Effect of plasma treatment on the peel bond strength between maxillofacial silicones and resins

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The study aimed to investigate the effects of surface treatments, including plasma, on the peel bond strength between two maxillofacial silicones and two resins with and without thermocycling. Forty-eight experimental groups (n=10) were generated incorporating the two different silicones (auto-polymerizing acrylic resin and light-curing urethane dimethacrylate resin [AR and LR, respectively]), two different silicones (M511 and Z004), aging (thermocycled/no thermocycling), and six different surface treatments, including polishing, grinding, polishing+argon plasma, polishing+oxygen plasma, grinding+argon plasma, and grinding+oxygen plasma. Surface topography of a specimen from each surface treatment group was examined by atomic force microscopy. After surface treatments, silicones were polymerized. The peel bond strength values of the control and thermocycled groups were determined. Atomic force microscopy showed that surface topographies of the ground specimens were irregular. Polished specimens showed higher peel bond strength than ground specimens. Plasma application appeared to have improved the bond strength between the resins and silicones.

Keywords: Maxillofacial silicones, Peel bond strength, Plasma treatment

INTRODUCTION

For over 50 years, silicone elastomers have been most widely used materials for fabrication of maxillofacial prostheses because of their desirable properties including biocompatibility, flexibility, ability to match skin color, translucency, chemical and physical inertness, and moldability. Silicone elastomers can be used in combination with a rigid material such as resins, alloys, or fiber-reinforced maxillofacial prostheses fabrication in cases in which a substructure is needed for retentive attachment of implant-supported prostheses or structural support is required for large prostheses. These prostheses consist of two layers such as a resin or metal base and silicone. An adequate and durable bond between the silicone and the base is a crucial factor for clinical success and service life of a maxillofacial prosthesis. However, the bond between silicone and resin is the most problematic aspect of a maxillofacial prosthesis due to differences in the basic chemical structure between these materials.

Strength and durability of the bond between the silicone elastomer and resin can be influenced by several factors, including composition of silicone elastomer, substructure material, adhesive primer used, and bonding interface surface properties. Most of these studies have focused on adhesive primers, which provide an increase in bond strength between two different chemical structure silicone elastomers and resin bases. However, the effects of surface topography and characteristics of bonding interface of resin and silicone have undergone limited investigation in this area. Some studies have advocated that roughening the resin base surface will enhance the maxillofacial silicone bond, whereas Jagger et al. suggested that roughening the resin base surface with a bur may cause a decrease in bond strength between acrylic resin and silicone denture relining material due to stress concentration that occurs in surface irregularities and gas or air entrapped at the interface. There is no consensus on the ideal surface treatment of the bonding surface of the resin base for enhancing bond strength between resin and silicone.

Plasma is a partially or wholly ionized gaseous mixture of electrons, free radicals, ions, ultraviolet photons, and reactive neutral species with high enough energy to break covalent bonds on the material surface. Thereby, plasma treatment can improve polymer surfaces in terms of hydrophilicity and wettability. Various advantages have been reported for modifying surfaces with plasma treatment. This treatment modifies polymer surfaces for a few nanometers in depth, thereby allowing surface alterations without inducing bulk modifications but with retention of the material’s physical properties. Materials are never subjected to high temperatures as gas ionization occurs at room temperature. Plasma irradiation does not cause environmental pollution because it does not require chemicals. Moreover, this treatment, which can be appropriate for a wide range of materials, is a rapid and dry technique. Despite these advantages, the technique has limited use in the field of dental materials. Studies have reported that plasma treatment improves the bond strength between heat polymerization...
denture base acrylic resin and auto polymerization repair resin\cite{9,29} and between denture base acrylic resin and soft liners\cite{13}. To date, there is no information about the use of plasma for bonding between maxillofacial silicones and resin substructure materials.

The purpose of this study was to investigate the effects of surface treatments, including plasma on the peel bond strength between two maxillofacial silicone elastomers and two resins with and without thermocycling. The study’s null hypothesis was the bond strength of maxillofacial silicone elastomers with resin substructures would not be affected by the type of silicone elastomer, the type of resin, the type of surface treatment of bonding surface of resin, and thermocycling.

