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Effect of Different Surface Treatment Protocols on Surface Roughness, Topography, Composition, Shear Bond Strength, and Failure Mode of Monolithic Translucent Multi-Layered Zirconia

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Abstract

This laboratory study evaluated the effect of different surface pretreatment protocols on surface roughness, surface topography, elemental composition, shear bond strength (SBS), and failure modes of two multi-layered monolithic partially stabilized zirconia materials (Katana STML and Cercon xt ML), single versus double application of an MDP-containing primer was also evaluated. The study aimed to clarify the balance between bond strength enhancement and preservation of zirconia structural integrity. A total of 160 specimens were randomly assigned to four groups: no treatment (control), Er,Cr:YSGG laser irradiation (6 W), airborne-particle abrasion (grit-blasting) with $<50\ \mu\text{m}\ \text{Al}_2\text{O}_3$, and lithium silicate coating followed by 9.5% hydrofluoric acid etching for 100 s ($n = 20$). Surface characteristics were analyzed using SEM and EDX. Specimens received either a single or a double primer application (Monobond N). Resin cement cylinders ($2\ \text{mm} \times 3\ \text{mm}$) were fabricated, stored at $37\ ^\circ\text{C}$ for 24 h, thermocycled (10,000 cycles), and tested for SBS. Failure modes were assessed microscopically. Data were analyzed using ANOVA and Welch's t-tests ($\alpha = 0.05$). Airborne-particle abrasion demonstrated the highest SBS values ($6.87 \pm 0.58\ \text{MPa}$) and ($8.87 \pm 1.74\ \text{MPa}$), whereas laser-treated groups showed the lowest ($2.73 \pm 0.31\ \text{MPa}$) and ($2.75 \pm 0.40\ \text{MPa}$) for Katana STML and Cercon xt ML, respectively. The Lithium disilicate coating and control groups had comparable intermediary values. Surface pretreatment and material type significantly influenced bond strength ($p < 0.001$) and ($p = 0.04$), respectively, while primer application was not significant. Double primer application did not

improve bond strength; although notable interaction with surface pretreatment was observed, its effect was limited.

Keywords: Monolithic zirconia; multi-layer translucent zirconia; air-abrasion; sandblasting; lithium silicate infiltrate; glass ceramic coating; Er,Cr:YSGG laser; shear bond strength; failure mode.

1. Introduction

Dental ceramics are tooth-colored restorations used extensively to restore missing parts of tooth structure. This is because of its chemical resistance, excellent aesthetics, and relatively high mechanical properties (Bacchi & Cesar, 2022). In the 1960s, dental ceramic materials were used for the veneering process of metallic substructure, multiple advancement have been made to their composition and processing techniques, that impacts the material positively on their properties and clinical uses (Bacchi & Cesar, 2022).

Yttrium stabilized tetragonal zirconia polycrystal (Y-TZP) is considered the strongest type of dental ceramics with multiple variants. Improvements in zirconia material translucency were established, with potentially compromising strength (Y. Zhang & Lawn, 2019). Zirconia restorations' layer structure may present in two forms: bilayer, with a zirconia substructure “core” and veneering porcelain (traditional); this form is subject to clinical failure due to delamination or chipping and the presence of residual thermal stress. The second form is a single layer; monolithic zirconia which differs from traditional by reducing the risk of clinical failure and providing a more aesthetic outcome without compromising the strength (Y. Zhang & Lawn, 2019).

Monolithic high translucent zirconia is a material that has both aesthetic and mechanical properties. This material is increasingly used in numerous types of indirect restorations in the field of aesthetic dentistry, such as crowns, onlays and veneers. Because of the crystalline structure of zirconia and the absence of both silica and the glassy phase, micromechanical interlocking is primarily difficult to achieve. Therefore, surface pretreatment of zirconia is considered a major element for zirconia bond durability (Liang, Yuan, Chen, & Sun, 2023).

Surface pretreatment of zirconia plays a major role in determining the surface quality for bonding (Sales et al., 2022). Effective resin bonding for dental zirconia is challenging due to its highly crystalline structure and, importantly, the absence of a glassy, etchable phase, which limits

the effectiveness of conventional chemical surface treatments (Li et al., 2020). Zirconia surfaces can be mechanically altered using diamond burs or micro-mechanically treated using air abrasion with either aluminum oxide or silica particles. It is claimed that silica particles enhance the chemical adhesion with resin cements (Yavuz et al., 2023). Air-abrasion or grit-blasting are the most common methods used for zirconia surface pretreatment, enhancing surface roughness, surface energy, and wettability. Air abrasion promotes an improvement in bonding area by producing micro-interlocking retention of resin-based dental cements (Li et al., 2020). However, some manufacturers suggested using alumina particles with a size of less than 50 μm to minimize the crystal phase transition (Li et al., 2020). Silane coupling agent containing 10-methacryloyloxydecyl hydrogen phosphate (MDP) monomer allows for chemical bonding to zirconia surface via the formation of a stable covalent bond (-P-O-Zr-), thus enhancing the adhesion between zirconia and resin cements surfaces (Li et al., 2020).

Another alternative for zirconia surface pretreatment is the irradiation with high-power lasers. This technique produces a rough surface that promotes micromechanical retention (A. O. Abdullah et al., 2020). Several laser systems that are used for zirconia surface pretreatment include carbon dioxide (CO_2), neodymium-doped yttrium aluminum garnet (Nd:YAG), and erbium-doped yttrium aluminum garnet (Er:YAG) (A. O. Abdullah et al., 2020). In general, high-powered lasers create better surface roughness; however, it causes more surface damage when compared to low-output-power lasers (A. O. Abdullah et al., 2020).

Fusion sputtering is a technique believed to increase the bond strength of zirconia, which involves coating the zirconia surface with a uniform layer of glass-ceramic material. The resulting layer can be treated like a lithium disilicate material using hydrofluoric acid. This method is claimed to enhance the bond strength and durability between the zirconia surface and the resin cement (Liang et al., 2023).

Existing research on the impact of laser treatment, compared with other surface pretreatment methods such as air-abrasion and fusion sputtering, on zirconia's shear bond strength is limited. Therefore, further investigation into the relationship between surface roughness, shear bond strength, and failure mode is warranted.

The purpose of this *in vitro* study was to evaluate the effect of different surface pretreatment protocols on surface roughness, surface topography, elemental composition, shear bond strength, and failure modes of two contemporary monolithic multi-layered zirconia systems (Katana STML,

Kuraray; Cercon xt ML, Dentsply Sirona). Unlike previous studies that primarily focus on bond strength outcomes, this study provides a combined analysis of surface characteristics, bonding performance, and failure behavior to elucidate the trade-off between adhesion enhancement and preservation of structural integrity in advanced translucent zirconia. Emphasis was placed on analyzing the independent and interactive effects of zirconia material, surface pretreatment, and primer application strategy on bonding performance and failure behavior. The null hypotheses were that (1) surface pretreatment, (2) zirconia material type, and (3) primer application strategy would have no significant effect on surface roughness, shear bond strength, or failure mode, and that (4) no significant interactions would exist among these factors.

2. Materials and Methods

2.1 Sample Preparation

Sample size was determined using the *pwr* package in R software (R package version 1.3-0). Using shear bond strength as the main outcome for the calculation, 10 samples per group would detect an effect size of 0.55 (f) with 0.80 power at $\alpha \leq 0.05$ based on the literature.

Square-shaped samples totaling 160 specimens (12 mm length & 2 mm thickness) were prepared from two partially stabilized multilayered zirconia materials: (Katana STML, Kuraray) and (Cercon xt ML, Dentsply Sirona). These specimens were sintered in a sintering furnace (Amann Girrback AG, Mader, Austria) from a few hundred °C to 1500 °C, gradually, for 8 h. After sintering, the samples were embedded using poly-vinyl-chloride (PVC) and orthodontic acryl (**Table. 1**). Each zirconia material was then randomly divided into four groups defined by surface pretreatment methodology. Following mounting and grouping, all groups were finished and then polished with 800-, 1000-, and 1200-grit silicon carbide grit paper, respectively. Surface pretreatments were applied as follows:

Group 1: Control (No surface pretreatment, only finishing and polishing).

Group 2: Er,Cr:YSGG Laser was operated in a zigzag pattern with an MZ6 tip (600 µm diameter, 6 mm length) perpendicular to the specimen surface at a fixed distance of 1 mm. The parameters used were advanced mode: power output (6.0 W), pulse mode (H), hard tissue mode, pulse repetition rate (20 Hz), and a water spray of 55% and an air pressure of 65%.

Group 3: Grit-blasting was performed using <50 µm aluminum oxide particles under a standardized pressure of 4 kg/cm². The nozzle was positioned perpendicular to the specimen

surface at a fixed distance of 10 mm and applied in a uniform sweeping motion for 10 s to ensure consistent surface treatment.

