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Original article

Effect of different surface treatments on shear bond strength of autopolymerizing repair resin to denture base materials processed with different technologies

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Abstract

Purpose: To evaluate the effect of chemical, mechanical, and combination surface treatments on the shear bond strength (SBS) of autopolymerizing repair resins to conventional heat-cured, computer aided design (CAD)-computer aided manufacturing (CAM) milled, and three-dimensionally (3D) printed denture base materials.

Methods: Specimens were fabricated and divided according to the surface treatment as follows: no surface treatment (control group), monomer treatment (monomer group), resin remover treatment (resin remover group), roughening with 180 FEPA grit abrasive paper followed by monomer treatment (180-grit plus monomer group), and air particle abrasion (air abrasion group). Autopolymerizing resin cylinders were attached before accelerated aging of the specimens in water at 100 °C for 16 h. The SBS was tested using a universal testing machine. Surface roughness was evaluated using a 3D optical profilometer. Scanning electron microscopy (SEM) and stereomicroscopy were used for surface analysis. Data was collected and analyzed using analysis of variance (ANOVA) and Kruskall–Wallis tests ($\alpha = 0.05$).

Results: The denture base material and surface treatment significantly affected the SBS. The milled Temp Basic Tissue demonstrated the highest SBS values across all surface treatments, whereas the two 3D-printed denture base materials exhibited the lowest SBS values.

Conclusions: The bond strength of CAD-CAM-milled denture base resins to autopolymerizing repair resins is comparable to that of heat-cured resins. Surface roughening using air particle abrasion or 180-grit carbide paper can enhance the bond strength of the autopolymerizing repair resin to 3D-printed denture base materials.

Keywords: Denture base, Bond strength, Air abrasion, Roughness, 3D printing

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1. Introduction

Partial and complete removable dentures are commonly used in clinical settings to replace missing teeth and restore oral function[1]. The denture base is an essential component for recuperating missing soft tissues, supporting artificial teeth, and withstanding diverse intraoral stresses[2,3]. Conventional denture bases are processed from polymethyl methacrylate (PMMA)-based polymers, being available and cost-effective. Furthermore, dentures can be digitally fabricated using computer-aided design and computer-aided manufacturing (CAD-CAM) technologies such as subtractive milling and additive manufacturing(3D printing)[4]. Digital operations can minimize the number of appointments and chair time and allow for replacement based on a pre-existing dataset[5,6]. Digital light processing (DLP) is a 3D printing technology for dental applications because of its quick manufacturing and superior resolution[7]. With the advancement of digital technologies, new 3D-printed materials from various dental

WHAT IS ALREADY KNOWN ABOUT THE TOPIC?

» *Prior research has extensively reported the bond strength achieved by surface treatments that applied repair resins to conventional denture base materials. However, the effect of these treatments in the case of digitally manufactured denture base materials has not been fully explored.*

WHAT THIS STUDY ADDS?

» *This study reports the bond strength between autopolymerizing resin and denture base materials. It highlights the effect of chemical composition of the denture base and demonstrates that mechanical roughening can enhance the bond strength between repair resin and 3D-printed resins.*

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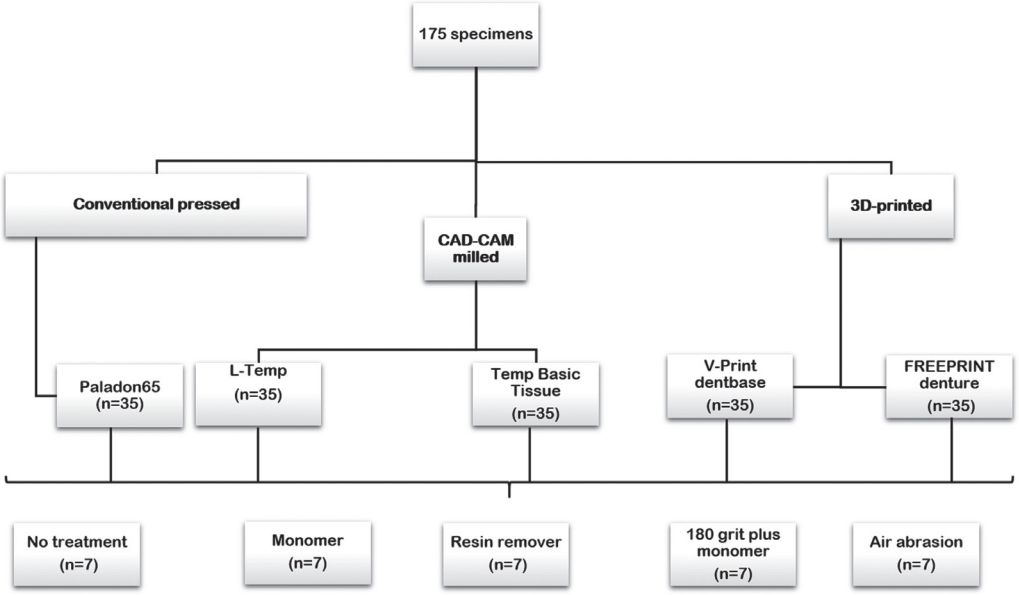

Fig. 1. Flowchart of experimental setup

manufacturers and additional CAD-CAM materials for denture base construction are now available. Denture base resins for DLP usually comprise a range of methacrylate or acrylate monomers and oligomers, with particular components frequently kept undisclosed because of trade secrets.

