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Fatigue and Fracture Resistance of Zirconia Crowns Prepared with Different Finish Line Designs

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Zirconia; design; fatigue; fracture resistance; strength; SEM; margin; finish line.

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Abstract

Purpose: The aim of this study was to evaluate the effect of finish line design on the fatigue, fracture resistance, and failure type of veneered zirconia restorations.
Materials and Methods: A CAD/CAM system (Cercon) was used to prepare zirconia frameworks (0.5 mm thick) for a maxillary central incisor. Three finish line designs were evaluated: a complete narrow chamfer, a narrow chamfer with a lingual ledge, and a complete ledge. The prepared frameworks were veneered using a press-on ceramic (Ceram Press) and were cemented on the corresponding prepared teeth using a resin cement (Panavia F2.0). The cemented specimens were thermocycled, subjected to dynamic fatigue, and finally loaded till fracture. Fractured specimens were examined under a scanning electron microscope to assess fracture type. One-way ANOVA and Bonferroni post hoc tests were used to analyze the data ($\alpha = 0.05$).
Results: The finish line design did not have any significant statistical influence on the fracture resistance ($F = 1.9$, $p = 0.346$) or on the failure type of the tested specimens. Adjusted R squared value ($R = 0.049$) indicated a weak correlation between finish line design and fracture load of the tested specimens. All specimens failed due to cracking and fracture of the veneer ceramic. Meanwhile, the framework remained entirely intact. Three narrow chamfer finish line specimens demonstrated adhesive fracture of the veneer ceramic during dynamic fatigue testing, related to overextension of the veneer ceramic during the layering procedure.
Conclusion: Within the limitations of this study, the finish line design did not influence the fatigue or the fracture resistance of veneered zirconia crowns. Selection of any of the finish line designs should be based on the clinical condition of the restored tooth.

The introduction of zirconia to the dental field changed the design and application limits of all-ceramic restorations. Currently, long-span zirconia restorations are possible with high success rates and high accuracy.[1] To obtain acceptable esthetics, the opaque framework is veneered with a layer of glass ceramic, giving the restorations the required color and shade.[2]

As zirconia is relatively new to the dental field, its fabrication guidelines were copied from the well-established metal ceramic systems.[3] Tooth preparation guidelines, framework design, and the layering technique are almost identical to metal ceramic restorations.[3,4] Even a masking opaquer (liner material) was used to camouflage the white color of zirconia frameworks imitating the opaquer used to mask the dark color of metallic frameworks.[4]

For metallic frameworks, a lingual ledge design is usually used to reinforce the thin metallic framework and to reduce chances of thermal deformation during firing the ceramic veneer.[5] Currently, most CAD/CAM systems produce zirconia frameworks with a circumferential ledge finish line for the same purpose, ignoring the fact that zirconia is stiffer, harder, and more stable at high temperatures than metallic casting alloys. Thus, a ledge finish line is not expected to offer any benefit for zirconia frameworks. On the contrary, a ledge finish line will require more reduction of the prepared tooth, produce objectionable esthetics in cases of supra-gingival margins, and may interfere with the emergence profile of the restoration.[6] The aim of this study was to evaluate the effect of finish line design on the fatigue, fracture resistance, and failure type of CAD/CAM veneered zirconia restorations.

Materials and methods

A maxillary central incisor received a full-crown preparation accounting for 2 mm incisal clearance and 1.8 mm axial reduction. Identical resin replicas of the prepared tooth (Tetric

