Effect of new zirconia surface coatings on the surface properties and bonding strength of veneering zirconia substrate

Firas Abdulameer Farhan, Eshamsul Sulaiman, Muralithran G. Kutty*

Department of Restorative Dentistry, Faculty of Dentistry, University of Malaya, Kuala Lumpur 50603, Malaysia

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Surface roughness
Shear bond strength
Zirconia substrate

ABSTRACT

Zirconia ceramic dental restorations showed a low bond strength to veneering ceramic because of there is no inherent glass content along with a nonpolar covalent bond in its matrix. Two zirconia coatings by airbrush spraying were used as a new surface treatment on zirconia substrate to create surface roughness and improved bond strength to the veneering ceramic. Unsintered yttria stabilized zirconia (YSZ) powder was partially sintered at 1100 °C to produce powders with two particle sizes; A = 26.0 ± 0.3 μm and B = 47.0 ± 0.5 μm. Unsintered YSZ blocks were sectioned into 50 discs of 25 mm in diameter and 2.5 mm in thickness. The discs were divided according to the surface treatments into three groups; ten sintered YSZ discs were blasted by airborne particle abrasion (APA) with 50 μm aluminium oxide particles as control group; twenty unsintered YSZ discs were coated with a mixture of glaze ceramic and YSZ powders (M1), and twenty unsintered YSZ discs were coated with a mixture of ceramic liner and YSZ powders (M2). Based on the sizes of the YSZ powders, the coated groups subdivided into M1A, M1B, M2A and M2B. The surface area roughness (Sa), surface morphology, elemental composition, phase transition and shear bond strength test (SBS) were assessed. The collected data were analysed with one-way ANOVA and Tukey HSD test at (P<0.05). The Sa results revealed significant differences among all groups (P<0.000). The coated groups showed higher Sa and SBS values with a significant difference than APA. The M1B group exhibited higher values of Sa (10.33 μm) and SBS (37.54 MPa) with significant differences among the other tested groups. The zirconia specimens treated with new coatings significantly improved the shear bond strength to the veneering ceramic.

1. Introduction

The zirconia core material used for all-ceramic fixed dental restorations is the tetragonal structure of yttria-stabilized zirconia (YSZ) because of its high flexural strength (900 to 1200 MPa), superior bio-compatibility and more aesthetic (metal-free substructure) [1,2]. Nowadays, YSZ has been used widely in the dental industry as a result of the transformation toughening mechanism, which can give it higher strength and toughness compared to other ceramics. These superior properties allow the use of YSZ in conditions of high mechanical stress, such as the framework substrate for fixed dental prosthesis like crowns, bridges, implant and post/core systems [3,4].

Although the superior mechanical properties of YSZ substrate, poor bond strength to the veneering ceramic have been reported which significantly affect its clinical performance [5]. This is mainly due to the chemical inaction of YSZ because there is no inherent glass content in the matrix and a nonpolar covalent bond [6]. The adhesion between YSZ core and veneering ceramic is affected by several factors including; chemical bonding, mechanical interlocking, wettability and the degree of compressive or tensile stress on the veneering ceramic [7,8]. In order to encourage adequate bonding between the YSZ substrate and veneer ceramic, surface treatments for the YSZ surface have been recommended. This can be attained by removing or adding materials to the YSZ surface [9,10].

The airborne particle abrasion (APA) is a common surface treatment used to create a rough surface and improved the micro mechanical interlocking between YSZ and the veneering ceramic. APA is applied to metals and YSZ frameworks as a way to clean the surface, increase the micro mechanical roughness and improve the contact area between treated materials to the veneering ceramic. Aluminium oxide particles (Al₂O₃) are used with various particle sizes (ranging from 50 to 110 μm) as a scratch material [11-13].

Many studies have revealed that APA and grinding surface treatments are responsible for a phase transition at the YSZ surface from tetragonal to monoclinic phase, which attended with volume change that generated the tensile stress and cracks susceptibility of veneering...
The ceramic liner is the common coating material used on YSZ substrate as an intermediate coating layer to mask the white colour and improve the wetting property of YSZ substrate [8]. Several studies concluded that the application of liner can reduce the bond strength between YSZ substrate and veneering ceramic. These studies proposed that it should be combined with air abrasion treatment to improve the bonding strength [10,13,15].