Denture base fractures are among the most frequently observed mechanical complications in clinical practice under the intricate intraoral strains created by mastication[8,9]. Moreover, fracture is a common mechanical consequence of overdentures, especially in thinner areas of the denture base. This can be attributed to the higher occlusal force generated by the implant support[10,11]. A number of repair materials have been used, including autopolymerizing[12–15], heat-[16], and light-cured[17] acrylic resins. Although heat-cured acrylic resins outperform autopolymerizing resins in terms of their mechanical and chemical characteristics, they require a series of time-consuming laboratory procedures[18,19]. Therefore, autopolymerizing polymethylmethacrylate is commonly used in the repair process[15,19].

Surface modifications using chemical and mechanical treatments efficiently enhance the bonding contact and minimize stress concentration[12,20]. Chemical surface treatments with methyl methacrylate (MMA) monomer and organic solvents such as acetone[21,22], methylene chloride[12,23], and chloroform[13,23,24] have been used to modify the surface morphology of the denture base material and promote adhesion. The goal is to swell the surface layer and allow monomer diffusion, forming an interpenetrating polymer network (IPN) between the PMMA denture base and repair resin[5]. Thanks to their applicability, monomers are the most dominant chemical treatments used for this purpose[19]. According to Vallittu *et al.*[20], wetting the repair surface with MMA dissolves the surface structure of the PMMA and improves its adhesion. Mechanical roughening of the repair surfaces by burr grinding[25] and airborne-particle abrasion with aluminum oxide (Al_2O_3) particles[1,22] is an appropriate method for improving repair strength by increasing the surface area for mechanical retention.

Denture repair commonly involves bonding two fractured sections with an autopolymerizing resin. Because repaired dentures are prone to re-fracture at the interface junction of the repair material and fractured surface, adequate bond strength is critical for long-term success after repair[12,26]. Therefore, this study aimed to evaluate the effect of chemical, mechanical, and combination surface treatments on the shear bond strength of autpolymerized repair resin to conventional heat-cured, CAD-CAM milled, and 3D-printed denture base materials. The null hypothesis was that neither the surface treatments nor the denture base materials affected the SBS.

2. Materials and Methods

2.1. Specimens preparation

In this study, one conventional heat-cured resin, two resins used for subtractive milling, and two resins used for 3D printing were investigated. A summary of the materials used is provided in **Table 1**. For testing, 175 specimens (five materials, n = 35/material) with rectangular geometries and dimensions of 20 mm × 10 mm × 3 mm were fabricated.

Conventional heat-cured resin specimens were fabricated using polytetrafluoroethylene (PTFE) molds. The powder and liquid components were mixed in the proper ratio (10 g powder: 4 mL liquid monomer), placed into the molds, and then polymerized in accordance with the manufacturer's instructions in a pneumatic polymerizing unit (Ivomat IP3; Ivoclar Vivadent AG, Schaan, Liechtenstein) at 90 °C under 0.2 MPa (2 bar) pressure for 20 min, then cooled down slowly in the water bath.

The CAD-CAM Pre-polymerized discs were cut into the desired dimensions using a low-speed water-cooled diamond saw (Secotom 50; Struers, Ballerup, Denmark). Using computer-aided design software (Autodesk Fusion 360, Autodesk, San Rafael, CA, USA), the 3D-printed test specimens were designed and imported as a standard tessellation file (STL) file. Specimens were printed vertically with a

Table 1. Materials used in study and chemical composition

Material	Description	Manufacturer	Chemical composition		Mass %
Paladon65	Heat-cured denture base material (Conventional)	Kulzer GmbH, Hanau, Germany	Liquid	methyl methacrylate	>90
				tetramethylene dimethacrylate	≥1-≤5
				P-Mentha-1,4-diene	<0.25
			Powder	based on methacrylate copolymer	-
				methylmethacrylate	≥1-≤5
				dibenzoyl peroxide	≥0.25-<1
L-Temp	Subtractive milled denture base material	Degos Dental GmbH, Bayern, Germany	polymethyl methacrylate		-
Temp Basic Tissue		Zirkonzahn, Gais, Italy	polymethyl methacrylate		-
V-Print dentbase	3D- printed denture base material	VOCO GmbH, Cuxhaven, Germany	aliphatic urethane dimethacrylate		50-100
			Ethoxylated bisphenol A dimethacrylate		25-50
			triethylene glycol dimethacrylate		5-10
			diphenyl(2,4,6-trimethylbenzoyl) phosphinoxid		≤2.5
FREEPRINT denture		Detax, Ettlingen, Germany	isopropylidenediphenol peg-2 dimethacrylate		35 - 60
			7,7,9(7,9,9)- trimethyl-4,13-dioxo-3,14-dioxa-5, 12-diazahexadecane-1,16-diyl bismethacrylate		30-35
			1,6-hexanediol dimethacrylate		1 - 5
			2-hydroxyethyl methacrylate		1 -< 5
			diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide		1-5
			Hydroxy propyl methacrylate		1 -5
			phenyl bis(2,4,6-trimethylbenzoyl)-phosphine oxide		<1
Palapress	Autopolymerizing repair resin	Kulzer GmbH, Hanau, Germany	Liquid	methylmethacrylate	>90
				tetramethylene dimethacrylate	≥1-≤5
				maleic acid	<0.1
				2-Hydroxy-4-methoxy benzophenone	<0.25
				mequinol	<1
				Quaternary ammonium compounds, tri-C8-10-alkylmethyl, chlorides	≥0.025-<0.25
			Powder	based on methacrylate copolymers	
				dibenzoyl peroxide	1-<2.5
				methyl methacrylate	≥1-≤5
				1-Benzyl-5-phenylbarbituric acid	≥0-≤5
GC RELINE II remover for resin	Chemical surface treatment	GC, Tokyo, Japan	ethyl acetate		45-70
			methyl methacrylate (MMA)		10-30
Aluminum oxide abrasive	Mechanical surface treatment	Cobra, Renfert, Germany	50 μm Al_2O_3		-