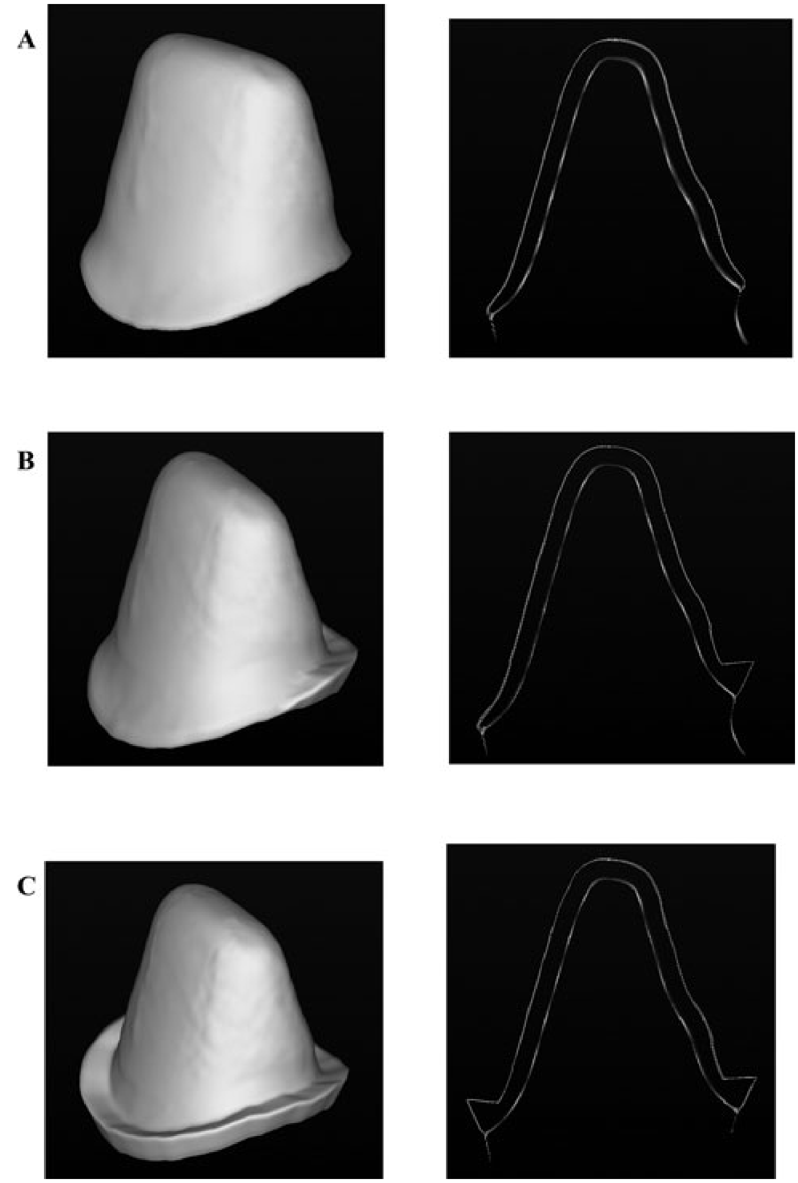

Figure 1 (A) 3D image of a zirconia framework design with a circumferential narrow chamfer finish line. (B) 3D image of a zirconia framework design with a narrow chamfer finish line and a lingual ledge. (C) 3D image of a zirconia framework design with a circumferential ledge.

Ceram [A3]; Ivoclar Vivadent, Schaan, Liechtenstein) were produced using a silicon impression mold (Impregum Penta Soft; 3M ESPE, Seefeld, Germany). The prepared replicas were laser scanned (Cercon Brain; Degudent GmbH, Hanau, Germany), and zirconia frameworks (0.5-mm thick) were designed using one of the following finish line designs:

1. Complete circumferential narrow chamfer (Fig 1A).
2. Circumferential narrow chamfer with a lingual ledge (Fig 1B).
3. Complete circumferential ledge used for many CAD/CAM systems (Fig 1C).

Fifteen frameworks were produced for every design by milling white CAD/CAM zirconia blocks (Cercon). After sintering (Cercon Heat uses a 6-hour sintering program at a maximum temperature of 1350°C), each framework was anatomically veneered with a layer of press-on glass ceramic (Cercon Press [A2]) using manufacturer recommendations. The press-on technique allowed identical contouring of the veneer ceramic for every specimen using standard wax patterns.

