Effect of different surface treatments on surface roughness, phase transformation, and biaxial flexural strength of dental zirconia

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Introduction
The increasing esthetic needs in dentistry have led to a focus on natural-appearing ceramic restorations. In this regard, the stabilized tetragonal zirconia (Y-TZP) exhibits some superiority over other ceramic types with improved mechanical properties, biocompatibility, and esthetic characteristics.¹⁻⁵ This introduction explains numerous benefits, including superior mechanical properties, compared to the monolithic lithium disilicate ceramics and manufacturing thinner restorations for more conservative dental preparations.⁶ This would also lead to the possibility of new standardization and cost reduction due to the CAD-CAM processing technique.⁶ Furthermore, Y-TZP zirconia has a unique characteristic that can transform from tetragonal to monolithic phase under mechanical stresses, resulting in extra toughness and strength and hindering crack propagation by 3%-5% volume expansion during phase transformation.²

Despite its robust mechanical properties, zirconia crowns clinically suffer from interfacial failures.³ They are commonly caused by the weak interfacial strength between the cement and ceramic crowns that cannot tolerate the mechanical stresses in the oral environment.⁸ There are different methods to improve the interfacial adhesion, and the purpose is to increase the surface area and decrease the stress levels at the interfaces.⁹ In restorative dentistry, this can be achieved by combining multiple methods, including some well-established treatments, such as grinding/abrasion with a diamond bur, sandblasting, acid etching, and silanization.⁹⁻¹² More recently, laser irradiation, including Er,Cr:YSGG laser, has been proposed in this regard.¹⁰⁻¹⁴ Lasers can gather and concentrate high magnitudes of energy on target areas. Lasers, in some cases, induce chemical reactions that alter...
the shape and, in other situations, only cause physical changes. Er,Cr:YSGG laser has the potential to remove particles through a mechanism called ablation, including micro-explosions and vaporization.\textsuperscript{15} During vaporization, the internal pressure builds up within the tissue until the inorganic material is explosively destroyed before the melting point is reached.\textsuperscript{13} However, laser treatment needs special care for any use in dental crown surface treatment.

Martins et al,\textsuperscript{16} Kurtulmus-Yilmaz et al,\textsuperscript{17} Liu et al,\textsuperscript{18} and Kosmac et al\textsuperscript{19} have determined the effects of different surface treatments on the zirconia and have reported contradictory results.

This study aimed to evaluate the effect of different surface treatments, including grinding by a bur, sandblasting, and laser irradiation, on the properties of dental graded zirconia. The null hypothesis was that these surface treatments do not affect the surface roughness, surface topography, and flexural strength of zirconia specimens.

### Methods

A pre-sintered 98-mm zirconia block (Shenzhen Upcera Dental Co., Ltd., China) was milled using a computer-aided design/manufacturing system to produce forty disk-shaped specimens with a diameter of 12 mm and a thickness of 1.2 (±0.2) mm. The disks were sintered at 1450°C according to the manufacturer’s instructions in the furnace (Ceramill Therm; Amman Girrbach, Austria) and then polished with 600-, 800-, and 1200-grit silicon carbide papers (Struers A/S) for a minimum of 30 minutes under a 10-N load using a grinding/polishing machine (Phoenix; Beta Grinder/Polisher, Buehler, USA) at 300 rpm.\textsuperscript{20}

The finished specimens were randomly divided into a nominally flaw-free control group evaluated directly (n = 10) and three other groups with different surface treatments as follows:

- **Grinding with bur (GB):** The specimens in this group were processed using a high-speed hand tool with a diamond bur (Drendel + Zweiling Diamant GmbH Inc., Germany) (Table 1) at 200-kPa pressure for 20 seconds with back-and-forth motions under water coolant and regarded as the grinding group.

- **Sandblasting with alumina (SA):** The specimens were subjected to sandblasting by 110-µm aluminum oxide particles with 2.5-bar pressure at a 30-mm distance for 30 seconds.