50 μm layer thickness using a DLP 3D printer (Asiga MAMT; SCHEU-DENTAL GmbH, Iserlohn, Germany) and then cleaned in isopropanol (>98%) (3 min × 2 times) within an ultrasonic cleaner (Quantrex® 90; L&R Ultrasonics, New Jersey, USA). Post-processing was then performed in a light chamber (Otoflash G171; NK Optics, Baierbrunn, Germany) under a protective nitrogen atmosphere (2000 flashes × 2 times), following the manufacturer's instructions.

The obtained specimens were mounted onto plastic holders (30 mm in diameter and 20 mm in thickness) using an autopolymerizing resin, and their flat surfaces were subsequently polished under water cooling with 500, 800, and 1200 FEPA grit silicon carbide abrasive papers (Struers, Copenhagen, Denmark) using a grinding machine (LaboPol-21; Struers, Copenhagen, Denmark).

2.2. Surface treatment

Specimens from each material were further divided into five groups based on the surface treatment (n = 7/group) as follows: no surface treatment (control group); Palapress liquid monomer treatment for 30 s (monomer group); GC RELINE II resin remover treatment for 30 s (resin remover group); roughening with 180 FEPA grit silicon carbide abrasive paper, followed by Palapress liquid monomer treatment for 30 s (180-grit plus monomer group); and air particle surface abrasion with 50 μm aluminum oxide particles at a distance of 10 mm with a pressure of 0.2 MPa (air abrasion group) (**Fig. 1**).

2.3. SBS assessment

Cylinders made of Palapress autopolymerizing acrylic resin were attached to the denture baseplates. A polyvinyl siloxane (PVS) mold (inner diameter of 3.6 mm and height of 3.0 mm) was positioned centrally on the flat substructure of the denture base material surface. The acrylic resin was mixed at a ratio of 10 g of powder to 7 mL of liquid monomer, as instructed by the manufacturer, and placed in the PVS mold. Polymerization was continued in a water bath at 55

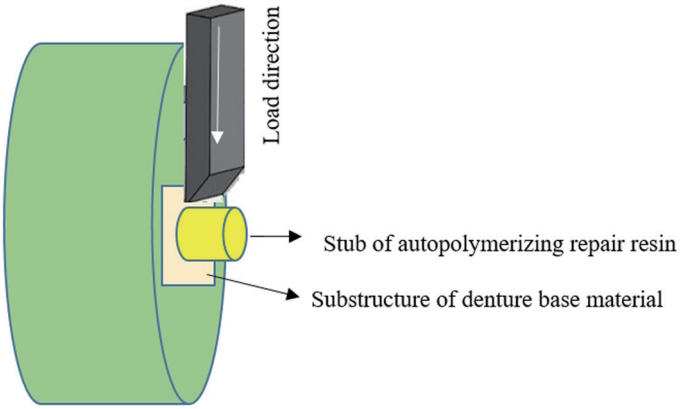

Fig. 2. Shear bond strength testing setup illustration

°C for 30 min under a pressure of 0.2 MPa (2 bar) before removing the mold.

The specimens were then subjected to accelerated aging by placing them in sealed glass containers filled with deionized distilled water. The containers were placed in an oven at 100 °C for 16 h. The specimens were cooled to room temperature before testing. For SBS testing, the specimens were properly aligned with the long axis of the testing machine and secured in a mounting jig (Danville Engineering Inc., San Ramon, CA, USA), and a shear blade was placed parallel to and against the interface between the autopolymerizing and denture base-resin layers. The specimens were then loaded until failure on a universal testing machine (Model LRX; Lloyd Instruments Ltd., Fareham, England) at room temperature (23 °C) and a crosshead speed of 1 mm/min (**Fig. 2**). A PC software (Nexygen; Lloyd Instruments Ltd., Fareham, England) was used to record the data. The SBS was determined using the formula S = F/A, where S is the SBS (MPa), F is the shear force at failure (N), and A is the bonding area (mm^2). The surfaces of the tested specimens were visually examined using a stereomicroscope (Wild M3Z, Wild Heerbrugg, Switzerland) at 25× magnification to categorize the failure modes. The failure modes were classified as cohesive (within the denture base resin or autopolymerizing repair resin), adhesive (at the denture base resin/autopolymerizing repair resin interface), or mixed (a mix of cohesive failures within the denture base resin or autopolymerizing repair resin and adhesive failures).

