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Original article

Bond strength of a silicon-based soft liner to three types of denture base materials

Israa Ali Mahmood[1], **Radhwan Himmadi Hasan**[2]
[1]College of Dentistry, University of Mosul, Mosul, Iraq
[2]Department of Prosthetic Dentistry, College of Dentistry, University of Mosul, Mosul, Iraq

ABSTRACT

Background: *Silicon-based soft liners have poor chemical adhesion to denture base resin, as they depend on mechanical interlocking. De-bonding between denture resin and soft liners is a common problem, as it shortens the life of a relined prosthesis.* ***Purpose:*** *The purpose of the study was to assess the tensile bond strength of three types of denture base materials—fabricated by conventional heat curing, computer-aided design/computer-aided manufacture, and three-dimensional printing, or milling—that are bonded to the silicon-based soft liner. The study also aimed to evaluate the effect of surface treatment (acetone; erbium- and chromium-doped yttrium, scandium, gallium, and garnet [Er,Cr:YSGG] laser) of denture base materials on the bonding capability of the soft liner.* ***Methods:*** *A total of 90 specimens were divided into three groups according to the denture base type (conventional, printed, and milled). The 30 specimens in each group were then subdivided into three sub-groups according to the surface treatment (untreated, acetone, and Er,Cr:YSGG), such that each sub-group included 10 specimens. The denture base was bonded to a ready-to-use paste of the silicon-based soft liner. The strength of the tensile bond was tested using a universal testing machine. Data were statistically analyzed using SPSS v.26 software, two-way ANOVA, and Duncan's test at a significance level of $p \leq 0.05$.* ***Results:*** *The milled denture base showed a higher mean tensile bonding strength compared with the conventional and printed denture base materials, at $p \leq 0.05$. The surface treatment with Er,Cr:YSGG and the acetone, respectively, showed a higher mean tensile bonding strength value than the untreated group, at $p \leq 0.05$.* ***Conclusion:*** *A milled denture is the most favorable denture base material for bonding to a silicon-based soft liner. The use of Er,Cr:YSGG and acetone surface treatment, respectively, enhances the tensile bonding strength.*

Keywords: *denture base; computer-aided design/computer-aided manufacture; Er,Cr:YSGG; silicon-based soft liner*
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Correspondence: Israa Ali Mahmood, College of Dentistry, University of Mosul, Mosul, Iraq. Email: israaali92@gmail.com

INTRODUCTION

Poly-methyl methacrylate (PMMA) resins are the chief materials used in denture bases fabricated by conventional heat-curing methods. These polymers have good physical properties, such as easy manipulation, toughness, wear resistance, and esthetics. However, in long-term use, a degradation process in the material causes color changes, which disturbs the esthetic.[1] Recently, denture bases have been fabricated using subtractive milling procedures, such as computer-aided design/computer-aided manufacture (CAD–CAM). These procedures have a minimum volumetric deviation compared with the conventional denture base procedure, which involves milling a disk from a pre-polymerized acrylic resin and transient further shrinkage due to polymerization. The many benefits of CAD–CAM denture bases include minimizing chair time, the improved fitting of the denture base and dental prostheses, and the digital archiving of patients data.[2,3]

An additive manufacturing process was chosen to construct the denture bases instead of the milling technique. A major convenience of additive manufacturing is its capability to construct any shape regardless of complexity or quantity; moreover, additive manufacturing also produces less waste than milling and can produce finer detail.[4]

Stress compression during function is harmful to the removable dental prosthesis and can cause serious damage to the supporting tissues, increase ridge resorption, and harm the denture-bearing areas. Therefore, it is advisable to use denture-lining materials, as they adapt to the intaglio

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surface of the denture to produce a better force distribution.[5] An unstable or non-retentive denture is associated with a knife-edged ridge, which can cause pain and discomfort.[6] Relining such a denture base can decrease the damage, preserving the denture base and the supporting tissues; this is an easy technique that can be done chair-side or in the laboratory. Moreover, it is a non-invasive and relatively economical procedure compared with remaking a denture.[7]