**MATERIALS AND METHODS**

The bond strength between the two maxillofacial silicone elastomers and resin base materials were evaluated using the 180° peel test\cite{24}. The specimen preparation procedure for the test was conducted at three stages: 1) fabricating resin blanks; 2) applying surface treatments on bonding surfaces; and 3) packing silicone elastomer on the resin blanks. Maxillofacial silicone elastomers, resin base materials, and adhesive primer used in the study are listed in Table 1.

Wax patterns for resin blanks were prepared with dimensions 75×10×3 mm and embedded in dental stone molds after which time the wax was removed. Auto-polymerizing acrylic and light-curing urethane dimethacrylate resins (AR and LR, respectively) were prepared, packed into molds, and polymerized according to the manufacturers’ instructions. For each resin, a total of 240 specimens was prepared and divided into six groups for undergoing surface treatments. After resin blanks were removed from the molds, excess material was trimmed, and resin bases measured with digital caliper (Powertectools, Zhejiang, China) to ensure dimensions of 75±0.25×10±0.25×3±0.25 mm. Another set of wax blanks with the dimensions 75×10×6 mm were used to prepare stone molds in which surface-treated resin bases would be inserted, and the silicone elastomer would be packed with the resin base.

Bonding surfaces of each group of resin base was received following surface treatments:
1. Polishing (Pol),
2. Grinding (Gr),
3. Polishing and argon plasma (Pol+AP),
4. Polishing and oxygen plasma (Pol+OP),
5. Grinding and argon plasma (Gr+AP),
6. Grinding and oxygen plasma (Gr+OP).

Grinding was performed by using a laboratory carbide bur (216, GC, Tokyo, Japan) to roughen the bonding surface by removing up to 0.2 mm material from the surface. The grinding speed was 10,000 rpm. In order to maintain a consistent amount of grit, the burs were replaced after surface treatment of the specimen group. The dimensions were confirmed by measuring them with an electronic digital micrometer.

Polishing of the resin blanks’ bonding surfaces was performed with sand paper of 320/400/600 grit, followed by polishing with a pumice slurry. Polished and ground specimens were ultrasonically cleaned in distilled water for 10 min. Bonding surfaces were treated with acetone and left to dry for 15 min according to manufacturerer recommendation. Before adhesive primer coating and

| Material | Brand name | Manufacturer | Chemical ingredients | Processing properties |
|----------|------------|--------------|----------------------|----------------------|
| Resin base | Paladent RR | Heraeus Kulzer, Wehrheim, Germany | Cold curing polymer: polymethyl metacrylate | Mixing time: 30 s, Working time: 2 min |
|          | Triad VLC Denture Base Material | Densply, York, PA, USA | Urethane dimethacrylate resin | 10 min visible light curing in the Triad 2,000 light source with an oxygen inhibiting layer (Triad Air Barrier Coating) |
| Silicone elastomer | M511 Silicone elastomer | Technovent, South Wales, UK | Fumed silica particles dispersed in vinyl terminated silicone fluid | 2-part material, Mixing ratio 1:1, Heat cured for 1 h at 100°C |
|          | Z004 Silicone elastomer | Technovent, South Wales, UK | | 2-part material, Mixing ratio 1:1, Heat cured for 2 h at 100°C |
| Adhesive primer | G611 Platinum primer | | | A thin layer is applied with a brush on the bonding surfaces |
silicone packing, 50 mm lengths of the resin blanks were isolated using adhesive tape to provide 25×10 mm bonded and 50×10 mm free silicone and resin parts for the peel test specimen. A thin coat of adhesive primer (G611 Platinum Primer, Technovent, Newport, UK) was then applied with a brush and allowed to dry for 10 min. Resin blanks were fixed inside the molds, and each silicone elastomer was mixed according to manufacturer’s instructions and packed over the resin bases.

