COMPARISON OF TENSILE BOND STRENGTH OF DENTURE RELINE MATERIALS ON DENTURE BASES FABRICATED WITH CAD-CAM TECHNOLOGY

A Thesis

by

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ABSTRACT

The purpose of this study was to evaluate the tensile bond strength of both hard and soft denture reline materials on denture bases fabricated by 3D printing and milling CAD-CAM technology.

One hundred fifty denture base samples (injected, milled, printed) were fabricated (n = 30) and bonded to five different denture reline materials (COE Soft, PermaSoft, Tokuyama Rebase ii, Kooliner, ProBase Cold). Samples of each reline material were divided into five groups (n = 10), and were placed in distilled water for 24 hours prior to tension testing by a universal testing machine. Maximum tensile stress values before failure were recorded, and the failure mode was also determined. The type of failure was analyzed by a scanning electron microscope (SEM). Statistics were analyzed with one-way ANOVA and the Independent Samples t-Test (α = .05).

Overall, there was no statistically significant difference of tensile bond strength among the injected, milled and printed denture groups. However, the printed denture base group demonstrated significantly lower values of tensile bond strength ($P < .05$), with PermaSoft, Tokuyama Rebase ii and ProBase Cold groups in comparison to other denture base groups (milled and injected). The milled denture bases had the highest mean value of tensile bond strength in four out of the five denture liners tested (Coe Soft, PermaSoft, Tokuyama Rebase ii and Kooliner). There was no statistically significant difference ($P < .05$), between the injected, milled and printed denture bases when relined with Kooliner. When comparing the denture reline type, the lowest values were seen with the soft chairside relining materials and highest values with the hard lab reline material. As for the modes of failure, adhesive failures were observed

predominantly with the printed denture base materials relined with soft chairside relining materials, while cohesive and mixed modes of failure were found in the milled and injected denture base groups.

The printed denture bases had statistically significant lower tensile bond strength values compared with the injection and milled denture bases with the PermaSoft, Tokuyama Rebase ii and ProBase Cold denture relines, while milled denture bases demonstrated the highest values of tensile bond strength for all chairside relining groups. In addition, the soft chairside relining materials showed the lowest tensile bond strength values regardless of denture processing method with respect to the denture base type (injected, printed, and milled) compared with the hard relining materials.

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CONTRIBUTORS AND FUNDING SOURCES

Contributors

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1. INTRODUCTION

Changes of oral tissues can occur with continuous residual ridge resorption, thereby necessitating a reline of removable dentures to improve their adaptation to the underlying supporting tissues.[1] The relining technique becomes paramount in cases where the patient needs adjustment of their prosthesis, as most edentulous patients experience continuous resorption of the ridge throughout their lifetime, which can result in pain and discomfort to the patient. Denture reline materials are recommended in the following scenarios: irregular bone resorption, thinning atrophic mucosa, bone undercuts, immediate prosthesis, during the bone healing process after implantation, and in patients with bruxism and dry mouth.[2]

In order to prevent the detachment of the denture reline from the base, a reliable adhesive bond must exist between these two surfaces.[3] According to some studies, a parameter that can affect this bond is the nature of the denture base material itself.[2-4] The bond properties of denture reline materials have been evaluated by using tensile, shear and peel tests.[2] However, the most commonly preferred test to assess the bond strength between lining materials and denture base materials was the tensile bond strength test.[2]

Up until recent years, the dominant denture material was polymethylmethacrylate (PMMA). This material is supplied as a two-component system, one component is a liquid, whereas the other is a fine, pink powder.[5] The liquid contains methyl methacrylate, glycol dimethacrylate, and hydroquinone. The methyl methacrylate in particular is what aides in polymerization while the glycol dimethacrylate serves as the crosslinking agent.[5] Hydroquinone is added as an adjunct to help prevent any premature polymerization of the liquid.[5] The powder, on the other hand, contains PMMA beads, colorants, and benzoyl peroxide. The addition of benzoyl peroxide is imperative, as it serves as the initiator for polymerization.[5] Once the liquid and powder components are mixed, an activator, in the form of heat or addition of other chemicals provide the ‘impetus’ to help initiate the polymerization of the PMMA denture base.[5,6] The heat-activated PMMA resins in particular are the ones most commonly used by means of compression, injection molding, or poured molding mechanisms.[7] The greatest disadvantage of heat-activated PMMA is the volumetric shrinkage of approximately 7%.[8]

Formerly, CAD-CAM denture bases could only be fabricated by the subtractive approach, or milled.[9] Milled CAD-CAM denture bases have less volumetric deviation, as the denture base is milled from a puck of acrylic that has already undergone the aforementioned polymerization shrinkage traditional PMMA denture bases endure.[9, 10] Other benefits of CAD-CAM denture bases include reduced chair time with the patient, improved fit, and electronic archiving to help fabricate a backup prosthesis.[11]

However, recently, rapid prototyping has provided successful application in the fabrication of CAD-CAM denture bases including implant surgical guides, maxillofacial prosthetics and frameworks for removable partial dentures.[12] Additive manufacturing (AM), also known as 3D printing, is the process of building the material layer by layer directly from digital data. There are several advantages of the AM approach in comparison to the subtractive method. AM can manufacture any object, regardless of its dimensional complexity or quantity.[12] AM also produces less waste and can achieve finer details in the final product than can be completed with a fine bur with milling.[12, 13]

3D printing methods can be differentiated into four broad categories: extrusion printing, inkjet printing, laser melting/sintering, and lithography printing.[14] Extrusion printing uses a material that is dispensed from a nozzle with computer controlled movement of a 3-axis stage.[15,16] With inkjet printing, small micrometer sized droplets of ink are dispensed. These droplets are typically a photopolymer.[14] Laser melting and sintering uses high temperature of the laser light to either sinter or weld specific regions in a powder bed while the stage moves as the material is added layer by layer, thereby creating the 3D product.[17] Finally, lithography printing uses photopolymers in a Z-axis controlled vat, where the 3D product results from the direct exposition of the polymer to light as the vat (or sample holder) moves superiorly or inferiorly.[18] Printing by using stereolithography (SLA) was initially developed by Charles Hull and was made commercially available in 1986.[13] With the lithography method, there are two equally common approaches, such as stereolithography (SLA) printing and digital projection printing (or DMD-DPP, which stands for digital micromirror device-digital projection printing).[14] In SLA printing, which is the 3D printer used in the present study, a galvano mirror scanner directs the laser to photopolymerize a photosensitive liquid polymer in consecutive layers to create 3D structures.[14] SLA offers high accuracy, overall smooth surface finish, and fine building details, which are all characteristics that make it ideal for dentistry.[19] Similarly, in DMD-DPP, a set of micromirrors help control the path of the light onto the specified surface of the build plate, where the layers are added in a shorter timeframe than SLA printing.[20] Hwang et al[21] assessed the fit of the maxillary denture and found that the DLP denture base had superior trueness than the milled and heat-processed denture bases. Clinically, the printed denture is now in use today, but knowledge regarding the bonding capabilities of resilient denture liners is minimal.

The bonding characteristics between denture reline materials and different denture base polymers have been researched extensively with special attention to the type of denture base resin, composition of the liner and the bonding agent used to contribute to bond strength.[22-26] Debonding of denture liners from the denture base is a recurring problem in relined dentures.[27]

Factors that can contribute to bond failure of denture liners include the chemical composition of the materials, liner thickness, nature of the adhesive, tear strength and thermal stresses.[25, 26]

Denture liners are used in the prevention of chronic soreness to help treat patients with higher residual bone resorption, thin and non-resilient mucosal tissue, bony undercuts, tendency to brux, defects that require obturation, xerostomia, or for modification purposes following dental surgery.[28] They can be divided into two categories: silicone-based and acrylic-based. Acrylic-based liners are composed of powder including acrylic polymers and copolymers and plasticizers such as ethyl alcohol and/or ethyl acetate, which softens the acrylic monomer and the acrylic.[14] The silicone-based liners consists mostly of dimethyl hexane elastomers.[14] Also, acrylic-based resilient lining materials showed higher bond strength values than the silicone-based ones.[2] The bond strength is crucial, as a weak bond is likely to cause bacterial accumulation, staining, compromised oral hygiene, and eventual detachment of the reline material.[29] Diffusion of the reline monomers into the denture base, with the eventual formation of the interpenetrating polymer network (IPN), bonds these two layers of materials.[29] Therefore, the bond strength is not entirely dependent on the chemical makeup of the reline material, but also the denture base type.