2.4. Surface topography and scanning electron microscopy assessments

Surface topographies (n = 6/group) were assessed after different surface treatments using a noncontact 3D optical profilometer (OP) (ContourGT-I; Bruker Nano GmbH, Berlin, Germany). The studied surfaces were 3-dimensionally generated using Vision 64. A 5× objective lens and a 0.5 multiplier were used with a back scan and length parameters of 25 µm and 60 µm in VSI/VXI mode to obtain a 3D rendering of the specimen surfaces. The arithmetic mean height was used to determine surface roughness. For each specimen, three random points were scanned to ensure measurement accuracy.

To assess the effects of surface treatments on the morphological characteristics of the denture base materials, the same specimens were gold sputtered and observed using SEM (JSM-5500; JEOL Ltd., Tokyo, Japan) with the microscope operating at 15 kV. Representative images were acquired at 500× magnification.

2.5. Statistical analysis

A statistical software program (IBM SPSS Statistics v24; IBM Corp., Armonk, NY) was used for statistical analysis. The SBS data had a normal distribution (Kolmogorova–Smirnov test, $P = 0.200$) and homogeneity of variance (Levene test, $P = 0.105$); therefore, they were subjected to ANOVA followed by a Tukey HSD post hoc test for pairwise comparisons. As surface roughness data were not normally distributed ($P < 0.05$), they were analyzed using the Kruskall–Wallis test and Dunn's post hoc analysis ($\alpha = 0.05$). Two-way ANOVA was used to evaluate the effects of the material, surface treatment, and their interaction on the SBS. The failure modes are presented as descriptive analyses.

3. Results

During accelerated aging, none of the specimens experienced prefailure in the form of debonding of the autopolymerizing resin build-up. **Table 2 and Figure 3** provide the mean values and standard deviations (SD) of the SBS (MPa). The two-way ANOVA demonstrated that the denture base material ($P = 0.001$) and surface treatment ($P = 0.019$) significantly affected the SBS. A significant interaction was also present between the two variables ($P < 0.001$).

The milled material, Temp Basic Tissue, demonstrated the highest SBS values across all surface treatments, whereas the two 3D-printed denture base materials had the lowest values. In Paladon65, the highest SBS values were observed in the resin-removal group. However, the values were not statistically significant among the different surface treatments in Paladon65 ($P = 0.077$), L-Temp ($P = 0.258$), and Temp Basic Tissue ($P = 0.486$). Without surface treatment, Paladon65 was statistically similar to Temp Basic Tissue ($P = 0.065$) and L-Temp ($P = 0.726$).

The SBS of the 3D-printed resins was substantially lower than that of the heat-cured and milled resins ($P < 0.05$) in the control, monomer, and resin remover groups. With air abrasion, the 3D-printed resin, V-Print dentbase, had a significantly higher SBS than the no-treatment ($P = 0.007$) and resin remover ($P = 0.048$) groups of the same material. In addition, for the FREEPRINT denture material, the SBS values of the 180-grit plus monomer and air abrasion groups were significantly higher than those of the no treatment ($P < 0.001$; $P = 0.002$), monomer ($P < 0.001$; $P = 0.002$), and resin remover groups ($P < 0.001$; $P = 0.833$).

The FREEPRINT, Paladon65, L-Temp, and Temp Basic dentures were statistically equivalent ($P = 0.072$ and $P = 0.181$, respectively) with 180-grit plus monomer and air-abrasion surface treatments. Meanwhile, the V-Print dentbase was not significantly different from Paladon65 and L-Temp ($P > 0.05$) when air abrasion was applied.

Figure 4 shows the outcomes of the failure patterns. Three types of failure were observed in the specimens: adhesive (interface), cohesive (base material), and mixed (interface and base materials). A 100% cohesive failure pattern was noticed for Temp Basic Tissue and FREEPRINT specimens (within the denture base resin), regardless of surface treatment. The same was observed in Paladon65, except for the air abrasion group, which showed 14% adhesive failure. Adhesive and mixed adhesive–cohesive failure modes were often observed in the V-Print dentbase material with no treatment, monomer, and

Table 2. Mean and standard deviation (SD) of shear bond strength (MPa) values of tested denture base materials with different surface treatments

Denture base material		Treatment					*P* value (ANOVA)
		No surface treatment	Monomer	Resin remover	180-grit plus monomer	Air abrasion	
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	
Conventional heat-cured	Paladon65	20.5 (2.9) ^{aAB}	21.9 (5.4) ^{aA}	26.1 (3.7) ^{aA}	20.9 (3.1) ^{aA}	22.1 (3.8) ^{aAB}	0.077
CAD-CAM milled	L-Temp	17.7 (5.2) ^{aA}	23.3 (3.9) ^{aAB}	19.2 (5.3) ^{aB}	21.3 (3.4) ^{aA}	19.5 (5.8) ^{aAB}	0.258
	Temp Basic Tissue	26.6 (5.6) ^{aB}	28.8 (5.3) ^{aB}	27.7 (3.6) ^{aA}	24.3 (4.4) ^{aA}	24.9 (6.9) ^{aA}	0.486
3D-printed	V-Print dentbase	7.5 (3.3) ^{aC}	10.9 (3.1) ^{abC}	9.1 (2.5) ^{aC}	12.1 (3.3) ^{abB}	15.0 (5.8) ^{bB}	0.010
	FREEPRINT denture	9.9 (2.9) ^{aC}	9.3 (3.4) ^{aC}	7.8 (1.4) ^{aC}	19.3 (5.8) ^{bA}	17.3 (3.0) ^{bAB}	<0.001
	P value (ANOVA)	<0.001	<0.001	<0.001	<0.001	0.012	

Different superscript lower case letters in each raw represent a statistically significant difference ($P < 0.05$) among surface treatments across the same material (Tukey's post hoc test). Different superscript upper case letters in each column represent a statistically significant difference ($P < 0.05$) among denture base materials across the same surface treatment (Tukey's post hoc test).