There are several potential drawbacks of the resilient lining materials, including the following: the loss of softness, occurrence of *Candida albicans* colonization, minimum tear strength, and porosity.[8] The most common drawback of these materials is the loss of bonding between the soft liner and the denture base. Some considerations that may minimize the bonding strength are water sorption, surface primers, and denture base content.[9]

The most serious problem associated with these materials is that the plasticizers and other soluble ingredients leach out. The absorption of water and saliva can cause bonding washout between the resilient denture liners and denture base, which leads to access of oral fluids and micro-organisms at their boundary, plaque aggregation, and displacement of the reline material from the denture base.[10] Silicon-based soft liners are more resilient and resistant to distortion due to age than acrylic-based denture liners, and they display better viscoelastic characteristics as well as providing an excellent refinement to masticatory function.[11]

Silicon-based soft liners have poor chemical adhesion with the denture base PMMA; therefore, the use of organic solvents, such as methyl methacrylate and ethyl acetate, is advised to enhance the silicon-based soft liners adhesion to PMMA. This is achieved through mechanical interlocking, as these solvents create softening and porosity on the bonding site at the PMMA surface, which improves the adhesive penetration for the silicon-based soft liners.[12,13] The purpose of this study is to evaluate the tensile bonding strength of three types of denture base materials—fabricated by a conventional technique, CAD–CAM printed, and milled technology—bonded to the silicon-based soft liner and to evaluate the effect of using surface treatment (acetone vs. laser) on the tensile bonding strength.

MATERIALS AND METHODS

In this study, 90 specimens were tested to investigate the tensile bonding strength. The specimens were divided into three key categories groups based on the denture base materials type: Group A—the control group for which no surface treatment was used; Group B—acetone surface treatment for 1 minute; Group C—erbium- and chromium-doped yttrium, scandium, gallium, and garnet (Er,Cr:YSGG) laser (3 watts, 20 hertz) surface treatment. Each group included 30 specimens and each subgroup included 10 specimens according to the surface treatment to be used.

(1) Preparation of the conventional heat cure denture base specimen: First, custom-made acrylic mold patterns were designed using computer software (AutoCAD 2021, Autodesk, USA). The designs were then saved in stereolithography (STL)-format files, and three-dimensional (3D) designed samples were exported to an Asiga Max 3D printer (Asiga, NSW, Australia). Asiga DentaBASE liquid (3D print material for denture bases) was used to prepare the dumbbell-shaped specimens constructed according to the American Society for Testing and Materials D412-1627 standard, as shown in Figure 1, with brass patterns of length 36 mm and widths of 7 and 12 mm.[14,15] Thirty specimens of the conventional denture base material were fabricated, and these resin specimens were used to make the mold using the conventional flask procedure for acrylic specimen preparation (SR Triplex® Hot, Ivoclar Vivadent) per the manufacturer's instructions.[15,16]

(2) Preparation of the 3D-printed denture base specimen: The specimens were printed using the Asiga 3D printer, which uses digital light processing technology with a high-power UV LED of wavelength 385 nm and a pixel resolution of 62 µm; the dumbbell-shaped specimen was constructed using an STL file via AutoCAD. Thirty specimens of denture base material were 3D-printed in resin Asiga DentaBASE.[17,18]