Alternatively, surface coating with different materials has been used to increase the bond between YSZ and veneering ceramic. One study proposed using a thin layer of YSZ powder (3 μm) mixed with glue over the YSZ surface to increase surface roughness and mechanical interlocking to veneering ceramic. The study concluded that altering of the YSZ surfaces significantly increased the bond strength [16].

Another study used a glaze ceramic material as coating material by a glaze-on technique which consists of applying a thin layer of glaze ceramic on the fitting surface (inner side) of the zirconia-based crown to create an intermediate etchable layer to improve the adhesive bond of luting cement to the prepared tooth surface [17].

The spraying coating technique by an airbrush is an innovative way used for coating ceramic slurries on the all-ceramic substrates with a simple or a complex form. This method was introduced as an efficient deposition approach to control the coating thickness and form [18].

The aim of the current study is to create a surface roughness of YSZ substrate by new zirconia surface coatings with different particle sizes and mixed with two ceramic materials to improve the bonding strength to the veneering ceramic without phase transition and compare with the airborne particle abrasion surface treatment. The coating carried out by an airbrush spraying technique to produce coating layer with even thickness and homogeneity.

### 2. Materials and methods

#### 2.1. Coating powder preparation

Unsintered YSZ powder (Sigma-Aldrich Co., USA) was pressed by the cold isostatic press to produce a compact tablet with a firm texture and regular density. The tablets were partially sintered at 1100 °C for 2 h using a hot air furnace (Xinyu-1700, Henan, China) and ground by using Planetary ball milling machine (XQM, Hunan, China) to produce a powder with different particle sizes. The resulted powder was sieved by a vibratory sieve shaker (Retsch GmbH-Allee Haan, Germany) to produce two powder sets which designed based on the pilot study. The first set was collected between meshes 25 and 30 μm as fine particles (size A) and the second set was collected between meshes 45 and 50 μm as coarse particles (size B) (Fig. 1).

![diagram](image)

**Fig. 1.** The diagram shows the sieving method and collection of the selected powder A: for the collection of powder between meshes 25–30 μm, B: between meshes 45–50 μm.

The average particle sizes were assessed by using the Image J software, which proposed by Wayne Rasband [19]. The software was used to measure the outline of the powder particles displayed in

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Type of surface treatment</th>
<th>Particle size used</th>
</tr>
</thead>
<tbody>
<tr>
<td>APA (control)</td>
<td>10</td>
<td>blasted by aluminium oxide particles</td>
<td>50 μm</td>
</tr>
<tr>
<td>M1A</td>
<td>10</td>
<td>coated by mixture of partially sintered YSZ powder (size A) and glaze porcelain</td>
<td>26 μm</td>
</tr>
<tr>
<td>M1B</td>
<td>10</td>
<td>coated by mixture of partially sintered YSZ powder (size B) and glaze porcelain</td>
<td>47 μm</td>
</tr>
<tr>
<td>M2A</td>
<td>10</td>
<td>coated with partially sintered YSZ powder (size A) and liner ceramic</td>
<td>26 μm</td>
</tr>
<tr>
<td>M2B</td>
<td>10</td>
<td>coated with partially sintered YSZ powder (size B) and liner ceramic</td>
<td>47 μm</td>
</tr>
</tbody>
</table>

### Table 2

Coating procedure parameters according to pilot study.

<table>
<thead>
<tr>
<th>Coating parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing ratio zirconia powder/glaze porcelain</td>
<td>50 wt%</td>
</tr>
<tr>
<td>Mixing speed and duration</td>
<td>500 rpm/min for 15 min</td>
</tr>
<tr>
<td>Air pressure for spraying</td>
<td>2.5 bars</td>
</tr>
<tr>
<td>Dilution with pure ethanol</td>
<td>1.5 mL</td>
</tr>
<tr>
<td>Distance between YSZ disc and airbrush nozzle</td>
<td>10 cm</td>
</tr>
<tr>
<td>Spray time</td>
<td>2 s</td>
</tr>
</tbody>
</table>
scanning electron microscope image (SEM) [20]. Two SEM images were used for each powder set.

