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The Effect of Different Surface Finishing Procedures on Surface Roughness and Fracture Toughness in All-Ceramic Restorations

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The aim of this study was to determine the effect of different surface treatments on the flexural strength of four different ceramic specimens. The four ceramic systems investigated in this study were lithium disilicate reinforced, zirconium oxide reinforced, glass-infiltrated alumina reinforced, and feldspathic ceramic. For the first group, grinding burs, for the second group polishing kit and for the third group glazing procedures were applied for surface treatment. Surface roughness, mean fracture toughness, and a SEM were used to describe surface features. The surface treatments affected the flexural strength and surface roughness of the ceramic systems evaluated.

Introduction

All-ceramic dental materials are becoming the first choice of restorative materials because of their superior biocompatibility and distinct esthetic appeal. However, brittle behavior combined with their extreme sensitivity to microcrack-like defects, has hampered their wider use and limited their application to relatively low stress-bearing areas.[1]

An all-ceramic fixed partial denture (FPD) may suffer from microcracking, surface flaws, and large defects induced during the manufacturing process. Therefore, the strength of all-ceramic systems is an important consideration.[2] Strength is a very important property of all-ceramic materials, however, because many variables, such as testing design, specimen geometry, polishing procedures, and testing environments affect strength measurements.[3,4] The most common steps of the fabrication of all-ceramic restorations are grinding, sandblasting, polishing, and heat treatment. Previous studies indicate that the influence of these steps on the ultimate strength of a restoration is

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contradictory and is linked to the nature of the material investigated and the operating conditions.[5] On the other hand, the surface flaws introduced by grinding and sandblasting act as stress concentrators and may cause strength degradation. The orientation of grinding can also influence the mechanical properties of ceramics.[6,7] All-ceramic materials are subjected to different fabrication procedures in the laboratory, and sometimes must be adjusted clinically to allow either proper fitting or occlusion. The processing procedures and/or clinical adjustments are more likely to initiate subcritical flaws or large defects, which, upon clinical loading and/or presence of moisture, may grow to a critical situation leading to catastrophic failure.[8] In addition, different surface roughness formed through different finishing procedures can cause various stress concentrations and, consequently, may be accompanied by a reduction in strength.[8]

The Empress 2 ceramic system utilizes the hot-pressing method and a high-strength ceramic material to produce crown and bridge substructures that are veneered with a porcelain.[9] This lithium disilicate glass–ceramic exhibits a dense network of lithium disilicate crystals. The crystal content of >60 vol% is higher than that of leucite glass–ceramics. The flexural strength and fracture toughness have been considerably increased compared with leucite–glass ceramics. An added advantage is the increased chemical durability of the new material.[10]

Yttria-stabilized tetragonal zirconia (Y-TZP) is gaining recognition as a candidate material in dentistry owing to its good mechanical properties. It is currently used as a core material in full-ceramic dental restorations,[11,12] implant superstructures, and orthodontic brackets.[13] Compared with other dental ceramics, its superior mechanical properties are due to the transformation toughening mechanism, similar to that in quenched steel. ZrO_2 is a polymorphic material that has three allotropes: the monoclinic phase is stable up to 1170°C, where it transforms into the tetragonal phase, which is stable up to 2370°C, and the cubic phase exists up to the melting point at 2680°C.[14]

InCeram is known as a high-strength ceramic, used for core crowns and for FPD frameworks.[15,16] An aluminum oxide slip-casting technique is used to build the framework, which is then fired to an open-pore microstructure. The material gains its strength by infiltration of the open-pore InCeram-Alumina microstructure with lanthanum glass. The framework is veneered with a feldspathic ceramic to restore natural tooth morphology in a functionally adequate and esthetically pleasing way.[17]

With the Cerec system, as developed by Mörmann and Brandestini in the years 1980–1986, individual restorations such as inlays, onlays, and veneers could be machined using Cerec 1, and now additionally overlays, crowns, and crown copings can be machined using Cerec 2. After taking a three-dimensional optical impression and CAD designing, the restoration is machined from a ceramic block.[18,19] Industrially prefabricated feldspathic ceramic blocks (Cerec 1 Vitablocs Mark I) have been used since 1985 for inlays, onlays, and veneers.[20] Since 1991, feldspathic ceramic blocks with improved mechanical properties (Vitablocs Mark II) have been used for Cerec inlays, onlays, veneers, and also for full crowns.[21–23]