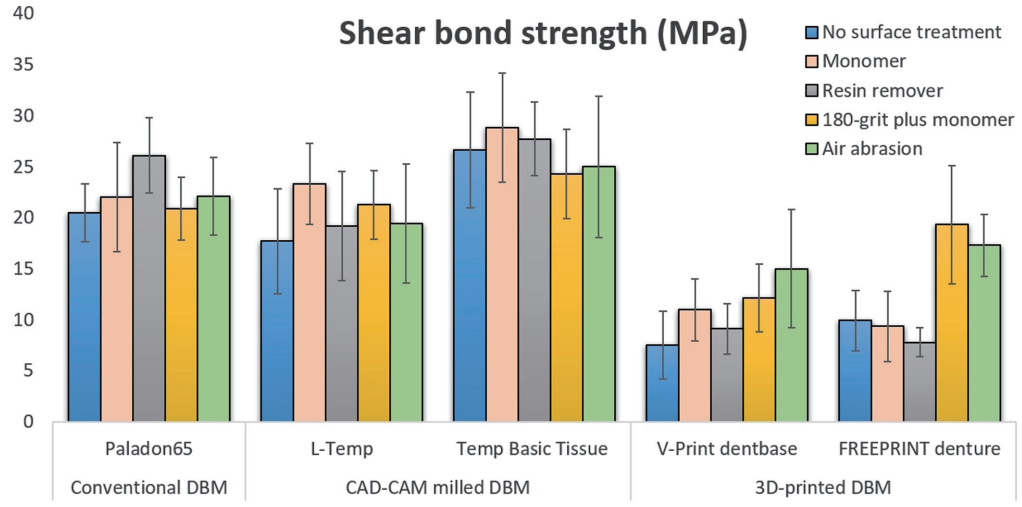

Fig. 3. Shear bond strength mean values (MPa) of evaluated denture base materials according to different surface treatments. Error bars represent standard deviation. DBM: denture base materials.

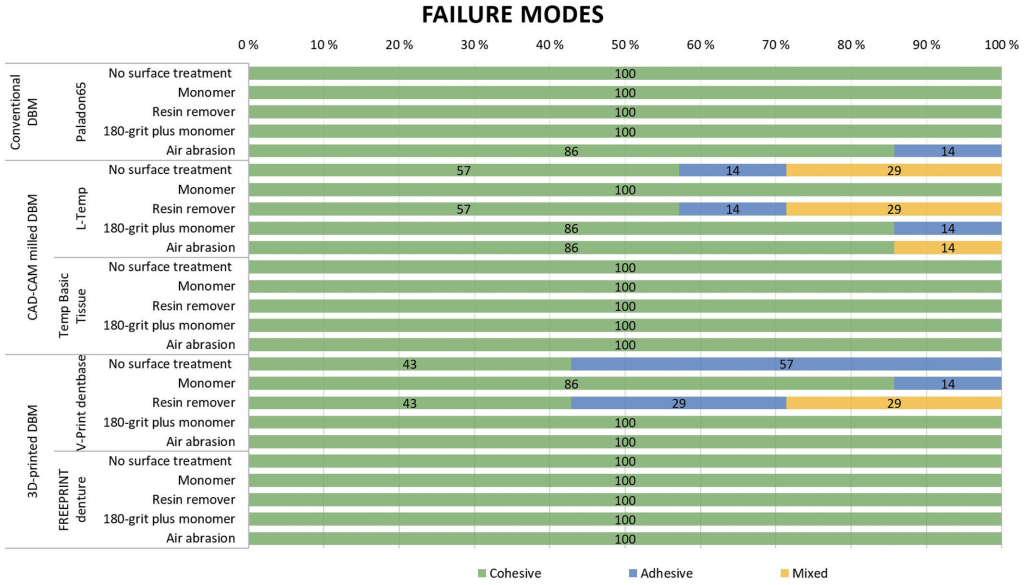

Fig. 4. Failure mode proportions (%) of denture base materials with different surface treatments. DBM: denture base materials.

