REVIEW PAPER

Comparative Evaluation of Bond Strength on Different Surface Treatment at Metal Ceramic Interface: An In Vitro Study

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ABSTRACT

Aim: To comparatively evaluate the effect of different surface treatment protocols on the bond strength of metal–ceramic restorations and to analyse the associated modes of bond failure.

Study Design: This in vitro experimental study was carried out in the Department of Prosthodontics, Crown and Bridge, Babu Banarasi Das College of Dental Sciences, Lucknow, Uttar Pradesh, India.

Materials and Methods: Thirty-five metal–ceramic specimens were fabricated and divided into five groups (n = 7) based on surface treatment: Group A (sandblasting – control), Group B (sandblasting + surface grinding), Group C (sandblasting + ultrasonic cleaning), Group D (sandblasting + grinding + ultrasonic cleaning), and Group E (sandblasting + grinding + ultrasonic cleaning + acid etching). Ceramic veneering was performed under standardised conditions. Bond strength was evaluated using a three-point bending test in accordance with ISO 9693-1 guidelines. Values were recorded in megapascals (MPa) and Newtons (N). Failure modes were assessed using scanning electron microscopy (SEM). Statistical analysis included one-way ANOVA, post hoc LSD test, and Chi-square test ($p < 0.05$).

Statistical Analysis Used: Metal–ceramic bond strength was analysed using the Shapiro–Wilk test, followed by one-way ANOVA and LSD post hoc analysis. Modes of bond failure were analysed using the Chi-square test.

Surface Analysis: Representative fractured specimens from each group were examined using scanning electron microscopy (SEM) to evaluate the metal–ceramic interface and characterise the modes of bond failure.

Results: A statistically significant difference in bond strength was observed among all groups ($p = 0.001$). Group A showed the lowest bond strength (638.47 ± 25.07 MPa; 952.95 ± 37.41 N) with predominantly adhesive failure. Groups B (727.45 ± 15.04 MPa; 1085.80 ± 22.45 N) and C (723.08 ± 23.60 MPa; 1079.20 ± 35.22 N) demonstrated intermediate values with mixed failure patterns and no significant difference ($p = 0.724$). Group D exhibited higher bond strength (774.48 ± 27.49 MPa; 1156.00 ± 41.03 N) with predominantly cohesive failure, while Group E showed the highest bond strength (802.58 ± 21.54 MPa; 1197.90 ± 32.14 N) with cohesive failure and no adhesive failures. A progressive increase in bond strength corresponded with a transition from adhesive to cohesive failure modes., which was further supported by SEM analysis.

Conclusion: Surface treatment protocols significantly influence the bond strength of metal–ceramic restorations. Multi-step surface treatments result in superior bond strength and more favourable cohesive failure patterns compared to single-step procedures. These findings suggest that combined surface treatment approaches may enhance interfacial integrity and improve the long-term clinical performance of metal–ceramic restorations.

Keywords: Bond Strength; Failure Mode; Fixed Prosthodontics; Metal–Ceramic Restorations; Scanning Electron Microscopy (SEM); Surface Treatment

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INTRODUCTION

Metal–ceramic restorations have remained the gold standard in fixed prosthodontics because they combine the superior mechanical properties of metal alloys with the esthetic characteristics of dental ceramics. The metal framework provides excellent strength, rigidity, fracture resistance, and marginal adaptation, whereas the ceramic veneer restores natural tooth colour, translucency, and surface texture. Consequently, porcelain-fused-to-metal

(PFM) restorations continue to be widely used, particularly for posterior crowns and long-span fixed dental prostheses where high functional demands and long-term clinical performance are essential despite the growing popularity of all-ceramic restorative systems [1,2]. Long-term clinical studies have demonstrated survival rates of approximately 85–95% over observation periods exceeding 10 years, confirming the predictable longevity of metal–ceramic restorations [3,4].