- **Laser treatment (LS):** The specimens were subjected to Er,Cr:YSGG laser irradiation (iPlus, Biolase, Inc. San Clemente, California, USA) with 2940-nm wavelength fiber-optic system (1 mm in diameter) and 400-µm diameter head handpiece for 10 seconds under 80% water (32 mL/min) and 80% air settings. The laser was irradiated at a 1-mm distance from the surface in non-contact mode. The laser pulse in this study was 74 μs at 1.5-W power output and the frequency of 15 Hz. The proper power output for the laser was selected through a pilot study on four extra disc-shaped samples irradiated at 1.5, 2.25, 3, and 3.75 W (equivalent to 100, 150, 200, and 250 mJ/pulse, respectively). Then, the surface topography of the specimens was examined under a scanning electron microscope (SEM) (ZEISS DSM-960A, Germany) at ×600 magnification. There was less surface damage in the specimens treated with 1.5-W power intensity (Figure 1). The specimens were then cleaned in distilled water in an ultrasonic bath and then air-dried.

The average surface roughness (Ra) and peak-to-valley height (Rz) of the specimens were assessed under an optical microscope (Keyence VH2000, USA) equipped with a ×1000 objective lens, following the ISO 25178 [ISO25178-2,2012].\textsuperscript{21} The images were captured at 1600×1200 pixels, which was equivalent to 400.0-300.0 μm field of view. Five measurements were performed for each specimen over a 240-μm length at a magnification of ×1000, and the means of measurements were reported as the roughness values for each specimen (Figure 2).

X-ray diffraction (XRD; Ultimate IV X-ray Diffractometer, Rigaku, Japan) was conducted to evaluate the relative percentage of the monoclinic phase on the treated specimens operated at 150 mA and 50 kV at 2Ø range, 5–80 degrees, 0.02º step size and 50-second stop at each step. Three specimens were randomly selected from each group for this measurement. The relative percentage of monoclinic phase and phase transformation were determined from the integral intensities of the monoclinic M (111) and M (111), and the tetragonal T (111) peaks according to the equation below\textsuperscript{22,23}:

\[
X_n = \left[ I_n - \frac{I_{n} (111)}{I_n (111) + I_{n} (111) + I_{n} (101)} \right] \\
V_n = 1.311X_n \left/ \left(1 + 0.311X_n \right) \right.
\]

### Table 1. Description of the materials used for the surface treatment

| Material | Main composition | Manufacturer |
|----------|------------------|--------------|
| Pre-sintered zirconia blanks (Yttrium partially stabilized zirconia) | Nanometer zirconia powder >98% Fe₂O₃: <0.3% P₂O₅: <0.2% Er₂O₃: <0.2% Other oxides: ≤0.5% | Shenzhen Upcera Dental Co. Ltd, China |
| Silicon carbide grinding paper | Silicon carbide Grit size: 600, 800, 1200 | Struers A/S Inc. |
| Cylindrical blue-yellow band diamond rotary instrument | Diamond particles (108-120 μm) and binder | Drendel + Zweiling Diamant GmbH, Germany |
where Xₘ is the ratio of monoclinic peak intensity, Vₘ is the volumetric percentage of the monoclinic phase content, Iₘ (-111) and Iₘ (111) are the severity of monoclinic peak at 2Ø = 28.2°, 2Ø = 31.4°, and Iₜ (111) is the intensity of tetragonal phase at 2Ø = 31.1°.

The biaxial flexural strengths were evaluated using a universal testing frame (Zwick Roell, Ulm, Germany) with a 1000-N load cell. The specimens were placed on a fixture with three equidistance stainless steel spherical balls, distributed on the periphery of a 10-mm diameter circle. The load was applied at a rate of 1 mm/min to the opposite side of the treated surface by a cylindrical head piston (1.4 mm in diameter) so that the treated surface was subjected to the flexural tension (ISO6872:2008).  

The biaxial flexural strength was calculated using the formula below:

\[
S = -0.2387 \frac{P(X-Y)}{d^2}
\]  

where S is the flexural strength, P is the load required for fracture, and d is the thickness of the specimen. X and Y were also calculated as follows:

**Figure 1.** Scanning electron micrographs of Zirconia surface treated by laser at different power. (A) 1.5 (B) 2.25 W (C) 3.00 W (D) 3.75 W.