Group 4: A lithium silicate coating system (Biomic LiSi Connect, Aidite, China) was applied to the zirconia surfaces according to the manufacturer’s instructions. After surface cleaning and drying, the bottle was shaken vigorously for 1 minute to ensure homogeneous dispersion. The material was sprayed from a fixed distance of 10 mm using a controlled “z” shaped motion under light pressure, and two thin layers were applied to achieve uniform coverage. Then, samples were sintered in a fast-sintering furnace to provide a layer thickness ranging between 6-10 μm (Lab brusher) with the following parameters: the firing cycle was performed by heating from 450°C to 800 °C at a heating rate of 80°C/min, with a 1-min drying step. Vacuum was initiated at 450°C and maintained until the final vacuum temperature of 895°C was reached, which was also the maximum firing temperature. The temperature was held for 1.5 min, after which the furnace cooled to a final temperature of 700°C. A shiny surface was observed after sintering, then converted to a matte surface after hydrofluoric acid (9.5%) was applied for 100 s (Peng et al., 2022), which reflects clinically relevant adhesive protocols and allows evaluation of the balance between bonding performance and mechanical integrity. All surface treatment procedures were performed by a single trained operator to ensure consistency and minimize variability.

Table 1. Material Specification details

Material	Brand Name	Composition	Shade	Manufacture	Lot No
Partially stabilized zirconia	KATANA STML	87-92% ZrO ₂ , 8- 11% Y ₂ O ₃ , <2% other oxides	A1	Kuraray Noritake Dental, Tokyo, Japan	EMUPB
Partially stabilized zirconia	Cercon xt ML	Zirconium oxide, yttrium oxide 9%, hafnium oxide <3%, (aluminum oxide, silicone oxide, other oxides <2%)	A1	Dentsply Sirona, Charlotte, USA	18052457

Variolink Esthetic Light Cure Resin Cement	Ivoclar Vivadent	Monomer matrix: UDMA and further methacrylate monomers.	Neutral	Ivoclar Vivadent AG, Lichtenstein	ZO/744T
		Inorganic fillers: ytterbium trifluoride and spheroid mixed oxide.			
		Particle size: 0.04-0.2 µm.			
Monobond N Refill	Ivoclar Vivadent	Inorganic fillers: Approx. 38% volume	-	Ivoclar Vivadent AG, Lichtenstein	Z06F4X
		Ethanol, 3- trimethoxysilylpropyl methacrylate, 10-MDP, disulfide acrylate			
		50 µm			
aluminum oxide particles	Cobra	Aluminum oxide	-	Renfert, Germany	-
Er,Cr:YSGG laser irradiating at 6W output power at high Wattage	Waterlase (Biolase, USA)	Wavelength 2790 nm	-	Waterlase	-
Lithium silicate coating	Biomic LiSi Connect	SiO ₂ 55%-60 wt%, Li ₂ O 20%-25 wt%, Al ₂ O ₃ 7%- 10 wt%, K ₂ O 9%-12 wt%, Nb ₂ O ₅ , etc.	-	Aidite (China)	20200710

2.2 Surface Roughness

Three measurement sites were captured using a 3-D optical non-contacting profilometer (BRUKER, Karlsruhe), and then the average surface roughness value (R_a) was calculated. Samples were cleaned with distilled water for 10 min and then air-dried before reading.

2.3 Scanning Electron Microscope and Energy Dispersive X-ray

A total of five representative specimens from each group were randomly allocated using a software randomizer ($n=5$). The specimens were scanned under a scanning electron microscope (SEM) at 1000x. Two representative samples from each group were analyzed by energy-dispersive x-ray for elemental analysis.

2.4 Resin Cement Build-up

Following surface pretreatment protocols. Two materials, each comprising 80 specimens, were subjected to Monobond N (Ivoclar Vivadent AG, Lichtenstein) application. Specimens were subdivided into two groups: single (S*) and double coat (D*), $n=10$. For the single coat group, Monobond N was applied and left to react for 60 s, then air-dried. This layer is doubled with the same technique in the double coat group. A light-cured resin cement, Variolink LC (Ivoclar Vivadent AG, Lichtenstein), was used to build 2 mm-diameter and 3 mm-high cylinders using a silicone mold to control the buildup size. Each buildup was light-cured for 20 s from the top of the zirconia discs at a light intensity of 1000 mW/cm² using a standard curing mode (3G Power LED L 7 LED curing light, Miami, USA), following the manufacturer's instructions. Light intensity was calibrated every 10 irradiation cycles to ensure a consistent light-curing efficiency. Specimens were stored in distilled water and incubated for 24 h at 37°C, allowing for post-curing polymerization (**Figure. 1**).

2.5 Aging Process

Thermocycling for 10,000 cycles in distilled water between 5°C and 55°C with a dwell time of 30 s and transfer time of 5 s using the thermocycler 1100It (SD-Mechatronic, Westerham, Germany) (**Figure. 1**).

2.6 Shear Bond Strength Test

Shear bond test was carried out with a knife-edge chisel shear test using an electromechanical testing machine (Model 5965, Instron Industrial Products. Norwood, MA, USA) at a crosshead speed of 0.5 mm/min to a point of fracture (**Figure 1**). The maximum stress of the resin cement was calculated using the following formula:

$$\text{Stress (MPa)} = \text{Load (N)} / \text{Area (mm}^2\text{)}.$$

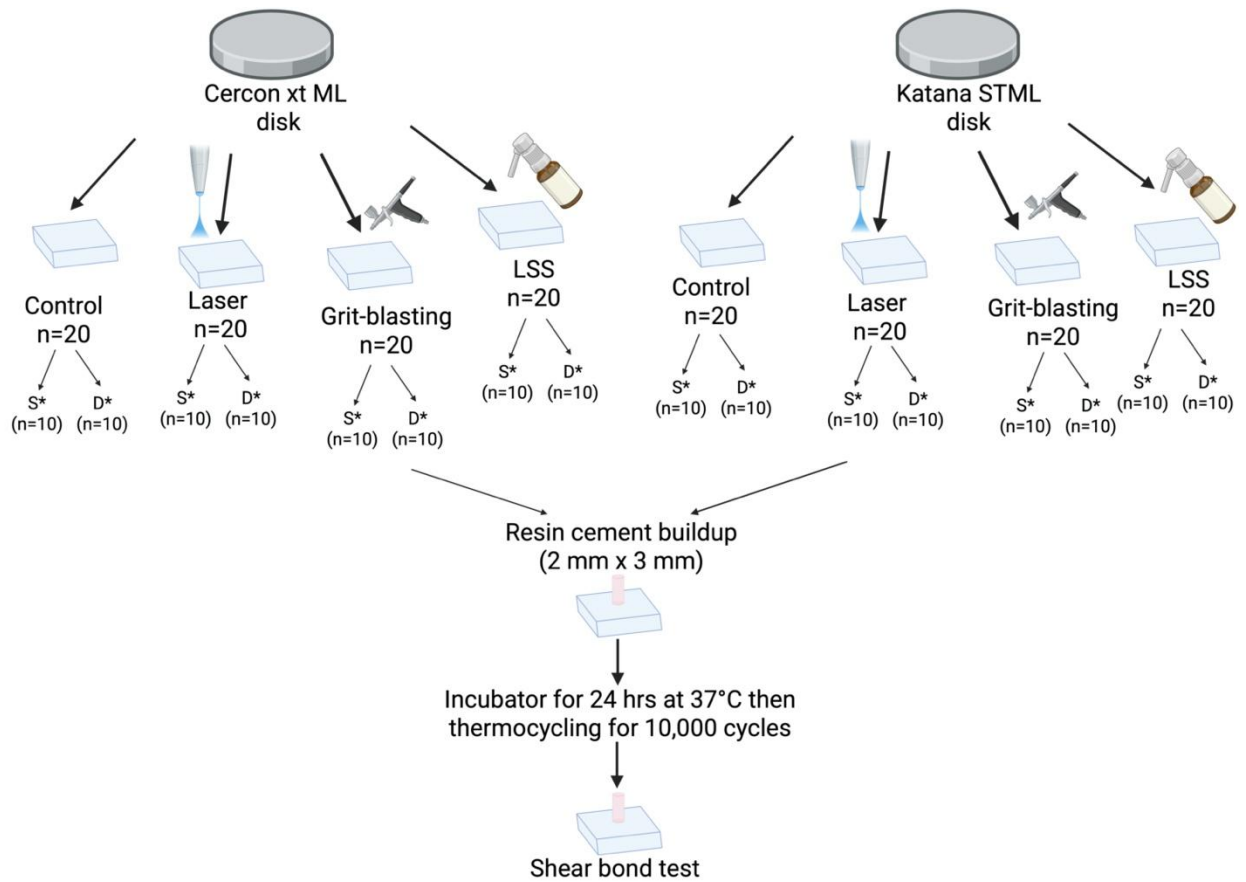


Figure 1. Schematic representation of the experimental design for shear bond strength (SBS) testing of two multi-layered zirconia materials (Cercon xt ML and Katana STML). Specimens were assigned to four surface pretreatment groups: control, Er,Cr:YSGG laser irradiation, airborne-particle abrasion (grit-blasting) with $<50 \mu\text{m Al}_2\text{O}_3$, and lithium silicate coating (LSS) ($n = 20$). Each group was subdivided into single-coat (S*) and double-coat (D*) MDP primer applications (Monobond N) ($n = 10$).

2.7 Failure Mode

After the shear bond strength test, the debonded specimens were evaluated under a Hirox digital microscope (Hirox Europe, Limonest, France) at X50 magnification to determine the type of failure; failures were categorized as adhesive, cohesive, or a combination.