The clinical success of these restorations depends primarily on the integrity of the bond between the metal framework and the ceramic veneer. Failure at the metal–ceramic interface commonly presents as porcelain chipping, fracture, or delamination, resulting in compromised esthetics, reduced function, and restoration failure[5].In the oral environment, metal–ceramic restorations are subjected to repeated tensile, compressive, shear, and flexural stresses, together with thermal fluctuations and moisture-related degradation, all of which challenge the durability of the metal–ceramic interface [6]. Therefore, achieving a strong and durable bond between metal and ceramic is essential for long-term clinical success.

The metal–ceramic bond is multifactorial and is established through chemical bonding, mechanical interlocking, residual compressive stresses generated by differences in the coefficients of thermal expansion between metal and ceramic, and secondary physical interactions [6,7].Among these mechanisms, chemical bonding through the formation of a controlled oxide layer and mechanical interlocking produced by surface roughness are regarded as the primary contributors to bond strength [7,8].Consequently, the characteristics of the metal surface before porcelain application have a significant influence on the quality and durability of the bond.

Nickel–chromium (Ni–Cr) alloys are widely used as framework materials because of their high strength, corrosion resistance, favourable modulus of elasticity, and economic advantages over noble metal alloys [2,9]. Surface treatment procedures such as airborne-particle abrasion, grinding, ultrasonic cleaning, oxidation, and acid treatment have been recommended to improve surface roughness, remove contaminants, and optimise oxide layer formation before porcelain application [8,10,11]. However, previous investigations have

reported inconsistent findings regarding the influence of different surface treatment protocols on metal–ceramic bond strength because of variations in alloy composition, ceramic systems, and testing methodologies [10,12].

Therefore, the present in vitro study was undertaken to comparatively evaluate the effect of different surface treatment protocols on the bond strength at the nickel–chromium metal–ceramic interface using the three-point bending test. Fractured specimens were further examined using scanning electron microscopy to analyse the modes of bond failure and correlate the interfacial characteristics with bond strength.

DETERMINATION OF SAMPLE SIZE

For metal–ceramic bond strength assessment, a total of 35 metal–ceramic specimens were prepared and divided into five groups of 7 specimens each.

Thirty-five CAD/CAM-milled specimens with dimensions 20x5x3mm were fabricated from wax patterns, which were milled from preformed wax blocks (Figure 1a). The completed wax patterns were then sprued, invested using a phosphate-bonded investment material, and cast in Nickel–Chromium alloy (Beryllium-free). The specimens were randomly divided into five groups (n = 7) according to the surface treatment protocol (Table 1).

Table 1. Distribution of Samples

Group	Surface Treatment Protocol	Sample Size(n)
Group A	Sandblasting (Control group)	7
Group B	Sandblasting + Surface grinding	7
Group C	Sandblasting + Ultrasonic scaling	7
Group D	Sandblasting + Surface grinding + Ultrasonic cleaning	7
Group E	Sandblasting + Surface grinding + Ultrasonic cleaning + Acid etching	7

All cast specimens were finished and polished using rotary rubber cups attached to a laboratory handpiece operating at 2000–5000 rpm to obtain a clinically relevant surface finish(Figure 1b). Dimensional accuracy was verified using a digital calliper with 0.01 mm resolution at three different points on each specimen.

To standardise the ceramic bonding area, 1 mm thick plastic tape was adapted on both sides of each specimen, leaving a central rectangular area of 4 mm exposed for ceramic application(Figure 1c).