**Figure 2.** Optical micrographs of surface treated Zirconia (A) Control (B) Grinding (C) Laser (D) Sandblasting.
\[ x = (1 - v) \ln \left( \frac{R_1}{r_3} \right)^2 + \left( \frac{1 - v}{2} \right) \left( \frac{R_2}{r_3} \right)^2 \]  
(4)

\[ y = (1 + v)(1 + \ln \left( \frac{R_1}{r_5} \right)^2) + (1 - v) \left( \frac{R_2}{r_5} \right)^2 \]  
(5)

where \( r_1 \) and \( r_2 \) are the radii of supported and loading balls, respectively, and \( r_3 \) is the radius of the zirconia disk. The value of 0.25 was used for the Poisson's ratio-\( v \) of dental zirconia in the equation above. In addition, the two-parameter Weibull analysis was applied to characterize the flaw size distribution of different groups in this study following the method introduced by Quinn and Quinn.\(^{25,26}\)

Based on the description of the Weibull distribution, the probability of failure can be defined as:

\[ P_f = 1 - \exp\left[-\frac{\sigma}{\sigma_0}\right]^m \]  
(6)

where \( \sigma \) is the failure strength for each test, \( \sigma_0 \) is the characteristic strength, and \( m \) is the Weibull modulus. Taking double algorithm of eq. 6 yields:

\[ \ln \left[ \ln \left( \frac{1}{1 - P_f} \right) \right] = m \ln \sigma - \ln \sigma_0 \]  
(7)

That would allow simple linear regression to calculate characteristic strength, \( \sigma_0 \), and Weibull modulus, \( m \).

**Statistical analysis**

One-way ANOVA and post hoc Tukey tests were conducted using SPSS 22 (SPSS Inc.) to compare different groups in this study regarding roughness, XRD, and flexural strength. The level of significance was set at \( P<0.05 \). Moreover, Pearson's correlation coefficient test was carried out to find potential correlations between the variables.

**Results**

Figure 2 presents the optical microscope images of the surface of control and treated specimens. All the samples exhibited irregular heterogeneous surfaces with random scratch lines except for GB, where the surface roughness was more pronounced due to the use of a dental bur. The surface roughness measurement confirmed the surface topography observations in the optical images. The mean values for the average (\( R_a \)) and peak-to-valley roughness (\( R_z \)) of different groups are summarized in Table 2. The \( R_a \) and \( R_z \) values for the control group were 0.19 ± 0.02 μm and 1.36±0.14 μm, respectively. Pairwise comparisons between the groups showed that \( R_a \) and \( R_z \) roughness values in GB were greater compared with the other three groups (\( P<0.005 \)). However, there were no significant differences in surface roughness between the control, LS, and SA groups (\( P>0.7 \)).

A representative XRD pattern for a dental zirconia disk is shown in Table 3, with peaks representing tetragonal and monoclinic phases. There were significant differences in the ratio of the monoclinic phase intensity and the

| Group | Minimum | Maximum | Mean | Standard deviation | \( P \) value |
|-------|---------|---------|------|--------------------|-------------|
| Control | Ra | 0.16 | 0.22 | 0.19 | 0.02 | <0.005 |
|        | Rz | 0.74 | 1.03 | 1.36 | 0.14 | <0.005 |
| GB     | Ra | 1.2 | 2.50 | 1.87 | 0.50 | <0.005 |
|        | Rz | 6.29 | 8.08 | 7.46 | 0.71 | <0.005 |
| LS     | Ra | 0.21 | 0.38 | 0.29 | 0.06 | <0.005 |
|        | Rz | 1.61 | 2.52 | 1.90 | 0.37 | <0.005 |
| SA     | Ra | 0.18 | 0.26 | 0.23 | 0.04 | <0.005 |
|        | Rz | 1.19 | 2.13 | 1.6 | 0.37 | <0.005 |

*Control: no treatment; GB: grinding with diamond bur; LS: Laser treatment; SA: sandblasting with alumina.

| Group | Minimum | Maximum | Mean | Standard deviation | \( P \) value |
|-------|---------|---------|------|--------------------|-------------|
| Control | Ra | 1.06 | 1.76 | 1.4 | 0.4 | <0.001 |
|        | Rz | 4.53 | 4.81 | 4.7 | 0.2 | <0.001 |
| GB     | Ra | 0.80 | 1.61 | 1.2 | 0.4 | <0.001 |
|        | Rz | 4.27 | 4.33 | 2.9 | 0.0 | <0.001 |

*Control: no treatment; GB: grinding with diamond bur; LS: Laser treatment; SA: sandblasting with alumina.
volumetric percentage of monoclinic phase content between different groups as a result of surface treatment ($P<0.001$). As evident in Table 3, sandblasting and grinding treatments exhibited a significantly larger amount of monoclinic phase content ($P<0.001$) than the laser and control groups.