Dentures that are constructed from two different materials are only as successful as the bond between them. This bond is affected during the immersion process. Resilient denture liners, in particular, undergo two separate processes: first, plasticizers and other soluble materials 'leach' out, and second, the liner absorbs water and saliva.[30] Following absorption, the material swells, stress builds between the bonding surfaces and the viscoelastic properties of the reline material changes.[30] According to Kawano et al, a resilient denture liner with a bond strength of 0.44 MPa (N/mm^2) is considered acceptable for clinical use.[24] There are several tests used to determine bond strength of resilient lining materials. In a 2018 systematic review that included 57 studies for bond strength of reline materials, 39 studies performed the tensile test, ten performed the shear test, and five completed the peal test.[2] Typically prior to testing, the samples would be immersed in water for a minimum of 24 hours.[3, 22-26, 27-30] Until recently, thermocycling was extensively used in dental research to simulate aging of the liner. A thermocycling regimen of 3000 cycles had been shown to correspond to a prosthesis that was in service for 3 years.[27] However, Botega et al[25] reported bond strength values were unchanged in relation to thermocycling. This was also demonstrated by another study conducted by Choi et al[27] where thermocycling did not significantly reduce the tensile bond strength of the resilient denture liners to denture base resins.

Currently, there are few studies that have analyzed the bond strength of resilient denture liners to milled denture bases.[27] However, to date, no research has investigated the tensile bond strength of denture liners to 3D printed denture bases. The purpose of this study was to evaluate the tensile bond strength of both hard and soft denture reline materials on denture bases fabricated by 3D printing and milling CAD-CAM technology. The null hypothesis was that the tensile bond strength of both soft and hard denture liners would not differ with the type of denture base material used.

2. MATERIAL AND METHODS

2.1 Denture bases and denture relines utilized

The denture base and resilient liners used in this study are listed in Table 1. For each reline material, 10 denture samples were prepared for each denture base type (injected, milled, and printed).

Table 1. Materials utilized

Brand	Material Type	Composition	Manufacturer
IvoBase High Impact	Injection molded denture base acrylic resin	PMMA	Ivoclar Vivadent AG
IvoBase CAD	CAD-CAM denture base acrylic resin	PMMA	Ivoclar Vivadent AG
Formlabs Denture Base	Light curable denture base resin	Methacrylate monomer, diurethane dimethacrylate, propylidynetrimethyl trimethacrylate	DENTCA
GC Reline Soft (COE Soft)	Autopolymerized soft chairside denture liner	Zinc undecylenate, methyl methacrylate, ethyl alcohol, isopropyl alcohol, methyl salicylate	GC America
PermaSoft	Autopolymerized soft chairside denture liner	Acrylic polymer (proprietary), dibutyl phthalate, ethyl acetate, ethyl alcohol	Dentsply Sirona
Tokuyama Rebase ii	Autopolymerized hard chairside denture liner	Benzoyl peroxide, titanium dioxide, acetoacetoxyethyl methacrylate, mequinol, nonamethylendiol dimethacrylate, acetone, ethyl acetate	Tokuyama Dental Corporation
GC Reline Hard (Kooliner)	Autopolymerized hard chairside denture liner	Dibenzoyl peroxide, silicon dioxide, titanium dioxide, isobutyl methacrylate, accelerant	GC America
ProBase Cold	Autopolymerized hard lab denture liner	Dibenzoyl peroxide, polymethylmethacrylate, methyl methacrylate, butanediol dimethacrylate	Ivoclar Vivadent AG

2.2 Preparation of specimens by using 3D CAD design

A virtual sample (10 mm x 10 mm x 20 mm) was designed by an open source CAD software (Meshmixer; Autodesk, Inc.) for 3D printing and milling (Figure 1).

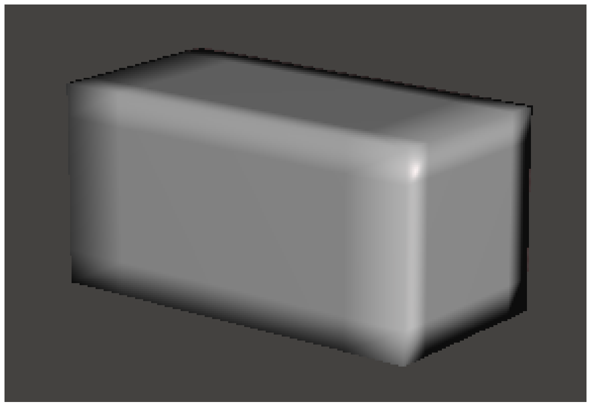

Figure 1. Virtual sample (10 mm x 10 mm x 20 mm) designed by CAD software

For the fabrication of the templates to be used for relining the denture specimens, a virtual bar (10 mm x 10 mm x 43 mm) was also designed by the same open source CAD software (Figure 2).

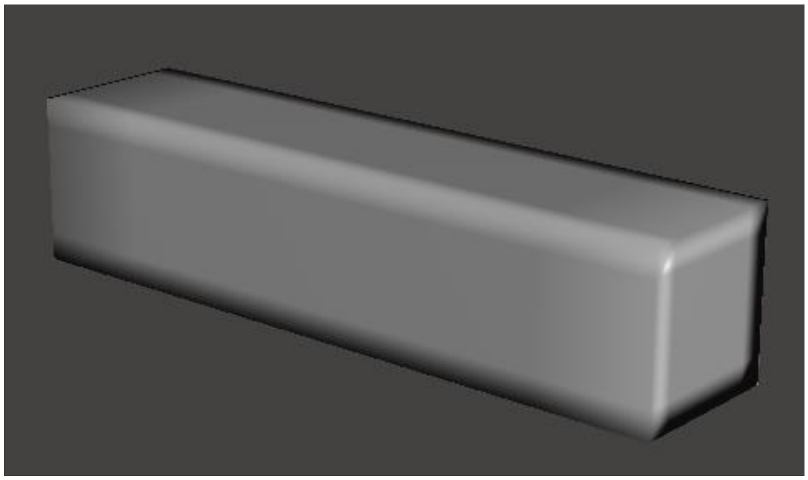

Figure 2. Virtual bar (10 mm x 10 mm x 43 mm) designed by CAD software

The samples and templates were then saved as Standard Tessellation Language (STL) files and exported into 3D printing software (PreForm Software 3.2.3; Formlabs Inc.).

2.3 Fabrication of 3D printed denture base specimens

One hundred denture specimens were printed with 3D denture base resin (Denture Base LP Resin; Formlabs, Inc.) with supports to a density of 1 and a point size of 50 μm (Figure 3) for the fabrication of 50 relined denture specimens.

Figure 3. 3D printed denture base specimens prior to post-processing

Four virtual bars were printed with 3D printing material (Clear Resin; Formlabs, Inc.) with supports to a density of 1 and a point size of 100 μm. Post-printing washing and curing were performed according to the manufacturer's instructions.

2.4 Fabrication of milled denture base specimens

By using the same virtual sample file (10 mm x 10 mm x 20 mm), pucks of PMMA, 98.5 mm in diameter, 30 mm thick (IvoBase CAD), were milled to fabricate 100 milled denture bases (Figures 4, 5).

Figure 4. IvoBase CAD PMMA disc (98.5 mm diameter, 30 mm thickness)

Figure 5. IvoBase CAD PMMA disc following subtractive manufacturing (10 mm x 10 mm x 20 mm)

2.5 Fabrication of injected denture bases

One hundred injected denture base specimens (10 mm x 10 mm x 20 mm) were processed by the IvoBase injection system (Ivoclar Vivadent, Inc.). The material used for processing was the IvoBase High Impact (Ivoclar Vivadent, Inc.) acrylic due to its high fracture toughness and its ability to absorb less water than the IvoBase Hybrid (Ivoclar Vivadent, Inc.) acrylic. Twelve printed virtual samples were invested into a hard, but flexible, silicone rubber (3M™ Express™ STD Putty; 3M Corp.) to allow for easy removal of the processed samples from the flask (Figure 6). One hundred injected denture base specimens were processed according to the manufacturer's instructions of the IvoBase High Impact system.