2.8 Statistical Analysis

All data were analyzed using statistical software (Stata, version 17). Data normality was assessed using the Shapiro–Wilk test ($p > 0.05$). Surface roughness data were analyzed using one-way analysis of variance (ANOVA). For shear bond strength (SBS), a three-way ANOVA was conducted to evaluate the main effects and interaction among material type, surface pretreatment protocol, and coat strategy on SBS. Followed by one-way ANOVA to detect the effect of surface roughness among each material type. Tukey's *post hoc* test was applied for multiple comparisons at a significance level of $p < 0.05$. Also, independent samples t-tests (Welch's t-test, two-tailed) were used to compare SBS between the two materials under the same surface pretreatment and coating condition.

3. Results

3.1 Surface Roughness

Surface roughness (R_a) values of both Katana STML and Cercon xt ML zirconia differed markedly among the experimental groups. For Katana STML, the grit-blasted specimens exhibited the highest mean R_a value (1.2614 ± 0.0853), followed by the LSS-treated group (0.3840 ± 0.1367). In contrast, both the control (0.0919 ± 0.0805) and laser-treated groups (0.0833 ± 0.0047) demonstrated substantially lower roughness values (**Figure 2**). One-way ANOVA revealed a highly significant group effect ($F(3,36) = 380.03, p < 0.001$), and Bartlett's test indicated heteroscedasticity ($\chi^2(3) = 46.44, p < 0.001$). Bonferroni-adjusted *post hoc* test comparisons showed that grit-blasting and LSS treatments resulted in significantly higher R_a values than both the control and laser groups (all $p < 0.001$), with grit-blasting also producing significantly higher roughness than LSS ($p < 0.001$). No significant difference was detected between the control and laser groups ($p = 1.000$) (**Table 2**).

Similarly, Cercon xt ML specimens demonstrated pronounced differences in surface roughness among the experimental groups. The grit-blasted group showed the highest R_a value ($1.3354 \pm$

0.0412), followed by the LSS-treated group (0.5220 ± 0.1070). The control group exhibited the lowest roughness (0.0492 ± 0.0084), while the laser-treated group showed a slightly higher value (0.0733 ± 0.0045). One-way ANOVA confirmed a highly significant group effect ($F(3,36) = 1091.16, p < 0.001$), with Bartlett's test indicating unequal variances ($\chi^2(3) = 72.12, p < 0.001$). Bonferroni *post hoc* analyses revealed that grit-blasting and LSS treatments significantly increased R_a values compared with the control and laser groups (all $p < 0.001$), and that grit-blasting produced significantly higher roughness than LSS ($p < 0.001$). No significant difference was observed between the control and laser groups (**Table 2**).

Table 2. Surface roughness (R_a , μm) of Katana STML and Cercon xt ML zirconia across surface pretreatment groups; letter superscripts indicate differences within treatments for each material.

Treatment	Katana STML	Cercon xt ML
	R_a Mean $\pm$ (SD)	R_a Mean $\pm$ (SD)
Control	$0.0919 \pm (0.0805)^c$	$0.0492 \pm (0.0084)^c$
Laser	$0.0833 \pm (0.0047)^c$	$0.0733 \pm (0.0045)^c$
Grit-blast	$1.2614 \pm (0.0853)^a$	$1.3354 \pm (0.0412)^a$
LSS	$0.3840 \pm (0.1367)^b$	$0.5220 \pm (0.1070)^b$
ANOVA	$F(3,36) = 380.03, p < 0.001$	
		$F(3,36) = 1091.16, p < 0.001$
Bartlett's	$\chi^2(3) = 46.44, p < 0.001$	$\chi^2(3) = 72.12, p < 0.001$

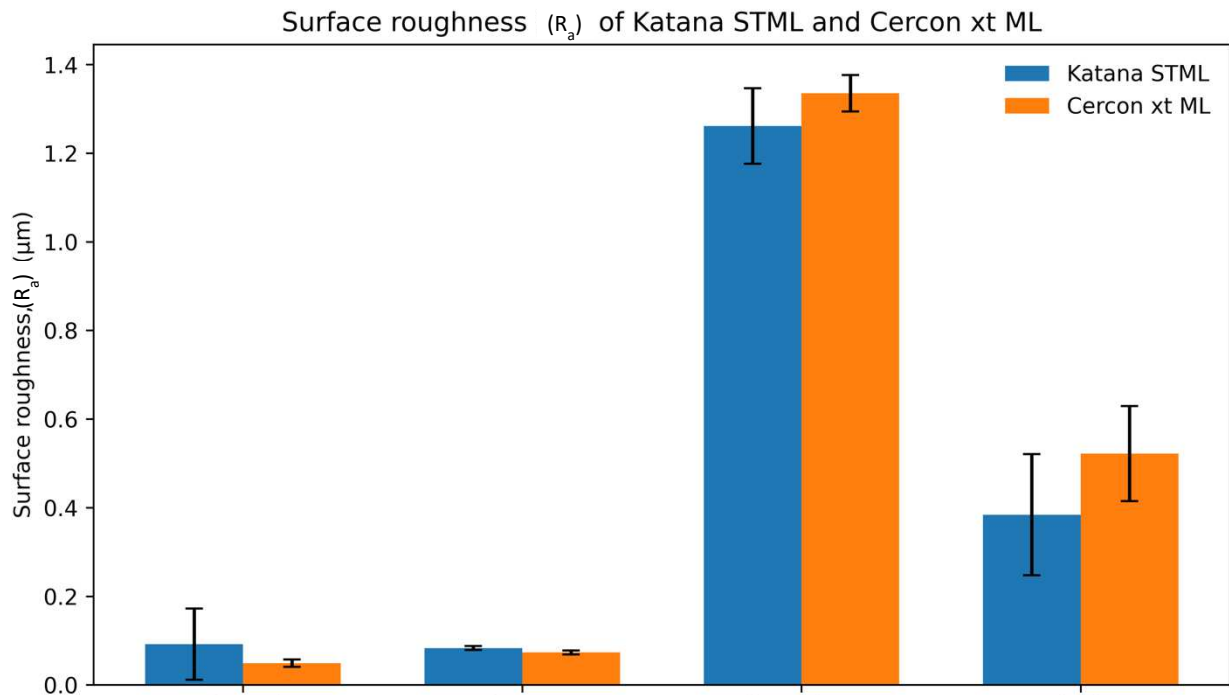


Figure 2. Surface roughness (R_a , μm) of Katana STML and Cercon xt ML zirconia following different surface pretreatment protocols: control (no treatment), Er,Cr:YSGG laser irradiation, airborne-particle abrasion (grit-blasting) with $<50\ \mu\text{m}\ \text{Al}_2\text{O}_3$, and lithium silicate coating (LSS). Bars represent mean values, and error bars indicate standard deviation.

3.2 Scanning Electron Microscope and Energy Dispersive X-ray

Through scanning electron microscopy, the surface morphologies of the experimental groups were shown to differ significantly. With very slight imperfections, the surfaces of the untreated control specimens were comparatively smooth. Specimens exposed to laser light exhibited localized changes and shallow linear grooves, consistent with partial surface ablation. The grit-blasted specimens showed surfaces that were considerably roughened, with extensive irregularities and clear flaws caused by the alumina particle residue. In Cercon xt ML, crystalline precipitates were clearly visible on the surfaces of materials treated with a lithium silicate coating. In contrast, in Katana STML, the coating had a more uniform appearance. According to these results, the surface topography was significantly influenced by the treatment strategy employed (**Figure 3**).

Energy dispersive X-ray (EDX) analysis was performed for surface elemental characterization. In the control Groups, both zirconia materials contained predominantly oxygen (O) and zirconium (Zr), which is the typical structural lattice of zirconia. Minor peaks of hafnium (Hf) and yttrium (Y) indicate the presence of stabilizers. Similarly, laser-treated specimens demonstrated no significant alteration in elemental composition compared to the control group. The EDX spectra showed predominant zirconium (Zr) and oxygen (O) peaks with minor yttrium (Y) and hafnium (Hf) components. In the grit-blasted group, both materials exhibited a significant amount of aluminum residue on the surface. Zirconium (Zr) and oxygen (O) remained the primary elements. However, lithium silicate coating groups exhibited substantial compositional changes, as evidenced by the detection of silicon (Si) and niobium (Nb) peaks and an increase in oxygen (O), which confirm the deposition of lithium silicate-based material. Differences in elemental

distribution between the two zirconia materials reflect variations in surface modification and may influence bonding behavior. A consistent glassy coating may have been present, as the intensity of the zirconium (Zr) element decreased. The surface is coated with silica-rich material due to the increased oxygen content (**Figure 4**).