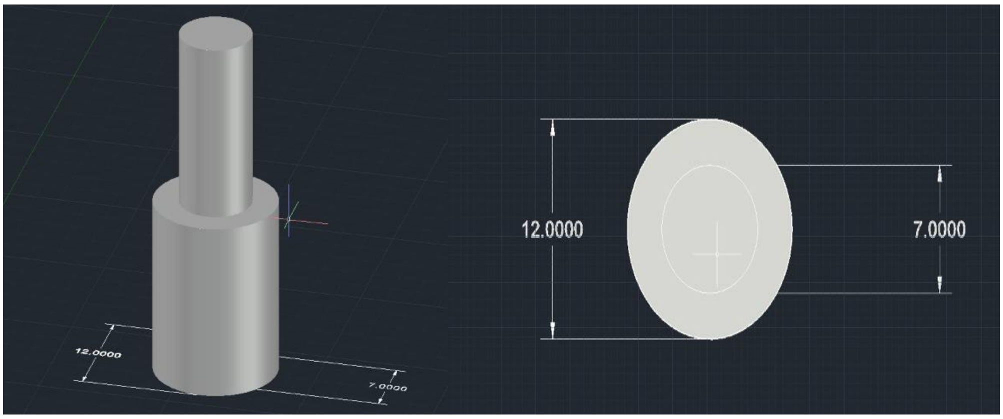

Figure 1. Dumbbell-shaped specimen design.

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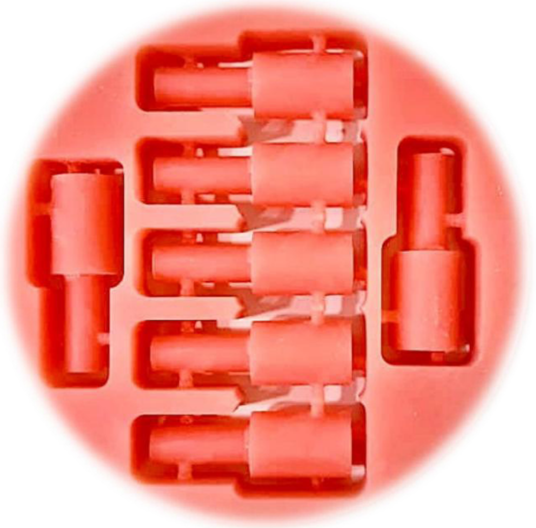

Figure 2. Acrylic block computer-aided design/computer-aided manufacture specimens preparation completed.

(3) Preparation of IvoBase milled denture base specimen: Milled CAD–CAM samples were fabricated using high-dense pressure processed PMMA (IvoBase CAD 30 mm puck; Ivoclar Vivadent). The milling process utilized a 5-axis CAD–CAM milling machine (MAXX DS 200-5Z, Korea), as shown in Figure 2.[19–21]

Preparation of the bonding site: Group A—the control group in which the acrylic side to be bonded to the silicon-based soft liner was not touched or treated with anything. Group B—the acetone group, in which the acrylic side was bonded to the silicon-based soft liner was treated with acetone for 1 minute.[22] Group C—the Er,Cr:YSGG laser group, in which the acrylic side to be bonded to the silicon-based soft liner was treated with an Er,Cr:YSGG laser (Water-lase; BIOLASE Technology, USA) The parameters of the machine were set as follows: reoccurrence rate 20 Hz, 20 pulses per second, pulse duration 140-200 µs, wavelength 2,780 nm, power output 3 W. An 85% air–water mixture was applied by sweeping the handpiece over the area treated. A fiber optic system delivered the

Figure 3. (A) Laser unit machine Er,Cr:YSGG (Water-lase, BIOLASE). (B) Application of laser on an acrylic surface.