The mean biaxial flexural strengths of the control and treated samples are shown in Figure 3. Overall, there was a significant difference in the mean flexural strengths between groups ($P<0.01$). The SA group (1023.0 ± 74.8 MPa) exhibited a significantly higher flexural strength than only the control group (926.3 ± 65.5 MPa) ($P=0.02$) and GB (909.8 ± 87.3 MPa) ($P<0.01$). However, there were no significant differences between the flexural strength of the LS group (994.5 ± 56.8 MPa) and the control, GB, and SA groups ($P>0.05$).

Regarding the Weibull analysis, the probability of the flaw distribution and Weibull parameters are presented in Figure 4b and Table 4. The Weibull modulus (m) values for the control and SA groups were similar (around 16). The lowest Weibull modulus (m) value was for the GB group (12.2). However, the specimens in the LS group exhibited higher reliability of data with Weibull modulus calculated at 20. In terms of characteristic strength ($\sigma_0$), the LS (1020.2 MPa) and SA groups (1023.0 MPa) exhibited similar and the highest values among the tested groups. Those values for the control and GB groups were 947.5 and 955.3 MPa, respectively.

Pearson’s correlation coefficient test indicated no significant relationship between the surface roughness ($R_a$ and $R_z$) and the biaxial flexural strength in control ($P=0.44$), LS ($P=0.63$), GB ($P=0.33$), and SA groups ($P=0.98$). Furthermore, there was no significant relationship between the volumetric percentage of the monoclinic phase and the flexural strength of zirconia in control ($P=0.560$), LS ($P=0.516$), GB ($P=0.632$), and SA

### Table 4. Weibull analysis of different surface treatments on zirconia

| Groups* | Weibull modulus (m) | Characteristic strength ($\sigma_0$) (MPa) |
|---------|---------------------|----------------------------------------|
| Control | 16.5                | 955.3                                  |
| GB      | 12.2                | 947.5                                  |
| LS      | 20.5                | 1020.2                                 |
| SA      | 16.3                | 1023.0                                 |

*Control: no treatment; GB: grinding with diamond bur; LS: Laser treatment; SA: sandblasting with alumina.
groups ($P = 0.396$).

**Discussion**

This study evaluated the effects of different surface treatments on the mechanical properties of zirconia. The results showed that sandblasting, grinding with a diamond bur, and laser treatments significantly affected the surface roughness, surface topography, and flexural strength of zirconia specimens; therefore, the null hypothesis of this study was rejected.

Concerning the surface roughness and topography, the results showed that the mean $R_s$ and $R_p$ values for the specimens ground with a diamond bur (GB group) were significantly higher than the corresponding values in other groups ($P < 0.005$). However, there were no significant differences in the surface roughness between the control, sandblasted (SA), and laser-treated (LS) specimens ($P > 0.05$).

Overall, surface roughening is considered a crucial method to increase the bonding quality of resin cement to ceramic by introducing a micromechanical interlocking mechanism. Roughening the internal surface of ceramic restorations increases the surface area for penetration and polymerization of resin cement, leading to better adhesion. Both grinding and sandblasting could result in contamination removal, increased surface area, and enhanced wettability. Surface roughening by Er,Cr:YSGG laser is caused by the ablation of surface particles that can improve adhesion. In some few cases, discoloration and microcracks have been reported following laser irradiation. Extreme roughening and micro-cracks were also observed in our pilot study at higher power. However, lower power laser treatments resulted in more moderate roughness with no microcracks or discoloration on the surface (Figure 1). Recent studies showed quite different outcomes on the effectiveness of different surface treatments on zirconia. In a study by Martins et al., the laser treatment resulted in more surface roughness than sandblasting, and the control group exhibited the least extent of roughness. However, the present study did not show significant differences in surface roughness between the control, SA, and LS groups. The discrepancies between different studies can be attributed to different surface treatment methods and settings, such as different laser types, wavelengths, energies, sandblasting particle sizes, zirconia type, etc.