The veneered zirconia restorations were cemented on the corresponding resin dies using adhesive resin (Panavia F2.0, Kuraray, Osaka, Japan) following manufacturer's instructions. An adjustable loading gig was used to ensure every restoration received the same load (400 g) during cementation. The loading gig allowed for an even 40 μm cement space to ensure even cement film thickness under each restoration. Excess cement was immediately wiped off using a micro-brush, and the specimens were light polymerized for 30 seconds from four directions using a high intensity light-emitting diode polymerizing unit (Elipar FreeLight 2, 3M ESPE). Light intensity (800 mW/cm^2)

was examined before every use (Demetron 100; Demetron Research Corp, Danbury, CT).

The root portion of cemented restorations was secured to the attachment unit, which accounted for a 0.5 mm thick silicon layer (Imprint II High Viscosity; 3M ESPE) representing the periodontal ligament in natural teeth. The specimens were subjected to the following accelerated artificial aging program: water storage at 37°C for 4 weeks, thermocycling (5–55°C for 5000 cycles), and dynamic cyclic loading (5–10 kg for 50,000 cycles) in an attempt to simulate the fatigue process under clinical conditions. Cyclic loading was performed in a customized pneumatic machine, which delivered a maximum load of 10 kg and maintained a minimal load of 5 kg to prevent contact surface damage of the ceramic veneer. A 1-mm thick silicon sheet (AKA Silicone Pad; CS Hyde, IL) was placed between the loading point and the brittle veneer ceramic to prevent generation of cone cracks.[7] Cyclic loading was performed in a water bath at 37°C to assist slow crack propagation.[8]

After artificial aging, all specimens were subjected to one-cycle load-to-failure compressive axial loading using a universal testing machine (Instron 6022; Instron Limited, High Wycombe, UK) at a 0.25 mm/min crosshead speed. The load cell (2 KN) was calibrated using a digital scale (Acculab Vicon VIC 711; Itin Scale Co., Brooklyn, NY), while the crosshead speed was monitored using a digital traveling microscope (Millitron; Feinpruf Perthen GmbH, Gottingen, Germany). To prevent cone cracking of the brittle veneer ceramic, a 1-mm thick silicon sheet was placed between the metallic indenter (3-mm) and the loaded restorations. The load displacement curve was monitored on a computer screen, and the test was stopped at the occurrence of the first sign of failure, characterized by a sudden drop in the applied load.

All tested specimens were cleaned in an ultrasonic bath for 20 minutes, dried in an electrical oven at 50°C for 2 hours, gold sputter coated (S150B sputter coater; Edwards, Crawly, UK), and examined under a scanning electron microscope (XL20; Philips, Eindhoven, The Netherlands). Failure type was classified as cohesive fracture of the veneer ceramic, adhesive failure of the veneer ceramic leading to exposure of the underlying zirconia framework, or catastrophic fracture of the framework.

One-way ANOVA and Bonferroni post hoc tests were used to analyze the data (SPSS 14.0; SPSS Inc, Chicago, IL). According to the chosen level of significance ($\alpha = 0.05$), sample size (n = 15), and medium effect size (F = 0.25), the statistical test of choice had adequate power ($1 - \beta = 1$) to detect significant differences among the three tested designs, which could be used to suggest clinical recommendations.

Results

Statistical analysis revealed that the finish line design did not have a significant influence ($F = 1.9$, $p = 0.346$) on the fracture resistance of veneered zirconia restorations. Adjusted R squared value ($R = 0.049$) also indicated a weak correlation between finish line design and fracture load of the tested specimens. All specimens failed due to either adhesive or cohesive fracture of the veneer ceramic. Meanwhile, the underlying framework remained entirely intact. Scanning electron microscopy (SEM) examination revealed that all specimens failed due propagation of slow crack growth from the loading point, which propagated in an apical direction, leading to cohesive fracture of the veneer ceramic, as there was always a layer of the veneer ceramic on top of the zirconia framework. The slow crack growth produced characteristic landmarks on the fracture site in the form curved crack steps (Fig 2). Obtained data are summarized in Table 1.