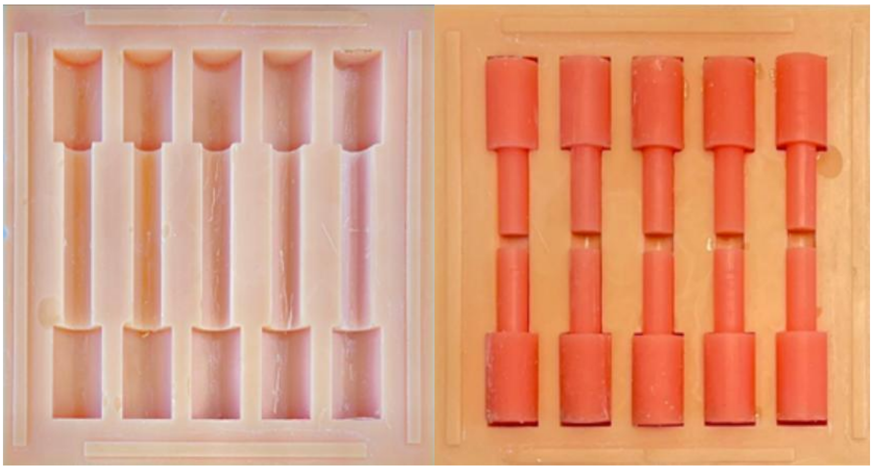

Figure 4. Resin template for specimen alignment and wax application (before and after specimen placement).

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laser energy through to a sapphire tip terminal of diameter 600 µm and length 6 mm. The laser beam was straightened perpendicularly and focused at 1 mm to the polymerized acrylic outer layer. This was controlled by using a surveyor, as shown in Figure 3. Each specimen was treated for approximately 1 minute.

After preparing the specimen, a spacer template was designed using AutoCAD to provide a space to apply the soft liner, a 3 mm spacer to preserve the bonding strength and other physical properties of the soft-liner material.[25] The Asiga 3D printer was utilized to build a resin template for the wax spacer. Then, the STL file was transferred to the printer to print the wax spacer template. The template was designed to provide a uniform thickness of the wax, correct alignment of denture base specimens, and easy removal, as shown in Figure 4. Each of the two specimens was joined together with a wax spacer laid centrally between them.[25,26]

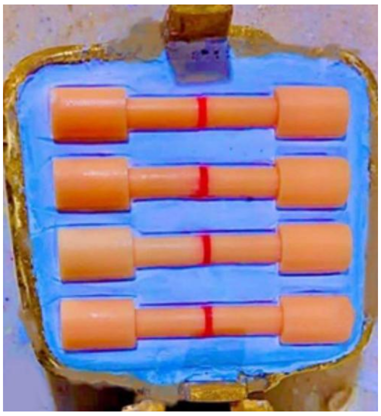


Figure 5. Specimens with wax spacer placed inside the flask.

Preparation using a conventional brass metal flask procedure: The flask was filled with Elite Stone type VI die stone (Zhermack, Italy) according to the manufacturer's instructions, and a vibrator was used to remove any trapped air. The surface of the acrylic specimens was cleaned, wiped, and wetted with a separating medium (alginic isolator, Zhermack). Then, the specimens were immersed inside the stone, as shown in Figure 5.[15,25] After that, the ready-to-use silicon-based soft liner paste Permaliner (DETAX, Germany) was applied and brushed all over with the separating medium. The other half of the flask was then placed over the first one and then heat-cured for two hours in a water bath according to the manufacturer's instructions.[15,25,27]

Finally, after the specimens had cooled down slowly on the bench, they were removed from the flask and kept in distilled water at 37°C for 24 hours.

Tensile bonding strength evaluation: The samples were clamped on both sides of the universal testing machine to measure the tensile bonding strength at a cross speed of 5 mm/min until failure occurred.[2,28] The tensile bonding strength (B) is calculated using the following formula:[29]

$$B\ (\text{MPa}) = {}^{F}\!/_{S}$$

Where F (N) is force, S is surface area in $\text{mm}^2 = \pi r^2$, with $S = 38.5\ \text{mm}^2$ and r (radius) = 3.5 mm

Statistical strategies were used to evaluate and interpret the results of the study using the SPSS v.26 software package. The Shapiro–Wilk test of normality was first conducted to analyze the results data of the study regarding the tensile bonding strength, revealing that the data were parametric and normally distributed. To evaluate the effect of interaction between different variables, two-way ANOVA and Duncan's multiple range test were conducted.