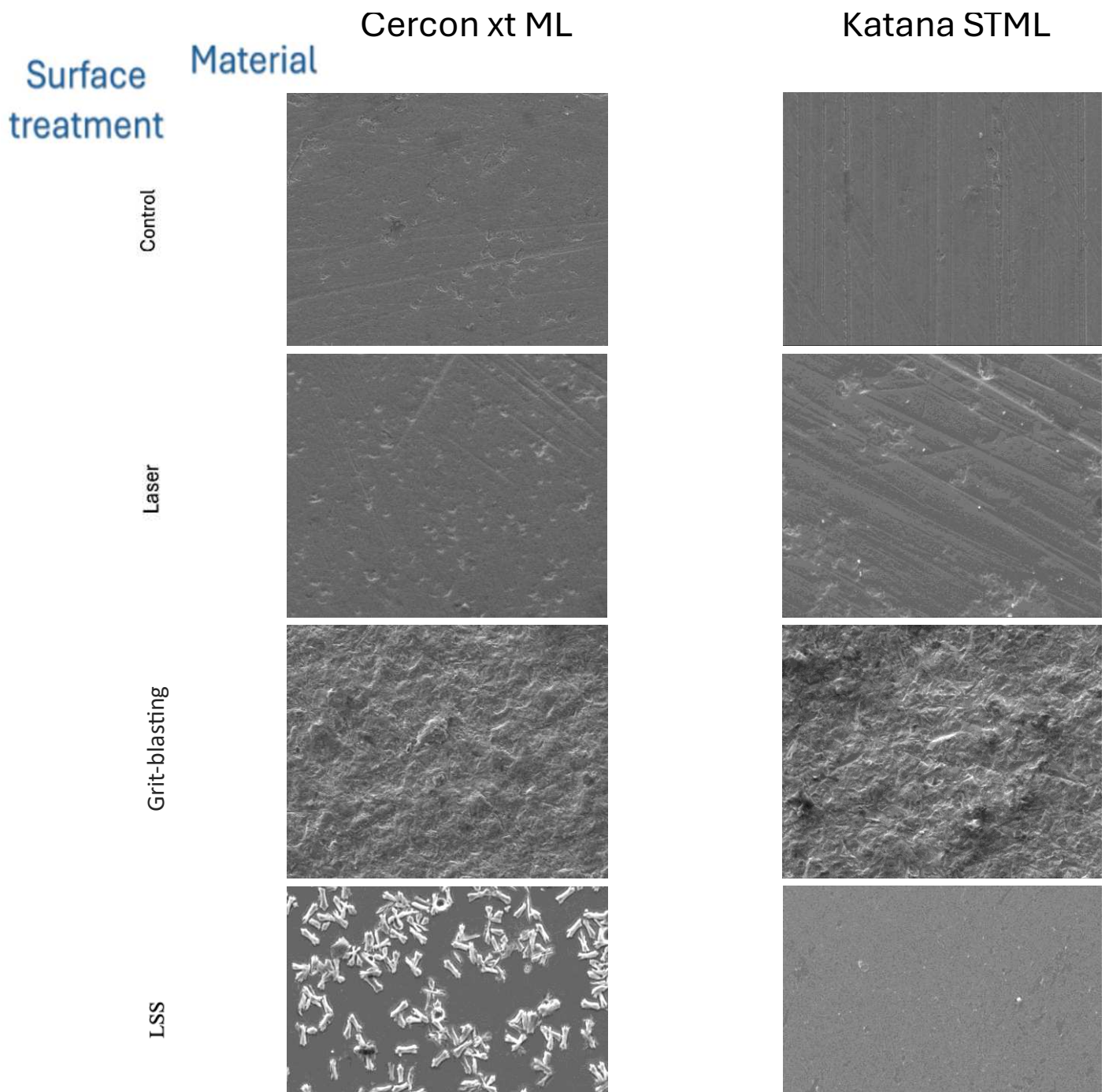


Figure 3. Representative SEM micrographs of Cercon xt ML and Katana STML zirconia surfaces following different surface pretreatment protocols: control (no treatment), Er,Cr:YSGG laser irradiation, airborne-particle abrasion (grit-blasting) with $<50\ \mu\text{m}\ \text{Al}_2\text{O}_3$, and lithium silicate coating (LSS). Control surfaces appear relatively smooth. Laser-treated surfaces exhibit localized surface alterations with irregular and non-uniform topography. Grit-blasting produces a highly roughened surface with pronounced microretentive features in both materials. LSS-treated surfaces show distinct material-dependent differences, with Cercon xt ML displaying dense needle-like crystalline deposits, while Katana STML exhibits a more uniform and less pronounced coating layer. (magnification 1000x).

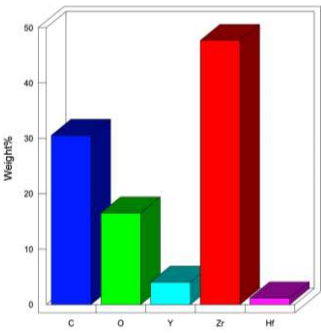
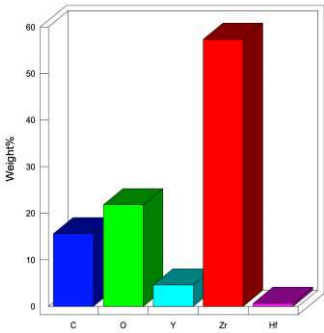
Surface
Treatment

Material

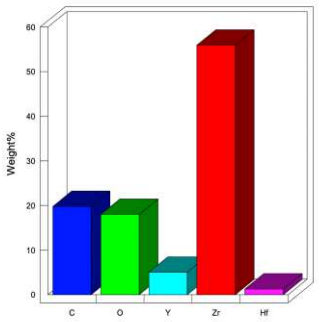
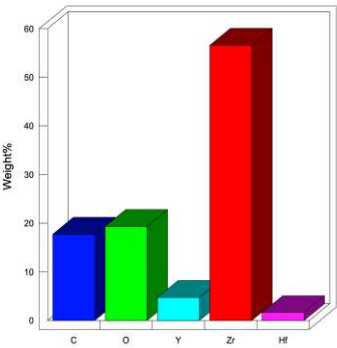
Cercon xt ML

Katana STML

Control



Laser



Grit-blasting

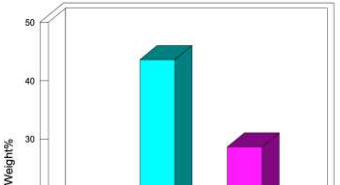
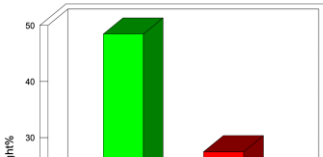
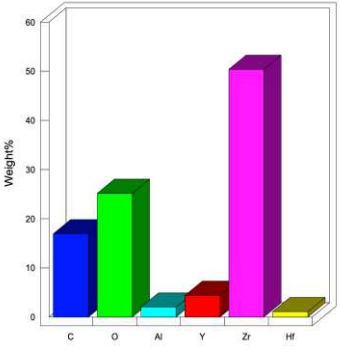
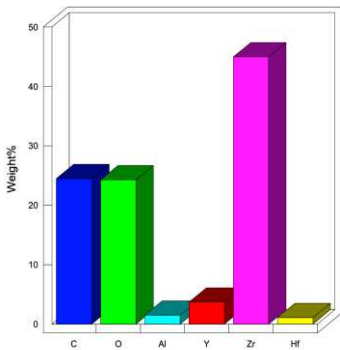


Figure 4. Elemental composition (weight %) of Cercon xt ML and Katana STML zirconia following different surface pretreatment protocols: control (no treatment), Er,Cr:YSGG laser irradiation, airborne-particle abrasion (grit-blasting) with $<50\ \mu\text{m}\ \text{Al}_2\text{O}_3$, and lithium silicate coating (LSS), as determined by energy-dispersive X-ray spectroscopy (EDX). The bar charts represent the relative distribution of carbon (C), oxygen (O), aluminum (Al), yttrium (Y), zirconium (Zr), hafnium (Hf), and niobium (Nb).

3.3 Shear Bond Strength

Three-Way ANOVA (Material $\times$ Coat $\times$ Surface Pretreatment)

A three-way ANOVA was performed to evaluate the effects of material type, coating strategy, and surface pretreatment on SBS (**Figure 5**). The overall model was significant ($F = 50.35$, $p < 0.001$). Significant main effects were observed for surface pretreatment ($F = 218.48$, $p < 0.001$) and material type ($F = 4.28$, $p = 0.0404$), whereas the main effect of coating was not statistically significant ($F = 2.17$, $p = 0.1425$).

Significant two-way interactions were detected for material $\times$ coat ($F = 13.18$, $p = 0.0004$), material $\times$ surface pretreatment ($F = 8.46$, $p < 0.001$), and coat $\times$ surface pretreatment ($F = 5.38$, $p = 0.0015$). Importantly, a significant three-way interaction among material, coat, and surface pretreatment was also observed ($F = 12.88$, $p < 0.001$), indicating that the influence of surface pretreatment on SBS depended on both the zirconia material and the coating protocol.