During cyclic dynamic fatigue, three specimens with a narrow chamfer finish line (representing 20% of this test group) demonstrated adhesive failure of the veneer ceramic at the restoration margins (Fig 3A). SEM examination revealed exposure of the zirconia framework at the site of fracture and presence of defects in the form of overextension of the veneer ceramic in this region (Fig 3B). Characteristic stepping pattern

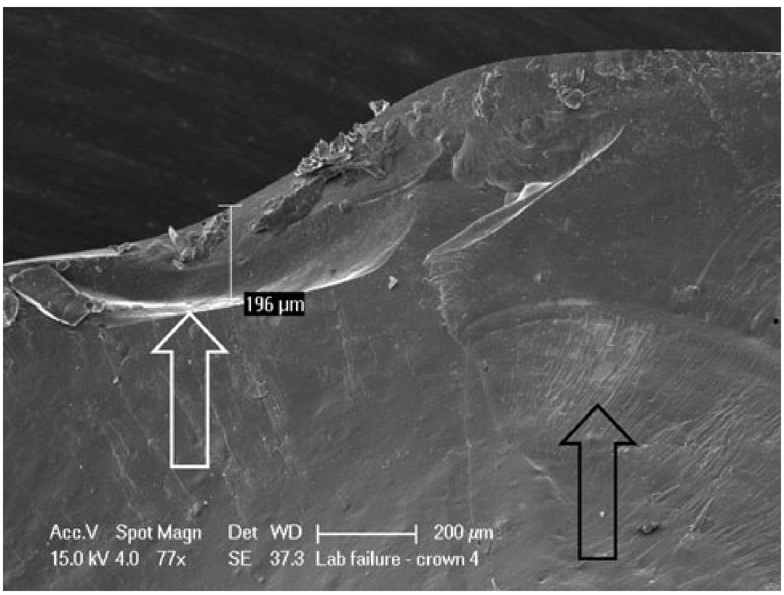

Figure 2 SEM image (77×) demonstrating fracture site located at the incisal edge of a loaded specimen (white arrow), which resulted in cohesive fracture of the veneer ceramic. Observe the characteristic stepping pattern of slow crack growth (black arrow) and absence of cone cracking at the loading site.

Table 1 Mean failure load (N) and standard deviation of finish line designs

Design	Mean	(SD)	Minimum	Maximum	Failure type
Circumferential chamfer	728.9	46.5	658	823	80% cohesive fracture 20% adhesive failure
Chamfer and lingual ledge	721.9	47.4	651	794	100% cohesive fracture
Circumferential ledge	745.1	37.9	678	798	100% cohesive fracture

There were no significant statistical differences ($F = 1.9$, $p = 0.346$) in the failure load among the three groups.

of the propagating slow crack growth was observed for these specimens.

Discussion

The one cycle load-to-failure test method is one of the most common techniques used to evaluate the mechanical properties of the loaded specimens.[9] Despite all efforts used to simulate the oral environment, there are concerns that this method does not result in clinically relevant data, as neither the failure load nor the failure pattern match clinical failure.[10] Under clinical conditions, the interaction between loading stresses, chemically assisted slow crack growth, and deterioration in material properties result in a slow failure process.[8,11] Nevertheless, a higher number of loading cycles is required to represent longer service time.

On the contrary, fracture strength tests rely on subjecting the specimens to high stresses (usually several fold compared to maximum chewing forces), leading to controlled failure at the site of stress concentration. These tests are conducted under controlled laboratory conditions and on well-standardized specimens, leading to better understanding of the variables under investigation. The direction and location of load application must be carefully considered in order to simulate functional loading during mastication. A silicon sheet is placed between the loading indenter and the restoration to prevent cone cracking and to simulate the cushion effect of food between opposing teeth.