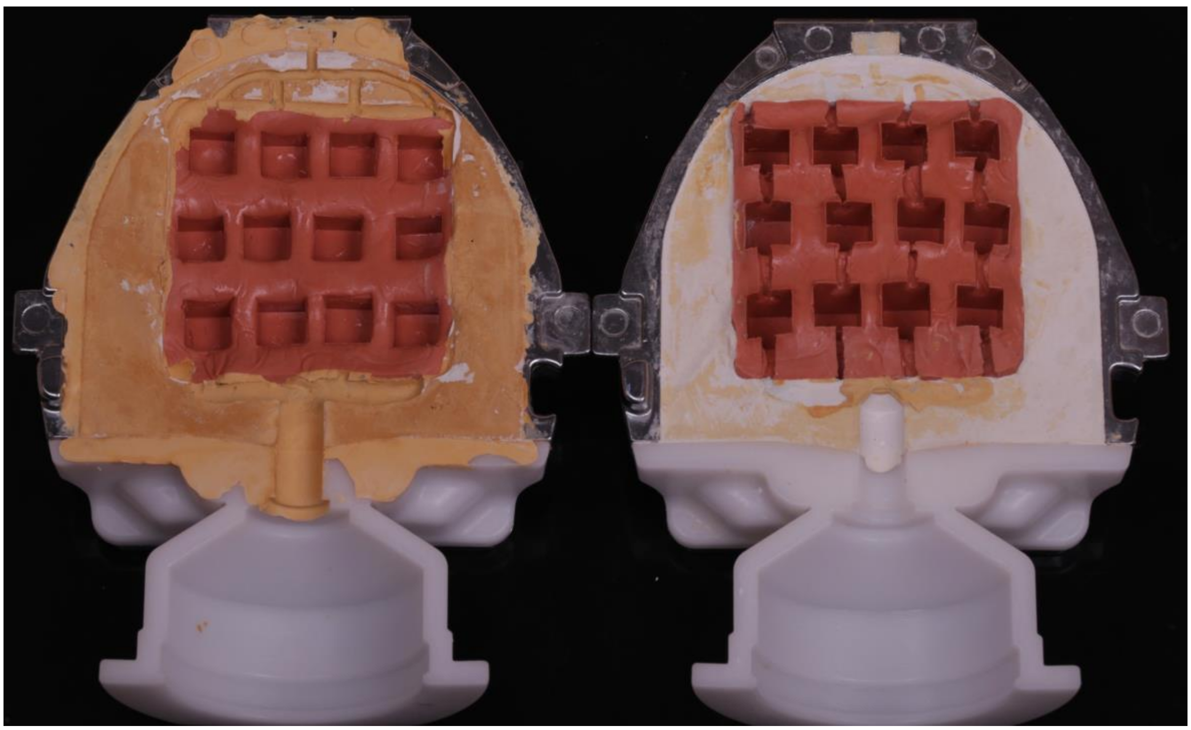

Figure 6. IvoBase flasks with silicone investments for fabrication of injected denture base samples.

2.6 Denture base reline of injected, milled and printed denture base specimens

A total of 300 denture base specimens were trimmed and surfaces to be bonded were smoothed with 240-grit aluminum oxide paper. The specimens were subsequently cleaned and dried. Template molds were fabricated by investing the 3D printed template bars (10 mm x 10 mm x 43 mm) in a metal flask (Hanau™ Varsity Ejector Flask; Whip Mix Corp.) with a hard silicone rubber (Zetalabor; Zhermack SpA) to allow for ease of removal of the denture samples following the denture reline (Figure 7).

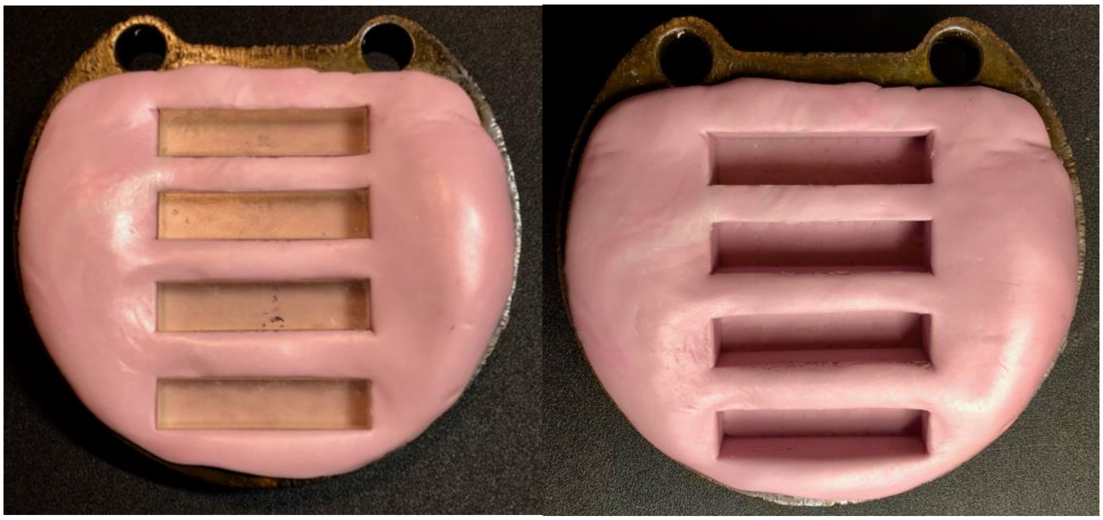

Figure 7. Template molds. Photo on left illustrates investment of the 3D printed template bars (10 mm x 10 mm x 43 mm). Addition of 3 mm was included to allow for 3 mm of space for reline material. Image on right illustrates spaces for denture base specimens after removal of 3D printed bars once rubber silicone had set.

A total of 150 experimental specimens (n = 30) were then made by processing the denture liner against the two opposing denture blocks (Figure 8). There were five groups of denture reline materials, two soft chairside reline materials (SC), two hard chairside reline materials (HC), and one hard laboratory reline material (HL) serving as the control. Each group (reline material), was further divided into three sub-groups depending on how the denture base was fabricated (i.e. injected (I), milled (M), 3D printed (P)). Table 2 shows a delineation of how the samples were grouped.

Table 2. Experimental groups

Group Name	Denture Liner Brand	Denture Liner Type
SCC – I **SCC – M** **SCC – P**	COE Soft (C)	Soft Chairside Reline (SC)
SCP – I **SCP – M** **SCP – P**	PermaSoft (P)	Soft Chairside Reline (SC)
HCT – I **HCT – M** **HCT – P**	Tokuyama Rebase ii (T)	Hard Chairside Reline (HC)
HCK – I **HCK – M** **HCK – P**	Kooliner (K)	Hard Chairside Reline (HC)
HLP – I **HLP – M** **HLP – P**	ProBase Cold (P)	Hard Lab Reline (HL)

Following polymerization (Figure 8), the experimental specimens were removed from the flask and trimmed. All specimens were placed in distilled water for 24 hours prior to tension testing.

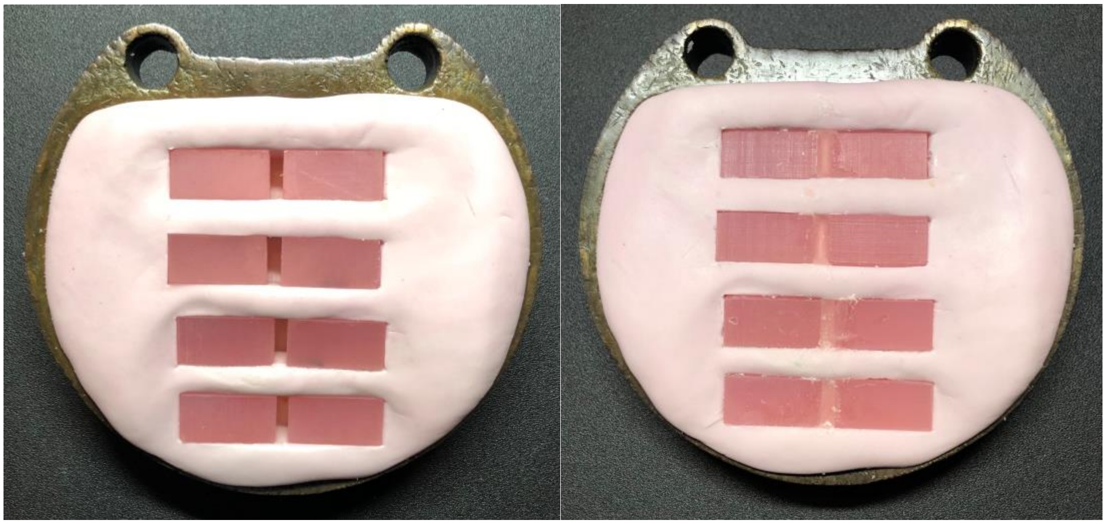

Figure 8. Fabrication of experimental specimens with denture liner. Image on left illustrates 3 mm of space provided for reline material between two denture base samples each measuring 20 mm in length. Image on right shows reline material bonded to both denture base samples prior to removal from rubber silicone investment.

2.7 Tensile bond strength test

Denture specimens were placed under tension until failure in a universal testing machine (Instron; Instron Corp.) at a crosshead speed of 5 mm/min (Figure 9). Maximum tensile stress values before failure was recorded in Newtons (N). The tensile bond strength values (in MPa) were calculated as the maximum load (N) divided by the cross sectional area of the interface (mm^2). The cross sectional area (10 mm x 10 mm) in this study was 100 mm^2 for all denture base specimens.