2.2. Preparation and grouping of specimens

Unsintered YSZ cylindrical blocks (Cercon Base 38; DeguDent GmbH, Hanau-Wolfgang, Germany) were sectioned into 50 discs of 25 mm in diameter and 2.5 mm in thickness using a cutting machine (MICRACUT® 176, Metkon, Turkey). All discs were ground finished with 600, 800 to 1000 grit silicon carbide paper on a polishing platform machine (Beta, Bueher, USA) to prepare a standard surface form. The discs were divided according to the kind of surface treatments into three groups as shown in Table 1.

Group APA: is made of ten YSZ discs that are sintered by an air atmosphere furnace (Cercon heat, DeguDent GmbH, Hanau, Germany) at 1350 °C according to the Cercon Smart System recommendations [21] and treated by airborne-particle abrasion as a control group. The discs were fixed perpendicularly to the nozzle of an air-abrasion machine (Basic Quattro, Renfert GmbH, Hilzingen, Germany) by a metal holder and blasted with 50 μm aluminium oxide powder (Korox®, Bego, Germany) at a constant pressure of 4 bars and 10 mm distance for 10 s [22]. For group M1: twenty unsintered YSZ discs were coated with a slurry prepared by mixing of glaze ceramic powder (Cercon® Ceram Kiss) and partially sintered YSZ powder and subdivided according to zirconia powder sizes (A for 26 μm and B for 47 μm) into M1A and M1B respectively, for each 10 specimens. For group M2: twenty unsintered YSZ discs were coated with a slurry prepared by mixing of the partially sintered YSZ powder mixed with a ceramic liner paste (Cercon® Ceram Kiss) and subdivided according to the zirconia powder sizes as in group M1 into M2A and M2B for each 10 specimens.

The coated YSZ discs were sintered by the Cercon furnace at

<table>
<thead>
<tr>
<th>Materials</th>
<th>Chemical composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cercon zirconia base and powder (A and B)</td>
<td>ZrO2; Y2O3 (3 mol); Hf2O3 and other oxides</td>
</tr>
<tr>
<td>Ceramic Liner paste (M2)</td>
<td>SiO2; Al2O3; Na2O; K2O; CaO, P2O5, F and other oxides</td>
</tr>
<tr>
<td>Glaze ceramic powder (M1)</td>
<td>SiO2; Al2O3; Na2O; K2O; ZnO; Ba, other oxide and pigment</td>
</tr>
</tbody>
</table>

Fig. 2. Coating procedure by airbrush spraying method of unsintered zirconia disc.

Table 3
The chemical composition of YSZ substrate and powder, ceramic liner and glaze ceramic according to manufacturer data.

Fig. 3. A—Separable silicon mould and zirconia disc adjusted in mould, B—Zirconia disc after sintering veneering layer, C—Veneered zirconia discs ready for SBS test and D—Specimen tested by Instron universal testing machine.
1350 °C, according to the manufacturer instructions.

2.3. Coating procedure

The selected particle sizes of partially sintered YSZ powder with 50 wt% were mixed with 50 wt% of the ceramic liner or glaze ceramic (the chemical components of the selected materials are listed in Table 2 according to the manufacturer data) and diluted with pure ethanol of 99.7% with 1.5 mL to form a slurry. The slurry was mixed by a magnetic stirrer at 500 rpm for 15 min to confirm mixture homogeneity. The coating spray was performed by a mini airbrush spray gun (model 130-dual action airbrush kit, Taiwan) that was fixed vertically to the YSZ disc by a clamp holder (Fig. 2) which was cleaned with pure ethanol before coating. The standard quantity and quality of the spraying slurry were preserved by controlling the air pressure (2.5 bars) and the spray time for 2 s at a distance of 13 cm. These parameters were designated on the basis of the pilot experiments. The coating parameters are summarized in Table 3.

2.4. Evaluation of surface area roughness

The surface area roughness (Sa) was measured by a three-dimensional (3D) optical surface analyser microscope (Infinity Focus, Alicona, Germany). Sa measurements were performed according to ISO 25178-601 [23] as a numeric value of total area roughness. The 3D digital image was taken for treated YSZ specimen with objective 20 and then analysed by a software to calculate the Sa value in micrometre (μm). In order to standardise the roughness measurement, five different locations were selected in each disc (one in the centre and four in the margins) and the Sa value for each specimen was obtained by calculating the mean of measurements.

