



The Effect of Different Polishing Methods on Monolithic and Multilayer Zirconium Restoration: An in Vitro Study

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Abstract

This in vitro study evaluated the effects of different polishing protocols on the microhardness and surface topography of multilayered (ML) and monolithic (MZ) yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) used in fixed dental restorations. The objective was to compare the influence of manual and semi-automatic polishing methods on both mechanical performance and surface quality, aiming to identify the most effective protocol for clinical application. Eighty disc-shaped zirconia specimens were prepared and divided into eight groups (40 MZ: A1, B1, C1, D1; and 40 ML: A, B, C, D) according to polishing protocol. Groups A and A1 served as controls, manually polished with a zirconia laboratory kit. Groups B/B1, C/C1, and D/D1 were polished semi-automatically using a grinder-polisher with 3 µm polycrystalline diamond suspension, 6 µm polycrystalline diamond suspension, and 0.04 µm colloidal silica, respectively. Microhardness was measured using a Vickers microhardness tester, and surface topography was examined via scanning electron microscopy (SEM). Statistical analysis was performed using one-way ANOVA and Tukey's post hoc test. Significant differences in microhardness were found among polishing methods for both zirconia types ($p < 0.001$). Groups C (1494.84 VHN) and C1 (1493.98 VHN) achieved the highest hardness values, while the control groups A (1378.42 VHN) and A1 (1376.13 VHN) recorded the lowest. SEM revealed that D/D1 exhibited the smoothest and most uniform surfaces, whereas A/A1 showed deep grooves. Findings indicate that semi-automatic polishing with 6 µm diamond maximizes hardness, while colloidal silica provides superior smoothness, guiding clinical selection for optimal zirconia restoration outcomes.

Introduction:

Yttria-stabilized tetragonal zirconia polycrystalline (Y-TZP) ceramics have been widely used for all-ceramic fixed prostheses, monolithic restorations, and implant abutments following the advancement of computer-aided design/computer-aided manufacturing (CAD/CAM) technology in dentistry(1-3). Monolithic zirconia (MZ) has gained considerable attention in dental applications due to its excellent mechanical properties and reduced incidence of veneer chipping(4-6). Zirconia (ZrO_2), a crystalline dental ceramic, combines high strength with outstanding biocompatibility (7-10). Early generations of zirconia include partially stabilized 3Y-TZP, which contains approximately 3 mol% yttria (Y_2O_3) and 0.25–0.5 wt% alumina (Al_2O_3), and exhibits a predominantly tetragonal crystalline phase that provides superior mechanical strength but limited translucency(11, 12). In contrast, newer fully stabilized 5Y-TZP contains about 5 mol% yttria and 0.5 wt% alumina, with a higher proportion of the cubic phase, which enhances translucency and esthetics but reduces mechanical strength compared to 3Y-TZ (8, 13, 14). Zirconia exists in three crystalline phases depending on temperature: monoclinic at room temperature, tetragonal above 1170 °C, and cubic above 2370 °C, with the cubic phase remaining stable until 2680 °C (15, 16). Surface quality significantly influences zirconia's clinical performance, affecting wear resistance, esthetics, and long-term mechanical stability. Among the most relevant mechanical properties is Vickers microhardness, which measures resistance to localized deformation. In dentistry, polishing is preferred over glazing because it reduces surface roughness and improves surface integrity without compromising the microstructure (17, 18). Diamond suspension and colloidal silica have been widely used as polishing abrasives in dental materials. Jassem et al. (2024) applied these materials to improve the surface roughness of reinforced polymethyl methacrylate