In this study, the veneered zirconia restorations were cemented on resin replicas, which allowed adequate standardization of specimen dimensions, but on the other hand, resin replicas could have an altered stress distribution pattern compared to natural teeth. Moreover, the performance of the adhesive interface over resin replicas could not be directly compared to natural enamel and dentine.[1]

Many CAD/CAM systems produce zirconia framework designs with a circumferential ledge, which is thought to increase the strength of the restorations.[12] Under clinical conditions, the chewing forces are transferred from the veneer ceramic to the underlying framework and become redistributed in the entire structure. The framework finally transfers the functional loads to the supporting tooth structure. For single-crown restorations, the occlusal area under functional loading is subjected to high stress concentration. Meanwhile, the remaining structure is not subjected to any risky peak stresses.[13] For fixed partial dentures, the tensile surface of the connectors represents a second site for stress concentration, indicating that the margins of zirconia frameworks are not subjected to high stresses.[14]

Studies concerned with finite element analysis of all-ceramic restorations revealed that different finish line designs resulted in minor changes in the peak stresses at the margin of the

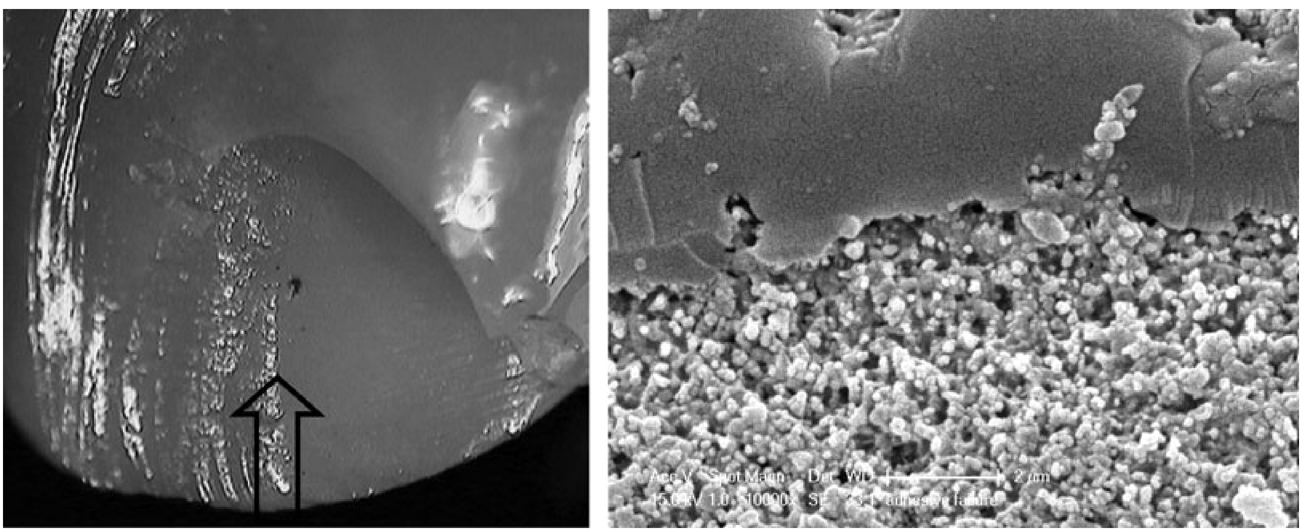

Figure 3 (A) Digital stereo photograph (120×) indicating adhesive failure (arrow) at narrow chamfer finish line specimen after cyclic loading. Observe the stepping pattern of slow crack growth on the left side of the image. (B) SEM image (10,000×) of previous specimen demonstrating exposure of zirconia surface (lower part of the image) after adhesive fracture of the veneer ceramic.

