Effect of ultraviolet light irradiation and sandblasting treatment on bond strengths between polyamide and chemical-cured resin

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The aim of this study was to evaluate the effects of ultraviolet light (UV) irradiation and sandblasting treatment on the shear bond strength between polyamide and chemical-cured resin. Three types of commercial polyamides were treated using UV irradiation, sandblasting treatment, and a combining sandblasting and UV irradiation. The shear bond strength was measured and analyzed using the Kruskal-Wallis test ($\alpha=0.05$). Comparing shear bond strengths without surface treatment, from 4.1 to 5.7 MPa, the UV irradiation significantly increased the shear bond strengths except for Valplast, whose shear bond strengths ranged from 5.2 to 9.3 MPa. The sandblasting treatment also significantly increased the shear bond strengths (8.0 to 11.4 MPa). The combining sandblasting and UV irradiation significantly increased the shear bond strengths (15.2 to 18.3 MPa) comparing without surface treatment. This combined treatment was considered the most effective at improving the shear bond strength between polyamide and chemical-cured resin.

Keywords: Flexible denture, Polyamide, Ultraviolet light irradiation, Sandblasting, Shear bond strength

INTRODUCTION

The use of flexible dentures has been increasing due to their preferable esthetic appearance and the potential reduced risk for metal and resin monomer allergies1-4. A wide variety of polymers, such as polyamide, polyacetal, polyethylene terephthalate, and polycarbonate3,5,6, have been used for flexible denture base resins. These polymers are thermoplastic resins; however, their bonding efficiency to a chemical-cured resin is usually poor. In particular, the bonding of polyamide using the chemical-cured resin was reported to be very difficult5-7. There are various types of polyamides with different molecule structures3,8, and they are difficult to dissolve in organic solvents. Therefore, the bonding efficiency of polyamide using chemical-cured resin may not be uniform. Several surface treatments have been suggested to improve the bonding efficiencies, such as 1) surface treatments that increase the roughness using sandblasting with $\text{Al}_2\text{O}_3$ particles5-7, 2) swelling and roughening the surface with organic solvent containing dichloromethane or ethyl acetate6,9, and 3) chemical improvement of the surface by ultraviolet light (UV) irradiation. The former two treatments mainly increase surface roughness and mechanical interlocking, while the latter cleans and chemically modifies the surface. The effects of UV irradiation have been evaluated, such as on a denture composite resin tooth10 and a fiber-reinforced composite post11. These evaluations indicated improvements in the mechanical bonding between chemical-cured resin and not only thermoplastic resins, such as polymethylmethacrylate (PMMA), but also with thermosetting resins. Therefore, UV irradiation is expected to improve bonding efficiencies for denture base resin.

UV irradiation is believed to clean the polymer surface by removing the organic contamination and to change the molecular structure of the shallow-surface region12-15. Therefore, during the UV exposure, the polyamide undergoes degradation of the polymer chain13,16,17. As a result, the UV-irradiated polyamide surface region can easily be dissolved or swelled by an organic solvent. The application of UV irradiation on polyamide is expected to be an effective surface treatment for improving the bonding with a chemical-cured resin. Moreover, the purpose of combining UV irradiation and sandblasting treatment is to change the surface morphology and take advantage of the synergistic effect between the polyamide and chemical-cured resin to improve the bonding. However, the UV irradiation conditions and effect of combining UV irradiation and sandblasting treatment for polyamide bonding have not been elucidated.

The purpose of the present study was to investigate the effects of UV irradiation and sandblasting treatment on polyamide to improve the shear bond strength using commercial polyamides. The null hypothesis of this in vitro study was that UV irradiation and sandblasting treatment would not influence the bonding between the polyamide and the chemical-cured resin, regardless the type of the commercial polyamide.