Table 1. Descriptive statistics, mean, and standard deviation of the tensile bonding strength for all the study groups

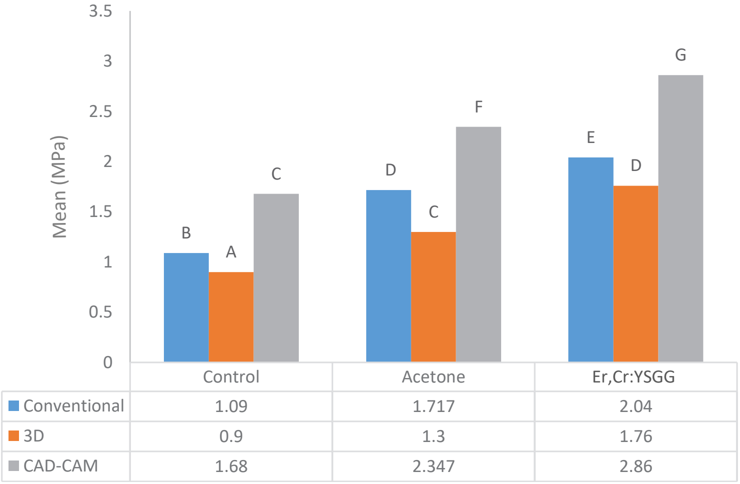
Denture base type	Surface treatment	Number	Mean (MPa)	Standard deviation
Conventional	Control	10	1.09	0.0348
	Acetone	10	1.717	0.0263
	Laser	10	2.040	0.030
Printed	Control	10	0.936	0.0138
	Acetone	10	1.30	0.027
	Laser	10	1.76	0.0163
Milled	Control	10	1.68	0.0219
	Acetone	10	2.347	0.0350
	Laser	10	2.86	0.0426

MPa = Mega Pascal.

Table 2. Two-way analysis of variance, a statistical test for the tensile bonding strength, the interaction between two different variables

Source	Type III SS	df	MS	F (N)	Sig.
Denture base type	14.755	2	7.378	874.542	0.000**
Surface treatment	14.531	2	7.266	861.291	0.000**
Denture base type * Surface treatment	0.441	4	0.110	13.056	0.000**
Total	305.822	90			

SS: sum of squares; df: degree of freedom; MS: mean of square; F: force; Sig.: significant; **: highly significant at $p < 0.001$.



	Control	Acetone	Er,Cr:YSGG
■ Conventional	1.09	1.717	2.04
■ 3D	0.9	1.3	1.76
■ CAD-CAM	1.68	2.347	2.86

Figure 6. Duncan's multiple range test of the tensile bonding strength among different denture base materials groups and different surface treatment groups. Different letters labeled mean there is a significant difference in the mean value.

RESULTS

Descriptive statistics of the study results regarding the tensile bonding strength showed that the mean and standard deviation of the milled denture base material had the highest value relative to other types of denture base materials, as shown in Table 1. Duncan's multiple range test regarding the interaction between different variables showed that the milled denture treated with Er,Cr:YSGG had a significantly higher mean tensile bonding strength, at $p < 0.001$, whereas the 3D printed control group had significantly the lowest mean tensile bonding strength, as shown in Figure 6.

Interaction between variables and ANOVA showed a significant difference in tensile bonding strength, at $p < 0.001$, regarding the interaction between variables. This indicates that the denture base materials' bonding strength improves when surface treatments are used, as shown in Table 2.