![Fig. 4. Particle size distributions for two zirconia coating powders (A and B) calculating by Image J software and SEM image.](image)

### Table 4

Descriptive analysis and one-way ANOVA test for Sa values of tested groups. M1A and M1B coated specimens by zirconia glaze mixture with particle sizes A and B, M2A and M2B coated specimens by zirconia liner mixture with particle sizes A and B. APA abraded specimens by airborne particle abrasion.

<table>
<thead>
<tr>
<th>Groups</th>
<th>N</th>
<th>Mean (μm)</th>
<th>SD</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>APA</td>
<td>10</td>
<td>0.92</td>
<td>0.14</td>
<td>567.89</td>
<td>&lt; 0.00</td>
</tr>
<tr>
<td>M1A</td>
<td>10</td>
<td>7.67</td>
<td>0.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1B</td>
<td>10</td>
<td>10.33</td>
<td>0.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2A</td>
<td>10</td>
<td>4.18</td>
<td>0.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2B</td>
<td>10</td>
<td>7.88</td>
<td>0.52</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Significant difference between groups at p < 0.05.
was performed according to ISO 9693[24]. 50 YSZ discs treated with (International Center for Di
Pro, PANalytical, Netherlands) in conjunction with the ICDD reference terns were identi
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were higher than group APA. Sa values by One-way ANOVA showed a

different surface roughness quantities. In the APA group, the YSZ surface showed the formation of shallow irregularities without
principal undercuts while for the coated groups M1B, M1A and M2B showed higher surface irregularities and deep undercuts formed from
coating projections. Group M2A showed fewer surface irregularities (Fig. 5). A cross-sectional view for all tested YSZ specimens showed the
uniform thickness and homogeneity (Fig. 6).

2.6. Crystallographic analysis
The relative amount of the monoclinic and tetragonal phases after surface treatments on the specimen surface was determined by an X-ray
diffraction (XRD) (Bruker-AXS, GmbH, Germany). The diffraction patterns were identified by using the XPert High Score program (XPert
Pro, PANalytical, Netherlands) in conjunction with the ICDD reference (International Center for Diffraction Data).

2.7. Shear bond strength test
The shear bond strength test (SBS) for multilayer ceramic system was performed according to ISO 9693 [24]. 50 YSZ discs treated with
different surface treatments (M1, M2 and APA) were veneered with a cylindrical shape (3 mm height × 3 mm diameter) in the centre of the
disc using a separable custom-made silicone mould. Ceramic slurry with appropriate amount and condensed to a silicone mould after lubricating with
epoxy resin and then sectioned by a high speed cutting machine into two halves. The cross-sectional part was investigated by SEM to analyse
the morphology and profile of all specimens.

2.8. Fractographic examination
All fractured specimens retrieved from the SBS test were visually observed and in order to support the visual results, the remaining veneered area of selected specimens was examined under a stereomicro-
scope (SZX7, Olympus, Japan) at 20 × magnification to confirm the classification of the fracture modes. Different fracture modes were de-
defined; an adhesive mode which occurred at the core/veneer interface, cohesive mode located in the veneering porcelain and mixed mode which included both modes. In order to approve the visual findings, the remaining veneered area of classified specimens was examined under a stereomicroscope. The SEM images were used to calculate the percentage of remaining ceramic in the fractured interface by determining and measuring the colour outline of the remaining ceramic area by using the colour profiler tool in Image J software [25] and were divided over the total area of the YSZ disc. The percentage was classified into the cohesive fracture (> 80%), mixed fracture (20–80%) and adhesive fracture (< 20%) [26].
particles of the abrasion method. For the M1 groups, in addition to zirconium, the glaze porcelain elements were present such as silicon, potassium, aluminium, and barium. For the M2 groups, zirconium element was seen with the liner ceramic elements including silicon, sodium, potassium and aluminium. These results revealed that the coating mixture components did not disappear or change after YSZ sintering. The silicon element is considered as the main element in the glaze, liner and veneering porcelain.

Fig. 5. SEM images of the all treated YSZ disc specimens. M1A, M1B YSZ discs coated with zirconia glaze mixture with sizes A and B. M2A, M2B YSZ discs coated with zirconia liner mixture with sizes A and B. APA for disc treated by airborne particle abrasion.
3.4. Phase compositions identification

The XRD patterns of all tested groups showed that the major peak of the tetragonal phase was seen at 30.57° corresponding to the crystallographic plane ICDD 014-0534. The monoclinic phase peaks were present at 28.47° corresponding to the crystallographic planes ICDD 002–0343. All coated specimens showed the presence of only the tetragonal phase in comparison to the APA specimens which exhibited both monoclinic and tetragonal phases (Fig. 8).