denture bases. Although their study focused on acrylic, the same polishing abrasives were adopted in the present work, but applied with a different polishing device and on zirconia specimens (19). Patil and Jebaseelan reported Vickers hardness exceeding 1400 HV with diamond and alumina-based polishing techniques (18). Yener et al. demonstrated that polishing resulted in higher hardness and better stability after thermal cycling compared to glazing (20, 21). In multilayer zirconia, which combines layers with varying yttria content, polishing responses differ. Layers rich in cubic phase (higher yttria) tend to be more sensitive to aggressive polishing, potentially compromising hardness, whereas tetragonal-rich layers maintain greater strength.(20, 22). The null hypothesis proposed that no significant difference would exist in the microhardness and surface topography of multilayered (ML) monolithic zirconia and ultra-translucent (MZ) zirconia ceramics compared to the control polished with a zirconia lab kit when subjected to the tested surface polishing approaches. The present study aimed to evaluate and compare the Vickers microhardness and surface morphology of multilayer and ultra-translucent monolithic zirconia after different polishing protocols, using a microhardness tester for quantitative measurements and Scanning Electron Microscopy (SEM) for qualitative topographical analysis.

Materials And Methods:

Preparation of specimens

The design and fabrication of the zirconia specimens were done using the CAD/CAM system in this in vitro study, conducted between December 2024 and March 2025. The sintering process and polishing of groups A and A1 were performed at the World of Dentistry Laboratory, Baghdad, Iraq. The grinding and polishing of groups B, B1, C, C1, D, and D1, along with the grinding of groups A and A1, were carried out at the Material Characterization Centre (MCC) for Research Studies, Kut, Iraq. Eighty disc-

shaped pre-sintered zirconia blocks were used: 3Y-TZP (ORALEAD[®], FDA, CE, ST, China) and 5Y-TZP (ORALEAD[®], FDA, CE, 3rdpro, China). The specimens were standard flat discs to ensure consistent testing conditions. Each zirconia type was divided into four groups (n = 10 per group) using a computer-generated randomization list to avoid selection bias. Specimens were designed in Autodesk Fusion 360 (Autodesk Inc., San Francisco, CA, USA) and fabricated via CAD/CAM milling with a five-axis milling machine (Lab MC X5, Dentsply Sirona, Bensheim, Germany), producing discs measuring (10 mm × 3 mm) (11, 23) following ISO 6872:2015 standards (24). Sintering was performed in a furnace (Fire HTC Speed, Dentsply Sirona, Germany) by heating to 800 °C at 20 °C/min, then to 1550 °C with a 2-hour hold. Preliminary surface finishing was achieved using a semi-automatic grinder-polisher (Metkon FORCIMAT-TS, Metkon Instruments Inc., Turkey) to ensure a standardized baseline before polishing and testing (25).

Surface Grinding and Polishing Protocol

Initial grinding was performed with silicon carbide (SiC) papers (AL-Alamain Ghalib, KSA) (600–3000 grit) under continuous water irrigation at 300 rpm platen speed, 150 rpm head speed, and 25–30 N force. (26). Specimens were randomly assigned to eight polishing groups (n = 10 per group):

Group A1 (MZ) / A (ML): Laboratory micromotor polishing (MARATHON-3, Republic of South Korea) with a three-step extraoral diamond wheel kit (yellow fine, blue extra-fine, white super-fine; NHT, China). Each step lasted 30 s at 10,000 rpm under light pressure; the handpiece was held at 90° to the surface. The polishing process was carried out sweepingly using both forward and backward motions. A single operator completed every specimen.

Group B1 (MZ) / B (ML): Velvet polishing pad on semi-automatic grinder-polisher; platen 150 rpm, head 100 rpm, 30 N force, 6 min polishing with 3 μm

polycrystalline diamond suspension (no water irrigation).

Group C1 (MZ) / C (ML): Micro Cloth[®] pad, same parameters as Group B1, using 6 μm diamond suspension.

Group D1 (MZ) / D (ML): Final chemo-mechanical polishing with colloidal silica suspension (0.04 μm; On Point, USA); platen 100 rpm, head 60 rpm, 20 N force, 3 min duration, as illustrated in Figures 1, 2, and 3.