The application of the indentation fracture technique (IF) in studying the behavior and properties of brittle materials is specifically appropriate because only small-dimensional specimens are required and the crack growth parameter similar to those cracks expected under clinical conditions.[24] It is a simple technique and requires only a few specimens for testing.[25]

The aim of this study was to determine the effect of different surface treatments (control, polishing, and glazing) on fracture toughness (three-point bending test) of four different all-ceramic specimens: lithium disilicate reinforced (LDR; IPS Empress 2), zirconium oxide reinforced (ZOR; Cercon), glass-infiltrated alumina reinforced (GAR; In-Ceram), and feldspathic ceramic (FC; Cerec Vita Blocks Mark II). The surface morphologies of ceramic specimens after different surface treatments were also investigated with SEM. The hypothesis tested was that the strength of different ceramic systems is affected by surface treatment and improved by glazing.

Experimental Procedure

The four ceramic systems investigated in this study and their respective suppliers are shown in Table I.

For each ceramic system, 45 specimens were produced in dimensions of $14\,mm \times 12\,mm \times 2\,mm$.[26,27] The specimens were randomly divided into three groups of 15 specimens each.

Preparation of Specimens

A special metal mold was used in the preparation of LDR and GAR core specimens ($14\,mm \times 12\,mm \times 1\,mm$). Wax patterns of the substructures were created

Table I. Ceramic Material Studied

	IPS Empress 2	TZP-CerS	In-Ceram	Vita Mark II
Framework material	$Li_2O \cdot 2SiO_2$ glass–ceramic	Yttria-stabilized ZrO_2 (3Y–TZP, Cercon)	Glass aluminium oxide ceramic	Feldspathic glass–ceramic
Veneer material	Fluorapatite glass–ceramic (IPS Empress 2)	Feldspathic glass (Cercon Ceram S)	Feldspathic glass (Vitadur Alpha)	No layering material
Manufacturer	Ivoclar Vivadent	Degudent	Vita Zahnfabrik	Vita Zahnfabrik

and the LDR specimens were fabricated according to the manufacturer's instructions (Ivoclar Vivadent AG, Schaan, Liechtenstein). After pressing and cooling, the specimens were divested, cleaned, dried, and airborne particle abraded. Then, a feldspathic ceramic (Ivoclar Vivadent AG) was applied on the substructure using the special metal mold. The final thickness for all-ceramic specimens was 2 mm (1 mm core material, 1 mm veneering porcelain).[9,28]

ZOR blocks (Cercon Smart Ceramic, Degussa Dental, Frankfurt, Germany) were prepared using an Isomet low-speed saw (Buehler, Lake Bluff, IL) (1 mm in height). The milled presintered coping or framework was then removed from its frame and sintered in a heat furnace (Cercon Smart Ceramic). The sintered-ZOR framework was ready to be veneered with the low-fusing veneering porcelain (Cercon Smart Ceramic) for zirconia.

The GAR specimens were fabricated according to the manufacturer's instructions. After placing three layers of die spacer, the working a special metal mold were duplicated with a condensation silicone (Zetaplus, Zhermack, Rovigo, Italy) to produce the special plaster (In-Ceram Spezial Plaster, Vita Zahnfabrik H. Rauter, Bad Sackingen, Germany) models. After covering the models with the slip-casting alumina to form the crown substructures, they were sintered for 10 h at 1120°C in an In-Ceramat 3 (Vita Zahnfabrik H. Rauter) special furnace. For glass infiltration, the models were fired for 4 h at 1100°C. After this process, the core was adjusted to 1 mm thickness. Then the cowns were fabricated with Vitadur alpha (Vita Zahnfabrik H. Rauter) using the silicon key.

FC blocks (Vita Blocks Mark II; Vita Zahnfabrik H. Rauter), the heights of the specimens were 2 mm and veneering porcelain was not applied. The specimens were prepared using an Isomet low-speed saw (Buehler Ltd.).