For plasma groups, resin blanks’ bonding surfaces prepared for plasma treatments were cleaned with acetone and left to dry for 15 min. The resin blanks were inserted into the plasma device by positioning the bonding surfaces at 90 degrees to the gas flow. First, the system was evacuated using a rotary vacuum pump until it reached a pressure of 0.013 mbar. Oxygen and argon gases were introduced into the reactor in order to displace the residual gases. This process was performed to ensure complete removal of impurities. Finally, the pressure was stabilized at 0.4 mbar by opening the inlet valve enough to allow the pressure to stabilize. A power of 60 W was applied to the system for plasma generation, and each plasma treatment was applied 10 min. Immediately after plasma treatment, adhesive primer coating and silicone packing were performed as described for the grinding and polishing groups.

Curing of each silicone elastomer was performed according to manufacturer’s instructions, and molds were left to cool to room temperature. After removing the cured specimens from the molds, excess silicone was cut using a blade and then stored for 24 h at room temperature. The final specimen was 6 mm in thickness with a 3 mm resin base and 3 mm silicone elastomer. These two layers were bonded at one end (25×10 mm)

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**Fig. 1** Workflow diagram of the study.

| 1. Fabricating resin base blanks |
|----------------------------------|
| Acrylic resin \(n=240\)          |
| Light-curing urethane dimethacrylate resin \(n=240\) |

| 2. Surface Treatments of bonding surfaces |
|-------------------------------------------|
| Polishing (Pol) \(n=40\)                  |
| Grinding (Gr) \(n=40\)                    |
| Polishing and argon plasma (Pol+AP) \(n=40\) |
| Polishing and oxygen plasma (Pol+OP) \(n=40\) |
| Grinding and argon plasma (Gr+AP) \(n=40\) |
| Grinding and oxygen plasma (Gr+OP) \(n=40\) |

| 3. Silicone packing |
|--------------------|
| M511 \(n=20 \) in each surface treatment group |
| Z004 \(n=20 \) in each surface treatment group |

| 4. Aging |
|----------|
| Control \(n=10 \) in each surface treatment group |
| Thermocycle \(n=10 \) in each surface treatment group |

| 5. Peel bond strength test |
|---------------------------|
and remained free at the other end (50×10 mm)\textsuperscript{24}. For each surface treatment, resin base, and silicone elastomer combination, a total of 480 specimens \((n=20 \text{ for each combination})\) were prepared. Half of the specimens \((n=10)\) were subjected to the peel test after 24 h of fabrication, and half were tested after thermocycling. The specimens in the thermal aging group were thermocycled between 5 and 55°C for 2,000 cycles with a 20 s dwell time in a thermocycler (MTE 101, MOD Dental, Esetron Smart Robotechnologies, Ankara, Turkey). The workflow diagram of the study, groups, and number of specimens in each group is summarized in Fig. 1. Free parts were gripped by the tested apparatus jaw while performing the test. The free end of the silicone was turned back at 180 degrees, the free silicone elastomer and resin base were gripped in a universal testing machine (MOD Dental, Esetron Smart Robotechnologies), and the specimen was tested under tension at a crosshead speed of 50 mm/min until failure occurred. The maximum force was recorded at the beginning of the peel failure. Peel strength \((N/mm)\) was determined using the formula\textsuperscript{24}:

\[
\text{Peel strength} = \frac{F}{W} \left(\frac{1+\lambda}{2}\right)
\]

Where \(F\) is the maximum force recorded \((N)\), \(W\) is the width of the specimen, and \(\lambda\) is the extension ratio of silicone elastomer \((\text{ratio of stretch and unstretched length})\).

After undergoing peel test to failure, each specimen was examined using a magnifying glass (Loupe option, Orange Dental, Biberach, Germany) at 2.7× magnification, and the type of failure was categorized as adhesive or cohesive. Adhesive failure indicates peeling of the silicone elastomer from the resin base, and cohesive failure indicates failure entirely within the silicone elastomer as a tear or snap of the silicone layer\textsuperscript{24-26}.

The surface topography of one specimen from each of six surface treatment groups was analyzed by atomic force microscopy (AFM). For AFM analysis, one specimen for each surface treatment group from AR and LR materials was prepared. Specimens from the Pol and Gr groups were analyzed using an atomic force microscope (Park systems, Suwon, Korea) after specimens underwent cleaning in an ultrasonic bath, and plasma groups were analyzed immediately after plasma treatment.