Microhardness Test

The dimensions of all zirconia specimens were measured using electronic digital calipers (LOUISWARE, China) to ensure standardized sizing before testing. Specimens were ultrasonically cleaned in distilled water for 10 minutes using a MESTRA[®] CALYPSO ultrasonic unit (Spain) and dried with absorbent paper. Vickers microhardness testing was performed using a Vickers microhardness tester (Model: HV-1000A, Laizhou Huayin Testing Instrument Co., Ltd., China) equipped with a diamond indenter, applying a load of 9.8 N (1 kgf) for 10 seconds. The diagonals of each indentation were measured under a 100× optical microscope, and the Vickers Hardness Number (HV) was calculated using the following formula:

$$HV = 1.854 \times F/d^2$$

Where F is the applied load in kilograms-force (kgf) and d is the mean diagonal length of the indentation in millimeters (27). For each specimen, three indentations were made at the center of the sample, spaced at least 1 mm apart, specifically to ensure readings reflected the same material layer, especially critical for multilayer zirconia. The average of the three values was recorded as the final VHN, as shown in Figure 4.

Scanning Electron Microscopy (SEM) analysis

A Scanning Electron Microscope (SEM) (Vega, TESCAN, Czech Republic) was used for extensive qualitative surface analysis. The SEM analysis occurred after

a gold coating was applied to the specimens using a vacuum sputter coater (MTI CORPORATION USA). The SEM examination was conducted at a scale of 500 μm and a magnification of 200X.

Statistical analysis

The statistical analysis was performed using IBM SPSS Statistics version 27.0 (IBM Corp., Chicago, IL, USA). After conducting a distribution test, the sample data were found to be normally distributed. A one-way Analysis of Variance (ANOVA) test was conducted to determine whether the different polishing techniques caused statistically significant differences in microhardness values among the tested groups. The Tukey test was used as a post-hoc analysis to determine which groups differed. A *p*-value less than 0.05 was considered statistically significant

Results and Discussion

Microhardness Results and Discussion

Monolithic zirconia (MZ)

The Vickers microhardness values (VHN) of MZ varied significantly across polishing protocols. The highest mean value was recorded in Group C1 (1493.98 \pm 64.37 VHN), followed by Group D1 (1429.86 \pm 47.71 VHN), Group B1 (1411.61 \pm 45.56 VHN), and the lowest in the control Group A1 (1376.13 \pm 49.07 VHN) (Table 1, Fig. 5). One-way ANOVA revealed a statistically significant difference among the groups ($F = 8.946$, $p < 0.001$) (Table 2), confirmed by Tukey's post-hoc analysis (Table 3).

Multilayer zirconia (ML)

For ML zirconia, the highest mean VHN was found in Group C (1494.84 \pm 65.84 VHN), with the lowest in the control Group A (1378.42 \pm 51.28 VHN). Groups B (1410.95 \pm 45.23 VHN) and D (1430.13 \pm 47.40 VHN) yielded intermediate values (Table 4, Fig. 6). ANOVA demonstrated significant differences ($F = 8.552$, $p < 0.001$) (Table 5), with post-hoc testing confirming multiple significant pairwise differences (Table 6).

Discussion of Microhardness results

Surface treatment following sintering is a critical determinant of zirconia's mechanical performance. The lowest VHN values were found in Groups A and A1, both finished using a conventional extraoral zirconia laboratory kit, suggesting that this method may be inadequate for achieving optimal surface densification and grain refinement. Similar trends have been reported by Preis et al. (2011), who observed that coarse finishing burs introduced microcracks and residual flaws that compromise microhardness (28). The enhanced microhardness observed in Groups C and C1 is likely owing to the regulated abrasive action of the 6 μm polycrystalline diamond suspension, which efficiently improves the zirconia surface without excessive material removal. This process reduced surface flaws, minimized subsurface microcracks, and promoted localized grain boundary compaction, all of which enhanced resistance to indentation. This result aligned with previous findings of Al-Haj Husain et al. (2016) as well as Flury et al. (2017), who emphasized that fine-grit diamond polishing followed by sequential smoothing enhanced hardness without inducing subsurface damage (29, 30). In addition, Groups D and D1, despite presenting smoother surfaces in SEM, showed slightly lower hardness than Groups C and C1. A possible explanation, supported by Zhang et al. (2019), is that overly fine polishing may remove the beneficial residual compressive stresses generated during intermediate abrasive polishing, thus lowering peak hardness despite optimal surface smoothness(31).