restoration. Nevertheless, these stresses were far below the internal strength of glass ceramic materials,[15,16] and a much stronger zirconia framework will not be influenced by such weak stresses.[17] In a study on glass ceramic crowns, Bernal et al reported that the strength of Dicor crowns was not influenced by the finish line design, which supports the findings of this study.[18] Reich et al reported that knife edge zirconia crowns demonstrated a 38% higher fracture strength compared to a chamfer finish line, which also support the findings of this study.[6] However, knife edge finish line design was not added to the tested groups, because it does not provide sufficient room to accommodate the minimal thickness of the framework material and the veneering ceramic, which could compromise both strength and esthetics. On the contrary, Beuer et al reported a significantly higher fracture load (2286 N) for zirconia crowns with a shoulder preparation compared to other conservative designs.[19] Aboushelib et al cemented 0.4 mm thick zirconia frameworks on metallic dies and loaded the cemented specimens to failure. This loading method is known to produce unrealistically high fracture loads due to the pattern of stress distribution between the loading point and the rigid metallic dies.[7] Functional loads are transferred from the opposing tooth to the food substance over a wider area of the occlusal table of veneer ceramic, which in turn distributes the load over the supporting framework. This mechanism of load transfer prevents generation of peak stresses and protects the restoration from fracture.[1]

Fractographic analysis of clinically fractured veneered zirconia restorations revealed that the axial walls of the framework could be subjected to internal circumferential stresses (Hoop stresses), which could lead to fracture of the framework.[20,21] These internal circumferential stresses could be related to improper seating of the framework or due to over-tapering of the prepared tooth.[22] Whether a thicker finish line design (chamfer or ledge) could reinforce the restoration in such cases needs further investigation.

The findings of this study clearly illustrate the contradiction between the finish line design that is most widely used, the reason for selecting that design, and the real needs of a good zirconia framework design. A circumferential ledge did not increase the fracture resistance for veneered zirconia crowns. On the contrary, such a finish line design has several drawbacks as previously described. A narrow chamfer finish line will allow conservation of sound tooth structure, produce more room for building the veneer ceramic, and allow better control of the emergence profile of the restoration, leading to the creation of not only better esthetics at the margins, but a healthy margin as well.[23] It should also be considered that the finish line design is not a factor that could influence the marginal adaptation of the restoration when the same processing technique is used.[24] In terms of marginal quality and expected clinical performance, a more conservative finish line is recommended compared to other finish line designs that require more tooth reduction. [25]

The accelerated artificial aging technique used in this study subjected the specimens to the influence of water-assisted crack propagation in combination with the influence of thermal and load cycling. Moreover, prevention of direct occlusal damage of the brittle veneer ceramic using a tough silicon sheet prevented generation of cone cracks, which represent the major failure mechanisms in vitro, during dynamic fatigue and axial loading. The cohesive failure pattern observed for all specimens reflects the good bond strength between the framework and the veneer ceramic, which is a direct attribute to the press-on technique.[26] The marginal adhesive failure (Fig 3A) observed for three specimens with a narrow chamfer finish line during artificial aging was related to the presence of defects at this region. Proper seating of the specimens and elimination of any interfering point contact could prevent such failure.

This study tested a veneered zirconia crown cemented on a maxillary central incisor; however, both loading stresses and loading direction differ considerably in the posterior region of the mouth. Furthermore, press-on veneer ceramic, which is produced under calibrated and controlled laboratory conditions leading to higher bond strength to zirconia and a defect-free interface, was used in this study. Different results could be expected using manually layered veneer ceramics. To produce long-term clinical predictions, a higher number of loading cycles is required in combination with a staircase loading approach.[27] These parameters deserve further investigation.

Regarding esthetics, the finish line design of zirconia frameworks could also influence the appearance of these restorations, especially when the cervical region is exposed due to a high smile line. In cases of tooth discoloration, a metallic core, or a metallic implant abutment, a thicker finish line could increase the opacity of the framework, and together with a thicker veneer ceramic, the underlying color could be properly masked.[28]

Conclusions

Within the limitations of this study, the finish line design did not influence the fatigue and fracture resistance of veneered zirconia crowns. Selection of either of the tested designs should be based on the clinical conditions of the restored tooth.

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