**Statistical analyses**

The normality of the peel bond strength data was assessed and confirmed using the Shapiro-Wilk test \((p>0.05)\). Accordingly, bond strength data were statistically analyzed by using a four-way analysis of variance (ANOVA) with resin type, silicone type, surface treatment, and aging as independent variables. To compare the groups’ failure type according to factors, including resin base and silicone types, and thermocycling, pairwise comparisons were performed using the chi-squared test. Failure types according to the surface treatments were compared using the Fisher exact test \((\alpha=0.05)\).

**RESULTS**

The four-way ANOVA results revealed statistically significant interactions among the resin, silicone, surface treatment, and aging variables \((p<0.05)\). For bond strength data, descriptive statistics and comparison of groups are shown in Table 2. AFM images of each group are represented in Figs. 2 and 3. AFM images demonstrated that the surface of the both the AR and LR groups were more irregular in the grinding groups than in the polishing groups. Oxygen plasma generated smoother surfaces than argon plasma.

After thermocycling, statistically significant decreases were observed in the bond strength of M511 applied to AR when Gr+OP was applied to the AR as surface treatment and to LR when Gr and Gr+AP was applied. The bond strength between the resin and Z004 groups generally decreased in cases in which significant differences were found for groups with Z004-AR Pol+AP, Z004-AR Pol+OP, Z004-AR Gr+AP, Z004-LR Pol+OP, Z004-LR Gr+AP, and Z004-LR Gr+OP. After comparing the bond strength of a silicone type to AR and LR bases, M511 showed significantly higher bond strength with the LR in groups in the Control Pol, Control Gr, and Thermocycling Pol groups, whereas M511 showed significantly higher bond strength with the AR in groups in the Control Gr+OP, Thermocycling Pol+AP, and Thermocycling Gr+AP groups. Z004 showed significantly higher bond strength with AR in Pol groups and Thermocycling Gr+OP, and higher bond strength with LR in the both Pol+AP, Control Gr+AP, and Control Gr+OP groups. After comparing the bond strength of the silicone types with the AR base, Z004 generally showed higher bond strength than M511, except in the group Gr+OP; however, differences were statistically significant for groups of Control Pol+AP, Control Pol+OP, Control Gr+AP, and Thermocycling Gr+AP. After comparing the bond strength of silicone types to LR, M511 demonstrated significantly higher bond strength than Z004 in the Control Pol and LR Thermocycling Pol groups. Z004 showed generally significantly higher bond strength than M511 in the plasma groups both for Control and Thermocycling.

After comparing the surface treatments, the Pol and Gr AR groups showed significantly lowest bond strength to M511 and Z004 than the plasma groups. Among the plasma-treated acrylic groups, the highest bond strength was observed with the Control Gr+OP-M511 and Control Pol+OP-Z004 combinations. After considering surface treatments of LR, M511’s bond strength was overall not significantly different between LR base applied on different surface treatments both for control and thermocycling groups. On the other hand, Z004 showed significantly lower bond strength when applied to Pol and Gr than plasma-treated LR groups. Pol+AP LR showed the significantly highest bond strength when treated with Z004 than other plasma-treated LR bases.

Failure types for resin type, silicone type, aging,
Table 2  Peel bond strength (N/mm) of the experimental groups

|                        | AR       | Z004     | LR       | Z004     |
|------------------------|----------|----------|----------|----------|
|                        | M511     |          | M511     |          |
|                        | Control  | Thermocycling | Control  | Thermocycling |
| Polishing (Pol)        | 2.57 (±1.07) a B 1 x | 2.19 (±0.41) a B 1 x | 2.62 (±0.78) a A 1 x | 2.34 (±1.00) a A 1 x |
| Grinding (Gr)          | 2.0 (±0.86) a B 1 x | 1.80 (±0.65) a A 1 x | 2.11 (±1.01) a A 1 x | 1.75 (±0.39) a B 1 x |
| Polishing and argon plasma (Pol+AP) | 5.83 (±0.85) a A 2 y | 6.04 (±0.50) a A 1 y | 7.98 (±1.88) a B 1 y | 5.89 (±1.02) b B 1 y |
| Polishing and oxygen plasma (Pol+OP) | 5.00 (±1.04) a A 2 y | 4.90 (±1.26) a A 1 y | 9.48 (±2.09) a A 1 z | 5.97 (±1.20) b A 1 y |
| Grinding and argon plasma (Gr+AP) | 5.50 (±0.74) a A 2 y | 5.28 (±0.70) a A 2 y | 8.73 (±2.31) b B 1 y | 7.47 (±1.90) b A 1 z |
| Grinding and oxygen plasma (Gr+OP) | 9.48 (±1.33) a B 1 z | 5.97 (±1.21) b A 2 y | 4.00 (±1.69) a B 2 w | 4.00 (±1.14) a A 1 w |