DISCUSSION

The statistical results revealed that the milled denture base showed a highly significant increase in the mean value of tensile bonding strength relative to other types of denture base materials, whereas the printed denture showed a lower mean value of the tensile bonding strength, as shown in Table 1. This contrast in tensile bonding strength among different denture base groups could be interpreted by the dissimilar chemical content of the denture bases to which the soft liner bonded. Conventional fabricated and milled denture base specimens are constructed from PMMA, whereas a printed denture base is made up of a light-polymerizable denture base resin that contains methacrylate monomer, urethane methacrylate, propylidynetrimethyl trimethacrylate, and pigments.[3] Moreover, the presence of uncured layers may affect the properties of the printed denture, leading to a lower tensile bonding strength.[30,31]

A study by Prpić et al.,[32] in which they compared the mechanical properties of the three types of denture materials that we used in this study, may help explain some of our results. Their study found that the 3D-printed acrylic denture base materials had lower-performing mechanical properties than the other denture base materials, which may affect the tensile bonding strength when bonded with a soft liner.

The milled PMMA blocks are manufactured under high heat and pressure conditions with a condensed acrylic resin, which produces minimal shrinkage, resulting in an ideal ready-to-use block of fully polymerized PMMA; this could be why milled PMMA blocks bonded to soft liner had significantly the highest tensile bonding strength value.[32,33]

Another reason that milled denture base material had the highest mean tensile bonding strength may be that it consists of more pores than other types of denture base materials. These pores could help to increase the mechanical interlocking between the soft liner and denture base, resulting in bonding improvement.[3]

A further reason for the difference in tensile bonding strength value among different denture-based materials is the difference in the material properties. In conventional construction techniques, the ratio of powder/monomer, the polymerization time, and the thermal degree are critical parameters for denture base processing. The lower value of tensile bonding strength for the printed denture base in this study may be explained by manufacturing procedure steps that may affect denture base properties, such as the print orientation (vertical vs. flat), which may cause incompatible characteristics. However, its effect on the properties may be minimal and could be less impactful than other considerations that cause negative effects on the material properties, such as the plasticizing effect of absorbed water.[34–36]

The outcome of this research is compatible with the results of Awad et al.,[3] who declared that milled denture base materials bonded to soft liners provide the highest mean tensile bonding strength, whereas the printed denture base produces the lowest tensile bonding strength, at $p < 0.05$. Furthermore, the observations attained in this study are compatible with the study of Azpiazu-Flores et al.,[15] who stated that the additive-manufactured 3D-printed denture base material had the lowest average value of tensile bonding strength. Furthermore, in line with the present study's findings, the study by Vuksic et al.[27] showed that there is a significant difference in tensile bonding strength values among different denture base materials that are bonded to silicon-based soft liners. The printed denture base materials showed lower values of tensile bonding strength relative to conventional and milled denture base materials.

However, the outcome of our research does not align with the study of Wemken et al.,[36] who stated that there was no statistically meaningful variation in the tensile bonding strength values between varied denture base materials (conventional heat cured, additive, and subtractive manufacturing) when bonded to a soft liner. Moreover, our results are in disagreement with Choi et al.'s study,[37] in which they stated that resilient denture liners bonded to milled denture bases, bringing the minimum tensile bonding strength, which contradicts the results of this study. This may be because they used one acrylate-based and two silicon-based soft denture liners in their study. When analyzing the result of this study with the aforementioned studies that disagreed with our findings, it should be noted that the materials used were from the same category of materials but not sourced from the same manufacturers. Moreover, the specimen's surface preparation and the methods of bonding testing are very different, which is likely a cause of dissimilarity in the results among the studies. Another possible reason for this dissimilarity is that the tensile bonding strength testing was also carried out using varied approaches with different displacement rates.

For the surface treatment groups, the statistical outcome reveals that the Er,Cr:YSGG laser group had significantly the highest increase in the mean value of tensile bonding strength in all types of denture base material, followed by the acetone surface treatment group, relative to the control group, as shown in Table 1. The increase in the tensile bonding strength values among the surface treatment group Er,Cr:YSGG laser at 3 W, 20 Hz is related to the fact that the laser application on the outer layer lies between the denture base and soft liner, which would require some chemical adjustments on the acrylic surface owing to the heat-induced breakdown. These incidents were assumed to be responsible for the noted rise in tensile bonding strength values of the acrylic specimens treated with the Er,Cr:YSGG laser. An important note about the Er,Cr:YSGG laser used in this study is that the air–water sprays from the hand-piece help in maintaining a low outer-surface temperature, thereby avoiding any potential detrimental unwanted harmful consequences, thus preserving the acrylic properties and improving the tensile bonding strength.