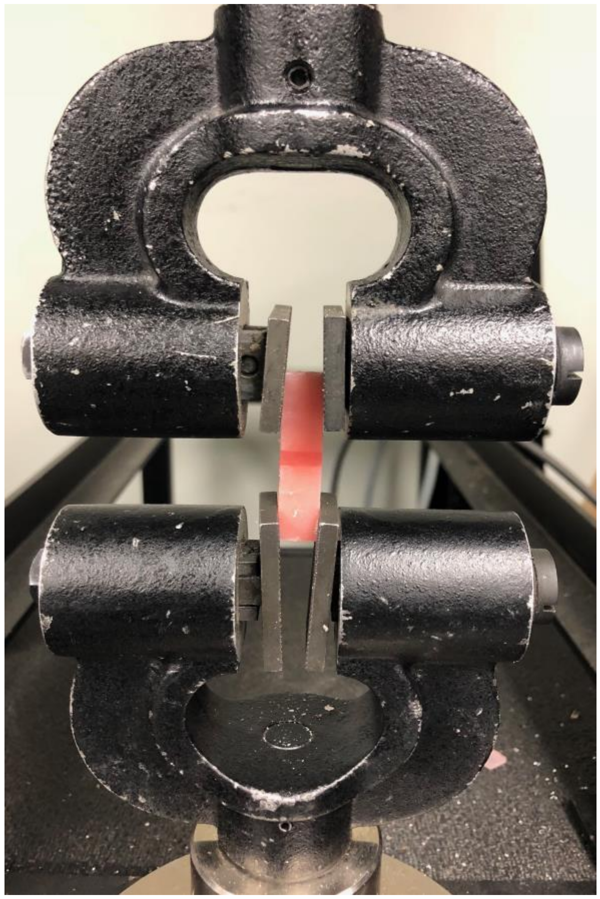

Figure 9. Tension testing using Instron universal testing machine

2.8 Mode of failure

The type of failure was analyzed by a scanning electron microscope (SEM). Failures were classified as adhesive (type 1), cohesive (type 2), or mixed mode (type 3). An adhesive failure refers to a complete separation at the interface between the liner material and denture base. A cohesive failure refers to a tear within the liner material, whereas a mixed failure has characteristics of both an adhesive and cohesive failure.

2.9 Statistical analyses

Global differences within each parameter were analyzed using one-way ANOVA and Tukey's multiple comparisons post-hoc test ($\alpha = .05$) using statistics software (IBM SPSS

Statistics, v23; IBM Corp). In instances where the Levene's test was significant ($P < .05$), equal variances could not be assumed; therefore, Welch's test for unequal variances, was utilized.[33] The post-hoc test performed instead of Tukey's was the Games-Howell test due to the significance noted in the test of homogeneity of variances (Levene's test). Differences between the two chairside reline groups (SCC, SCP and HCT, HCK) were evaluated with an Independent Samples t-Test.

3. RESULTS

The different denture base specimens were compared based on the reline material used. Table 3 and Figure 10 illustrate the mean ± standard deviation (SD) values of tensile bond strength for the five different reline groups (SCC, SCP, HCT, HCK, and HLP).

Table 3. Mean maximum tensile bond strength (N/mm^2) of all groups

Group / Subgroup	SCC	SCP	HCT	HK	HLP
I	0.17 ± 0.01	0.52 ± 0.03	6.02 ± 0.56	5.88 ± 0.58	16.92 ± 0.98
M	0.22 ± 0.02*	0.53 ± 0.02	6.02 ± 1.51	6.44 ± 1.21	16.40 ± 1.18
P	0.17 ± 0.03	0.40 ± 0.04*	4.21 ± 0.68*	5.50 ± 0.76	14.65 ± 1.25*

Note: * mark indicates significant difference within the group of the same column

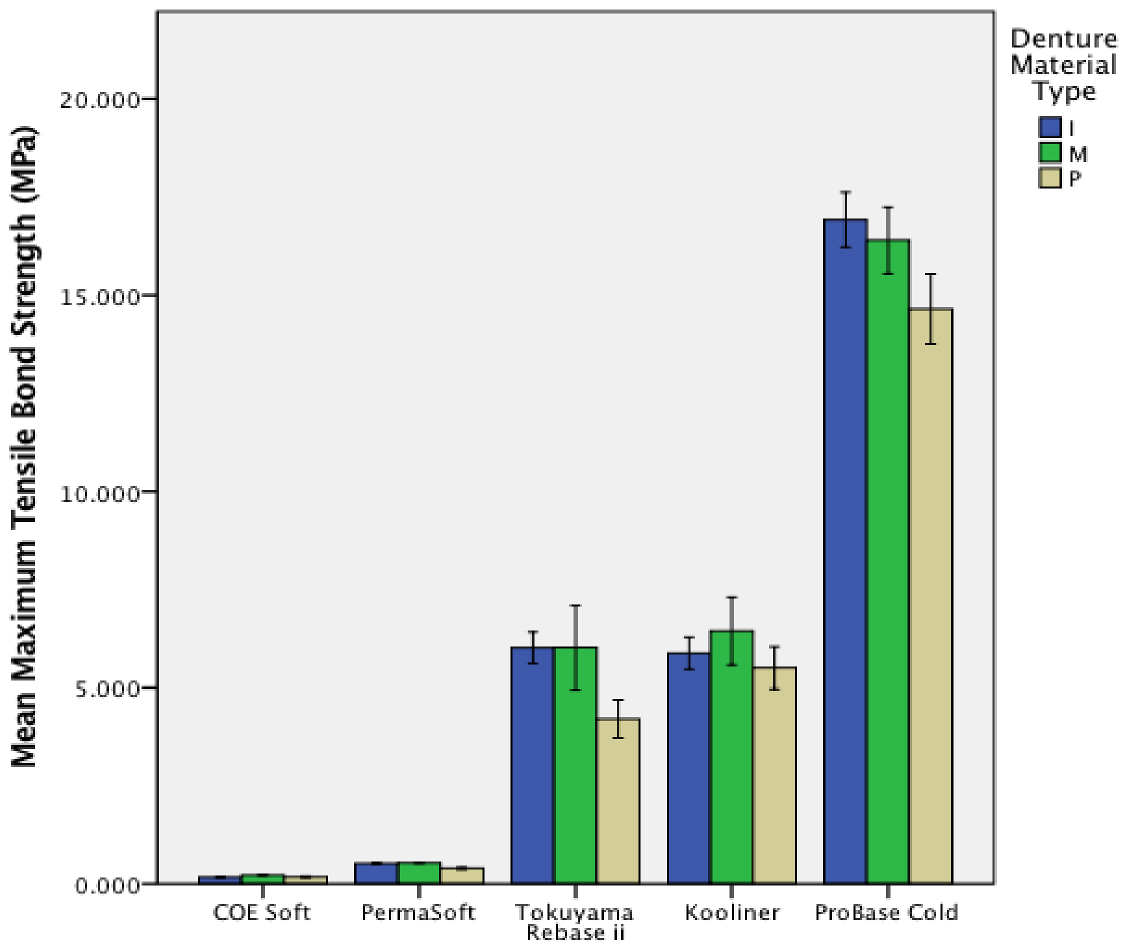

Figure 10. Mean maximum tensile bond strength among denture reline groups

The greatest mean value of tensile bond strength in the SCC group was found with the milled specimens. Tukey post hoc testing revealed that there was not a significant difference between I and P groups, but both were statistically different from M ($P < .05$).

For the SCP group, the greatest mean tensile bond strength was found with the milled samples. Games-Howell post hoc testing revealed that there was not a significant difference between I and M groups, but both were statistically different from the printed group ($P < .05$). For the HCT group, the greatest mean tensile bond strength was found with the milled specimens. Games-Howell post hoc testing revealed there was not a significant difference between I and M groups, but both were statistically different from the printed group ($P < .05$). For the HCK group, the greatest mean tensile bond strength was again found with the milled specimens. There was not a significant difference among the I, M and P groups ($P > .05$). The HLP group was the only reline group that showed the greatest mean tensile bond strength for the injected specimens. Tukey post hoc testing revealed that there was not a significant difference between I and M groups, but both were statistically different from the printed group ($P < .05$).

Moreover, the SCC, SCP, HCT, HCK differences were evaluated with an Independent Samples t-Test. The tensile bond strength values between the soft chairside reline groups (SCC and SCP) were statistically significant ($P < .05$). Furthermore, the tensile bond strength values between both hard chairside reline groups (HCT and HCK) were not statistically significant ($P = .079$). Overall, the hard reline groups (HCT, HCK, HCP) had greater mean tensile bond strength values in comparison to the soft reline groups (SCC, SCP).

Table 4 shows the comparisons among the different categories (soft chairside (SC), hard chairside (HC) and hard laboratory (HL) materials) of the denture reline materials. Among the three different categories (SC, HC and HL), there was a significant difference ($P < .05$). The soft chairside relining material group demonstrated the lowest tensile bond strength in comparison with hard relining materials of both chairside and laboratory methods.