Partial eta squared (η^2p) values were calculated from the ANOVA sums of squares to quantify the magnitude of each effect. Effect size analysis (partial η^2) revealed that surface pretreatment exerted the strongest influence ($\eta^2p = 0.8199$), followed by the three-way interaction ($\eta^2p = 0.2116$), material $\times$ surface interaction ($\eta^2p = 0.1499$), and coat $\times$ surface interaction ($\eta^2p =$

0.1008). These results highlight the primary role of surface pretreatment, with secondary contributions from interactions between material and application variables. **(Figure 5)**

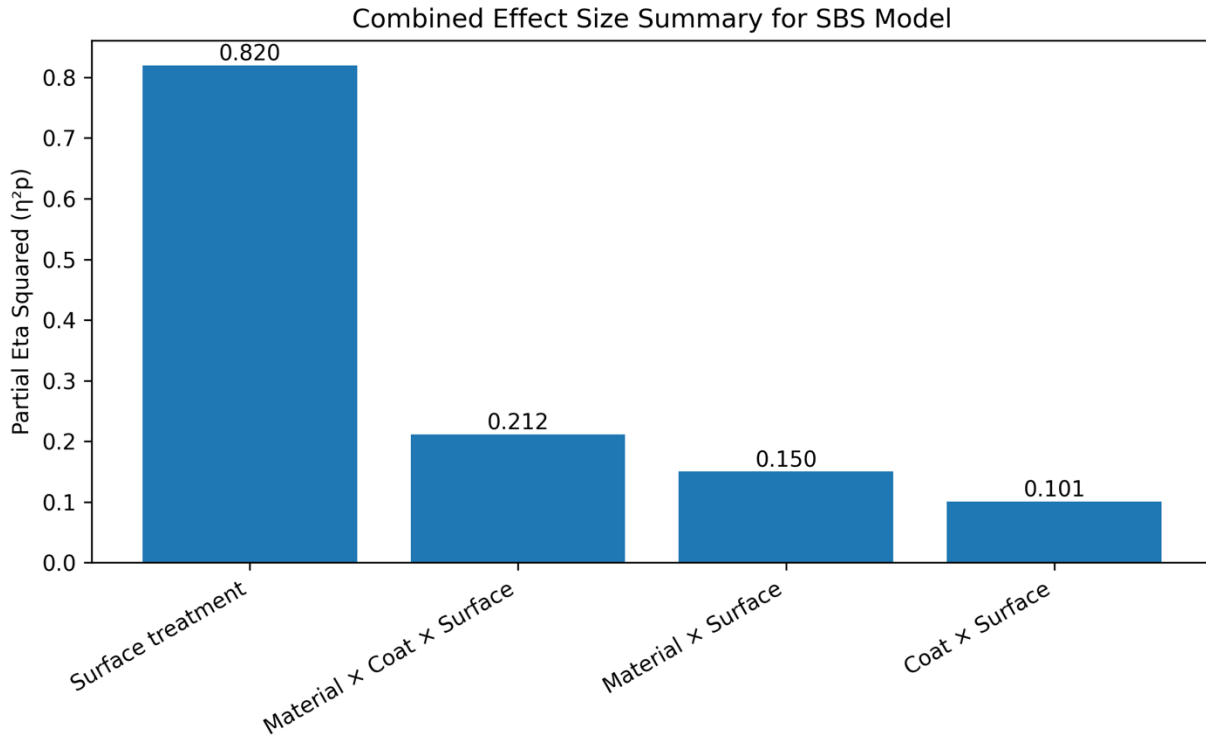


Figure 5. Effect size estimates expressed as partial eta squared (η^2p) for the three-way ANOVA model evaluating shear bond strength (SBS). The factors included surface pretreatment, material type (Cercon xt ML and Katana STML), primer application (single vs. double coat), and their interactions. Surface pretreatment exhibited the largest effect on SBS ($\eta^2p = 0.820$), indicating its dominant influence on bonding performance. This was followed by the three-way interaction (material $\times$ coat $\times$ surface), material $\times$ surface interaction, and coat $\times$ surface interaction, all demonstrating smaller but notable contributions.

One-Way ANOVA Within Each Material after Single Coat Application

Shear bond strength (SBS) values of both Katana STML and Cercon xt ML zirconia differed significantly among the experimental groups. For Katana STML, the grit-blasted specimens exhibited the highest mean SBS value (6.87 ± 0.58), followed by the LSS-treated group (5.28 ± 1.21). The control group demonstrated a moderate SBS value (4.49 ± 0.57), whereas the laser-treated group showed the lowest mean SBS value (2.73 ± 0.31) **(Figure 6)**. One-way ANOVA revealed a highly significant group effect ($F(3,36) = 53.57, p < 0.001$), and Bartlett's test indicated heteroscedasticity ($\chi^2(3) = 15.90, p = 0.001$). Bonferroni-adjusted *post hoc* test comparisons

demonstrated that grit-blasting resulted in significantly higher SBS values compared to both the control and laser groups, and that the LSS-treated and control groups showed significantly higher SBS than the laser group. However, no significant difference was observed between the LSS and control groups (**Table 3**).

Similarly, Cercon xt ML specimens exhibited pronounced differences in SBS among the experimental groups. The grit-blasted group showed the highest SBS value (8.87 ± 1.74), followed by the LSS-treated group (6.04 ± 0.70). The control group displayed a moderate SBS value (5.02 ± 0.93), whereas the laser-treated group showed the lowest SBS (2.75 ± 0.40). One-way ANOVA confirmed a highly significant group effect ($F(3,36) = 56.84, p < 0.001$), with Bartlett's test indicating unequal variances ($\chi^2(3) = 17.88, p < 0.001$). Bonferroni *post hoc* analyses revealed that grit-blasting significantly increased SBS compared with all groups, whereas laser treatment significantly decreased SBS compared with all groups. No significant difference was found between the LSS and control groups (**Table 3**).

Table 3. Shear bond strength (SBS) of Cercon xt ML and Katana STML across surface pretreatment groups with single-coat application; letter superscripts show differences within treatments for each material.

	Katana STML (mean $\pm$ SD)	Cercon xt ML
Control	$4.49 \pm (0.57)^b$	$5.02 \pm (0.93)^b$
Laser	$2.73 \pm (0.31)^c$	$2.75 \pm (0.40)^c$
Grit-blast	$6.87 \pm (0.58)^a$	$8.87 \pm (1.74)^a$
Lithium-silicate spray LSS	$5.28 \pm (1.21)^b$	$6.04 \pm (0.70)^b$
ANOVA	$F(3,36) = 53.57, p < 0.001$	$F(3,36) = 56.84, p < 0.001$
Bartlett's	$\chi^2(3) = 15.90, p = 0.001$	$\chi^2(3) = 17.88, p < 0.001$

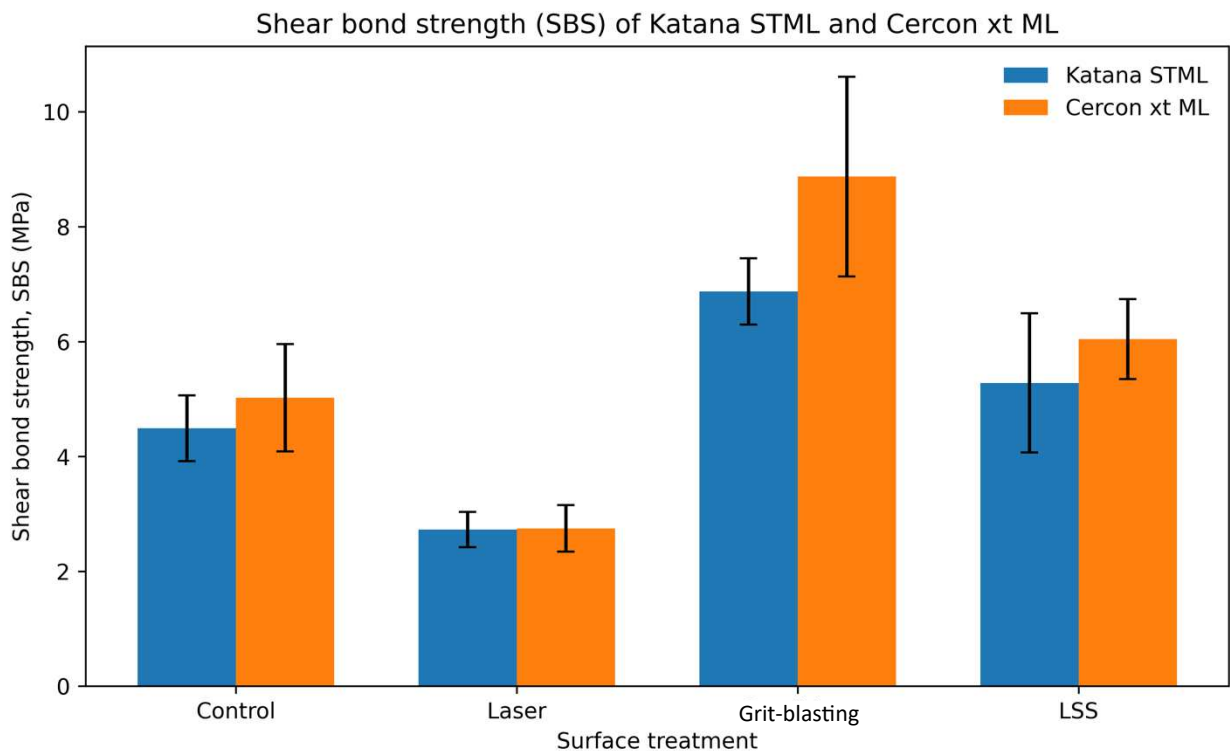


Figure 6. Shear bond strength (SBS, MPa) of Cercon xt ML and Katana STML zirconia following different surface pretreatment protocols: control (no treatment), Er,Cr:YSGG laser irradiation, airborne-particle abrasion (grit-blasting) with $<50\ \mu\text{m}\ \text{Al}_2\text{O}_3$, and lithium silicate coating (LSS), after single-coat application of an MDP-containing primer. Bars represent mean values, and error bars indicate standard deviation.