This improvement in tensile bonding strength in the Er,Cr:YSGG laser group could also be attributed to the high energy of the Er,Cr:YSGG laser, which could interact with the water droplets, creating water molecule excitation and leading to micro-expansion of the water drops. This would increase the outer-surface layer area and melt the surrounding material. This increase in the surface outer layer may help with mechanical interlocking and improve tensile bonding strength. A further important explanation for this result is that the employment of the Er,Cr:YSGG laser on the acrylic outer layer increases the surface roughness, leading to minimization of the angle formed between PMMA and their liquids, which provides the benefit of penetration of the soft liner into the acrylic micro-inconsistencies.[23]

Using acetone improves the tensile bonding strength but not as effectively as the laser group. This result could be attributed to the fact that the acetone moistens the surface, and using it may result in superficial crack generation and the formation of several pits and evaporation of the solvent on the surface of the acrylic, creating roughness in the outer layer and thereby improving the adhesive penetration and providing mechanical interlocking of the polymer chains.[7] The same idea is explored by Osathananda and Wiwatwarrapan.,[38] who stated that the decomposition of resin by chemical solvent could cause the bloating of outer-surface layers and dissipation of the solvent. The liner monomers spread through and infiltrate the resin pores, forming a percolating polymeric network. The greater the surface bloating is, the greater the porous outer layer, and, thus, there is an increase in the attachment between the liner and denture base.

Akin et al.[39] showed that when chemical solvents and PMMA interact with each other, the surface roughness increases and leads to an increase in the bonding strength. Another important chemical explanation for why the acetone group improves the tensile bonding strength is that acetone can penetrate deeply through the polymer chains and make the invasion of adhesive primer easier. This is also related to the alkyl groups of the methacrylate may form hydrogen bonds with the C-H groups. These chemicals have solvent effects on the surface of the denture base resins leading to surface roughening and increasing the bond strength.[40]

This insight conforms with the results obtained in this study concerning the surface treatment groups. The study of Yildirim et al.[41] stated that denture liner materials penetrate the cracks or inconsistencies modified by the laser, maximizing roughness in the bonding site and, thus, improving the bonding strength. The study of Korkmaz et al.,[23] which declared that the Er,Cr:YSGG laser helps maximize the liners' bonding strength to the denture base, also agrees with the findings of the current study. Our study outcome supports the study of Kreve et al.[7] and Surapaneni et al.,[22] which stated that the acetone surface treatment increases the adhesion by providing interlocking of the polymer chains.

The outcome of the current study does not agree with the study of Gundogdu et al.,[42] who found that the use of Er:YAG laser treatment increased the surface roughness, although the increase in tensile bonding strength over specimens was not statistically significant. Furthermore, the results of our study do not conform with the study of Fatah et al.,[43] who stated that surface treatment using an Nd:YAG laser was statistically insignificant. This may be due to the sweeping movement of the laser handpiece at the time of treatment, leading to different extents of micro-pores formulated, which may not facilitate the flow of liner material. Moreover; different parameters of the laser were used in this study, which may also lead to a different result.

The diverse types of denture base materials significantly affect the tensile bonding strength of denture base soft liner. The milled denture base materials had the highest tensile bonding strength in comparison with other types of denture base materials, whereas the printed denture base materials had the lowest tensile bonding strength with denture base liners. Moreover, this study demonstrates that surface treatment with an Er,Cr:YSGG laser and acetone refine the tensile bonding strength of all types of denture base materials to a silicon-based soft liner.

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