3.5. Shear bond strength results

The SBS values for all experimental coated specimens were higher than APA specimens which represent in M1B group recorded 37.54 MPa while APA group 25.71 MPa. One-way ANOVA indicated a significant difference between all tested groups at \( P < 0.05 \) as shown in (Tables 4–6). The Tukey HSD test for multiple comparisons indicated that group M1B specimens were significantly higher mean SBS compared to other coated and APA groups. In addition, all coated groups, except the M1B group showed a non-significant difference between them as shown in Table 5.

3.6. Fracture modes evaluation

The results of fracture mode after the SBS test revealed that all tested groups showed a high percentage of mixed fracture mode (Table 7). Cohesive fracture with high percentage was exhibited in group M1B 40%, while was 20% for groups M1A and 10% for M2B. APA group showed a higher percentage of adhesive fracture mode 60%. All fracture modes ratio displayed in Table 8 and the fracture morphologies by using a stereomicroscope Fig. 9. The EDX at the interface area of fracture specimens showed there is a higher percentage of elemental compositions of veneering ceramic which represent by a high percentage of silicon Si within the coated groups than APA group as a result of noticeable mechanical interlocking between coated YSZ disc and veneering ceramic (Fig. 10).

4. Discussion

Clinical studies of YSZ ceramic restorations have shown that the chipping and delamination of veneer ceramic layer are a common cause of failure, with a report incidence ranging from 11.4% to 25.0% of all fixed dental prosthesis [27,28]. These fractures can be regarded as a serious complication for clinicians and patients.

Several studies on YSZ ceramic restorations have tried to clarify the cause of veneering chipping and many hypotheses have been put forward, such as insufficient micromechanical interlocking with a lack of chemical bonding at YSZ core/veneer ceramic interface and tensile stress on veneering ceramic caused by different surface treatments [14,29]. The weakest feature of YSZ ceramic restorations is the bonding between veneering ceramic and the YSZ core [30].

To enhance the bond strength between YSZ core and its corresponding veneer ceramic, a satisfactory mechanical interlocking at the core-veneer interface should be achieved by increasing surface roughness and producing undercuts [31]. Surface treatments were suggested for YSZ substrate to enhance better bond strength with veneer ceramic which accomplished by removing or adding surface materials.

In the current study, sintering of a uniform thin layer of a new zirconia coating mixture which composed of partially sintered YSZ powder with two particle average sizes (\( A = 26.0 \pm 0.3 \mu m \)) and (\( B = 47.0 \pm 0.5 \mu m \)). The powder mixed with either glaze ceramic powder (M1) or liner ceramic paste (M2) which is considered as a new surface treatment used for YSZ substrate. The particle sizes used in the current study were bigger than the particle size used by Teng et al., after mixed with glue. Their study concluded that the altering of YSZ surface by unsintered zirconia powder with particle size of 3 \( \mu m \) could significantly increase the SBS values [16].

In the present study, the two coarser particle sizes of YSZ powders were selected to increase the surface roughness, in addition, the two ceramic materials selected to mixed with YSZ powder because have the same composition of veneer ceramic shown in Table 2, which may enhanced the chemical bonding of YSZ substrate to veneering ceramic. The selection of the particle sizes and materials were according to a preliminary study after obtaining coating layer with a constant thickness and abundant irregularities.

An airbrush spraying method used to produce a coating with a
homogenous and uniform thickness as shown in Fig. 6 which was affected by different parameters, i.e. spraying pressure, dilution of the mixture, the distance of airbrush nozzle to the YSZ disc and the spray total time [18]. All of these parameters were selected on the basis of a preliminary pilot study. According to these limits, the coating thickness was persistent with the regular surface roughness. As a result of using this method, the bonding strength was enhanced due to an increase of the mechanical interlocking of YSZ surface with the veneer ceramic.