Independent samples t-tests

Independent samples t-tests compared shear bond strength (SBS) between Cercon xt ML and Katana STML within each surface pretreatment and coating condition (**Table 4**).

For single-coat specimens, no significant material differences were found in the control ($p = 0.144$), laser-treated ($p = 0.901$), or LSS-treated groups ($p = 0.105$). However, under grit-blasting, Cercon xt ML showed significantly higher SBS than Katana STML (8.87 ± 1.74 vs. 6.87 ± 0.58 MPa; $p = 0.005$).

For double-coat specimens, material-dependent differences were observed in several groups. No significant difference was found in the control group ($p = 0.083$). Katana STML

demonstrated significantly higher SBS in the laser-treated ($p = 0.017$) and grit-blasted groups ($p = 0.001$), whereas Cercon xt ML showed significantly higher SBS in the LSS-treated group ($p = 0.001$).

Overall, the effect of material on SBS depended on the surface pretreatment and coating protocol, consistent with the significant interaction effects found in the three-way ANOVA.

Table 4. Comparison of shear bond strength (SBS; mean $\pm$ SD) between Cercon xt ML and Katana STML for each coating protocol and surface pretreatment. Independent samples *t*-tests were used. $p < 0.05$ indicates significant differences (*).

Coat	Surface	Cercon xt ML (Mean $\pm$ SD)	Katana STML (Mean $\pm$ SD)	t-value	df	p-value
Single coat	Control	5.02 $\pm$ 0.93	4.49 $\pm$ 0.57	1.5441	14.9181	0.1435
Single coat	Laser	2.75 $\pm$ 0.40	2.73 $\pm$ 0.31	0.1269	16.7852	0.9005
Single coat	SB	8.87 $\pm$ 1.74	6.87 $\pm$ 0.58	3.4526	10.954	0.0054*
Single coat	LSS	6.04 $\pm$ 0.70	5.28 $\pm$ 1.21	1.7299	14.3652	0.1051
Double coat	Control	3.19 $\pm$ 0.67	3.89 $\pm$ 0.99	-1.8527	15.9001	0.0826
Double coat	Laser	2.56 $\pm$ 0.30	3.42 $\pm$ 0.92	-2.8301	10.8555	0.0166*
Double coat	SB	7.04 $\pm$ 1.07	8.65 $\pm$ 0.67	-4.0234	15.1691	0.0011*
Double coat	LSS	6.92 $\pm$ 1.53	4.66 $\pm$ 0.71	4.2433	12.6573	0.001*

Independent samples t-tests

Independent samples *t*-tests compared shear bond strength (SBS) between Cercon xt ML and Katana STML within each surface pretreatment and coating condition (**Table 4**).

3.4 Failure Mode

The distribution of failure modes was predominantly influenced by surface pretreatment and zirconia type, with minimal variation attributable to the number of coating applications (**Figure 7 & 8**). For both Katana STML and Cercon xt ML zirconia, the control and laser-treated groups were characterized predominantly by adhesive failures, irrespective of the coating strategy. In Katana STML, 100% of failures were adhesive. Similarly, Cercon xt ML specimens exhibited mainly adhesive failures, with 90% adhesive and 10% mixed failures in the control single-coat subgroup, and 100% adhesive failures in all remaining control and laser-treated subgroups.

In contrast, the grit-blasted groups showed a notable shift toward mixed and cohesive failure patterns. In Katana STML, 90% of failures were mixed and 10% were cohesive for both single- and double-coat protocols. For Cercon xt ML, the single-coat SB subgroup exhibited 80% mixed and 20% cohesive failures. In contrast, the double-coat subgroup showed a higher proportion of cohesive failures (60%), with the remaining 40% being mixed. This trend suggests improved interfacial bonding following grit-blasting, particularly when combined with a double-coating protocol.

The lithium silicate coating (LSS) groups demonstrated exclusively cohesive failures (100%) for both zirconia materials and coating strategies.

Surface
Treatment
with single
coat primer

Material

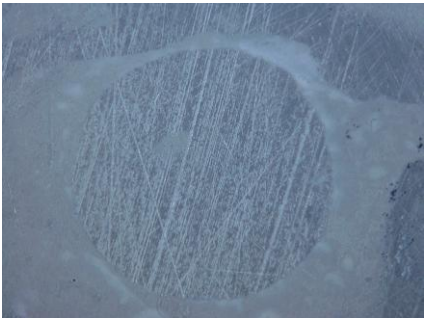
Cercon xt ML

Katana STML

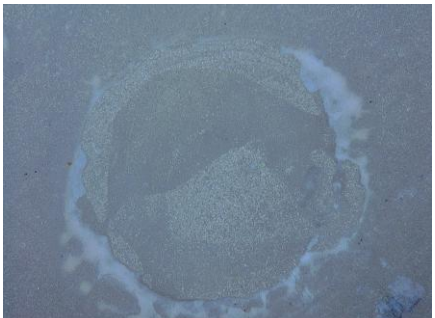
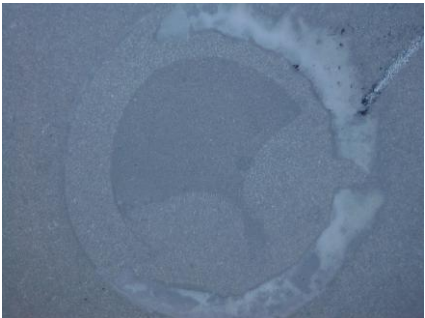
Control



Laser



Grit-blasting



LSS

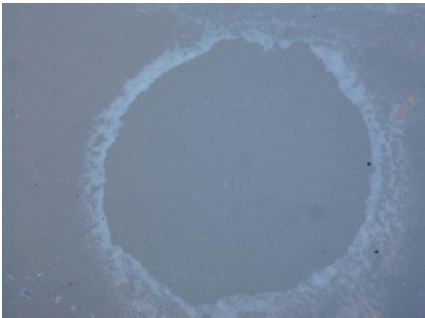


Figure 7. Representative failure modes observed after shear bond strength (SBS) testing of Cercon xt ML and Katana STML zirconia specimens following different surface pretreatment protocols (control, Er,Cr:YSGG laser irradiation, airborne-particle abrasion (grit-blasting), and lithium silicate coating (LSS)) with single-coat application of an MDP-containing primer (Monobond N). Control and laser-treated groups predominantly exhibit adhesive failures at the zirconia–resin interface. In contrast, grit-blasted and LSS-treated specimens exhibit increased mixed-failure patterns.

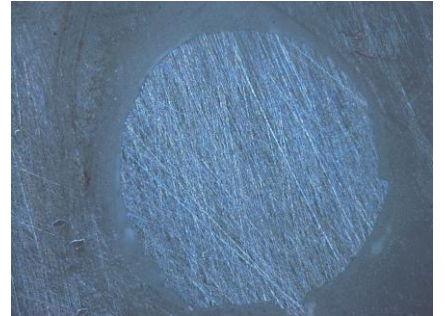
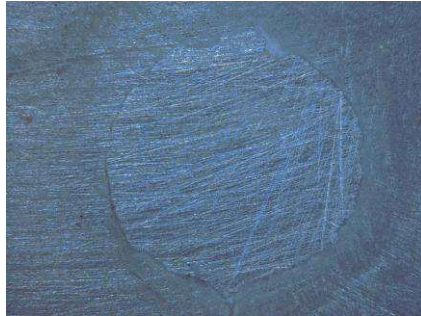
Surface
Treatment
with double
coat primer

Material

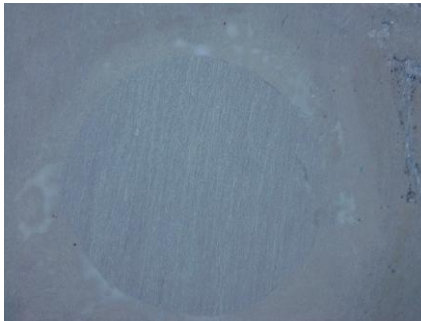
Cercon xt ML

Katana STML

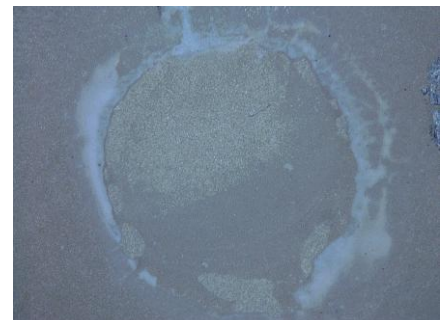
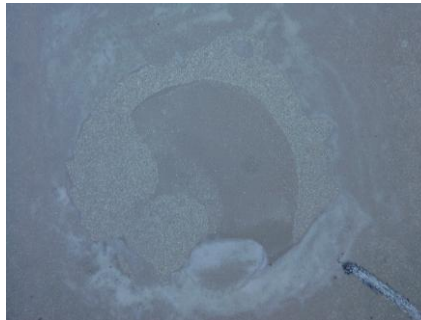
Control



Laser



Grit-blasting



LSS

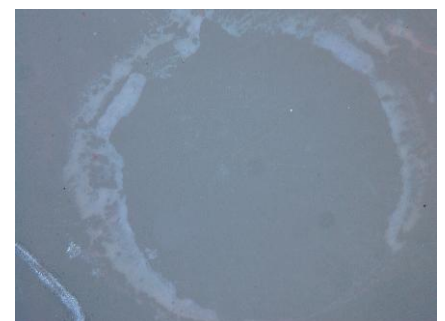


Figure 8. Representative failure modes observed after shear bond strength (SBS) testing of Cercon xt ML and Katana STML zirconia specimens following different surface pretreatment protocols (control, Er,Cr:YSGG laser irradiation, airborne-particle abrasion (grit-blasting), and lithium silicate coating (LSS)) with double-coat application of an MDP-containing primer (Monobond N). Control and laser-treated groups predominantly exhibit adhesive failures at the zirconia–resin interface. In contrast, grit-blasted and LSS-treated specimens exhibit increased mixed-failure patterns. The overall failure mode distribution is comparable to that observed with single-coat application.

