R and Kaur P. "An insight into current concepts and techniques in resin bonding to high strength ceramics". *Australian Dental Journal* 61.2 (2016): 163-173.

75. Bona AD., *et al*. "Zirconia as a Dental Biomaterial". *Materials (Basel)* 8.8 (2015): 4978-4991.

76. Li RWL., *et al*. "Ceramic Dental Biomaterials and CAD/CAM Technology: State of the Art". *Journal of Prosthodontic Research* 58.4 (2014): 208-216.

77. Kasraei S., *et al*. "Bond Strength of Resin Cement to Co2 and Er:YAG Laser-Treated Zirconia Ceramic". *Restorative Dentistry and Endodontics* 39.4 (2014): 296-302.

78. Wang C., *et al*. "Bonding of Resin Cement to Ziroconia with High Pressure Primer Coatings". *PLOS ONE* 9.7 (2014): e101174.

79. Chuang S-F., *et al*. "Morphological analysis of proximal contacts in class II direct restorations with 3D image reconstruction". *Journal of Dentistry* 39.6 (2011): 448-456.

80. Liebenberg W H. "Assuring restorative integrity in extensive posterior resin composite restorations: Pushing the envelope". *Quintessence International* 31.3 (2000): 153-164.

81. Peumans M., *et al*. "Do condensable composites help to achieve better proximal contacts?". *Dental Materials* 17.6 (2001): 533-541.

82. Teich S T., *et al*. "Dental floss selection and its impact on evaluation of interproximal contacts in licensure exams". *Journal of Dental Education* 78.6 (2014): 921-926.

83. Ren S., *et al*. "Clinical evaluation of all ceramic crowns fabricated from intraoral digital impressions based on the principle of active wave-front sampling". *The Journal of Prosthetic Dentistry* 115.4 (2016): 437-440.

84. Gohil K S., *et al*. "Proximal contacts in posterior teeth and factors influencing interproximal caries". *The Journal of Prosthetic Dentistry* 30.3 (1973): 295-302.

85. Keogh T P and Bertolotti R L. "Creating tight, anatomically correct interproximal contacts". *Dental Clinics of North America* 45.1 (2001): 83-102.

86. Dörfer C E., *et al*. "Factors influencing proximal dental contact strengths". *European Journal of Oral Sciences* 108.5 (2000): 368-377.

87. Jernberg G R., *et al*. "Relationship between proximal tooth open contacts and periodontal disease". *Journal of Periodontology* 54.9 (1983): 529-533.

88. Hancock EB., *et al*. "Influence of interdental contacts on periodontal status". *Journal of Periodontology* 51.8 (1980): 445-449.

89. Jurić H. "Current possibilities in occlusal caries management". *Acta Medica Academica* 42.2 (2013): 216-222.

90. Brazzelli M., *et al*. "Systematic review of the effectiveness and cost-effectiveness of HealOzone® for the treatment of occlusal pit/fissure caries and root caries". *Health Technology Assessment* 10.16 (2006): Chapter 2.

91. Eskandarian T., *et al*. "Comparison of clinical success of applying a kind of fissure sealant on the lower permanent molar teeth in dry and wet conditions". *Journal of dentistry, Shiraz University of Medical Sciences* 16.3 (2015): 162-168.

92. Sreedevi A., *et al*. "Sealants, pit and fissure". StatPearls StatPearls Publishing, Treasure Island, FL (2017): 9.

93. Ikeda M., *et al*. "Effect of surface characteristics on adherence of S mutans biofilms to indirect resin composites". *Dental Materials Journal* 26.6 (2007): 915-923.

94. Simonsen RJ., *et al*. "A review of the clinical application and performance of pit and fissure sealants". *Australian Dental Journal* 56.1(2011): 45-58.

95. Wang J-D., *et al*. "Dental caries and first permanent molar pit and fissure morphology in 7- to 8-year-old children in Wuhan, China". *International Journal of Oral Science* 4.3 (2012): 157-160.

96. Van Dijik J., *et al*. "Surface free energy and bacterial adhesion". *Journal of Clinical Periodontology* 14.5 (1987): 300-304.

97. Quirynen M., *et al*. "The influence of surface free-energy on planimetric plaque growth in man". *Journal of Dental Research* 68.5 (1989): 796-799.

98. Christersson CE., *et al*. "Effect of critical surface tension on retention of oral microorganisms". *Scandanavian Journal of Dental Research* 97.3 (1989): 247-256.

99. Rǿlla G., *et al*. "Enhancement and inhibition of dental plaque formation-some old and new concepts". *Biofouling* 3.3 (1991): 175-181.

100. Jarman-Smith M. "Advantages of PEEK dental prosthetic frameworks over metal". Invibio Biomaterial Solutions INSIDER Annually (2017): 22-23.

101. Jarman-Smith M and Siewert B. "A retrospective, single centre clinical evaluation using PEEK frameworks for full arch implant supported prosthetics". Invibio Biomaterial Solutions INSIDER Annually (2017): 24-25.

102. Jarman-Smith M. "Changing the face of prosthetic dentistry". Invibio Biomaterial Solutions INSIDER Annually (2017): 26-27.

103. Valentine C. "FDA reclassification paves regulatory pathway for Invibio PEEK-Optima spinal rods". *Invibio Biomaterial Solutions* INSIDER Annually (2017): 14-15.