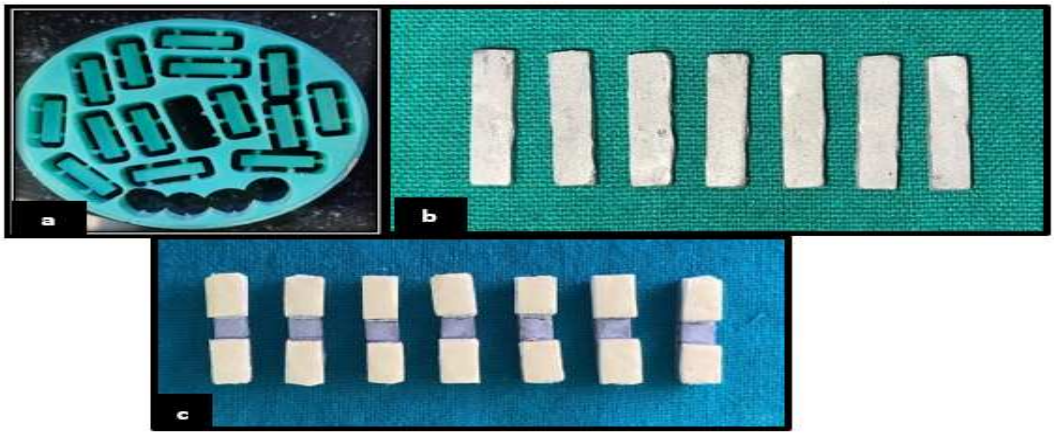


Figure 1 (a) CAD-CAM milling of wax pattern,(b) Nickel Chromium metal block (Beryllium-free), (c) Tape adapted on both sides leaving 4mm of rectangular area.

The specimens were randomly divided into five groups (n = 7) according to the surface treatment protocol employed prior to porcelain application.

Group A (Control Group): Specimens were subjected only to airborne-particle abrasion using 120 µm aluminium oxide particles at 70 psi under standardised conditions (Figure 2a).

Group B: Specimens underwent sandblasting followed by surface grinding using a 0.5 mm carbide bur to increase surface roughness and surface area (Figure 2b).

Group C: After sandblasting, specimens were ultrasonically cleaned in distilled water for 10 minutes to remove residual abrasive particles and contaminants (Figure 2c).

Group D: Specimens received combined surface treatment consisting of sandblasting, surface grinding with a 0.5 mm carbide bur, and ultrasonic cleaning in distilled water for 10 minutes.

Group E: Specimens were subjected to sandblasting, surface grinding, ultrasonic cleaning, and acid etching with 10% hydrofluoric acid for 20 seconds to further enhance surface irregularities (Figure2d).

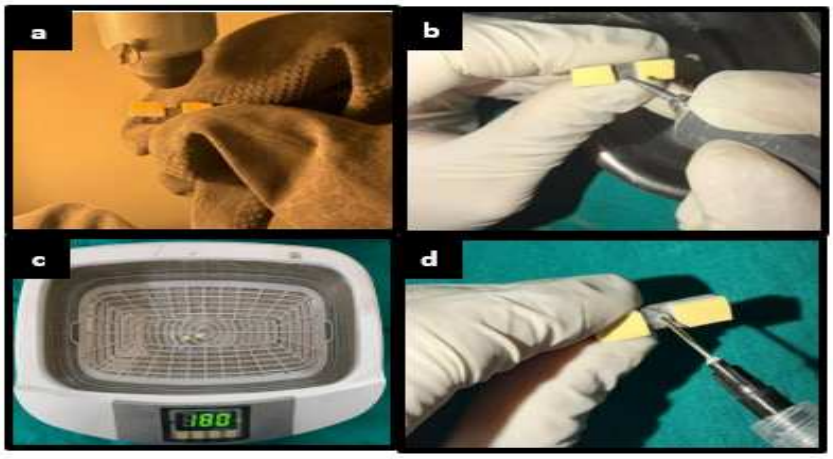


Figure 2 (a) Sandblasting,(b) Surface grinding,(c) Ultrasonic cleaning,(d)Acid etching

Following surface treatment, all specimens were rinsed, air-dried, and stored until porcelain application.

Ceramic porcelain was applied to the standardized central bonding area of each specimen. Following porcelain application, the plastic tape was removed and the

specimens were fired in a porcelain furnace Ivoclar Programat P310 under standardised conditions (Figure 3a).

Each specimen was subsequently embedded in an autopolymerizing polymethyl methacrylate (PMMA) resin block measuring 35 mm × 10 mm to facilitate stabilisation during bond strength evaluation using a universal testing machine with a three-point bending test setup (Figure 3b).