The Sa values for YSZ surface were significantly higher in all coated experimental groups than the control group (APA) due to the larger particle sizes of YSZ coating powder. APA group revealed the lowest Sa value which may be due to the size of the alumina particle and/or the duration of abrasion [13,22]. The Sa value of the glaze mixture (M1B) was significantly higher than the other coated groups as presented in Table 5. Even though M1A and M2A used the same YSZ powders of a similar particle size, the results showed that the glaze mixture (M1A) had higher roughness. This was probably attributed to the fact that the glaze mixture (M1A) is made up of a combination of powder mixtures.

Fig. 7. EDX results of YSZ disc specimens with different surface treatments; M1- zirconia glaze mixture; M2-, zirconia liner mixture and APA- airborne particle abrasion.
compared to the liner mixture (M2A) which is powder and paste. Moreover, the form of the ceramic liner paste in M2 may disturb the surface roughness as the liner ceramic paste filled a portion of the undercuts created by YSZ powder coating [13,15].

The surface morphology for all coated YSZ specimens exhibited a thin layer of coating with irregularities and undercuts depending on the type of coating mixture for M1 and M2. Abundant and well prominent irregularities with obvious depression areas (valleys) that created a rougher surface and provide more undercuts were visible in group M1B compared to other coated groups, while the APA group exhibited superficial irregularities and undercuts. This may be attributed to the bigger particle sizes of the coating and the glaze powder.

For all-ceramic multilayered systems, there is no consistent method for bond strength assessment [32]. Numerous bond strength test methods have been utilised to calculate the bond strength between YSZ core and veneer ceramic. In this study, the SBS test was applied because this method is simple to use and the applied forces are perpendicular to the bonding zone. Furthermore, the small cross-sectional area of the bonded surface to test the material eliminates the inner structural flaws which significantly affect the test readings [33].

The SBS values in the current study showed that all coated groups had higher strength values than the APA and there was a significant

<table>
<thead>
<tr>
<th>Groups</th>
<th>N</th>
<th>Mean (MPa)</th>
<th>SD</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>APA</td>
<td>10</td>
<td>25.71</td>
<td>4.79</td>
<td>8.048</td>
<td>P &lt; 0.00</td>
</tr>
<tr>
<td>M1A</td>
<td>10</td>
<td>31.04</td>
<td>5.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1B</td>
<td>10</td>
<td>37.54</td>
<td>4.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2A</td>
<td>10</td>
<td>27.27</td>
<td>5.70</td>
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<tr>
<td>M2B</td>
<td>10</td>
<td>29.88</td>
<td>4.98</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Significant difference between groups at p < 0.05.
difference (p < 0.05) between all groups. This difference can be attributed to the increase in surface roughness of the coated specimens compared to the APA specimens which lead to improved bond strength between YSZ and veneer ceramic by creating micromechanical interlocking. The M1B specimens had the highest strength value (37.05 ± 3.34 MPa) because it has the highest Sa value than the other tested groups as shown in Table 6.

According to the studies by Kim et al. [13] and Kosmač et al. [14], the APA was unfavourable for achieving effective bond strength because of the mechanical stresses on YSZ surface produced by the shooting force of APA treatment generated phase transition from tetragonal to monoclinic. This phase transition accompanied by a volume expansion of about 3–5% resulted in compressive stress on veneering layer and induced crack propagation at core/veneer interface [34]. While for the coated specimens the surface was contained YSZ powder with tetragonal phase. The XRD analysis results of the current study are agreed with the previously mentioned studies through the presence of the monoclinic phase in the APA specimens as shown in (Fig. 8).

EDX analysis indicated that there were no elemental changes in the coating mixture after the sintering process. As shown in (Table 3), the chemical composition for the liner and glaze were similar to the veneer ceramic composition. Wang et al., [15] proposed that when the chemical composition of the liner is similar to the veneering ceramic, the mechanical properties are similar too. This may be the reason for a stronger bond with the veneer ceramic compared to the bond with the YSZ core. Consequently, this chemical bond of the liner and glaze to the veneering ceramic at interface area was showed in the current study after analysing the fractured disc with SBS test by using EDX analysis as shown in (Fig. 10). Furthermore, the high surface roughness may be the reason for the increase in bond strength values in the coated specimens [7].