SEM results and discussion

The SEM imaging qualitatively assessed post-polishing surface topography. The SEM analysis of groups A and A1 displayed pronounced grooves, irregular pits, and directional striations characteristic of coarse finishing tools. In contrast, the SEM analysis of groups B, B1, C, and C1 exhibited more uniform linear patterns, reduced defect density, and overall smoother topographies. However, the SEM analysis of groups C and C1, in particular, showed a combination of high

smoothness and minimal defects, while groups D and D1 achieved the smoothest, most featureless surfaces. These SEM observations supported the microhardness findings: rougher surfaces in groups A and A1 corresponded with their lower VHN, consistent with the premise that residual surface defects diminished mechanical performance. Besides, groups C and C1 showed a balanced combination of defect removal and microstructural compaction yielded the highest hardness values, whereas the ultra-smooth finish of Groups D and D1 did not translate to maximum hardness due to reduced compressive stress effects. (Figures 7 and 8). These SEM outcomes observations agreed with earlier work by Lawson et al. (2018), who noted that laboratory polishing systems often leave characteristic directional striations that may influence mechanical outcomes.(32). In our study, rougher surfaces in groups A and A1 corresponded with their lower VHN, supporting the premise that residual surface defects diminish mechanical performance. Interestingly, groups C and C1 demonstrated both relatively smooth morphology and the highest hardness values, indicating that the ideal polishing protocol balances surface defect removal with sufficient microstructural compaction. This finding is consistent with the outcomes of Flury et al. (2017), who observed that optimal hardness was attained by polishing reduced fault depth without over-smoothing (28). However, Groups D and D1 achieved the smoothest surfaces overall, despite somewhat lower hardness values. This result is consistent with Zhang et al. (2018)'s finding that extreme smoothness may not correspond to maximum hardness, as positive compressive stress effects are diminished (30).

Impact of Surface Defects on Long-Term Performance

Surface irregularities such as grooves, linear marks, and microstructural flaws act as stress concentrators, which can significantly compromise the mechanical integrity of zirconia restorations over time. These defects facilitate crack initiation and propagation under cyclic masticatory loading, accelerating fatigue-related

failure. Additionally, rough surfaces may promote plaque retention and increase the abrasive wear of opposing dentition, thereby raising the risk of both biological and mechanical complications. Optimizing polishing protocols to minimize these defects is therefore critical for extending the clinical service life of zirconia restorations.

Clinical Implications and Recommendations

Polishing using 6 μm polycrystalline diamond suspension results in the highest microhardness values, making it ideal for fixed dental restorations (especially posterior teeth) under severe occlusal loads. In contrast, colloidal silica polishing produced improved surface smoothness, which may reduce opposing wear and improve cosmetic outcomes, both of which are extremely crucial for anterior dental restorations. Clinicians and technicians should employ a case-specific selection strategy, balancing the necessity for optimum mechanical strength and the demand for ideal surface smoothness.

Conclusions

This study found that polishing techniques greatly increased the microhardness of both monolithic and layered zirconia. Groups polished with 6 μm polycrystalline diamond suspension (C1) had the highest hardness values, likely due to effective surface imperfection elimination and grain boundary refinement. The SEM study revealed that the control groups (A, A1) had uneven, grooved surfaces, whereas polished groups, particularly the colloidal silica group (D1), had smoother, more uniform topographies. The study found that 6 μm diamond polishing maximizes hardness, and colloidal silica improves surface smoothness. One-way ANOVA analysis revealed significant differences between groups ($p < 0.05$), indicating that these polishing techniques are effective extraoral finishing approaches for zirconia dental restorations.