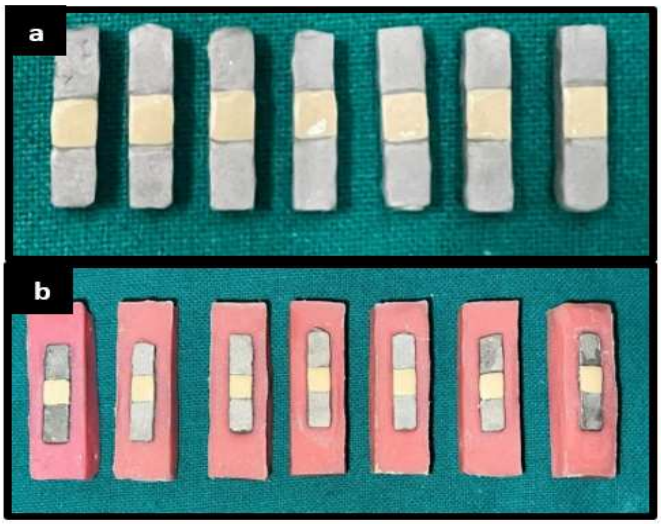


Figure 3 (a) Metal block with a 4-mm porcelain layer applied,

(b) Metal specimen mounted in acrylic block.

The metal–ceramic bond strength was evaluated using a three-point bending test in accordance with ISO 9693 standards for metal–ceramic dental restorative systems[20].Testing was performed using a computerized universal testing machine (Instron WDW, Taiwan) equipped with a 5 kN load cell.

During testing, the specimens were positioned with the metal substrate resting on two supports and the ceramic veneer facing upward. A steel plunger of 5 mm diameter applied a compressive load at the midpoint of the specimen. The supporting span length was maintained at 25 mm, and the crosshead speed was set at 1 mm/min to allow gradual stress accumulation (Figure 4a). The test was continued until fracture occurred, and the maximum load at failure (F) was recorded in Newtons (N). (Figure 4b)

The bond strength was calculated using the ISO-recommended formula [20].:

$\tau b = k \times F$where

• τ_β = metal–ceramic bond strength (MPa),

• F = load at failure (N),

• k = proportionality constant dependent on the thickness and elastic modulus of the metal substrate, obtained from ISO 9693 reference tables.

SPECIMEN PREPARATION

Following completion of the universal testing machine (UTM) test, the fractured metal–ceramic specimens were cleaned, air-dried, and sectioned to obtain the 4 mm ceramic-coated region. The specimens were then mounted on aluminium SEM stubs for scanning electron microscopy analysis.

The fractured specimens were mounted on aluminium SEM stubs using conductive carbon adhesive tape, with the fractured surface oriented upward for examination. Multiple specimens were mounted simultaneously to facilitate efficient SEM analysis (Figure 4c).

As the ceramic-coated specimens were non-conductive, sputter coating was performed to prevent surface charging during SEM examination. The mounted specimens were coated with a thin gold/palladium layer using an auto fine sputter coater (JEOL JEC-3000FC) under vacuum conditions to obtain a uniform conductive coating (Figure 4d).