Furthermore, phase transformation in the zirconia is a crucial tool to consider to evaluate surface treatment. The stresses induced during surface roughening processes could result in phase transformation in zirconia. Surface treatment of zirconia can cause localized stress concentration and facilitate tetragonal-to-monoclinic phase transformation, which adversely affects the mechanical properties of zirconia, such as its flexural strength, hardness, and modulus of elasticity. Therefore, developing a surface treatment modality that can roughen the surface with minimal phase transformation is much desired. In this study, the mechanical surface roughening methods, including grinding and sandblasting, resulted in a greater extent of the monoclinic phase. However, surface roughness induced by Er,Cr:YSGG laser did not significantly increase the extent of the monoclinic phase on the surface. Both roughness and phase transformation can negatively influence the mechanical strength of zirconia.

In this regard, sandblasted specimens showed higher flexural strength than grinding by a diamond bur. The laser treatment also did not show a statistically significant difference in the strength than the grinding and sandblasting methods ($P > 0.05$). However, Weibull analysis showed that the laser-treated specimens exhibited more reliable flexural strength (greater $m$ value), implying that the distribution of flaw generated in laser treatment was more controlled and uniform.

This study showed that laser could roughen the surface, while the percentage of monoclinic phase in the laser-treated specimens was significantly lower than that of sandblasted ones ($P < 0.001$) with comparable flexural strengths. These results are consistent with those of previous studies, which reported that zirconia's structural integrity after laser treatment had promising durability. In this study, there were no significant differences in the flexural strength between the control, GB, and LS groups ($P = 0.05$). However, the Weibull characteristic strength and Weibull modulus showed that the GB group had lower reliability among all the other treatment methods. Furthermore, the monoclinic phase on the surfaces of the GB group increased significantly ($P < 0.001$). This finding contrasts with Kurtulmus-Yilmaz et al., who reported superior reliability from the highest to lowest in the post-sintered grinding, post-sintered laser irradiation, and post-sintered sandblasting, respectively. On the other hand, Kosmač et al. reported that the highest Weibull modulus was obtained in the control group, followed by the sandblasted and grinding treatment groups.

In the present study, the unexpected finding was for the SA and control groups. The surface roughness of the control group was comparable with the sandblasting and laser irradiation groups. This could be due to the finishing of specimens by the silicon carbide papers. In addition, while the extent of phase transformation in the sandblasted zirconia specimens (the SA group) was significantly higher than the control and LS groups, the mean flexural strength value and Weibull modulus for the SA group were significantly higher than the control and LS groups. This finding contrasts with a study by Hallmann et al., where the flexural strength for the control group was higher than treatment with plasma gas, and the latter was higher than that of sandblasting with zirconia particles. It is noteworthy that the lowest flexural strength was observed after sandblasting with 150-µm alumina particles. The authors concluded that the lower flexural strength of the sandblasting group was attributed to the dominant phase.
of the zirconia specimens, which was identified to be the cubic phase. Similar to the present study, the laser-treated samples showed the most promising results where the flexural strength was maintained with the least phase transformation.

On the other hand, Çağlar and Yankoğlu reported that the flexural strengths of the sandblasted and laser-treated zirconia samples were higher than the control group. However, no significant difference in the flexural strength was observed between the sandblasted and laser groups, consistent with the present study. In general, discrepancies in the flexural results can also be attributed to numerous differences in the treatment protocols, testing configuration, zirconia types, and sample size.

Pearson's correlation coefficient demonstrated no significant relationship between either the surface roughness or the volumetric percentage of the monoclinic phase and the biaxial flexural strength (P > 0.05). This finding is consistent with another study. The authors stated that despite phase transformation in the samples as a result of treatment, the mechanical performance of Yttrium-Stabilized Tetragonal Zirconia (Y-TZP) did not deteriorate. Perhaps, volumetric phase transformation on the surface caused by different treatments is not large enough to adversely affect zirconia's biaxial flexural strength. Other studies have also reported that grinding, laser, and sandblasting treatments on the post-sintered samples positively affected zirconia's flexural strength.

Despite some promising results in some of the surface treatment methods for zirconia, the results of this study clearly showed the lack of common knowledge in the form of a standardized surface treatment method for zirconia. Finally, the effect of other variables, such as different surface treatments, different sandblasting particles, different grinding burs, different laser types and energies, aging and environmental durability, and fatigue responses, on the mechanical properties of zirconia should be evaluated further.

Conclusion
Under the limitations of this study, the grinding of zirconia surfaces with a diamond bur resulted in high surface roughness, phase transformation, and deterioration of the flexural strength of zirconia. Sandblasting of zirconia surfaces by alumina with a great extent of phase transformation exhibited the highest flexural strength. However, a more reliable mechanical property concerning the flexural strength was obtained by the Er,Cr:YSGG laser treatment with less surface roughness and phase transformation in the zirconia. In addition, there was no significant relationship between the surface roughness or the extent of phase transformation and the biaxial flexural strength of zirconia.