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MATERIALS AND METHODS

Specimen preparation

The materials used in the present study are listed in Table 1; three commercial polyamide products and one commercial heat-polymerized acrylic resin product were selected. A bar-shaped specimen (75.0 mm long, 11.0 mm wide, and 3.0 mm thick) for the polyamides was prepared by respective manufacturer. A rod-shaped specimen (10 mm in diameter and 70 mm long) for the acrylic resin was prepared according a conventional wet heat curing method in which the temperatures were 70°C for 90 min and 100°C for 30 min. The rectangular-shaped (10 mm long, 11 mm wide, and 3 mm thick) and disk-shaped (10 mm diameter and 3 mm thick) specimens were obtained by cutting individual resin specimen. Three hundred sixty specimens for the shear bond test, surface roughness measurement, and Fourier transform infrared spectroscopy (FTIR) observation, were embedded in an acrylic resin tube (16 mm inner diameter and 10 mm thick) with a chemical-cured resin (Palapress Vario, Heraeus Kulzer GmbH, Hanau, Germany). After polymerization, the surfaces of all specimens were polished with #800 to #1,200 SiC papers using a polishing machine (Dialap ML150P, Maruto Instrument Co., Tokyo, Japan). After ultrasonic cleaning using deionized water for 15 min, all the specimens were stored in deionized water for 7 days at 37°C.

Surface treatment

The specimens were divided into the following nine groups according to the surface pretreatment: 1) non-treated (NT group); 2) UV-irradiated for exposure periods of 30 s (UV-30 group); 3) UV-irradiated for 60 s (UV-60 group); 4) UV-irradiated for 90 s (UV-90 group); 5) UV-irradiated for 120 s (UV-120 group); 6) UV irradiated for 180 s (UV-180 group); 7) sandblasted (SB group); 8) SB and UV-irradiated (SBUV) for 60 s (SBUV-60 group); and 9) SBUV for 180 s (SBUV-180 group).

The conditions for sandblasting were as follows: 50-μm Al2O3 particles for 15 s at 0.25 MPa from a distance of 15 mm using a pencil type sandblaster (Pencil Jet II, Yoshida, Tokyo, Japan). The specimens were then ultrasonically cleaned for 5 min with deionized water.

UV irradiation was performed in an ultraviolet sterilizing oven (DM5, Daishin Kogyo Co., Osaka, Japan) equipped with a diamond pick-up (tip radius: 2 μm, load 0.7 mN). For the surface roughness measurements, the tracing length was 4 mm, the stylus speed was 0.3 mm/s, and the cut-off was 0.8 mm. The mean surface roughness (Ra) values of individual specimen were measured before and after surface treatment. The surface of the specimen was divided into two parts and one half was covered with aluminum foil. The exposed surface was subjected to the above-mentioned UV irradiation for 30 s, and the Ra was determined again. The UV irradiation and roughness measurements were repeated so that the total UV irradiation time period was 180 s. The remaining half surface was exposed and targeted for sandblasting, then the Ra was determined. After that the sandblasted surface was UV-irradiated for 60 and 180 s, the Ra was determined again.

Surface observation

The specimen surfaces before and after 60-s UV irradiation, sandblasting treatment, and sandblasting and 60-s UV irradiation were prepared by carbon-coating them. They were then observed using a digital CCD microscope (×1000, VHX1000, KEYENCE Corp., Osaka, Japan).

Surface roughness

Six specimens of each resin were selected. Their surface roughness was determined with a profilometer (Surfcomflex-50, Tokyo Seimitsu Co., Tokyo, Japan) equipped with a diamond pick-up (tip radius: 2 μm, load 0.7 mN). For the surface roughness measurements, the tracing length was 4 mm, the stylus speed was 0.3 mm/s, and the cut-off was 0.8 mm. The mean surface roughness (Ra) values of individual specimen were measured before and after surface treatment. The surface of the specimen was divided into two parts and one half was covered with aluminum foil. The exposed surface was subjected to the above-mentioned UV irradiation for 30 s, and the Ra was determined again. The UV irradiation and roughness measurements were repeated so that the total UV irradiation time period was 180 s. The remaining half surface was exposed and targeted for sandblasting, then the Ra was determined. After that the sandblasted surface was UV-irradiated for 60 and 180 s, the Ra was determined again.