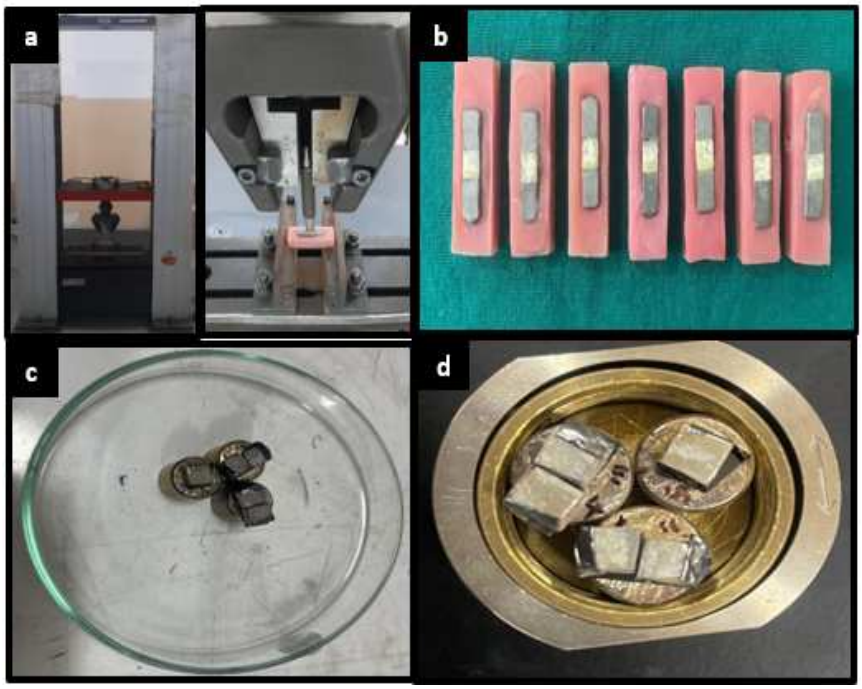


Figure 4(a) Universal Testing Machine, (b) Fractured specimen,(c) Fractured specimen with conductive carbon adhesive tape ,(d) Coated specimen.

The coated specimens were examined using a field emission scanning electron microscope (JEOL JSM-7610F) under high vacuum conditions. SEM micrographs at 100x and 500x magnifications were obtained to evaluate surface morphology and fracture characteristics of the metal–ceramic interface.

RESULTS

Intergroup comparison showed a statistically significant difference in bond strength among all groups ($p = 0.001$). Group A exhibited the lowest mean bond strength (638.47 ± 25.07 MPa) with predominantly adhesive failure, whereas Group E demonstrated the highest bond strength (802.58 ± 21.54 MPa) with cohesive failure. Groups B, C, and D showed intermediate values, indicating a progressive increase in bond strength from adhesive to cohesive failure patterns (Table 1).

Table 1: Comparison Of Bond Strength In MPA

	Mean	Std. Deviation	Std. Error	95% CI Lower	95% CI Upper	Minimum	Maximum	P value
Group A	638.470	25.067	9.475	615.289	661.656	611.880	684.570	
Group B	727.450	15.042	5.685	713.538	741.362	709.260	752.750	
Group C	723.080	23.598	8.919	701.259	744.907	675.590	751.230	0.001(Sig)
Group D	774.480	27.490	10.390	749.057	799.906	728.480	813.120	
Group E	802.580	21.538	8.141	782.659	822.498	779.770	839.010	

Post hoc LSD analysis revealed that Group A had significantly lower bond strength than all other groups ($p < 0.001$). No significant difference was observed between Groups B and C ($p = 0.724$), whereas Group D showed significantly higher values than Groups B and C ($p \leq 0.001$). Group E demonstrated significantly greater bond

strength than all other groups, including Group D (p = 0.029) (Table 2)

Table 2: Post HOC LSD Analysis

—	(J) GP	Mean Difference	Std. Error	Sig.	95% CI Lower	95% CI Upper
Group A	Group B	-88.977*	12.262	0.000	-114.019	-63.936
Group A	Group C	-84.610*	12.262	0.000	-109.652	-59.568
Group A	Group D	-136.009*	12.262	0.000	-161.050	-110.967
Group A	Group E	-164.106*	12.262	0.000	-189.147	-139.064
Group B	Group C	4.367	12.262	0.724	-20.675	29.409
Group B	Group D	-47.031*	12.262	0.001	-72.073	-21.990
Group B	Group E	-75.129*	12.262	0.000	-100.170	-50.087
Group C	Group D	-51.399*	12.262	0.000	-76.440	-26.357
Group C	Group E	-79.496*	12.262	0.000	-104.537	-54.454
Group D	Group E	-28.097*	12.262	0.029	-53.139	-3.056

Intergroup Comparison of Bond Failure Mode Between Groups

Table 3: Comparison Of Bond Failure Mode

Group	Adhesive Bond Failure	Cohesive Bond Failure	Mixed	P value
Group A (predominantly adhesive)	5 (71.4%)	1 (14.3%)	1 (14.3%)	0.001(Sig)
Group B (mixed and good bond)	2 (28.6%)	2 (28.6%)	3 (42.9%)	
Group C (mixed and moderate bond)	2 (28.6%)	1 (14.3%)	4 (57.1%)	
Group D (predominantly cohesive)	1 (14.3%)	4 (57.1%)	2 (28.6%)	
Group E (cohesive)	0 (0.0%)	6 (85.7%)	1 (14.3%)	

Intergroup comparison of bond failure modes showed a statistically significant difference among the five groups (p = 0.001), indicating variation in failure patterns according to bond integrity.