Fracture modes classification was consistent with previous studies using the SBS test [17,35]. In the present study, the fractographic analysis of SBS tested specimens by using a stereomicroscope and SEM exhibited different fracture modes for the tested groups as shown in (Table 8). The cohesive mode represented a strong bond between core and veneer ceramic. The M1B group revealed a higher percentage (40%) than the other tested groups. For other coated groups the cohesive mode was exhibited in the M1A group (20%) and in the M2B group (10%) and this can be supported by the fact that when the surface becomes rougher, the bond strength will increase [7]. Interestingly, a high percentage of the adhesive mode of fracture obtained for both APA and M2A groups were 60% and 50% respectively, due to the lower roughness values. The mixed mode of fracture was presented in a high percentage for all tested groups as a main fractographic result. In this in-vitro study, the YSZ specimens were not similar to the configuration of dental restorations but it provides sufficient information about the behavior of coated YSZ with veneer ceramic that helps in the increase of YSZ restoration success.

Within the limitation of the study, the surface and SBS results showing a new coating surface mixture are suitable to improve the bonding strength between YSZ and veneer ceramic. Further in-vitro or in-vivo studies are needed to evaluate the effects of coatings on the bonding strength of the simulated zirconia-base crown.

5. Conclusions

The APA is a common surface treatment used to YSZ ceramic restorations to create surface roughness and enhanced bonding between YSZ core and veneer ceramic. However, an adverse effect of APA treatment by altering the YSZ phase from tetragonal to the monoclinic phase, which accompanied by stress generation on veneering layer and backwards the bonding strength to zirconia substrate. The new zirconia surface coatings are promising surface treatment and an easy technique to obtain a rougher surface which subsequently improves the bond strength to veneer ceramic without phase changes. The coated specimens with zirconia glaze mixture (M1B) showed significant increase in shear bond strength values than APA and other coated (MIA, M2A and M2B) specimens. Furthermore, this treatment is applicable for YSZ core with a conventional and complex shape of a single crown and bridge of fixed zirconia ceramic restorations.

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**Table 7**

Multiple comparisons of the SBS values between the tested groups with different surface treatments by Tukey HSD test. Each group compared with control (APA) group and coated groups (M1A, M1B, M2A and M2B).

<table>
<thead>
<tr>
<th>(I) Group</th>
<th>(J) Group</th>
<th>Mean difference (I−J)</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>APA</td>
<td>M1A</td>
<td>−5.330</td>
<td>0.151</td>
</tr>
<tr>
<td>M1B</td>
<td>−11.836</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>M2A</td>
<td>−1.568</td>
<td>0.958</td>
<td></td>
</tr>
<tr>
<td>M2B</td>
<td>−4.171</td>
<td>0.368</td>
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</tr>
<tr>
<td>M1A</td>
<td>M1B</td>
<td>−6.506</td>
<td>0.048</td>
</tr>
<tr>
<td>M2A</td>
<td>3.762</td>
<td>0.473</td>
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</tr>
<tr>
<td>M2B</td>
<td>1.159</td>
<td>0.986</td>
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</tr>
<tr>
<td>M1B</td>
<td>M2A</td>
<td>10.268</td>
<td>0.000</td>
</tr>
<tr>
<td>M2B</td>
<td>7.665</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>M2A</td>
<td>M2B</td>
<td>2.603</td>
<td>0.783</td>
</tr>
</tbody>
</table>

* Significant difference between groups at p < 0.05.

**Table 8**

Fracture mode percentage of SBS tested groups.

<table>
<thead>
<tr>
<th>Groups</th>
<th>N</th>
<th>Cohesive %</th>
<th>Mixed %</th>
<th>Adhesive %</th>
</tr>
</thead>
<tbody>
<tr>
<td>APA</td>
<td>10</td>
<td>0</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>M1A</td>
<td>10</td>
<td>20</td>
<td>70</td>
<td>10</td>
</tr>
<tr>
<td>M1B</td>
<td>10</td>
<td>40</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>M2A</td>
<td>10</td>
<td>0</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>M2B</td>
<td>10</td>
<td>10</td>
<td>60</td>
<td>30</td>
</tr>
</tbody>
</table>

---

**Fig. 9.** Fracture modes examined by a stereomicroscope. A—Adhesive mode, B—Mixed mode and C—Cohesive mode.
Acknowledgements

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References

[24] ISO 9693, Metal-ceramic dental restorative systems, International Organization for...