Table 4. Total mean maximum tensile bond strength (N/mm^2) comparing different denture liners

Category	SC	HC	HL
	0.34 ± 0.16^{a}	5.68 ± 1.16^{b}	15.99 ± 1.48^{c}

Note: different superscript alphabet indicates significant difference

Finally, significant differences among I, M and P denture base specimens were also evaluated for all denture reline groups. Tukey post hoc testing also revealed that there was no significant difference among I, M and P groups (P = 0.702).

As for the modes of failure, adhesive (type 1 failure) was observed in all the denture base samples bonded with different types of denture liners. Cohesive failures (type 2) were found in the specimens lined with COE Soft, Kooliner and Probase. Mixed failures (type 3) were found mostly in the samples relined with Permasoft and Tokuyama Rebase ii. Only the printed denture base specimens relined with Probase fractured within the sample itself, not at the site of the reline. Table 5 outlines all the different modes of failure based on the reline and denture base type. Select SEM images of the different failure types are illustrated in Figures 10 – 17.

Table 5. Failure modes of each denture liner to each denture base material

Denture Base Material	Mode of Failure
COE Soft	
Processed	Predominantly cohesive, some adhesive
Milled	Predominantly cohesive, some adhesive
Printed	Adhesive
PermaSoft	
Processed	Predominantly adhesive, some cohesive
Milled	Predominantly adhesive, some cohesive
Printed	Adhesive
Tokuyama Rebase ii	
Processed	Predominantly mixed, some adhesive
Milled	Predominantly mixed, some adhesive
Printed	Some mixed, some adhesive
Kooliner	
Processed	Predominantly cohesive, few adhesive, few mixed
Milled	Predominantly cohesive, few adhesive, few mixed
Printed	Predominantly cohesive, some mixed
ProBase Cold	
Processed	Predominantly cohesive, few adhesive
Milled	Predominantly cohesive, few adhesive
Printed	Not applicable, fracture in specimen, not at reline

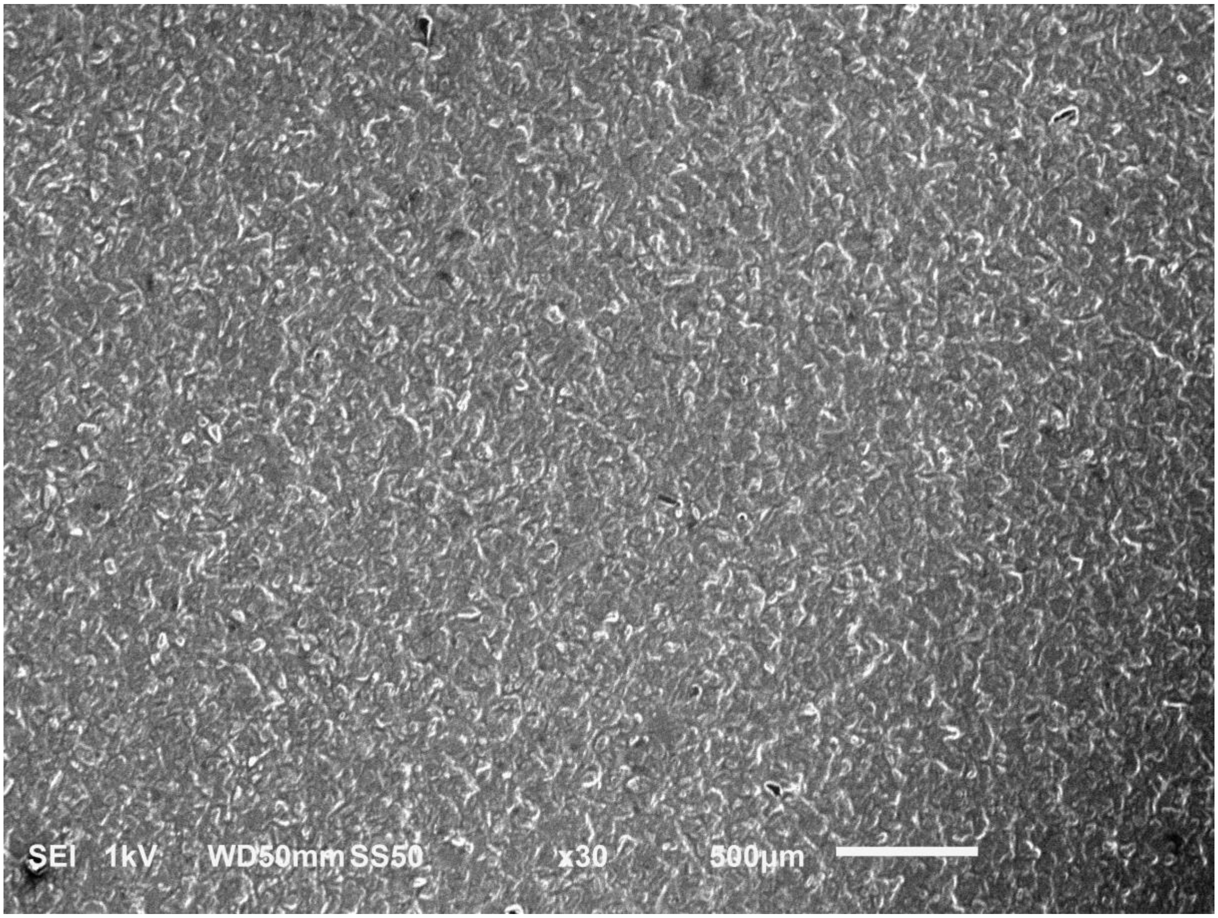

Figure 11. SEM image of failure of printed denture base relined with PermaSoft. Image illustrates type 1, adhesive failure (magnification x30) and shows remaining adhesive residue present on surface of sample, despite complete debonding of soft reline denture material.

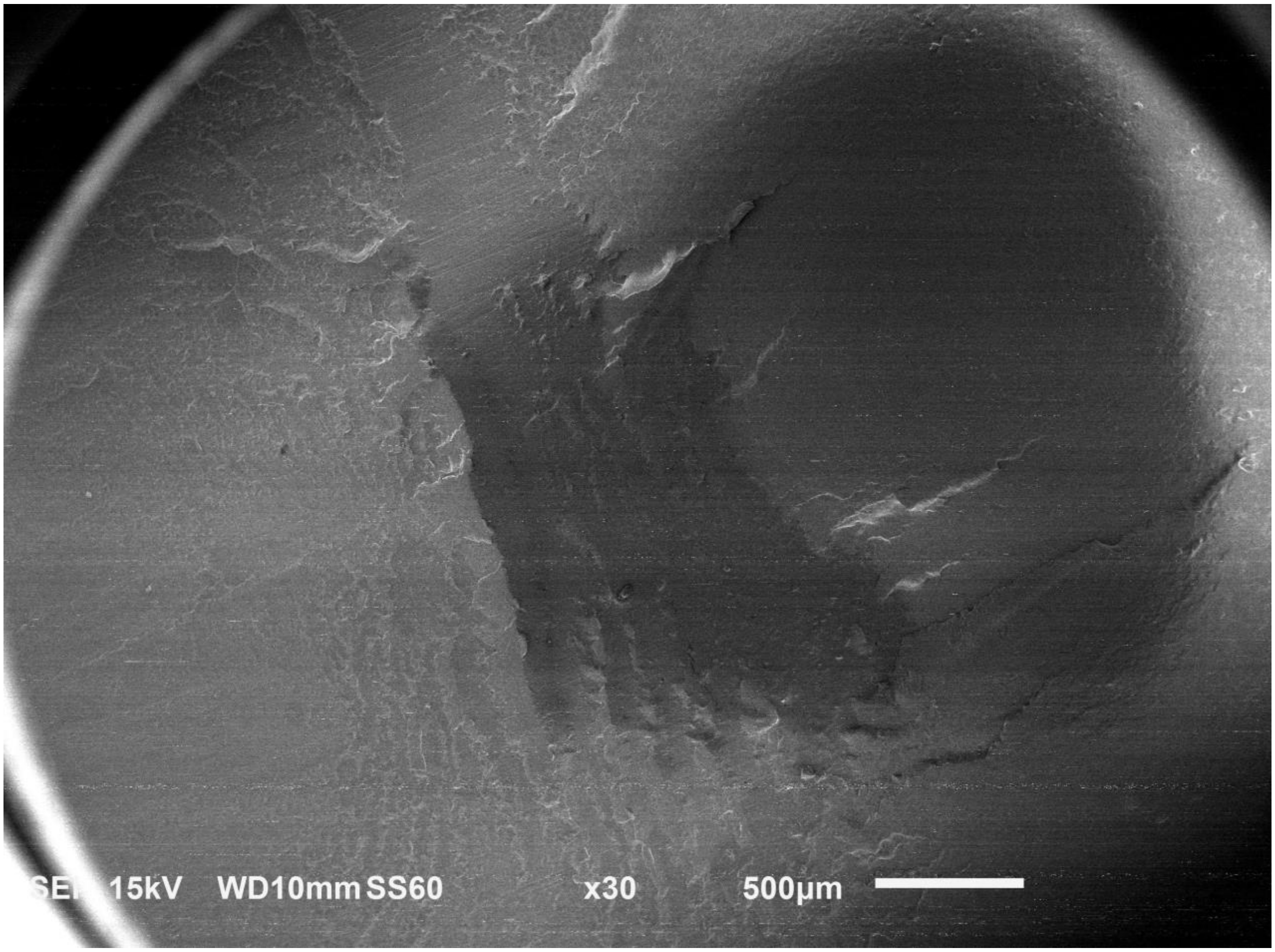

Figure 12. SEM image of failure of injected denture base relined with Tokuyama Rebase ii. Image illustrates type 3, mixed failure (magnification x30).