GROUP A

Group A demonstrated predominantly adhesive failure, with 5 of 7 specimens (71.4%) exhibiting adhesive bond failure, while cohesive and mixed failures were minimal (14.3% each) (Figure 5a1,a2).

GROUP B

In contrast, Group B exhibited a more balanced distribution of failure modes, with mixed failure being the most common pattern (42.9%), followed by equal proportions of adhesive and cohesive failures (28.6% each) (Figure 5b1,b2).

GROUP C

Group C demonstrated predominantly mixed failure, observed in 57.1% of specimens, with lower frequencies of adhesive (28.6%) and cohesive (14.3%) failures, indicating a moderate bonding pattern (Figure 5c1,c2).

GROUP D

Group D showed predominantly cohesive failure, observed in 57.1% of specimens, while mixed and adhesive failures accounted for 28.6% and 14.3% of cases, respectively, indicating improved bond integrity(Figure 5d1,d2).

GROUP E

Group E demonstrated the highest prevalence of cohesive failure, with 85.7% of specimens showing cohesive failure and no instances of adhesive failure, indicating superior metal–ceramic bond integrity (Figure 5e1,e2).

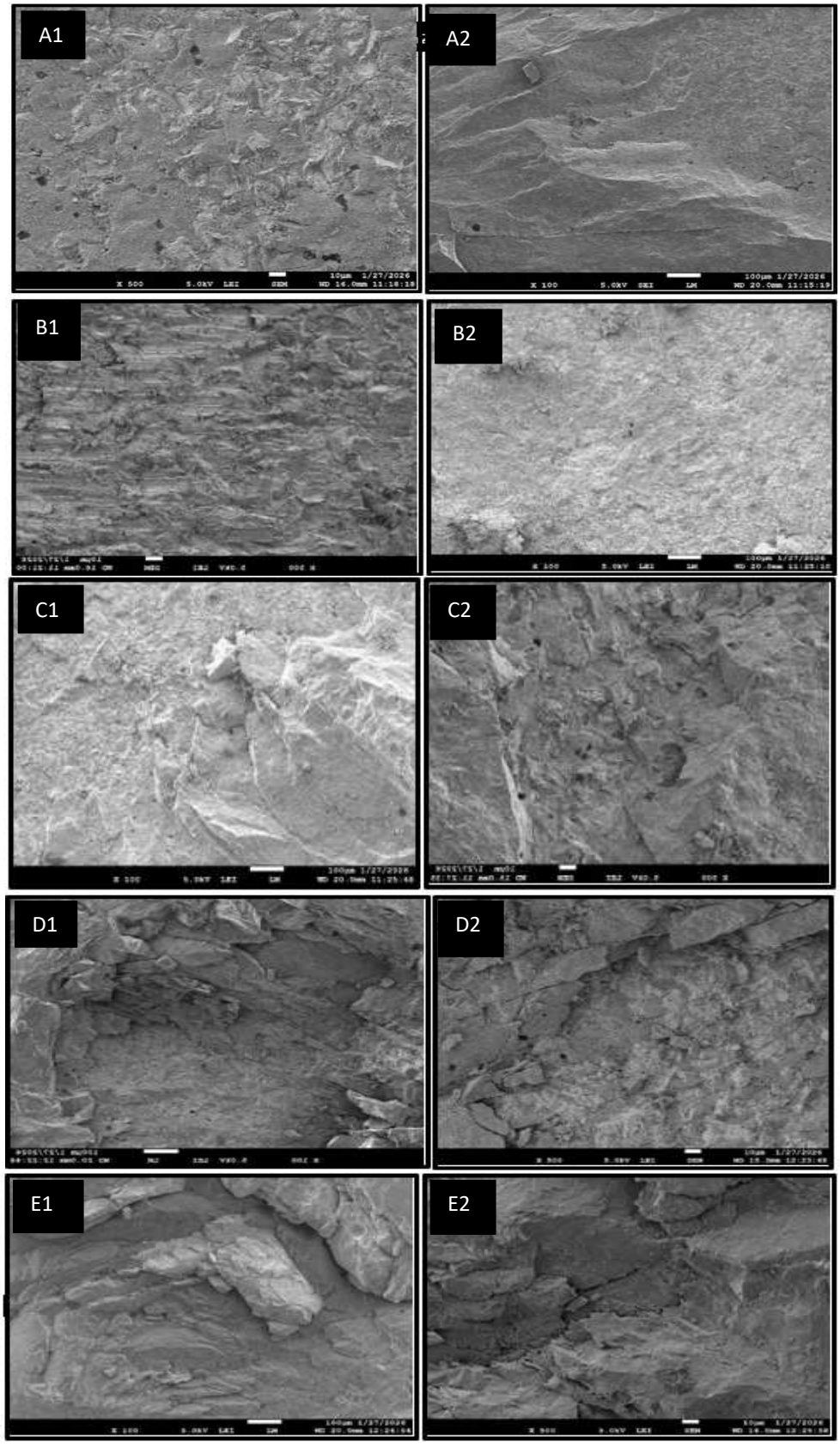

A1
A2
B1
B2
C1
C2
D1
D2
E1
E2

Figure5. SEM images groupA(a1)100X (a2)500x, groupB(b1)100X (b2)500x, groupC(c1)100X (c2)500x,groupD(d1)100X (d2)500x, groupE(e1)100X (e2)500x

DISCUSSION

Metal–ceramic restorations are widely used in fixed prosthodontics because they combine the strength of metal with the esthetic properties of ceramic. Bonding is influenced by mechanical interlocking, chemical interaction with the metal oxide layer, and residual stresses generated during firing [4–6]. Surface treatment therefore plays an important role in optimizing the metal–ceramic interface. The present in vitro study compared different surface-treatment protocols using the three-point bending test according to ISO 9693-1 guidelines [7].