Table 3. Mean and median of surface roughness (μm) values of tested denture base materials (DBM) with different surface treatments

	Conventional heat-cured DBM		CAD-CAM milled DBM				3D-printed DBM			
	Paladon65		L-Temp		Temp Basic Tissue		V-Print dentbase		FREEPRINT denture	
	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
No surface treatment	0.23 (0.03)	0.24 (0.04) ^{a}	0.51 (0.04)	0.51 (0.06) ^{ad}	0.37 (0.03)	0.37 (0.05) ^{a}	1.33 (0.17)	1.30 (0.33) ^{ac}	2.48 (0.11)	2.47 (0.15) ^{ac}
Monomer	0.94 (0.05)	0.94 (0.07) ^{a}	0.44 (0.04)	0.44 (0.07) ^{ab}	2.64 (0.41)	2.63 (0.74) ^{b}	0.34 (0.03)	0.35 (0.07) ^{b}	1.52 (0.07)	1.53 (0.12) ^{b}
Resin remover	1.48 (0.18)	1.49 (0.34) ^{ac}	0.24 (0.04)	0.23 (0.09) ^{b}	0.33 (0.04)	0.31 (0.06) ^{a}	0.30 (0.08)	0.30 (0.14) ^{bc}	2.14 (0.24)	2.09 (0.47) ^{a}
180-grit plus monomer	3.84 (0.27)	3.86 (0.55) ^{b}	3.08 (0.26)	3.07 (0.48) ^{c}	2.59 (0.27)	2.53 (0.46) ^{b}	2.68 (0.15)	2.70 (0.30) ^{a}	2.85 (0.25)	2.86 (0.42) ^{c}
Air particle abrasion	2.39 (0.33)	2.41 (0.48) ^{bc}	2.82 (0.18)	2.47 (0.18) ^{cd}	2.82 (0.23)	2.75 (0.33) ^{b}	2.65 (0.35)	2.74 (0.60) ^{a}	2.71 (0.17)	2.75 (0.18) ^{c}
P value (Kruskall-Wallis)	<0.001		<0.001		<0.001		<0.001		<0.001	

Different superscript lower-case letters in each column represent a statistically significant difference ($P < 0.05$) among different surface treatments across the same material (Dunn's post hoc analysis). SD: standard deviation. IQR: interquartile range.

resin remover groups, as well as in all L-temp groups except the monomer group.

The mean values of surface roughness (μm) for the tested materials are provided in **Table 3**. Without surface treatment, the 3D-printed materials displayed the roughest surfaces. The roughest surfaces were observed in the 180-grit plus monomer and air particle abrasion groups, regardless of the tested material. For the heat-cured resin, Paladon65, chemical surface treatment with a monomer or resin remover significantly increased the roughness compared to the untreated surface ($P < 0.05$). Temp Basic Tissue specimens treated with monomers, 180-grit plus monomers, or air abrasion displayed significantly higher roughness than the controls ($P = 0.013$, $P = 0.026$, $P = 0.002$, respectively).

Figure 5 shows the reconstructed 3-dimensional surface topography and roughness of all the materials with the applied surface treatments. After application of the monomer and resin remover, the surface integrity of Paladon65 was observed to dissolve, thereby exposing the polymer beads. By contrast, no dissolution was observed when the milled and 3D-printed materials were subjected to the same surface treatments.

Representative SEM images of the test materials and surface treatments are shown in **Figure 6**. The polymer beads detected in the roughness analysis of the monomer and resin-removal surface treatments on the Paladon65 surface were verified. In addition, the same beads were observed in the 180-grit plus monomer group of the same material. Some surface changes were noticed after the monomer and resin removal applications to the surface of the Temp-Basic tissue. While the 180-grit abrasive paper caused several transverse scratches in all groups, fewer such scratches were observed with the Temp Basic Tissue material. All the sandblasted surfaces exhibited deep and irregular cavities.

4. Discussion

Although the repairability of conventional denture base materials has been extensively investigated, to our knowledge, only two studies[1,27] have been conducted on the repairability of 3D-printed denture base materials. This study evaluated the effects of different surface treatments on the bond strength of autopolymerizing repair resins to conventional, CAD-CAM milled, and 3D-printed denture base materials. Owing to the significant effects observed across different denture base resins and surface treatments, the null hypothesis was rejected.

Accelerated aging in boiling water is one of the most commonly used methods for evaluating the stability of dental materials against distress. Boiling water aging can reveal weaknesses or vulnerabilities in the structure or composition of a material that may not be apparent under normal conditions, such as thermal expansion, water absorption, degradation, or loss of mechanical properties[28]. The objective of this aging approach is to accelerate aging and assess the impact of hydrolytic and thermal breakdowns within a short timeframe[29,30]. Accelerated aging may cause significant changes in dimensional and chemical stability, mechanical properties, color stability, discoloration, polymerization shrinkage, and surface roughness[29–31].

The bond strength between the fractured denture base and the repair material is crucial for the success of the repair process[1,22,27]. When a bonding system is overloaded, mechanical breakdowns are more likely to occur at the weakest point. Accordingly, the repaired dentures are prone to re-fracture at the repair site, indicating a concentration of stress in that area, which might be explained by the poor bond strength between the repair resin and denture base resin as well as the lower strength of the autopolymerizing resin[26,32].

The use of an organic solvent to change a polymer surface is a common surface treatment approach[33]. Methyl methacrylate monomer dissolves and smooths the surface of conventional denture base materials, forming an interwoven network[12,20]. As seen in **Figure 5**, MMA and resin remover dissolved the surface of the conventional heat-cured resin. However, the SBS values were not significantly higher than those of the control group. On the other hand, no notable surface morphological changes were noticed when 3D-printed denture base materials were exposed to the same substances. Consequently, for PMMA-based resins, chemical interactions tend to play a major role in the bonding mechanism rather than the roughness of the bonding surface. According to Usumez *et al.*[34], air particle abrasion of a PMMA denture base resin did not significantly improve the tensile bond strength of the lining material.