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Figure 1. Dual-disc semi-automatic grinder–polisher equipped with independent pressure heads, utilized for standardized surface preparation of zirconia specimens before testing.

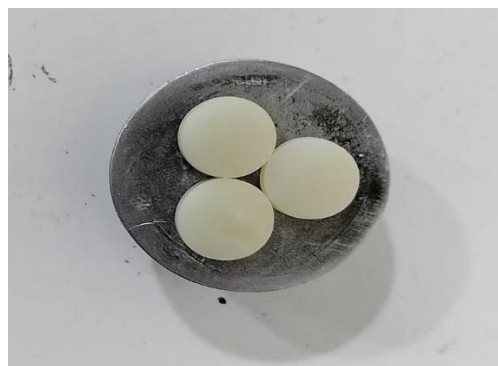


Figure 2. Zirconia discs mounted in a metallic specimen holder, arranged symmetrically to ensure even distribution of force during the polishing process.



Figure 3. Close-up view of the polishing head applying consistent vertical load to the specimen holder, enabling reproducible and uniform surface finishing across all samples.



Figure 4. Vickers microhardness testing device applying a controlled load via a diamond indenter to evaluate the surface hardness of monolithic and multilayer zirconia specimens.

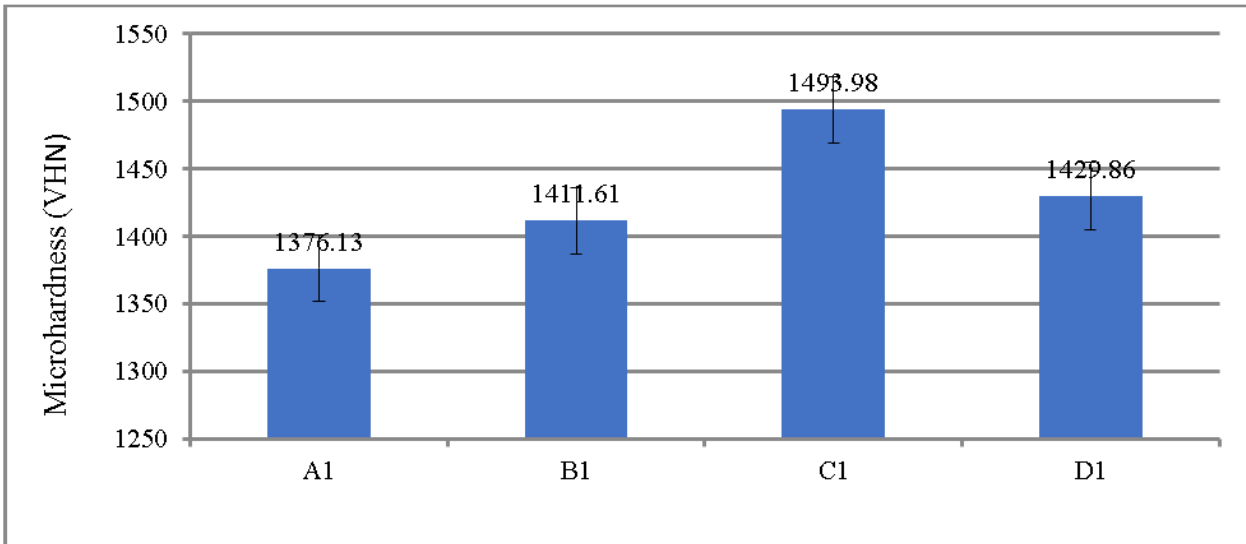


Figure 5: Bar chart showing MZ samples' mean microhardness (VHN) values across polishing groups. The highest value was observed in the group (C1) and the lowest in group A1.