Group A, treated with sandblasting alone, demonstrated the lowest bond strength, with a mean value of 638.47 ± 25.07 MPa and a failure load of 952.95 ± 37.41 N. Adhesive failure was predominant (71.4%), while cohesive and mixed failures each accounted for 14.3%. Sandblasting with aluminium oxide increases surface roughness and promotes micromechanical retention; however, sandblasting alone may not adequately optimize all factors involved in interfacial bonding. Anusavice et al. emphasized the importance of surface characteristics in establishing effective metal–ceramic bonding [11,12].Özcan and Vallittu reported that airborne-particle abrasion alone may provide limited improvement when other interfacial factors, including surface chemistry and oxide characteristics, are not adequately controlled [14,15].Thus, the lower bond strength in Group A may be associated with the limited surface modification produced by sandblasting alone.

Groups B and C demonstrated intermediate bond strength values. Group B, treated with sandblasting and surface grinding, showed a mean bond strength of 727.45 ± 15.04 MPa and a failure load of 1085.80 ± 22.45 N. Group C, treated with sandblasting and ultrasonic cleaning, showed 723.08 ± 23.60 MPa and 1079.20 ± 35.22 N, respectively. The difference was not statistically significant ($p = 0.724$), indicating comparable bond strength. Both groups demonstrated a shift toward mixed failure, with mixed failures occurring in 42.9% of Group B and 57.1% of Group C.

Craig and Powers emphasized the importance of adequate interfacial bonding for metal–ceramic restorations [2]. Mackert and Parry, Li et al., and Manne et al. reported that surface treatment influences bond strength through changes in surface roughness, cleanliness, oxide characteristics, and interfacial interaction [6,12,16]. The comparable results of Groups B and C suggest that both procedures contributed to improved surface conditions, although neither demonstrated a statistically significant advantage over the other.