4. Discussion

The present study aimed to evaluate how different surface pretreatment protocols (control, laser irradiation, grit-blasting, and lithium silicate coating) influence the balance between surface modification and bonding performance of two multi-layered partially stabilized zirconia materials (Katana STML, Kuraray Noritake, and Cercon xt ML, Dentsply Sirona). Surface roughness, morphology, and elemental composition were analyzed to elucidate the underlying micromechanical and chemical changes induced by each treatment. These surface characteristics were then correlated with shear bond strength and failure modes to provide a mechanistic understanding of zirconia–resin adhesion. The first and second null hypotheses were rejected because significant differences were observed in surface characteristics, bond strength, and elemental composition across the different pretreatment protocols and materials. In addition, the fourth null hypothesis, concerning the interaction effect between primer application and surface pretreatment, was also rejected. Although this interaction was statistically significant, its effect size was relatively small compared with the dominant influence of surface pretreatment, and no consistent improvement in bond strength was observed with double-coat application across most groups, suggesting limited practical significance.

The surface roughness findings demonstrated pronounced differences among the evaluated surface pretreatment protocols, with grit-blasting and lithium silicate coating (LSS) producing significantly rougher topographies compared with the control and laser-treated surfaces. This increase in surface roughness is attributed to the formation of micro-retentive features and

irregularities that enhance micromechanical interlocking with resin-based materials. Previous studies have similarly reported that airborne-particle abrasion using alumina particles increases surface roughness by inducing plastic deformation, grain pull-out, and microcrack formation, thereby improving surface energy and wettability with increase aluminum content (Łagodzińska, Dejak, Krasowski, & Konieczny, 2023). The high surface roughness values recorded for Cercon xt ML following LSS treatment correspond to the presence of dense crystalline precipitates, irregular clusters, and heterogeneous surface features. These surface deposits likely increased both the arithmetic roughness (R_a) and the peak-to-valley amplitude (R_z), indicating enhanced micro-retentive potential. In contrast, Katana STML exhibited comparatively lower roughness values and a more uniform topography, consistent with SEM images showing fewer surface precipitates and a smoother zirconia matrix. This behavior may be related to its multilayered gradient structure and varying yttrium distribution, which may restrict uniform chemical interaction with the lithium silicate layer and limit extensive surface crystallization.

On the other hand, laser-treated specimens exhibited relatively smoother and more heterogeneous surfaces, which may be associated with localized melting and re-solidification of the zirconia surface (Craciun et al., 2002). Although laser irradiation has been proposed as a non-contact surface conditioning method, its effects remain highly dependent on the irradiation parameters, and excessive thermal input may result in surface vitrification rather than effective roughening (Bitencourt et al., 2021). This explains the inferior bonding performance observed in the laser-treated groups in the present study.

Laser surface treatment of zirconia is highly dependent on the type of laser and irradiation parameters, including energy density, pulse duration, and frequency. Different laser systems, such as Er:YAG, Nd:YAG, CO₂, and Er,Cr:YSGG, have been reported to produce distinct surface morphologies and bonding outcomes (Souza et al., 2023). While some studies have shown bond strength values comparable to or higher than grit-blasted surfaces under optimized conditions, others have reported no improvement or even reduced bonding performance, highlighting the variability of laser-zirconia interactions. For instance, Nd:YAG laser irradiation at higher energy levels has been associated with improved bond strength, whereas lower-energy settings may yield results similar to those of conventional surface treatments (Akin, Tugut, Topcuoglu, & Kirmali, 2013). In contrast, Er,Cr:YSGG laser treatment may induce surface melting and re-solidification, resulting in irregular topography that does not consistently enhance micromechanical

retention (Ozevcimen & Kirmali, 2019). Therefore, the lower bond strength observed in the present study may be attributed to the specific laser parameters used rather than the laser treatment itself.

SEM and EDX analyses were used to characterize the surface modifications induced by different pretreatment protocols and to relate these changes to bonding performance. The observed differences in surface morphology between the two zirconia materials, despite identical lithium silicate coating (LSS) treatment, suggest a material-dependent response to surface modification. Cercon xt ML exhibited a dense distribution of needle-like crystalline deposits, whereas Katana STML showed a smoother and less densely precipitated surface. These morphological differences likely influenced resin infiltration and micromechanical interlocking, contributing to the relatively higher bond strength observed for Cercon xt ML.

The LSS-treated surfaces demonstrate increased silicon- and oxygen-related components, indicating the formation of a silica-based coating layer that improved bonding performance, as confirmed by EDX analysis. This silica-based coating enables silane-mediated chemical adhesion in addition to micromechanical retention. This dual bonding mechanism contrasts with untreated and laser-treated surfaces, where the absence of a reactive silica phase limits chemical interaction. However, the effectiveness of this approach depends on controlled surface modification, as excessive alteration may introduce defects or affect phase stability, potentially compromising long-term durability. The long-term performance of zirconia-resin bonding in LSS-treated groups, depends not only on initial bond strength but also on its hydrolytic stability under oral conditions (Lung & Matinlinna, 2012).

Furthermore, while LSS provided a favorable balance between surface modification and bonding enhancement, laser-treated surfaces exhibited lower bond strength, which may be explained by irregular topography and localized melting observed in SEM images. Such features can hinder uniform resin penetration and reduce effective bonding area. Therefore, the bond strength outcomes in this study can be directly linked to the nature and quality of surface modifications, highlighting that both micromechanical and chemical interactions must be optimized to achieve durable zirconia-resin adhesion (Poulon-Quintin et al., 2021; Shen et al., 2023).

Cercon xt ML, with a higher yttrium content of ≥ 5 mol percent Y_2O_3 (9 wt%), exhibits a greater proportion of cubic phase and a reduced potential for tetragonal-to-monoclinic transformation

(Sato, Yamada, Pezzotti, Nawa, & Ban, 2008; Yu Zhang & Lawn, 2017). By lowering grain-boundary energy and increasing the surface diffusion of silica-containing species during firing, the higher cubic content encourages the nucleation and crystallization of lithium disilicate or lithium meta. Katana STML exact wt% or mol% of yttrium is not explicitly provided in the company's public brochures; functionally, it behaves as a high-translucent multi-layer Y-TZP formulated for a balance of esthetics and strength. However, the Y_2O_3 content of STML appears to be lower, with some authors citing 8.15 wt% yttrium (Bruhnke, Awwad, Müller, Beuer, & Schmidt, 2023).

Shear bond strength was also assessed in this study. Grit-blasting produced the highest shear bond strength among all surface pretreatment groups for both zirconia materials, followed by lithium silicate coating (LSS), while the control had an intermediate value, and the laser groups consistently produced the lowest values. SB's ability to produce significant micromechanical retention and raise surface energy for MDP-based bonding is consistent with its superior performance (Abdou, Hussein, Kusumasari, Abo-Alazm, & Rizk, 2023). LSS enhanced bonding in comparison to the control and laser by moderate roughening and forming a thin layer of silica that allows silane coupling. This layer is an added ceramic layer which is amiable to etching by HF, allowing for selective glass matrix dissolution (Kang et al., 2022). As a result, LSS improves wettability and interfacial chemistry but falls short of SB's micromechanical interlocking, which explains its intermediate bond strengths. Of note, cohesive bond failure within the luting resin layer was predominant (100%) for LSS treated zirconia; this uniform cohesive failure pattern could possibly indicate a stronger bond between the luting cement and acid etched lithium silicate layer, which surpasses the cohesive strength of the luting cement, reflecting superior bonding performance associated with the LSS surface pretreatment.

Overall, surface pretreatment had a pronounced effect on the mode of failure. Adhesive failures predominated in untreated and laser-treated groups, whereas more aggressive or chemically active surface pretreatments (SB and LSS) promoted mixed and cohesive failures. The progressive shift from adhesive to cohesive failure modes reflects enhanced interfacial integrity, with LSS producing the most favorable bonding behavior among all tested conditions. This reflects improved micromechanical interlocking and chemical bonding. The distribution of failure modes corresponds with the observed differences in bond strength among surface pretreatment groups.

Specimens treated with the Er,Cr:YSGG laser exhibited the lowest shear bond strength values among all groups, with adhesive failure. While laser irradiation can produce localized ablation and

micro-grooving, which can improve surface roughness to a certain degree, its impact was not strong enough to increase bonding efficacy in this study. According to previous articles, the laser process primarily causes ablation and modification of the surface topography without promoting noteworthy phase transformation or micromechanical interlocking, which may account for the observed weak adhesion (Craciun et al., 2002; Han et al., 2021). Furthermore, Jauregui-Ulloa *et al* reported that laser treatment resulted in local energy concentration on the zirconia surface leading to localized melting and rapid re-solidification, causing smooth melted areas and microcracks on the zirconia surface. These changes could account for the reduced roughness and bond strength with this treatment (Jauregui-Ulloa et al., 2025). The effectiveness of laser surface modification depends on variables such as output power, wavelength, pulse duration, and spot overlap. These factors may explain the inconsistent results reported in the literature (H. Abdullah, Abdulsamee, Farouk, & Saba, 2024; Ergun Kunt & Duran, 2018).