After the grinding procedure, the specimens were then divested using an air abrasion unit (Type 5423, Kawo EWL, Biberach, Germany) with 50 μm Al_2O_3 at a pressure 5 MPa for a period of 20 s, and then the specimens were cleaned in an ultrasonic cleaner. Specimens were randomly divided into three groups of 15 each. Only finishing burs (Edenta AG, St. Gallen, Switzerland, size ø1/10 mm 050, ISO no: 807 104 174 523 050) were used in the first group. In the second group, a custom-polishing protocol was used. Then the surface was polished using one polishing system (Edenta AG). The polishing system was applied to the specimens using a slow-speed handpiece (KaVo Model K9; KaVo America, Lake Zurich, IL) rotating at approximately 10,000 rpm, as instructed by the manufacturer. Polishing was performed by the same investigator. Then the polishing wheel was used for 20 s. The glazing procedure was applied to the last group according to the manufacturer's instructions.

Surface Roughness

After surface treatments, specimens were ultrasonically cleaned with acetone for 5 min and rinsed with distilled water and then dried with air. The surface roughness of the same specimens was evaluated using a profilometer (Mitutoyo Surftest-B and Surftest 402 Analyzer; Mitutoyo, Kawasaki, Japan). To measure the roughness profile value in mm, the diamond stylus (5 μm tip radius) was moved across the surface under a constant load of 3.9 mN and a speed of 0.100 mm/s during testing. This procedure was repeated five times at a different location for each specimen to obtain the general surface characteristics of the specimens. The average values of these measurements were considered to be the R_a values. The cutoff value was 0.8 mm. The measuring range was 20×5 μm.[29] The R_a value describes the average roughness value for a surface that has been traced by the profilometer. A lower R_a value indicates a smoother surface.

In addition, SEM (JEOL JSM-5600, JEOL, Tokyo, Japan) was utilized to qualitatively evaluate the effects of control, polishing, and glazing on the surface of the specimens. The surfaces of the specimens were evaluated with the help of photographs.

Fracture Toughness Measurement

The three-point bending test was used to calculate the modulus of rupture (M) as follows[30]:

$$M = \frac{3Wl}{2bd^2}$$

where W is the breaking load (N), l is the test span (mm), b is the width of the specimen (mm), and d is the thickness of the specimen (mm). The indenter (Vickers) was used during application of stress. The treated surface was placed on a jig consisting of two supports at a span distance of 10.5 mm. The opposite surface was loaded with a universal testing machine (TSTM 02500, Elista, Istanbul, Turkey) at a crosshead speed of 0.5 mm/min (Fig. 1).

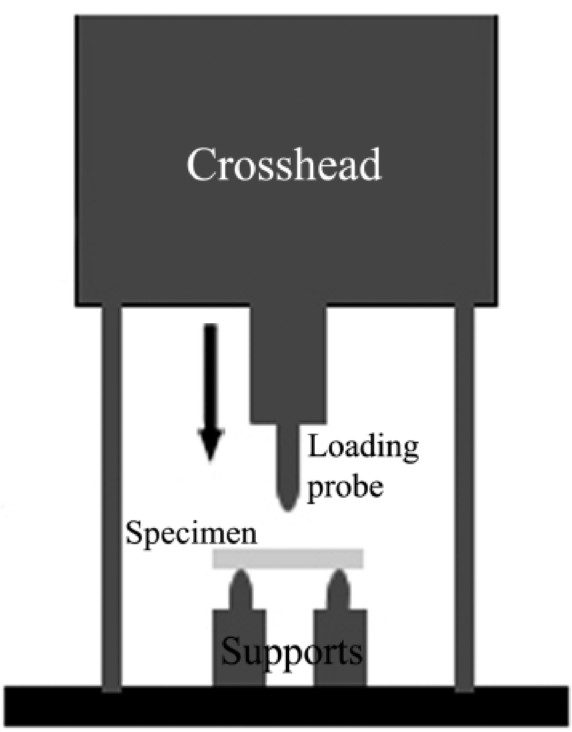

Fig. 1. Schematic presentation of the test procedure.

SEM Observation

The SEM (JEOL JSM-5600, JEOL) was used to analyze the treated surface of randomly selected specimen surfaces with a magnification of $\times 750$. The specimens were attached to SEM stubs with cyanoacrylate cement (UHU) and sputtercoated with gold–palladium (Hummer Sputter Coater; Technics, Alexandria, VA) for 60 s. The surfaces of the specimens were evaluated with the help of photographs.