Authors' Contributions
NY, MY, and TH were responsible for investigation and writing the original draft. SSS contributed to the concept, supervision, writing, reviewing, and editing. MAZ was responsible for formal analysis, data collection, writing, reviewing and, editing. SMRH contributed to the methodology, supervision, writing, reviewing, and editing.

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References
1. Vagkopoulou T, Koutayas SO, Koidis P, Strub JR. Zirconia in dentistry: Part 1. Discovering the nature of an upcoming bioceramic. Eur J Esthet Dent. 2009;4(2):130-51.
2. Amat NF, Muchtar A, Yahaya N, Ghazali MJ. A review of zirconia as a dental restorative material. Aust J Basic Appl Sci. 2012;6(12):9-13.
3. Preis V, Schmalzbauer M, Bougeard D, Schneider-Feyrer S, Rosentritt M. Surface properties of monolithic zirconia after dental adjustment treatments and in vitro wear simulation. J Dent. 2015;43(1):133-9. doi: 10.1016/j.jdent.2014.08.011.
4. Khamverdi Z, Moshiri Z. Zirconia: an up-to-date literature review. Avicenna J Dent Res. 2012;4(1):1-15.
5. Rodrigues SA Jr, Ferracane JL, Della Bona A. Influence of surface treatments on the bond strength of repaired resin composite restorative materials. Dent Mater. 2009;25(4):442-51. doi: 10.1016/j.dental.2008.09.009.
6. Atsu SS, Kilicalarslan MA, Kucukesmen HC, Aka PS. Effect of zirconium-oxide ceramic surface treatments on the bond strength to adhesive resin. J Prostheth Dent. 2006;95(6):430-6. doi: 10.1016/j.prosdent.2006.03.016.
7. Keshvad A, Hakimaneh SMR. Microtensile bond strength of a resin cement to silica-based and Y-TZP ceramics using different surface treatments. J Prosthodont. 2018;27(1):67-74. doi: 10.1111/jopr.12622.
8. Amaral R, Ozcan M, Bottino MA, Valandro LF. Microtensile bond strength of a resin cement to glass infiltrated zirconia-reinforced ceramic: the effect of surface conditioning. Dent Mater. 2006;22(3):283-90. doi: 10.1016/j.dental.2005.04.021.
9. Ruyter El, Vajeeston N, Knarvang T, Kvam K. A novel etching technique for surface treatment of zirconia ceramics to improve adhesion of resin-based luting cements. Acta Biomater Odontol Scand. 2017;3(1):36-46. doi: 10.1080/23337931.2017.1399658.
10. European Prestandard (ENV) 843-5:2007: Advanced technical ceramics - Mechanical properties of monolithic ceramics at room temperature - Part 5: Statistical analysis Sweden: European Prestandard (ENV); 2007.
11. Egilmez F, Ergun G, Cekic-Nagas I, Vallittu PK, Lassila LV. Factors affecting the mechanical behavior of Y-TZP. J Mech Behav Biomed Mater. 2014;37:78-87. doi: 10.1016/j.jmbbm.2014.05.013.
12. Flury S, Peutzfeldt A, Lussi A. Influence of surface roughness on mechanical properties of two computer-
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Aided design/computer-aided manufacturing (CAD/CAM) ceramic materials. Oper Dent. 2012;37(6):617-24. doi: 10.2341/11-391-1.

13. Usmezn A, Aykent F. Bond strengths of porcelain laminate veneers to tooth surfaces prepared with acid and Er:Cr:YSGG laser etching. J Prosthodont. 2003;90(1):24-30. doi: 10.1016/s0022-3913(03)00235-x.

14. Kursoglu P, Motro PF, Yurdaguen H. Shear bond strength of resin cement to an acid etched and a laser irradiated ceramic surface. J Adv Prosthodont. 2013;5(2):98-103. doi: 10.4047/jap.2013.5.2.98.

15. Cavalcanti AN, Foxton RM, Watson TF, Oliveira MT, Giannini M, Marchi GM. Bond strength of resin cements to a zirconia ceramic with different surface treatments. Oper Dent. 2009;34(3):280-7. doi: 10.2341/08-80.