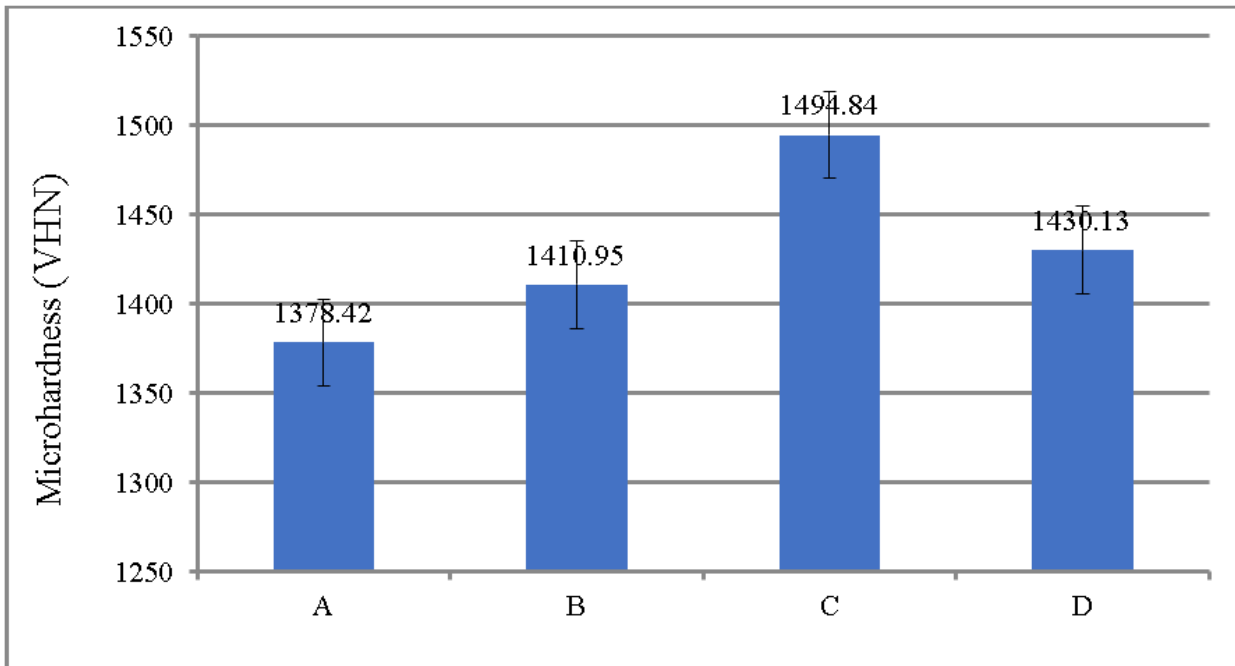


Figure 6: Bar chart displaying the mean microhardness (VHN) values of ML zirconia samples across polishing groups.