Mean (±SD), n=10
Same lowercase characters indicate that bond strengths were not statistically significantly different between control and thermocycle groups for the same resin type, silicone type, and surface treatment (p>0.05).
Same uppercase characters indicate that bond strengths were not statistically significantly different between resin types (AR and LR) for the same silicone type, surface treatment, and aging (thermocycled or not) (p>0.05).
Same numbers indicate that bond strengths were not statistically significantly different between silicone types (M511 and Z004) for the same resin type, surface treatment, and aging (thermocycled or not) (p>0.05).
Same x,y,z,w, and q characters indicate that bond strength were not statistically significantly different among the surface treatment groups and for the same resin type, silicone type, and aging (thermocycled or not) (p>0.05).

Fig. 2  AFM images of the AR.
Fig. 3  AFM images of the LR.
Table 3  Failure types of experimental groups

|                       | Adhesive (Count/%) | Cohesive (Count/%) | Total |
|-----------------------|--------------------|--------------------|-------|
| **Resin type**        |                    |                    |       |
| AR                    | 107/44.6           | 133/55.4           | 240   |
| LR                    | 62/25.8            | 178/74.2           | 240   |
| **Silicone type**     |                    |                    |       |
| M511                  | 47/19.6            | 193/80.4           | 240   |
| Z004                  | 122/50.8           | 118/49.2           | 240   |
| **Aging**             |                    |                    |       |
| Control               | 80/47.3            | 160/51.4           | 240   |
| Thermocycling         | 89/52.7            | 151/48.6           | 240   |
| **Surface treatment** |                    |                    |       |
| Pol                   | 57/71.3            | 23/28.7            | 80    |
| Gr                    | 70/87.5            | 10/12.5            | 80    |
| Pol+AP                | 20/25              | 60/75              | 80    |
| Pol+OP                | 0/0                | 80/100             | 80    |
| Gr+AP                 | 2/2.5              | 78/92.5            | 80    |
| Gr+OP                 | 20/25              | 60/75              | 80    |
| **Total**             | 169/35.2           | 311/64.8           | 480   |

Comparison of failure types of groups revealed that the cohesive mode more frequently produced failures for both resin based materials (p<0.05). For silicone types, M511 showed the most frequent cohesive failures, while Z004 showed adhesive failure (p<0.05). After comparing surface treatments, the Pol and Gr groups revealed frequent adhesive failures with >70%, while the remaining surface treatment groups, which include plasma applications, showed the most frequent cohesive failures (p<0.05).

**DISCUSSION**

The null hypothesis of the study was rejected as the silicone elastomer and resin types, treatment of bonding surface of resin, and thermocycling affected bond strength between maxillofacial silicone elastomers and substructure resins. Bonding of silicone elastomers to resin substructures is an important factor in maxillofacial prostheses success and longevity especially for implant-retained prostheses with highly retentive attachments. Considerable forces are applied by a patient that can detach a prosthesis from the implants; this action can commonly lead to failure of the bonding interface. Therefore, studies focused on enhancing the bond between silicone and substructure are needed. In this context, these studies should consider the type of adhesive primer, silicone elastomer, substructure material, and surface properties of the bonding interface.

The use of adhesive primers is a currently the standard procedure for achieving an effective bond between the silicone and the base. Primers include an organic solvent and adhesive monomer, which collectively serve as a chemical intermediate of the silicone and resin substructure. The bonding surface of the resin is etched, wettability is increased, hydrogen bonding and covalent coupling increase, and the interpenetrating network at the boundary interphase is formed by the use of primers. The use of primer enhances the silicone-resin bond strength and the type of the primer affected the bond strength of different silicone elastomers to acrylic resin bases. In the present study, an adhesive primer (G611) advocated by the tested silicone elastomers’ manufacturer was used.