16. Martins FV, Mattos CT, Cordeiro WJB, Fonseca EM. Evaluation of zirconia surface roughness after aluminum oxide airborne-particle abrasion and the erbium-YAG, neodymium-doped YAG, or CO2 lasers: a systematic review and meta-analysis. J Prosthodont. 2019;121(6):895-903. e2. doi: 10.1016/j.prosdent.2018.07.001.

17. Kurtulmus-Yilmaz S, Aktore H. Effect of the application of surface treatments before and after sintering on the flexural strength, phase transformation and surface topography of zirconia. J Dent. 2018;72:29-38. doi: 10.1016/j.jdent.2018.02.006.

18. Liu D, Matinlinna JP, Tsoi JK, Pow EH, Miyazaki T, Shibata Y, et al. A new modified laser pretreatment for porcelain zirconia bonding. Dent Mater. 2013;29(5):559-65. doi: 10.1016/j.dental.2013.03.002.

19. Kosmač T, Oblak C, Jevnikar P, Funduk N, Marion L. The effect of surface grinding and sandblasting on flexural strength and reliability of Y-TZP zirconia ceramic. Dent Mater. 1999;15(6):426-33. doi: 10.1016/s0109-5641(99)00070-6.

20. Işıeri U, Ozkurt Z, Yalnuz A, Kazazoglu E. Comparison of different grinding procedures on the flexural strength of zirconia. J Prosthodont. 2012;107(5):309-15. doi: 10.1016/j.prosdent.2012.10.007.

21. International Organization for Standardization for Standardization 2012 ISO 25178-2:2012: Geometrical Product Specifications (GPS)—Surface Texture: Areal—Part 2: Terms, Definitions and Surface Texture Parameters. Geneva: International Organization for Standardization (ISO); 2012.

22. Garvie RC, Nicholson PS. Phase analysis in zirconia systems. J Am Ceram Soc. 1972;55(6):303-5. doi: 10.1111/j.1551-2967.1972.tb11920.x.

23. Toraya H, Yoshimura M, Somiya S. Calibration curve for quantitative analysis of the Monoclinic-Tetragonal ZrO2 system by X-ray diffraction. J Am Ceram Soc. 1984;67(6):C119-C21. doi: 10.1111/j.1551-2967.1984.tb19715.x.

24. International Organization for Standardization 2008 ISO 6872:2008: Dentistry – Ceramic materials Geneva: International Organization for Standardization (ISO); 2008.

25. Weibull W. A statistical distribution function of wide applicability. J Appl Mech. 1951;18(3):293-7.

26. Quinn JB, Quinn GD. A practical and systematic review of Weibull statistics for reporting strengths of dental materials. Dent Mater. 2010;26(2):135-47. doi: 10.1016/j.dental.2009.09.006.

27. Youssef SA. Comparing the bonding of a resin luting agent to different all ceramic systems with different surface treatments. EC Dent Sci. 2019;18:354-9.

28. Yang L, Chen B, Meng H, Zhang H, He F, Xie H, et al. Bond durability when applying phosphate ester monomer-containing primers vs. self-adhesive resin cements to zirconia: evaluation after different aging conditions. J Prosthodont Res. 2020;64(2):193-201. doi: 10.1016/j.jpor.2019.06.008.

29. Liu X, Jiang X, Xu T, Zhao Q, Zhu S. Investigating the shear bond strength of five resin-based luting agents to zirconia ceramics. J Oral Sci. 2020;62(1):84-8. doi: 10.2334/josnusd.18-0480.

30. Pereira GKR, Fraga S, Montagner AF, Soares FZM, Kleverlaan CJ, Valandro LE. The effect of grinding on the mechanical behavior of Y-TZP ceramics: a systematic review and meta-analyses. J Mech Behav Biomed Mater. 2016;63:417-42. doi: 10.1016/j.jmbbm.2016.06.028.

31. Aurélio IL, Marchionatti AM, Montagner AF, May LG, Soares FZ. Does air particle abrasion affect the flexural strength and phase transformation of Y-TZP? a systematic review and meta-analysis. Dent Mater. 2016;32(6):827-45. doi: 10.1016/j.dental.2016.03.021.

32. Subaşi MG, Inan Ö. Evaluation of the topographical surface changes and roughness of zirconia after different surface treatments. Lasers Med Sci. 2012;27(4):735-42. doi: 10.1007/s10103-011-0965-3.