Statistical Analysis

For analyzing fracture toughness and surface roughness values, the results of testing were analyzed with statistical software (SPSS PC, Vers.10.0; SPSS, Chicago, IL). Two-way analysis of variance (ANOVA) was used to analyze the data (ceramic system, surface treatment) for significant differences. The Tukey HSD test and paired two-tailed tests were used to perform multiple comparisons ($\alpha = 05$).

Results

Surface roughness and flexural strength values of the four different ceramic systems that were applied for two different surface treatments are given in Figs 2 and 3.

Surface roughness values varied significantly depending on the ceramic systems (LDR, ZOR, GAR, and FC) and the surface treatments (Glazing, polishing, and control) used ($P < 0.05$). Significant interactions were present between ceramic systems and surface treatments ($P < 0.05$) (Table II). The highest surface roughness values were recorded for ZOR (3.39 ± 2.15) specimens and the lowest surface roughness values were recorded for GAR (2.31 ± 0.95) and FC (2.39 ± 1.75) specimens ($P < 0.05$). The highest surface roughness values were recorded for control group spec-

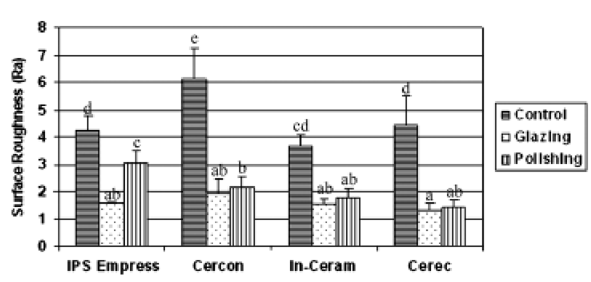

Fig. 2. Surface roughness values.

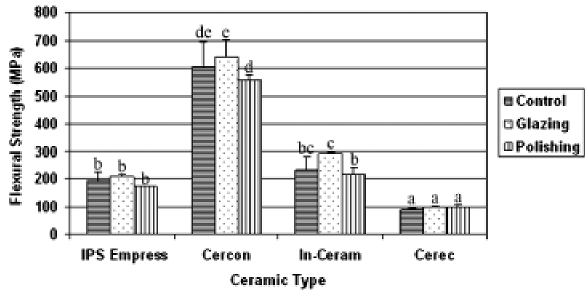

Fig. 3. Fracture toughness values.

Table II. Two-Way Analysis of Variance of Surface Roughness Values

	SS	DF	MS	F	*P*
Ceramic system	34.85	3	11.61	25.35	.000
Surface treatment	314.58	2	157.29	343.24	.000
Ceramic system * surface treatment	40.13	6	6.69	14.59	.000

SS, sum of square; DF, degree of freedom; MS, mean square.

imens (4.61 ± 1.10) and the lowest surface roughness values were recorded for glazed specimens ($1.58 \pm .05$) in all-ceramic systems ($P < 0.05$).

Fracture resistance values varied significantly depending on the ceramic systems (LDR, ZOR, GAR, and FC) and the surface treatments (Glazing, polishing, and control) used ($P < 0.05$); however, there were no significant interactions between ceramic systems and surface treatments ($P = 0.07$) (Table III). The highest fracture resistance values were recorded for ZOR (599.8 ± 71.3 MPa) specimens and the lowest fracture resistance values were recorded for FC (95.8 ± 4.9 MPa) specimens ($P < 0.05$). The highest fracture resistance values were recorded for glazed specimens and the lowest surface roughness values were recorded for polished specimens in LDR, ZOR, and GAR ceramic systems ($P < 0.05$), but not for the FC system ($P = 0.95$).

SEM Analysis

The SEM photomicrograph of control groups' surface showed that a rough surface was generated. Surface roughness measurements indicated that this surface had deeper grooves than other treated surfaces. The results of the profilometric measurements were consistent with the SEM photographs. The control groups' surface showed coarse scratches in random directions (Fig. 4). However, dispersion of spherical and irregular types of porosities were observed throughout the control groups, whereas fewer spherical pores were observed in the polishing groups. The polished surface of the specimens is characterized by displaced material at the scratch edge beside relatively small smooth areas and large defects. SEM photomicrograph of the polished surface showed uniform shallow surface damage and superficial grooves (Fig. 6). The SEM analysis of the treated surfaces of these materials showed that fine glazing produced the smoothest surface. SEM photomicrograph of glazed surface showing very few small spherical-shaped pores. All material surfaces were smooth and clear of cracks and flaws after the glazing procedures (Fig. 5).