Two maxillofacial silicone elastomers, M511 and Z004, with different mechanical properties were used in the study. M511 is a widely used silicone elastomer material in maxillofacial prostheses fabrication, while Z004 is preferred for prostheses that need extra strength material. Both materials are mainly composed of polydimethylsiloxane rubber chains with surface treated silica fillers. Differences in properties arise from the polymer chain lengths and amount of silica fillers. These compositional differences may lead to chemical affinity with the primer material and substructure resin. In the present study, higher bond strength was found for the Z004-AR combination when compared with M511-AR in agreement with a previous study. This may have resulted from the occurrence of greater stress at the bonding interface during the peel strength test in cases on which a stiffer silicone material is used. Previous studies also have reported that the type of silicone elastomer significantly affects the bond strength of the material on the resin base.

Acrylic resins are commonly used in maxillofacial prosthetics in combination with silicone elastomers as a rigid substructure material. However, residual monomers from the polymerization and unavoidable inherent porosity of the polymerized material are two disadvantages of these resins and may lead the use of alternative materials. In the present study, LR has been compared to AR. Generally, the differences were not statistically different between base materials in accordance with a study by Polyzois et al.
similar bond strength for these two base materials, which was higher than heat-cured acrylic resins after aging. On the other hand Kosor et al.\textsuperscript{10} reported significantly higher bond strength for aliphatic urethane acrylate compared with acrylic resin attributing the result to residual monomer of the acrylic resin material.

In addition to the chemical structures of surfaces in involved in the bonding mechanism, surface characteristics are also important. In the present study, ground and polished surfaces for different silicone and base material combinations revealed peel bond strengths between 1.33 and 5.95, which is in accordance with a previous study\textsuperscript{11}. Differences between these two surface treatments were not statistically significantly different, while a noticeable increase was observed for plasma groups. Previously, two studies have reported that plasma treatment could be effective in enhancing the bond strength of soft liners to acrylic resin denture base\textsuperscript{15,28}. However, there is no information on the plasma’s effects on the bonding efficiency of maxillofacial silicone elastomers applied to resin base materials. In the present study, both argon and oxygen plasmas caused an increase in bond strength for all silicone-based material combinations. The bond strength values of M511 silicone when combined with both resin materials were not statistically different when oxygen and argon plasmas were applied, while Z004 silicone showed higher bond strength when applied to resin bases that had undergone argon plasma compared with oxygen plasma treatment. These differences may be due to the mechanism of plasma gases’s actions. Oxygen plasma treatment generates chemical oxidation reactions and chemical etching processes via the polymer surfaces. With oxidation reactions, hydrophilicity of the surface is enhanced by new functional groups such as the hydroxyl groups (-OH). The chemical etching process generates roughening on the polymer surface that promotes more intimate molecular contact between the silicone elastomer and the base material. The surface modification mechanism of argon plasma depends on increasing surface roughness by bombardment of highly energetic electrons, ions, free radicals, and other metastable excited gas species that enhance interlocking between silicone and resin base surface\textsuperscript{15}. Although there is no accepted minimum bond strength value indicating the maxillofacial prostheses that are applicable to clinical use, all peel bond strength values are \textgreater;0.44 MPa, which is the sufficient bond strength value accepted for bonding soft liners to be used with acrylic denture resins in dental prostheses\textsuperscript{29}.

Plasma-treated polymer surfaces, which have improved surface hydrophilicity, generally exhibit time-dependent properties\textsuperscript{29} because the process partially restores the original hydrophobic surface\textsuperscript{30,31}. In addition, air exposure contaminates the plasma applied surfaces\textsuperscript{28,32}. Therefore, primer application and silicone packing on the plasma treated resin bases should be performed soon after plasma treatment to obtain the optimal bond.