Control specimens showed the second lowest bond strength and exhibited mainly adhesive failures. This indicates that zirconia's lack of a silica phase and low surface energy limit its chemical reactivity (Yoshida, Tsuo, & Atsuta, 2006). Consequently, the poor adhesion observed underscores the necessity for surface modification, either chemical or mechanical, prior to bonding. Surface microcracks and tetragonal-to-monoclinic (t→m) transformation may weaken the near-surface layer. Grit-blasting increased surface roughness but produced decreased or inconsistent bond strength (Sato et al., 2008). Even though micromechanical retention was improved, the majority of adhesive or mixed failures seen in this group can be explained by high stress concentrations weakening interfacial durability (Inokoshi et al., 2021; Yoshida, 2020).

In support of the quantitative findings, failure mode analysis showed that adhesive failures were more common in the control and laser groups, whereas cohesive and mixed failures were more common in groups with higher SBS values (SB and LSS).

The purpose of ceramic primers is to improve the SBS between ceramics and resin cements. Primers containing phosphoric acid monomers react with resin cements by chemically bonding to metal oxides like zirconium dioxide and other ends of the double bond (Saleh, Guven, Yildirim, & Erol, 2019). Zirconia primers contain organofunctional monomers with a bifunctional structure that enables bonding between zirconia and resin materials. These monomers typically consist of three components: (i) a polymerizable functional group (PG) that copolymerizes with resin monomers during polymerization, (ii) an adhesion-promoting group (AG), such as phosphate or

carboxylate groups, that chemically binds to the zirconia surface, and (iii) a connecting group that links the PG and AG, facilitating the formation of a stable chemical bridge between the substrate and the resin matrix. (Klaisiri et al., 2022; Lung & Matinlinna, 2012).

The results of the current study showed that the main effect of coating was not statistically significant, therefore, the third null hypothesis was accepted. However, the number of primer coat applications could affect the formation of a durable, stable bond between the two surfaces. A single layer of zirconia primer may result in partial surface coverage, leaving unreacted or unevenly distributed functional monomers on the zirconia substrate (Klaisiri et al., 2022; Saleh et al., 2019). In contrast, double coating likely promotes more uniform wetting and facilitates improved penetration of phosphate monomers such as 10-MDP into micro-irregularities created by surface pretreatments (Saleh et al., 2019). The adhesion-promoting group (AG), particularly the phosphate functional group of MDP-containing primers, chemically interacts with hydroxyl groups on the zirconium oxide surface to form stable zirconium–phosphate (Zr–O–P) bonds; a second application may further enhance this chemisorption, potentially improving the durability of the resin–zirconia interface (Lung & Matinlinna, 2012; Nagaoka et al., 2017).

Previous studies consistently reported that increasing the concentration or exposure time to MDP-based primers enhances chemical adhesion by promoting more complete monolayer formation. The improved coupling effect observed with double coating in these studies may also result from reduced solvent residue after the first application, which ensures better polymerization and cross-linking during resin cement curing (Opatragoon, Klaisiri, Sriamporn, & Thamrongananskul, 2024). In contrast, while a second primer application might improve surface wetting and facilitate the distribution of phosphate monomers, it may also introduce an additional interfacial layer that could act as a weak link due to its potentially brittle nature. In the present study, double application did not result in a significant improvement in bond strength, suggesting that a single primer application may be sufficient to achieve effective adhesion. This finding could suggest that a standard single primer layer may provide sufficient functional monomer saturation and chemical bonding to zirconia, particularly when the surface is adequately activated by treatments such as grit-blasting or lithium silicate coating. Also, the absence of a significant difference may be attributed to the formation of the thin and highly reactive nature of modern universal primers, which contain ameliorated concentration of MDP and solvents that facilitate rapid and uniform spreading. Consequently, the effectiveness of standard or double coating may

depend on the primer formulation, zirconia microtopography, and the degree of surface energy achieved after pretreatment. When the zirconia surface is optimally conditioned, the standard primer application may achieve complete surface coverage and stable phosphate bonding, rendering additional layers unnecessary. Such findings have been reported by Russo *et al* (Scaminaci Russo, Cinelli, Sarti, & Giachetti, 2019), who noted that further MDP application does not significantly enhance bond strength due to the self-limiting nature of monolayer chemisorption, which is established by a certain threshold.

The fourth null hypothesis, which proposed that no significant interactions would exist among surface pretreatment, material type, and primer application strategy, was rejected. Although statistically significant interaction effects were identified, their contribution to bonding performance was notably smaller than the primary effect of surface pretreatment. The three-way interaction (material $\times$ coat $\times$ surface) demonstrated a moderate influence, while the material $\times$ surface and coat $\times$ surface interactions showed comparatively lower effects. This suggests that the response of zirconia to primer application and material variation is influenced by the type of surface modification; however, these interactions do not override the dominant role of surface pretreatment. In particular, the interaction involving primer application did not translate into a consistent improvement in bond strength with double-coat application across most groups, indicating limited practical relevance. Therefore, while interaction effects exist, their clinical significance appears secondary to the primary influence of surface pretreatment in determining zirconia–resin adhesion.

The findings of the present study highlight a clinically relevant trade-off between adhesion enhancement and surface alteration induced by different pretreatment strategies. While grit-blasting improved bond strength through increased surface roughness and micromechanical interlocking, it may also introduce surface defects. In contrast, lithium silicate coating provided favorable bonding with potentially less surface damage, whereas laser treatment resulted in inferior bonding performance, likely due to its ablative effect and inconsistent surface modification. These observations emphasize that optimizing zirconia bonding requires balancing micromechanical retention with preservation of surface integrity.

This study has several limitations. The use of shear bond strength (SBS) testing, although widely adopted, is associated with non-uniform stress distribution and limited correlation with clinical performance; alternative methods such as micro-tensile bond strength testing or fatigue-

based loading may provide more reliable evaluation of interfacial behavior. Aging was limited to thermocycling, which may not fully replicate long-term intraoral conditions; extended water storage (e.g., 3–6 months) and cyclic mechanical loading should be considered in future studies. In addition, lithium silicate coating techniques may introduce a weak interfacial layer or variability in coating thickness. At the same time, laser surface treatment outcomes remain highly dependent on irradiation parameters and may induce surface damage or microcracks. Therefore, the results should be interpreted with caution, and further investigations are required to validate long-term performance. Future studies should evaluate the long-term durability of zirconia–resin bonding under extended aging and cyclic loading, as well as the influence of different laser parameters on surface modification. Clinical studies are also needed to confirm the applicability of these findings.

5. Conclusions

Grit-blasting produced the highest shear bond strength for both Katana STML and Cercon xt ML, followed by lithium silicate coating, whereas laser treatment resulted in the lowest values. Double primer application did not significantly improve bond strength compared with a single application across most surface pretreatments. Cercon xt ML generally exhibited higher bond strength values than Katana STML, indicating a material-dependent effect. These findings provide insight into the balance between adhesion enhancement and potential surface modification effects associated with different pretreatment strategies.

Author Contributions:

- (A.A.) (PhD candidate) Had primary responsibility for this study, including conceptualization and study design, execution of all experimental procedures, data collection, statistical analysis, interpretation of results, preparation of figures and tables, and writing of the original manuscript draft.
- (N.S.) Contributed to methodological development, supported data interpretation, and reviewed and edited the manuscript.
- (H.A.) Provided overall supervision of the research, contributed to study design refinement, offered scientific and academic guidance, and critically revised the manuscript for important intellectual content.

All authors reviewed, provided feedback, and approved the final version of the manuscript.

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Data Availability Statement: All data generated or analyzed during this study are included in this published article. The raw data and results of statistical analysis are available upon request from corresponding author.

Acknowledgments: This study was registered and approved by the College of Dentistry Research Center (registration number: PR 0169). This manuscript is part of a DScD dissertation. Generative artificial intelligence (GenAI) tools were used solely to assist in the generation of illustrative figures and graphical representations. No GenAI tools were used in study design, data collection, data analysis, data interpretation, or generation of scientific conclusions. All figures were reviewed and validated by the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Clinical trial number: Not applicable.

Consent to Publish: Not applicable.

Abbreviations

The following abbreviations are used in this manuscript:

Er,Cr:YSGG	Erbium, Chromium: Yttrium-Scandium-Gallium-Garnet
W	Watt
Al ₂ O ₃	Aluminum Oxide
LSS	Lithium Silicate Coating
HF	Hydrofluoric Acid
SBS	Shear Bond Strength
Y-PSZ	Yttrium Partially Stabilized Zirconia
Cercon xt ML	Cercon extra translucent Multi-Layered

Katana STML
CAD/CAM
LTD

Katana Super Translucent Multi-Layered
Computer-Aided Design/Computer-Aided Manufacture
Low Temperature Degradation

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