Discussion

This *in vitro* study determined the effects of surface treatments on the flexural strengths and surface roughnesses of four different types of ceramic systems. The results support the hypothesis that the surface treatments affect the flexural strength and surface roughness of different all-ceramic specimens. The highest surface roughness and flexural strength values were recorded for ZOR specimens, and the lowest surface roughness and flexural strength values were recorded for FC specimens. The highest surface roughness values were recorded for control group specimens and the lowest surface roughness values were recorded for glazed specimens in all-ceramic systems.

Table III. Two-Way Analysis of Variance of Fracture Toughness Values

	SS	DF	MS	F	*P*
Ceramic system	34,174,401.03	3	11,391,467.01	673.93	.000
Surface treatment	368,808.70	2	184,404.35	10.91	.000
Ceramic system * surface treatment	200,099.43	6	33,349.90	1.97	.072

SS, sum of square; DF, degree of freedom; MS, mean square.

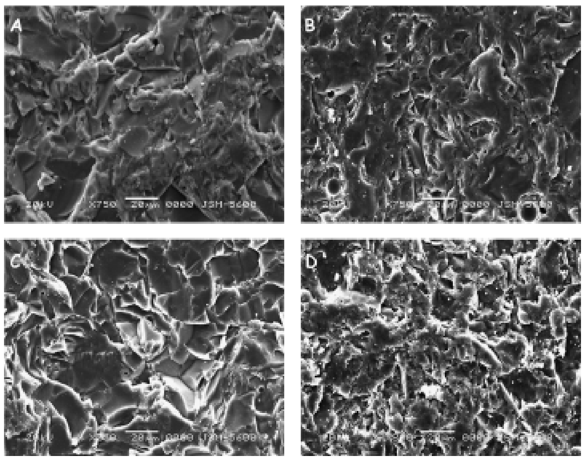

Fig. 4. SEM photomicrograph of control groups' surface showing a rough surface with some pores. Surface roughness measurements indicated that these surface had deeper grooves than other treated surfaces [(A) LDR, (B) ZOR, (C) GAR, (D) FC].

The ISB method has shown good agreement with conventional fracture mechanics tests.[31–33] Few investigations have evaluated the influence of the configuration of the test, as three-point, four-point, and biaxial bending tests could be used in the ISB test. These test configurations may demonstrate different strength values in general because different areas and volumes are exposed to stress.[34,35] The indentation strength technique has been less frequently used than the IF. It is performed by introducing a flaw into a specimen with an indenter (Knoop or Vickers), followed by the application of tensile stress on the indented surface of the specimen until fracture in either a three-point or a four-point bending, or a biaxial flexure test.[32] In the current study, an indenter (Vickers) was used during application of the stress.

Although polishing is defined as the process of making a rough surface smooth to the touch and glossy to the eye, polishing of porcelain, in particular, is usually carried out to achieve an esthetically pleasing appearance and to prevent a roughened surface from abrading an opposing tooth.[36] However, polished and control groups recorded lower strength values than the glazed groups for all materials. During polishing or sandblasting, heat, cracking, chipping, and residual stress may be generated, from which strength-reducing flaws are initiated.[1] In the case of the control group, severe random or localized removal may occur due to the impact of the sand particles with the