104. Callister WD. "Materials Science and Engineering 4th edition". John Wiley and Sons, New York appendix c Table C.4 (1997): 785.

105. Hak DJ. "Is locking screw fixation in carbon fiber composite plates mechanically equivalent to stainless steel plates?". *Invibio Biomaterial Solutions INSIDER* Annually (2017): 18-19.

106. O'Farrel S and Brady M. "Using evidence-based medicine to evaluate interbody spinal fusion device materials". *Invibio Biomaterial Solutions INSIDER* annually (2017): 8-13.

107. Uhrenbacher J., *et al*. "The effect of surface modification on the retention strength of polyetheretherketone crown adhesively bonded to dentin abutments". *Journal of Prosthetic Dentistry* 112.6 (2014): 1489-1497.

108. Quinn GD., *et al.* "Chipping fracture resistance of dental CAD/CAM restorative materials: Part I, procedures and results". *Dental Materials* 30.5 (2014): e99-e111.

109. Chai H and Lawn BR. "A universal relation for edge chipping from sharp contacts in brittle materials: A simple means of toughness evaluation". *Acta Materialia* 55.7 (2007): 2555-2561.

110. Tsitrou EA., *et al.* "Brittleness index of machinable dental materials and its relation to the marginal chipping factor". *Journal of Dentistry* 35.12 (2007): 897-902.

111. Petit F., *et al.* "Ceramic toughness assessment through edge chipping measurements-influence of interfacial friction". *Journal of the European Ceramic Society* 29.11 (2009): 2135-2141.

112. Zhang Y., *et al.* "Edge chipping and flexural resistance of monolithic ceramics". *Dental Materials* 29.12 (2013): 1201-1208.

113. Peck CC. "Biomechanics of occlusion-implications for oral rehabilitation". *Journal Oral Rehabilitation* 43.3 (2016): 205-214.

114. Slutzky H., *et al.* "Antibacterial properties of temporary filling materials". *Journal of Endodontics* 32.3 (2006): 214-217.

115. Malkoc S., *et al.* "The effect on shear bond strength of different antimicrobial agents after acid etching". *European Journal of Orthodontics* 27.5 (2005): 484-488.

116. Kerr Dental "TempBond, TempBond NE, and TempBond Clear with Triclosan temporary dental cement".

117. IvoclarVivadent. "System.inlay/Systemp.onlay" (2012).

118. Murdie N., *et al.* "Microstructure of worn pitch/resin/CVI C-C composites". *Carbon* 29.3 (1991): 335-342.

119. Yen BK., *et al.* "The surface morphology and structure of carbon-carbon composites in high-energy sliding contact". *Wear* 174.1-2 (1994): 111-117.

120. Cheng D., *et al.* "Friction and wear behavior of carbon fiber reinforced brake materials". *Frontiers of Materials Science* 3.1 (2009): 56-60.

121. Kim SH., *et al* "Friction and vibration of brake friction materials reinforced with chopped glass fibers". *Tribology Letters* 52.2 (2013): 341-349.

122. Gbadeyan OJ., *et al.* "Tribological behaviors of polymer-based hybrid nanocomposites brake pad". *Journal of Tribology* 140.3 032003 (2018): 7.

123. Cho MH., *et al.* "Effects of ingredients on tribological characteristics of a brake lining: an experimental case study". *Wear* 258.11-12 (2005): 1682-1687.

124. Lim D-S., *et al.* "Effect of carbon nanotube addition on the tribological behavior of carbon/carbon composites". *Wear* 252.5-6 (2002): 512-517.

125. Rhee SK., *et al.* "The role of friction film in friction, wear and noise of automotive brakes". *Wear* 146.1 (1991): 89-97.

126. Sherif JA., *et al.* "Relationship between normal and tangential contact stiffness of nominally flat surfaces". *Wear* 151.1 (1991): 49-62.

127. Lee SM., *et al.* "The correlation between contact stiffness and stick-slip of brake friction materials". *Wear* 302.1-2 (2013): 1414-1420.

128. Yin L., *et al*. "A review of engineered zirconia surfaces in biomedical applications". Procedia CIRP 65 (2017): 284-290.

129. Chawla KK. "In: Composite Materials 2nd edition". Springer, New York Chapter 4. Interfaces (1998): 101-129.

130. Callister WD. "Thermoplastic and Thermosetting Polymers In: Materials Science and Engineering 4th edition". John Wiley and Sons, Inc, New York 16.5 (1997): 477.

131. Rodriquez F. "Chapter 12 Fabrication Processes. 12.4 One-Dimensional Processes In: Polymer Systems 4th edition". Taylor and Francis, Ithaca, NY (1996): 430-451.

132. Joon Park and Roderic Lakes. "Biomaterials 2nd Edition Plenum Press New York (1992): 205, 293 300-302.

133. Quinn JB., *et al*. "Ceramic "machinability"-What does it mean?". *Ceramic Engineering and Science Proceedings* 24.4 (2003): 511-516.

134. Huang TW and Malkin S. "Upper Bound Analysis for Specific Energy in Grinding of Ceramics". Wear 231.2 (1999): 161-171.

Volume 18 Issue 7 July 2019