The GC RELINE II resin remover is often included in the introductory kit for silicone-based soft denture relining materials. This allows for easy removal of the old reline material. Because of its composition, ethyl acetate, it was tested as a surface treatment in this study. Ethyl acetate causes the surface to swell and allows the repair resin to diffuse[35]. Ethyl acetate-containing adhesives effectively increase

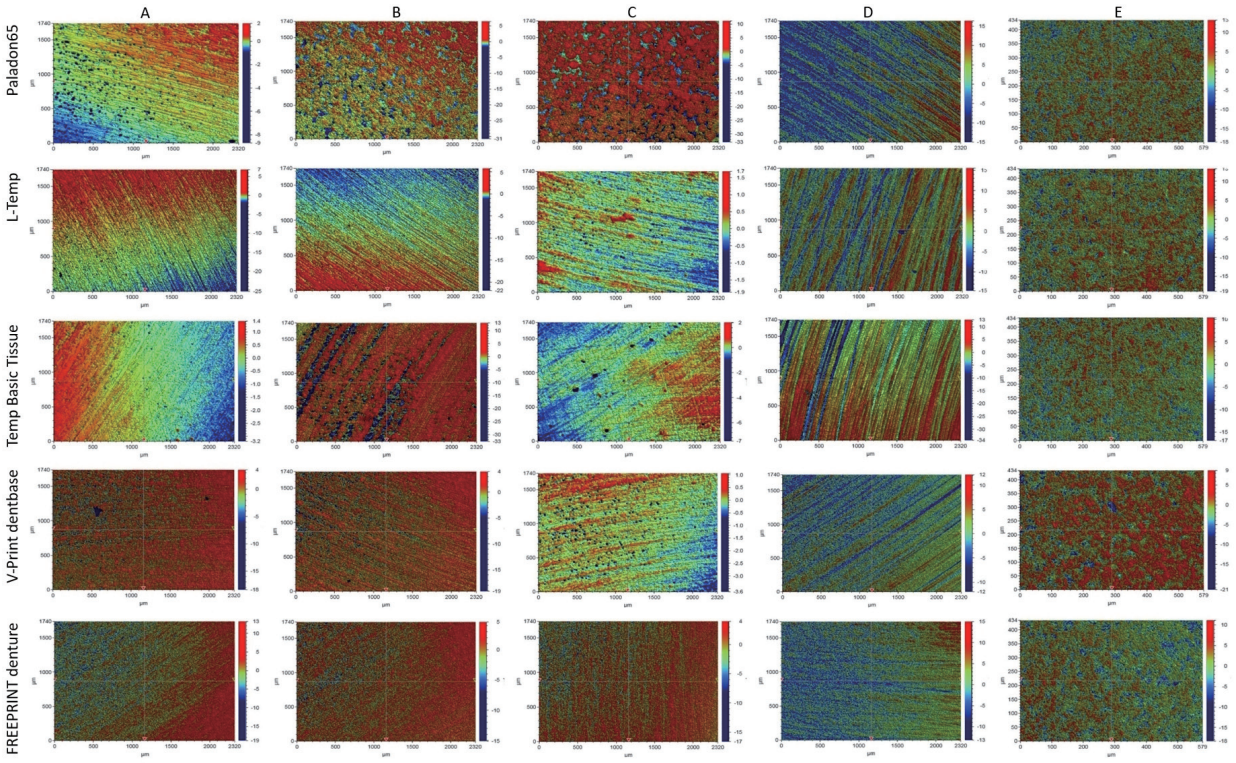

Fig. 5. Reconstructed 3-dimensional surface topographies of tested denture base materials. A. No surface treatment; B. Monomer; C. Resin remover; D. 180-grit plus monomer; E. Air particle abrasion.