33. Arami S, Tabatabae MH, Namdar SF, Chiniforush N. Effects of different lasers and particle abrasion on surface characteristics of zirconia ceramics. J Dent (Tehran). 2014;11(2):233-41.

34. Kirmali O, Kustarci A, Kapdan A, Er K. Efficacy of surface roughness and bond strength of Y-TZP zirconia after various pre-treatments. Photomed Laser Surg. 2015;33(1):15-21. doi: 10.1089/pho.2014.3825.

35. Turp V, Akgungor G, Sen D, Tuncelli B. Evaluation of surface topography of zirconia ceramic after Er:YAG laser etching. Photomed Laser Surg. 2014;32(10):533-9. doi: 10.1089/pho.2014.3730.

36. Botelho MG, Dangay S, Shih K, Lam WYH. The effect of surface treatments on dental zirconia: An analysis of biaxial flexural strength, surface roughness and phase transformation. J Dent. 2018;75:65-73. doi: 10.1016/j.jdent.2018.05.016.

37. Kelch M, Schulz J, Edelhoff D, Sener B, Stawarczyk B. Impact of different pretreatments and aging procedures on the flexural strength and phase structure of zirconia ceramics. Dent Mater. 2019;35(10):1439-49. doi: 10.1016/j.dental.2019.07.020.

38. Sundh A, Kou W, Sjögren G. Effects of pretreatment, specimen thickness, and artificial aging on biaxial flexural strength of two types of Y-TZP ceramics. Oper Dent. 2019;44(4):615-24. doi: 10.2341/18-071-1.

39. Amarante JEV, Pereira MVS, de Souza GM, Pais Alves MFR, Simba BG, dos Santos C. Roughness and its effects on flexural strength of dental yttria-stabilized zirconia ceramics. Mater Sci Eng A. 2019;739:149-57. doi: 10.1016/j.msea.2018.10.027.

40. Abdullah AO, Yu H, Pollington S, Muhammed FK, Xudong S, Liu Y. Effect of repeated laser surface treatments on shear bond strength between zirconia and veneering ceramic. J Prosthodont. 2020;123(2):338.e1-338.e6. doi: 10.1016/j.jprosdent.2019.10.007.
41. Abdullah AO, Hui Y, Sun X, Pollington S, Muhammed FK, Liu Y. Effects of different surface treatments on the shear bond strength of veneering ceramic materials to zirconia. J Adv Prosthodont. 2019;11(1):65-74. doi: 10.4047/jap.2019.11.1.65.

42. Tada K, Sato T, Yoshinari M. Influence of surface treatment on bond strength of veneering ceramics fused to zirconia. Dent Mater J. 2012;31(2):287-96. doi: 10.4012/dmj.2011-163.

43. Kurtulmus-Yilmaz S, Önöral Ö, Aktore H, Ozan O. Does the application of surface treatments in different sintering stages affect flexural strength and optical properties of zirconia? J Esthet Restor Dent. 2020;32(1):81-90. doi: 10.1111/jerd.12552.

44. Hallmann L, Ulmer P, Wille S, Polonskyi O, Köbel S, Trottenberg T, et al. Effect of surface treatments on the properties and morphological change of dental zirconia. J Prosthet Dent. 2016;115(3):341-9. doi: 10.1016/j.prosdent.2015.09.007.

45. Çağlår I, Yamkoğlu N. The effect of sandblasting, Er:YAG laser, and heat treatment on the mechanical properties of different zirconia cores. Photomed Laser Surg. 2016;34(1):17-26. doi: 10.1089/pho.2015.3980.

46. Fiorin L, Moris ICM, Faria ACL, Ribeiro RF, Rodrigues RCS. Effect of different grinding protocols on surface characteristics and fatigue behavior of yttria-stabilized zirconia polycrystalline: an in vitro study. J Prosthet Dent. 2020;124(4):486.e1-486.e8. doi: 10.1016/j.prosdent.2020.03.016.

47. Martins SB, Trindade FZ, Góes MS, Adabo GL, Dovigo LN, Fonseca RG. Does airborne-particle abrasion before, rather than after, zirconia sintering lead to higher mechanical strength even under aging challenge? J Prosthet Dent. 2020;123(1):155-62. doi: 10.1016/j.prosdent.2018.10.022.