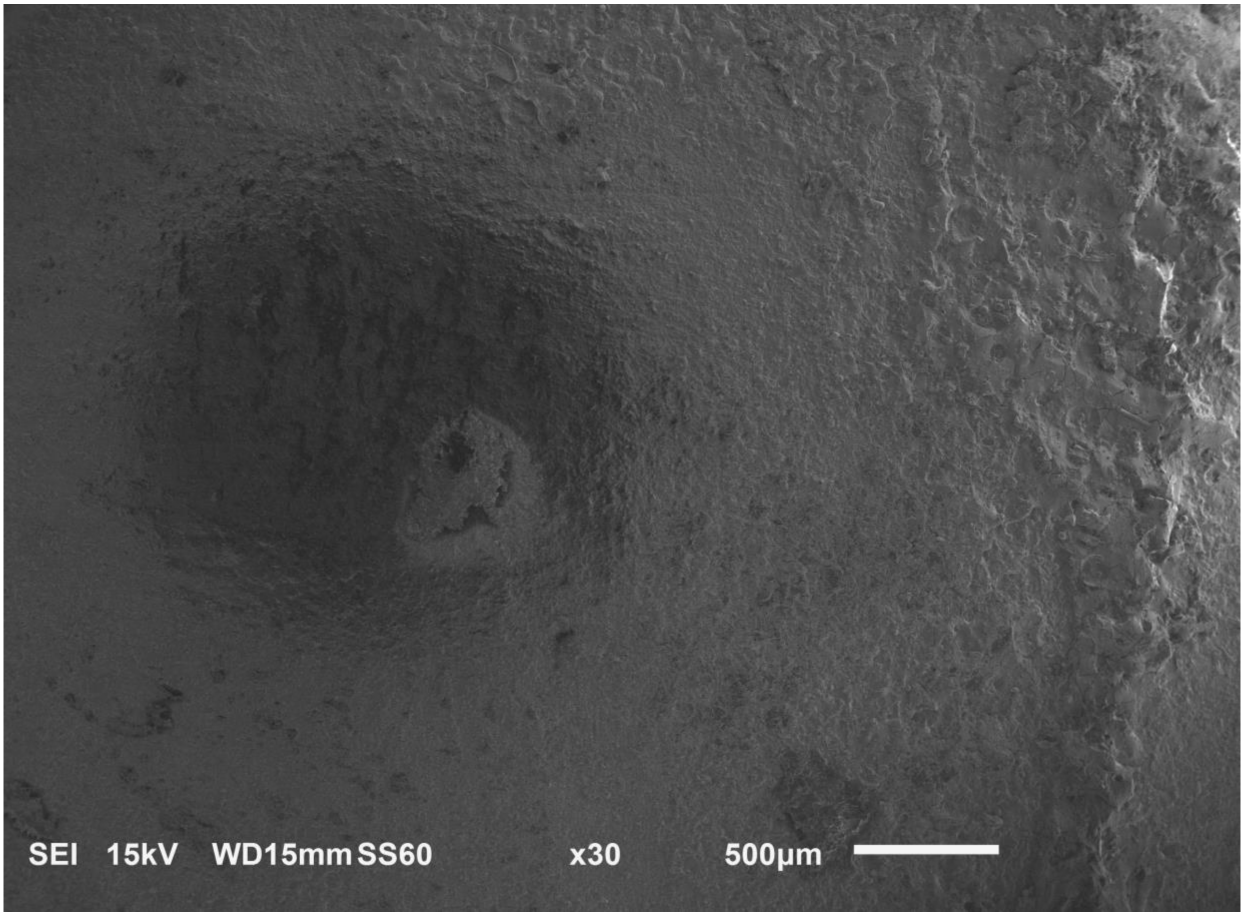

Figure 13. SEM image of failure of milled denture base relined with Tokuyama Rebase ii. Image illustrates type 3, mixed failure (magnification x30). There were also greater number of porosities present in milled denture base sample in comparison to injected and printed samples.

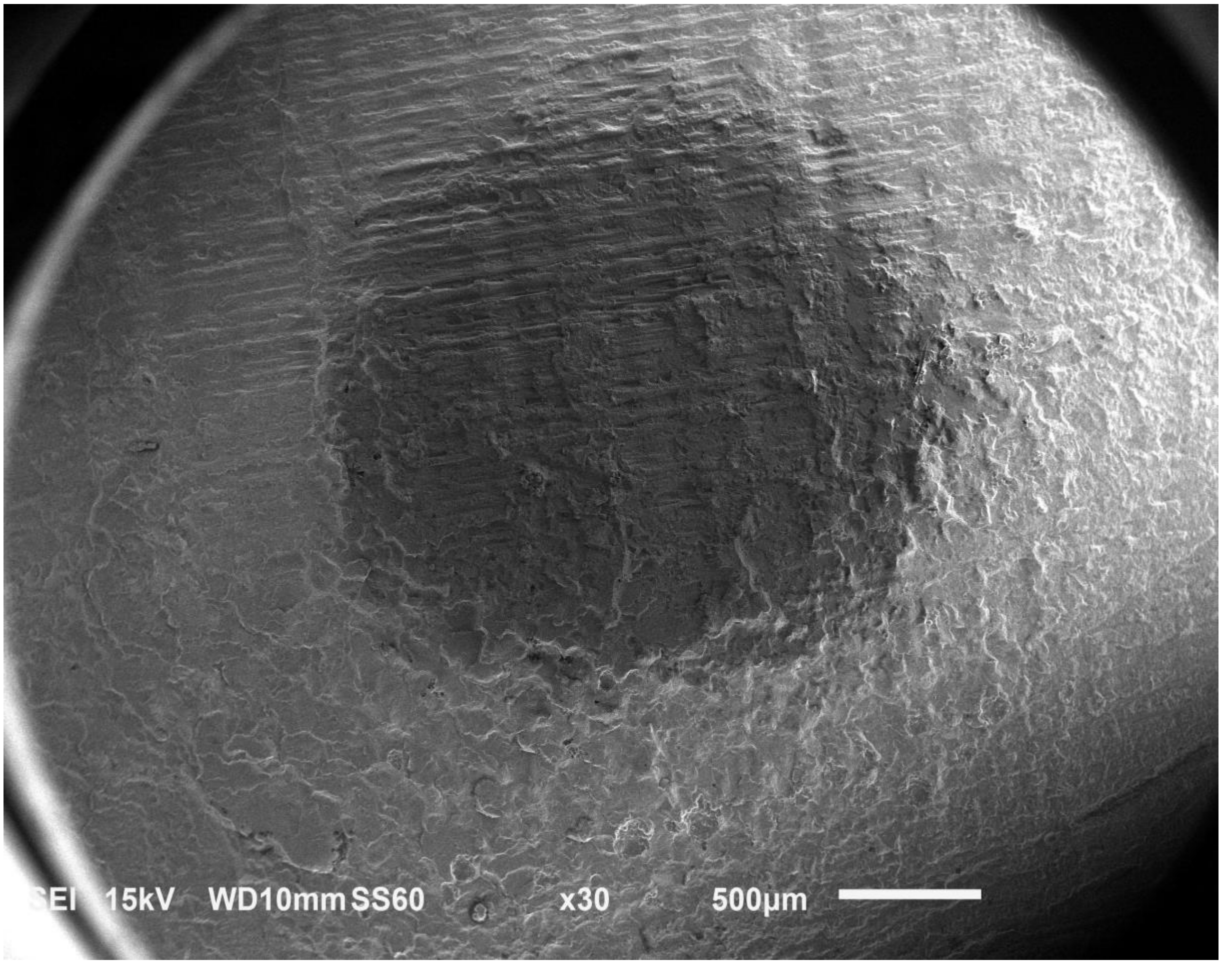

Figure 14. SEM image of failure of printed denture base relined with Tokuyama Rebase ii. Image illustrates type 3, mixed failure (magnification x30).