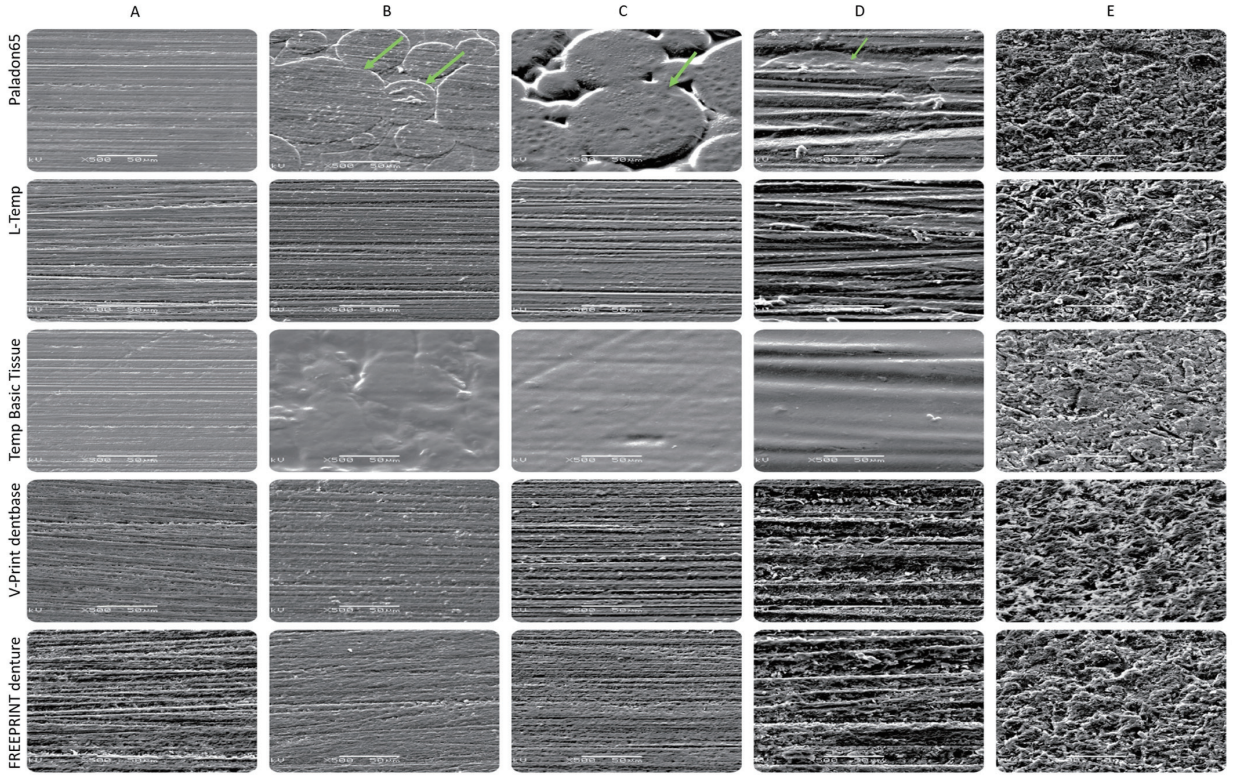

Fig. 6. Scanning electron microscopy images of tested denture base materials with different surface treatments. A. No surface treatment; B. Monomer; C. Resin remover; D. 180-grit plus monomer; E. Air particle abrasion. Green arrows refer to polymer beads.

the bond strength between polyvinylsiloxane denture soft liners and heat-processed acrylic resin dentures[36]. Shimizu *et al.*[35] observed that applying ethyl acetate to the repair surfaces of a heat-cured denture base resin for 120 s provided maximum repair strength compared to 30 and 60 s because of the extremely volatile nature of ethyl acetate.

In this study, the SBS values of the CAD-CAM milled denture bases were comparable to those of the heat-cured ones. These values were significantly lower for the 3D-printed resins except for the mechanically treated groups. This may be explained by differences in the composition and manufacturing processes[27]. The high temperature and pressure used during the CAD-CAM disc processing promoted the formation of longer polymer chains with minimal intermolecular distances and fewer residual monomers[2]. In addition, conventional and CAD-CAM milled resins are PMMA-based, whereas photopolymerizable 3D-printed polymers are usually MMA-free dimethacrylate monomers and oligomers[37]. The MMA bonding pretreatment might be incompatible with light-curing denture base materials, as it does not copolymerize with bifunctional monomers[38]. Consequently, a poor SBS may suggest a mismatch between the dissolving properties of MMA and the polymer.

The results showed that mechanical surface treatments of the 3D-printed resins effectively increased the SBS values. This was consistent with the findings of Gad *et al.*[27], who concluded that sandblasting increased the SBS of the repair resins to the 3D-printed resins by making surface morphological changes, which enhanced retention by increasing the surface area for bonding[26,32]. Given the favorable impact of such mechanical treatments, the mechanism of action should be further investigated. It would also be interesting to investigate how such surface treatments would affect the bonding strength of different denture baseliners to the same 3D-printed denture base material.

This study revealed that surface roughness cannot be used to predict the SBS because low roughness values can reveal both high and low SBS values, as indicated by the roughness data. Accordingly, more attention should be directed toward the chemical composition of the denture base material when considering denture base repair. Although mechanical surface treatments have demonstrated the potential to improve the bond between the repair resin and 3D-printed denture base materials, their use with conventional and CAD-CAM materials may not be essential. Furthermore, a compelling need has emerged to explore new surface treatment methodologies to enhance the bonding between repair resins and 3D-printed denture base materials.

Despite efforts to standardize the experimental setup for the shear bond test, certain groups consistently showed high standard deviations. This phenomenon is attributed to factors associated with base material heterogeneity, sample size, and complexity of the bonding process. However, several studies[22,27,39,40] have reported similarly high standard deviations in SBS values within some groups.

One limitation of the current study is that the specimens were analyzed only after accelerated aging in boiling water. In addition, the *in vitro* design did not accurately simulate a clinical situation.

5. Conclusions

Within the limitations of this study, the following can be concluded:

1. The bond strength of the CAD-CAM milled denture base resins to autopolymerizing repair resins was comparable to that of heat-cured resins.
2. The bond strength between the repair resin and 3D printed resins was enhanced when the surface was mechanically roughened using air particle abrasion or 180-grit carbide paper.
3. The composition and manufacturing procedures of the denture base resin can affect its bond strength to the repair resin.
4. SBS cannot be predicted based on surface roughness.

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Conflict of interest

The authors declare no conflict of interest.

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