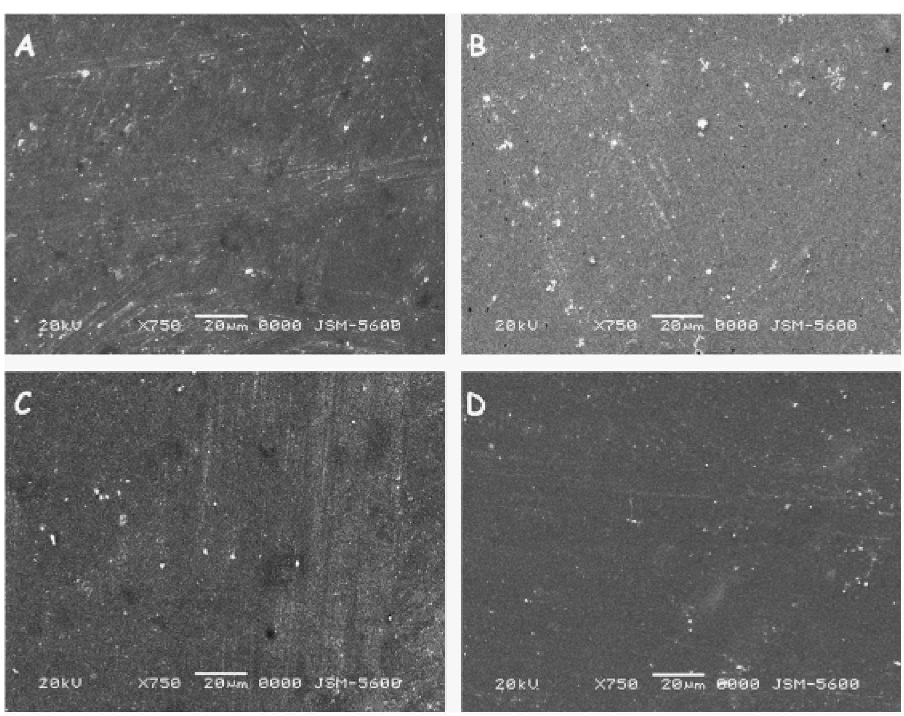

Fig. 5. SEM photomicrograph of glazing groups' surface showing that fine glazing produced the smoothest surfaces [(A) LDR, (B) ZOR, (C) GAR, (D) FC].

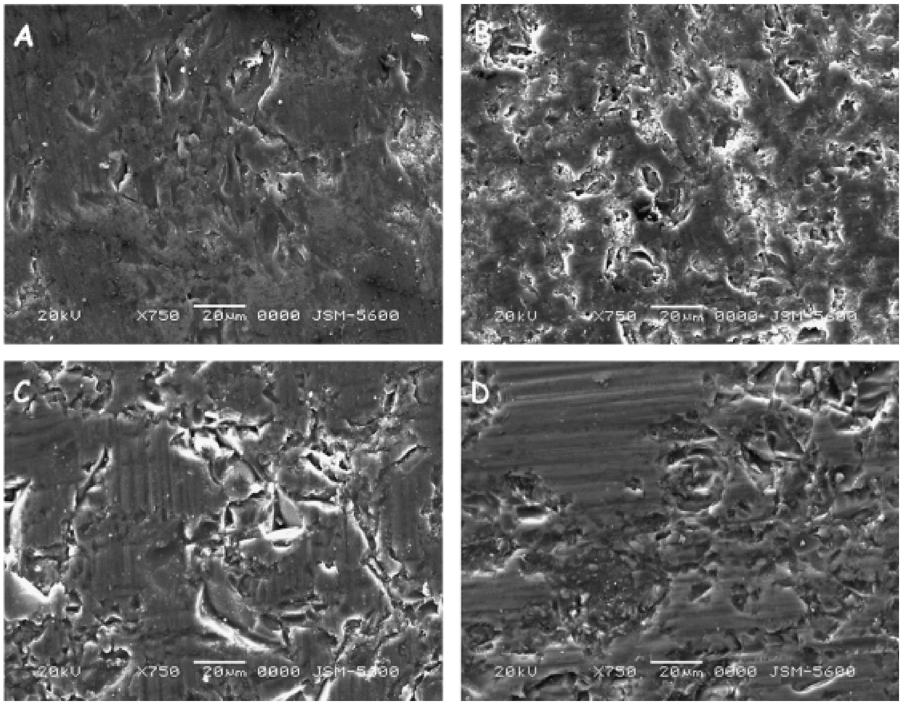

Fig. 6. SEM photomicrograph of polishing groups' surface showing irregular shallow surface damage and superficial grooves [(A) LDR, (B) ZOR, (C) GAR, (D) FC].

surface, which might induce fracture on the impingement site, various deep grooves and valleys, and, consequently, increased roughness values.[1,37] The cracking associated with such treatments is equivalent to that of a pointed indenter, and leads to the development of median, radial, and lateral cracks.