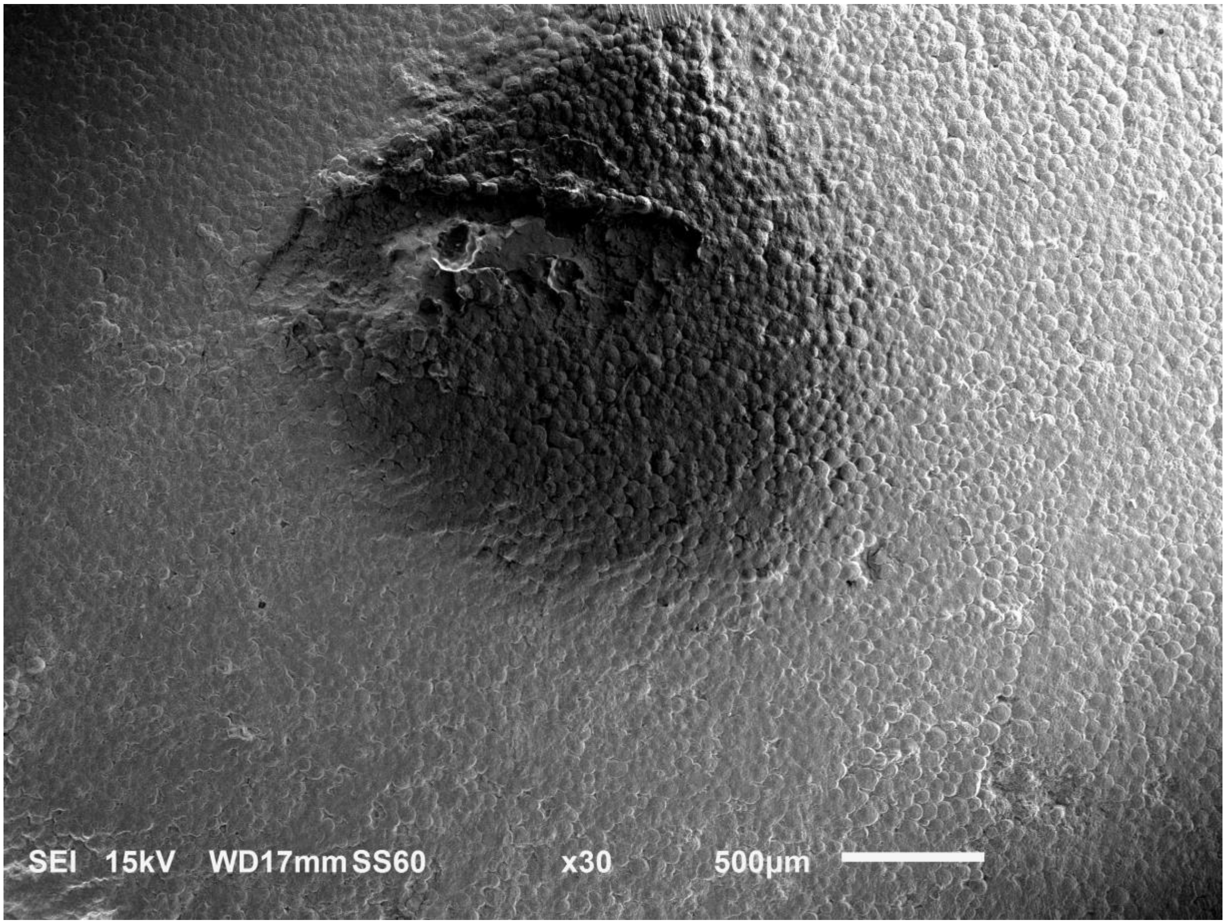

Figure 15. SEM image of failure of injected denture base relined with Kooliner. Image illustrates type 2, cohesive failure (magnification x30).

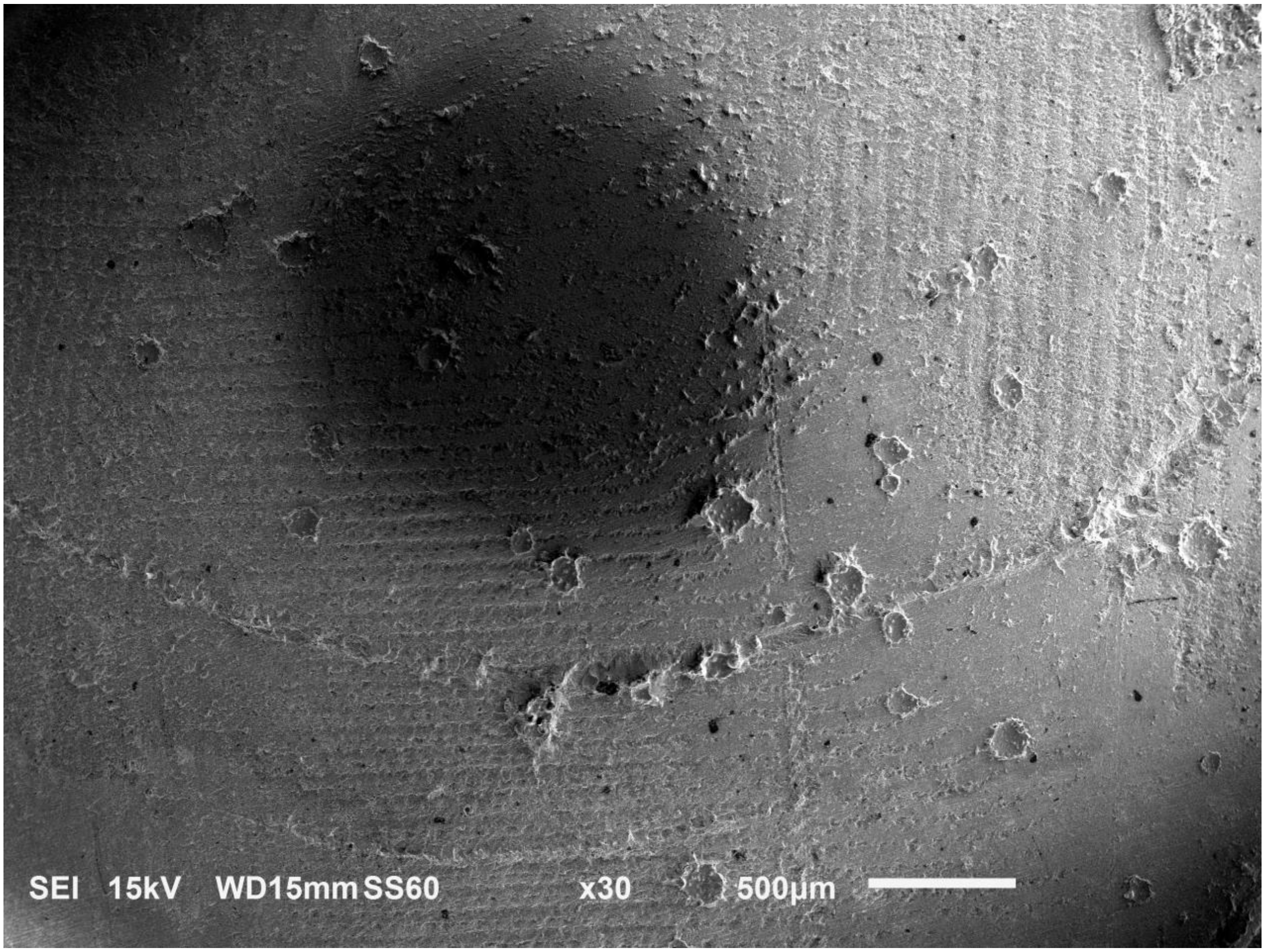

Figure 16. SEM image of failure of milled denture base relined with Kooliner. Image illustrates type 3, mixed failure (magnification x30). Again, this image illustrates greater number of porosities present in milled denture base samples.