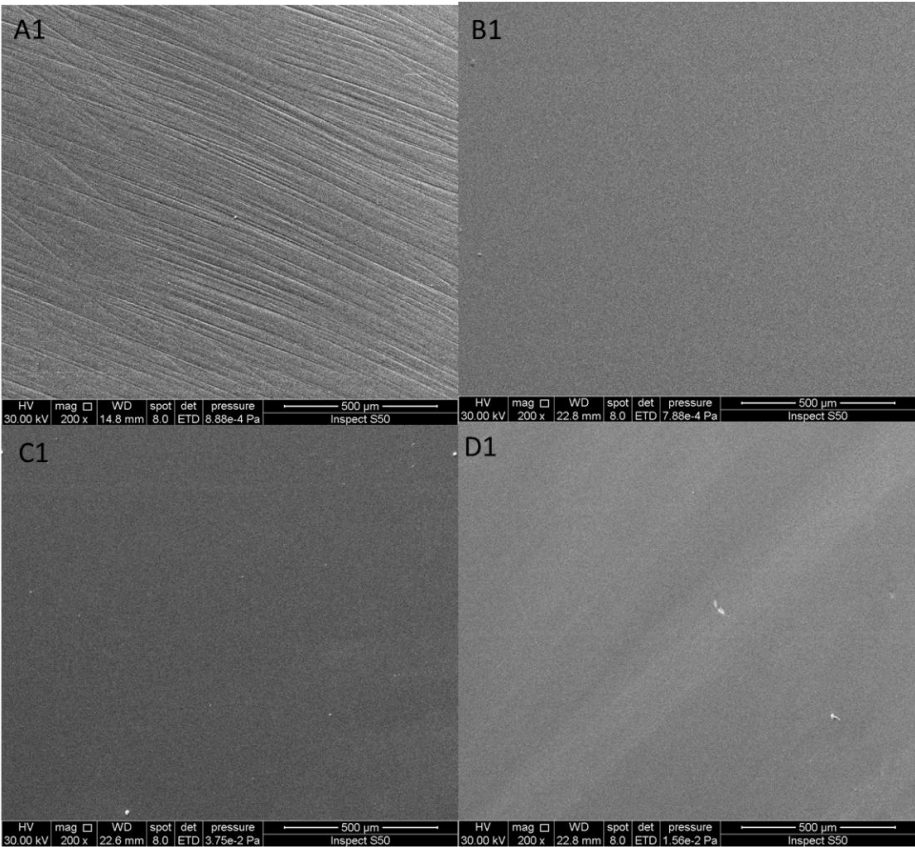


Figure 7: SEM evaluation of monolithic zirconia (MZ) of group A1, group B1, group C1, and group D1, scale bars are 500µm.