Group D, treated with sandblasting, grinding, and ultrasonic cleaning, demonstrated a further increase in bond strength, with a mean value of 774.48 ± 27.49 MPa and a failure load of 1156.00 ± 41.03 N. Cohesive failure was observed in 57.1%, whereas adhesive failure decreased to 14.3%. Mackert and Parry emphasized the importance of interfacial characteristics and stress distribution [6,13]. The improved performance of Group D may therefore be associated with the combined effects of surface roughening and improved surface cleanliness.

Group E, which received sandblasting, grinding, ultrasonic cleaning, and acid etching, demonstrated the highest bond strength, with a mean value of 802.58 ± 21.54 MPa and a failure load of 1197.90 ± 32.14 N. Cohesive failure was predominant (85.7%), mixed failure occurred in 14.3%, and no adhesive failure was observed. This indicates that failure occurred mainly within the ceramic or an adjacent cohesive region rather than directly at the interface. Sandblasting and grinding modify surface topography and may enhance micromechanical retention, ultrasonic cleaning improves surface cleanliness, and acid treatment provides additional surface modification. Anusavice, Jochen et al., and Wagner et al. emphasized the importance of surface treatment, metal–ceramic compatibility, and interfacial variables [8,19,30].Ansarifard et al. and Wagner et al. also reported improved bond strength following appropriate surface-treatment protocols [17,30].

Overall, bond strength increased progressively from Group A to Group E, accompanied by a transition from predominantly adhesive to predominantly cohesive failure. Group A showed the lowest bond strength and greatest adhesive failure, whereas Group E demonstrated the highest bond strength and predominant cohesive failure. However, because Group E incorporated several sequential treatments, the independent contribution of acid etching cannot be established. The in vitro design also does not fully reproduce thermocycling, fatigue, moisture, and complex intraoral stresses. Further studies, within the limitations of the present experimental design, incorporating aging, cyclic loading, and standardized clinical protocols are required to evaluate the long-term durability of these surface-treatment procedures.

A clear correlation was observed between increasing bond strength and the transition from adhesive to cohesive failure modes. Group A showed predominantly adhesive failure, whereas Groups D and E demonstrated mainly cohesive failure, indicating superior bond quality and interfacial integrity[21,23]. According to ISO 9693-1, cohesive or mixed failures with adequate bond strength are considered clinically acceptable for metal–ceramic systems[20].

SEM evaluation showed that adhesive failure specimens had smooth metal surfaces with minimal ceramic remnants, indicating weak interfacial bonding, whereas

cohesive failure specimens showed extensive ceramic remnants on the metal surface, suggesting strong adhesion. Similar SEM findings have been reported in previous studies, where increased ceramic remnants correlated with improved bond strength and effective oxide-mediated bonding[11,29]. These observations supported the mechanical testing results and confirmed that advanced surface treatments enhance bond integrity.

CONCLUSION

Within the limitations of the present in vitro study, different surface-treatment protocols significantly influenced the bond strength and failure pattern at the nickel–chromium metal–ceramic interface. The control group treated with sandblasting alone demonstrated the lowest bond strength and predominantly adhesive failure. Progressive improvement in bond strength was observed with the addition of surface grinding and ultrasonic cleaning. The combined surface-treatment protocol involving sandblasting, grinding, and ultrasonic cleaning produced a further increase in bond strength and a greater proportion of cohesive failure.

The group receiving sandblasting, grinding, ultrasonic cleaning, and acid etching demonstrated the highest mean bond strength (802.58 ± 21.54 MPa) and failure load (1197.90 ± 32.14 N), with predominantly cohesive failure (85.7%) and no adhesive failure. Thus, within the conditions of this study, the combined surface-treatment protocol produced the highest bond strength and was associated with a favourable shift in failure mode from adhesive toward cohesive failure.

Overall, the findings indicate that appropriate surface modification can improve the bond strength and alter the failure behaviour of nickel–chromium metal–ceramic restorations. Further studies incorporating thermocycling, cyclic loading, and long-term aging are required to evaluate the durability of these surface-treatment protocols under clinically relevant conditions.

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