Maxillofacial prostheses are exposed to sunlight, moisture, and temperature during a patient’s daily use. Therefore, artificial aging under simulated conditions is an essential part of an in vitro study that tests prosthetic materials’ clinical performances. Light’s effects on the aging properties of maxillofacial silicone elastomers have been widely studied, and these studies revealed that sun-associated ultraviolet radiation negatively affects the color stability and ideal physical properties of maxillofacial silicones\textsuperscript{33-35}. With regard to bond strength between silicone and acrylic resin substructure, studies have revealed that both light and heat cause an increase in aging due to further silicone photo-polymerization and reactions with pendant C=C bonds from reactive free radicals of resin material\textsuperscript{36,37}. On the other hand, prolonged aging was reported to cause a decrease in the bond strength in addition to the elasticity and tear strength of silicone\textsuperscript{38}. However, there is limited information on the effects of hydrothermal cycling, which can be a more reliable method than light aging to evaluate bonding interfaces\textsuperscript{39}. Because water may directly infiltrate the bond site, leading to swelling and consequent stress buildup at the resin base interface. Therefore hydrothermal aging accelerate the degradation of the bond between silicone and base material; however, light mainly affects the body of the materials, not the bonding interface\textsuperscript{39}. Therefore, hydrothermal cycling was chosen as the aging method in the present study. Comparison of hydrothermocycled and control groups revealed a general decrease in bond strengths; however, statistically significant decreases were observed for both plasma-treated and resin based-Z004 groups. This may be attributed to Z004’s higher viscosity before the curing process. More viscous silicone material would show less wettability and contact angle on the resin base surface; therefore, it would be unsuccessful when used to fill surface irregularities. Although a strong bond initially exists, microleakage of the bonded surface during thermocycling may lead to decrease in the bond strength.

Failure analyses after the peel bond strength test revealed different failure types according to silicone and resin base types, thermocycling, and applied surface treatments to the bonding surfaces. The silicone M511 produced cohesive failure more frequently (80.4%) than adhesive failure, while cohesive and adhesive failures were similar for the Z004 silicone. These findings may indicate that the bond strength between the M511 silicone, which is softer and mechanically weaker than Z004, and the resin base was stronger than that of the silicone itself. The bond strength of the stronger Z004, which probably affects bonding, should be considered. Evaluating failure types according to surface treatments revealed a tendency toward cohesive failures between maxillofacial silicones and plasma-treated resin surfaces. This supports the higher bond strength values observed for plasma-treated groups. However, the cohesive type of peel bond test failures should be interpreted with caution when a strong bond exists between two materials. It is likely that tearing may be initiated by small imperfections or voids in
the silicone mixture. Previously, the effects of silicone elastomer's internal porosity, which depends on mixing technique, has been reported<sup>40</sup>. As manual mixing was performed in the present study, lower peel bond strength values might have been obtained in for strongly bonded plasma groups due to tear of the silicone instead of bonding surfaces’ separation. Bond strength between maxillofacial silicone elastomer and resin base material can be evaluated by tensile, shear, and peel tests<sup>41</sup>. In clinical use, a maxillofacial prosthesis is removed by a patient by peeling and rotating away from implants or skin. The forces generated during these movements can be well-simulated in the peel test<sup>5,7</sup>. Therefore, the bond strength between silicone elastomers and resin bases was evaluated using a 180° peel test. However, maxillofacial prostheses are exposed to forces in different directions during use. Each test measuring bond strength between silicone and base applies forces to bonding interface in one direction. Therefore, none of the bond strength tests can simulate the clinical forces that to which maxillofacial prostheses are exposed. Another limitation of the study is statical testing the bonded interface may be inaccurate because the actual stress is dynamic in nature during repeated removals of the prostheses. Therefore, fatigue type laboratory tests should also be carried out. Furthermore, bonding properties of maxillofacial silicone elastomers applied to resin bases may be affected by coloring pigments, which is an essential step in fabricating esthetic prostheses. The effect of different pigments and pigment concentrations on the bond strength of maxillofacial silicones should be investigated in future studies.

### CONCLUSION

Bonding failures between resins and maxillofacial silicones are the most commonly encountered problems with facial prostheses. Polishing, argon plasma, and oxygen plasma are effective in improving the bonding between resins and maxillofacial silicones.

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### CONFLICTS OF INTEREST

The authors declare no conflicts of interest, real or perceived, financial or nonfinancial.

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