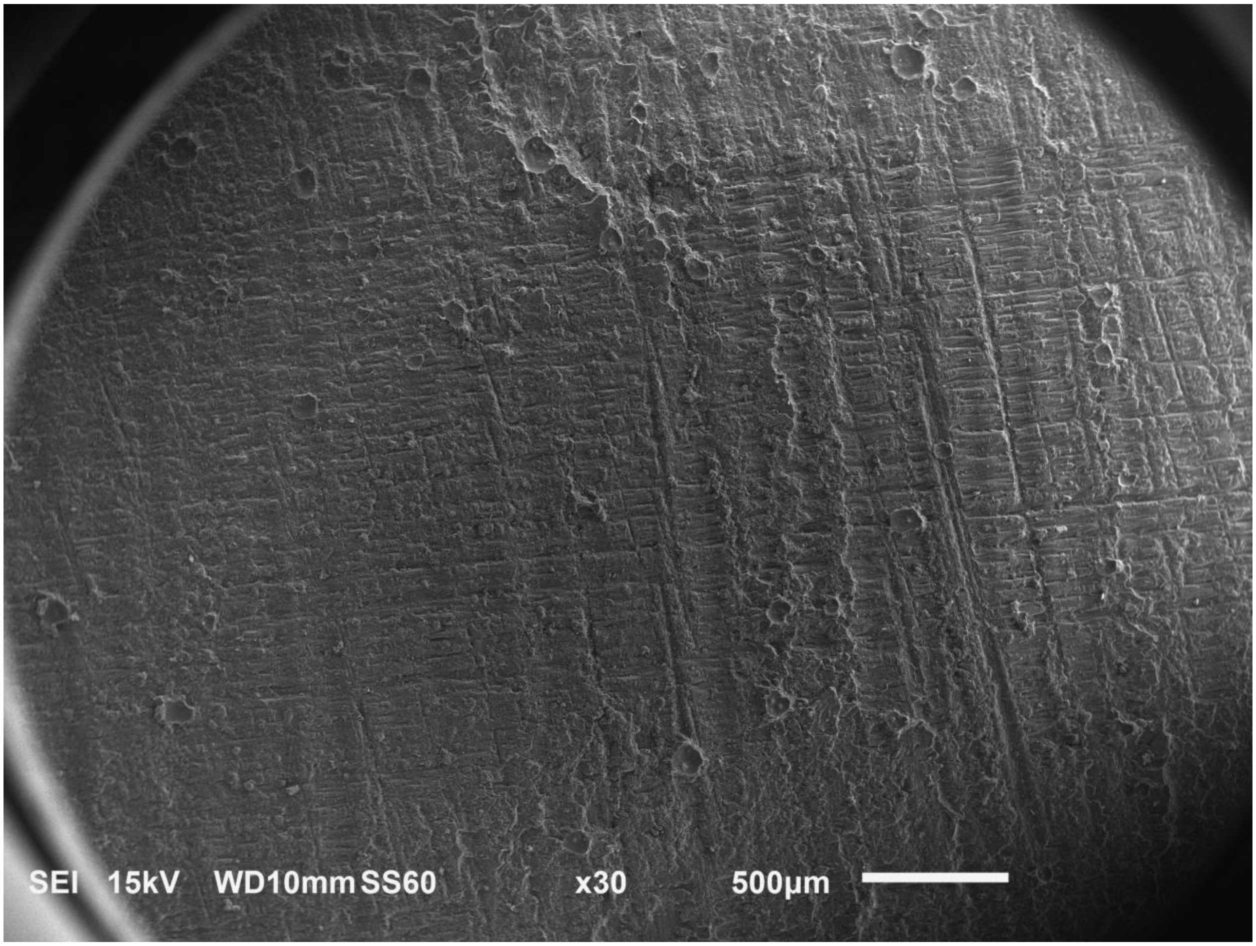

Figure 17. SEM image of failure of printed denture base relined with Kooliner. The image illustrates type 3, mixed failure (magnification x30).

4. DISCUSSION

Debonding of denture liners from the denture base is a recurring problem.[27] The present study evaluated the tensile bond strength of both soft and hard denture chairside reline materials on denture bases fabricated by 3D printing and milling technology. The null hypothesis that there was no significant difference in tensile bond strength among the soft and hard denture liners was both accepted and rejected depending on the variables that were rejected.

An explanation for the difference in tensile bond strength between the reline groups (SCC, SCP, HCT, HCK, HLP) could be due to the difference in the chemical composition of the denture bases that they are bonded to. The processed and milled denture base specimens are fabricated from PMMA, whereas the printed denture base is made from a light curable denture base resin, specifically one containing methacrylate monomer, diurethane dimethacrylate, propylidynetrimethyl trimethacrylate and pigments.[31] Overall, the printed denture bases had the lowest mean values of tensile bond strength in four out of the five denture liners tested (SCP, HCT, HCK, HLP). However, statistically significant differences were found in the tensile bond strength of the SCP, HCT and HLP groups only. Also, the mode of failure in the printed denture bases lined with ProBase was not due to the failure of the reline itself, but due to the lower flexural strength of the printed denture base (> 65 MPa) in comparison to the hard laboratory reline material (> 67 MPa). During tension testing, the printed denture base would fracture before any break would occur in the ProBase reline. Therefore, we were unable to acquire true tensile bond strength scores for the HLP group and was one of the limitations in this study.

Furthermore, the milled denture bases had the greatest mean tensile bond strength in four out of the five denture liners tested (SCC, SCP, HCT, HCK). In the SCC group alone, it was statistically significantly higher than the I and P denture base groups. Figures 11 and 14 show a greater number of ‘pores’ in the CAD-CAM milled denture bases in comparison to the other denture base samples. The greater mean tensile bond strength values of the CAD-CAM milled denture bases could result from the increased mechanical retention provided by these pores.

Moreover, there was no statistical difference between the I, M and P denture base groups relined with Kooliner. The other group that showed partial similarity with the HCK reline group was the SCC reline group, where the I and P groups did not show any statistical difference in tensile bond strength. One possible reason for this is the denture liner’s similar chemical composition to the denture bases. The Kooliner liquid monomer has a composition of 90-100% isobutyl methacrylate, whereas the COE Soft powder contains methyl methacrylate. According to Mutluay et al,[23] the existence of the Kooliner’s isobutyl methacrylate and COE Soft’s methyl methacrylate aids in the cross-linking to the existing methacrylate in the varying denture bases (I, M and P). On the other hand, Tokuyama Rebase ii also has a similar composition of methacrylate, however, its protocol includes the application of a primer prior to applying the reline material. According to a study by Bayati et al,[32] the primer could be the cause of the lower mean tensile bond strength of HCT in comparison to HCK. In the SEM analysis, mixed fractures were observed at the bonding surface in most of the Tokuyama Rebase ii specimens. Based on the study by Bayati et al,[32] the adhesive can act as a site for fracture initiation, which can lower bond strength. As the solvent in the primer evaporates, the polymeric ingredients precipitate and shrinkage ensues, thereby producing a lower bond strength.[23]

Furthermore, soft chairside, hard chairside and hard laboratory reline tensile bond strength values were all statistically significant with ProBase Cold yielding the greatest bond strengths. Independent Samples t-Tests were completed to compare the soft and hard chairside relines among themselves. In the soft chairside reline Independent Samples t-Test, PermaSoft had statistically significant higher tensile bond strength values than COE Soft. According to a study by Yoeli et al,[33] COE Soft is a "softer" material in comparison to PermaSoft. This also explains why the mode of failure for COE Soft was predominantly cohesive, whereas PermaSoft had a failure that was mostly adhesive. With the hard chairside reline Independent Samples t-Test, no statistical significance was seen between Tokuyama Rebase ii and Kooliner. However, the mean tensile bond strength was slightly greater with the HCK reline group. As discussed previously, this could be due to the addition of the primer with the HCT reline group.

Finally, the second component of the statistical analysis evaluated to see if there were any statistical differences between I, M, and P denture base groups, regardless of the reline material applied. ANOVA test results showed that there were no statistically significant differences in tensile bond strength when only evaluating the denture base variable (I, M, and P). The small effect size also showed that there was a 0.6% chance of variance between I, M, and P denture base groups. Therefore, the different denture base types could possibly reline similarly in a clinical setting regardless of the denture reline material used. However, a follow-up in vivo study would need to be completed in order to evaluate this further. Follow-up studies should also investigate if any correlation exists between tensile bond strength and mode of failure. Based on the modes of failure presented in this study (types I, II, III), the statistical analysis would most likely be a non-parametric one (Spearman's rho). We were unable to complete this analysis with this in vitro study, as these tests typically require a greater number of samples to measure any true strength of association to prevent mistaking causal relationships for associations.[34] Also, the samples in this study were only stored in water for 24 hours and tested shortly thereafter. However, soft reline materials normally last in the patient's mouth for approximately 3 months and can become less “soft” with time.[33] With hard reline materials, the reline can last approximately 2 years. A systematic review by Kreve et al,[35] showed that changes in the acrylic (hard) chairside liners can be seen after 1 month of use by patients. These changes in the physical properties of soft and hard denture reline materials could also potentially have an effect on the mode of failure as well.

5. CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn:

1. When comparing the overall denture base materials, there was no statistical difference among the injected, milled and printed denture base groups.
2. The printed denture bases had statistically significant lower tensile bond strength values compared to the injection and milled denture in the SCP, HCT and HLP, while milled denture bases demonstrated the highest values of tensile bond strength for all chairside relining groups.
3. In addition, the soft chairside relining material showed a statistically significant lower tensile bond strength, regardless of the denture base processing method, as compared to the hard relining materials.

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