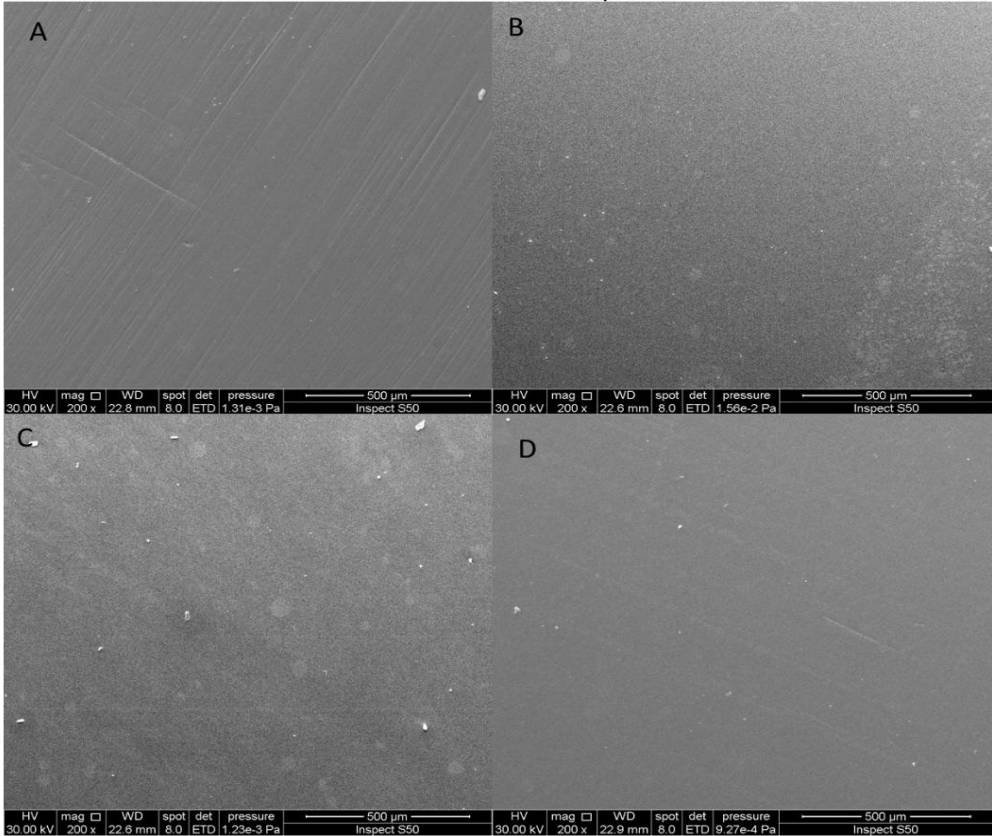


Figure 8: SEM evaluation of multi-layer zirconia (ML) of group A, group B, group C, and group D, scale bars are 500µm.

Table 1: Descriptive statistics of Vickers microhardness (VHN) values for MZ across different polishing groups. The group (C1) recorded the highest mean hardness, while the group (A1) had the lowest.

Groups	Sample No.	Mean	SD	Std. Error	Minimum	Maximum
A1	10	1376.1300	49.073	15.518	1306.50	1443.70
B1	10	1411.6100	45.562	14.408	1345.00	1473.20
C1	10	1493.9800	64.372	20.356	1424.10	1589.70
D1	10	1429.8600	47.711	15.087	1336.20	1492.00

Table 2: One-way ANOVA results for microhardness of MZ. A statistically significant difference was observed between groups ($p < 0.001$).

	Sum of Squares	df	Mean Square	F	P-value
Between Groups	73159.049	3	24386.350	8.946	0.000 (HS)
Within Groups	98136.71	36	2726.020		
Total	171295.76	39			

Table 3: Tukey’s post-hoc comparison of MZ groups. Significant differences were found in favor of the group (C1) compared to other groups.

Study variables		Mean Difference	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
A1	B1	-35.48000	23.34960	0.437	-98.3658	27.4058
	C1	-117.85000*	23.34960	0.000	-180.7358	-54.9642
	D1	-53.73000	23.34960	0.117	-116.6158	9.1558
B1	C1	-82.37000*	23.34960	0.006	-145.2558	-19.4842
	D1	-18.25000	23.34960	0.862	-81.1358	44.6358
C1	D1	64.12000*	23.34960	0.044	1.2342	127.0058

* The mean difference is significant at the 0.05 level.

Table 4: Descriptive statistics of Vickers microhardness (VHN) values for ML zirconia across different polishing groups. The group (C) recorded the highest mean hardness, while the group (A) had the lowest.

Groups	Sample No.	Mean	SD*	SE	Minimum	Maximum
A	10	1378.42	51.28	16.21	1303.00	1445.00
B	10	1410.95	45.22805	14.30236	1344.20	1470.70
C	10	1494.84	65.84	20.82	1422.50	1593.10
D	10	1430.13	47.40	14.99	1339.20	1490.90

Table 5: One-way ANOVA results for microhardness of ML zirconia. A statistically significant difference was observed between groups ($p < 0.001$)

	Sum of Squares	df	Mean Square	F	p-value
Between Groups	72196.325	3	24065.442	8.552	0.000 (HS)
Within Groups	101304.206	36	2814.006		
Total	173500.531	39			

Table 6: Tukey’s post hoc comparison of ML zirconia groups. Significant differences were found in favor of group C compared to the other groups.

Study variables		Mean Difference	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
A	B	32.53	23.72343	0.53	-96.4226	31.3626
	C	116.42*	23.72343	0.000	-180.3126	-52.5274
	D	51.71	23.72343	0.15	-115.6026	12.1826
B	C	83.89*	23.72343	0.01	-147.7826	-19.9974
	D	19.18	23.72343	0.850	-83.0726	44.7126
C	D	64.71*	23.72343	0.05	0.8174	128.6026

* The mean difference is significant at the 0.05 level.

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