TZP and other zirconia-based ceramics are particularly suitable for all-ceramic dental bridges due to the high inert strength and enhanced toughness conferred by the tetragonal–monoclinic phase transformation.[38] In the current study, fracture strength of TZP system was the highest in all-ceramic systems.

Three other kinds of ceramic systems tested were LDR, GAR, and FC without a ceramic layer. The veneer layer directly affects the stress distribution and thermal properties of restorations.[39] In the results of the current study, the fracture strength of the control group was significantly higher than the polishing group in ceramic systems with a veneer layer material (LDR, ZOR, GAR); however, there were no significant differences in the fracture strength values between the polishing and the control group in the ceramic system without veneer layer material (FC).

Another concern with the polishing and sandblasting treatment procedures is the effect of heat treatment (glazing). Glazing can either be the application of a low fusing glass overcoat or auto glazing, which is based on firing for a certain time, held at the maximum temperature. Auto glazing and/or the application of glazing material after grinding are believed to increase the strength of ceramic materials by reducing the depth and/or the sharpness of critical flaws, and glazed porcelain has been reported to have resistance to fracture than unglazed porcelain.[40–42] Brackett *et al.*[43] showed that the fracture toughness of five porcelains treated with overglaze was greater than porcelains treated with autoglaze or autoglaze and polish; however, no significant difference in fracture toughness was noted between autoglazed porcelain and porcelain autoglazed with polishing. Using only one brand of porcelain, Fairhurst *et al.*[44] reported that glazing did not improve the biaxial strength of the test specimens. Rosenstiel *et al.*[45] reported a higher fracture toughness in a polished porcelain than in the glazed version. Baharav *et al.*[46] reported that different rates of cooling after firing a glazed alumina-reinforced porcelain created various degrees of crack propagation, and fast cooling resulted in greater fracture toughness but had no effect on the hardness. The current study concluded that subjecting these materials to a heat treatment that is typically encountered during dental laboratory processing improves the strength.

Based on the results of this study, the hypothesis that the strength is affected by surface treatment and is improved by glazing and that the roughness determines the strength is partly accepted. Stress concentration can be initiated not only from surface roughness but also from other factors, such as internal stresses (within the microstructure), porosity, inherently developed cracks, and thin sectional areas close to tensile stresses. Thus, surface roughness can dictate strength if no stress concentration greater than that of surface roughness occurs.[47] Kitazaki *et al.*[48] reported that surface roughness is not the only factor that determines strength. Furthermore, some ceramic materials exhibit different crystalline concentrations between their surfaces and the internal portions, which may occur as a result of different surface treatments and may act to strengthen the materials significantly.

Polishing procedures may have removed the defects created during fabrication. Furthermore, polishing procedures probably produced surface compressive stresses because heat was generated at the polishing surface as a result of friction between the polishing wheel and the ceramic surface. Polishing may also have overheated the surface layer and aided in producing plastic deformation. This process can also generate a thermal mismatch between the outer and the inner layers of the ceramic specimens, which may lead to the development of tensile stresses in the inner layer and desirable compressive stresses on the outer layer.[48] Porosity of the ceramic surface also plays a role in this reaction because porosity allows the acid to penetrate the ceramic surface and allows the reaction to continue inside the ceramic specimens. Therefore, the amount and the size of surface porosities may act as a reservoir for the acid to remain and induce surface flaws, which could explain why most of these surface flaws were related to surface voids. In general, surface flaws were the weakest points on the ceramic surface. Cracks initiate from these flaws, which may lead to future ceramic failure.[49]

This *in vitro* study determined the effects of surface treatments on the fracture toughnesss and surface roughness of four different types of ceramic systems. Neither thermal cycling nor acid etching was applied to surfaces. Further research is needed to investigate the effects of acid[47] or thermal cycling on the surface roughness and strength of ceramic materials that were applied for different surface treatments.

Conclusion

Within the limitations of this *in vitro* study, the following conclusions were drawn:

1. The surface treatments affect the fracture toughness and surface roughness of the ceramic systems evaluated.
2. The highest fracture toughness (599.8 ± 71.3 MPa) was recorded for ZOR specimens and glazing groups ($P < 0.05$).
3. The highest surface roughness values were recorded for control group specimens (4.61 μm) and the lowest for glazed specimens (1.58 μm) in all-ceramic systems.

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