Wetting tension

The changes in the wettability of the surfaces before and after treatment were analyzed using wetting tension measurements according to JIS K 6768 (1999) Bar-shaped specimens (75.0 mm long, 10.0 mm wide, and 2.4 mm thick) for the polyamides and PMMA were prepared using the specimens for wetting tension observation. The surfaces of all the specimens were polished with #1,200 SiC papers using a polishing machine. The specimen

Table 1 Materials used in the present study

| Material                        | Product name | Code | Lot No.  | Manufacturer                        |
|---------------------------------|--------------|------|----------|-------------------------------------|
| Polyamide                       | Bioplast     | BP   | 0901050  | High Dental Japan Co., Osaka, Japan |
|                                 | Biotone      | BT   | 1201117  | High Dental Japan Co., Osaka, Japan |
|                                 | Valplast     | VP   | 130112   | KK. Unival, Tokyo, Japan            |
| Heat-polymerized acrylic resin  | Acron        | PMMA | Powder: 230651, Liquid: 0910051 | GC Corp., Tokyo, Japan |
The wetting tension was evaluated within one minute and 60 and 180 s, the wetting tension was determined again. After that, the sandblasted surface was UV-irradiated for sandblasting, then the wetting tension was determined. The remaining half surface was exposed and targeted for the total UV irradiation time period was 180 s. The wetting tension measurements were repeated so that the tension was determined again. The UV irradiation and foil. The exposed surface was subjected to the above-mentioned UV irradiation for 30 s, and the wetting tension was determined again. The UV irradiation and wetting tension measurements were repeated so that the total UV irradiation time period was 180 s. The remaining half surface was exposed and targeted for sandblasting, then the wetting tension was determined. After that, the sandblasted surface was UV-irradiated for 60 and 180 s, the wetting tension was determined again. The wetting tension was evaluated within one minute after UV irradiation; three specimens of each condition were examined.

**Shear bond strength**

Immediately after surface treatment, the bonding area (4 mm in diameter) was defined using a polypropylene tape (50 μm thick; Toumeibisyoku, Sumitomo 3M Ltd., Tokyo, Japan) placed on the surface before build-up. A stainless steel ring (6 mm inner diameter and 2 mm thick) was placed on the polypropylene tape, and then another chemical-cured resin (Unifast Trad, Ivory, GC Corp., Tokyo, Japan) was built up within the ring using the brush-on technique. After polymerization, the specimens were then stored in deionized water at 37°C for 24 h in an incubator (CI-310, Advantec Toyo Kaisha, Tokyo, Japan) before the shear bond test. Eight specimens for each condition were prepared.

Each specimen was then inserted into a test jig, which ensured that the force applied was parallel to the bonding interface. The specimens were subjected to a shear bond test using a universal testing machine (AG-X, Shimadzu Corp., Kyoto, Japan) at a crosshead speed of 1.0 mm/min. The maximum load at failure was recorded. The shear bond strength (MPa) was determined as the maximum load divided by the bonding area (mm²).

All the fractured surfaces after the shear bond test were observed using a stereoscope (×30, SZ-Tr-1, Olympus Co., Tokyo, Japan) to determine the fracture mode. The fracture modes of the specimens were classified into three categories as follows: 1) interfacial fracture (between the denture base resin and chemical-cured resin), 2) cohesive fracture (denture base resin), and 3) mixed fracture (combination of interfacial fracture and cohesive fracture of the chemical-cured resin or denture base resin).

**FTIR observation**

The molecular structural changes of the UV-irradiated surface were observed with FTIR. The surfaces before (without UV irradiation) and after 180-s, and 48-h UV irradiation were observed with an FTIR spectrophotometer (FTIR8300, Shimadzu Co., Kyoto, Japan) equipped with an attenuated total reflectance (ATR) accessory (DRUraSampIIIR, ASI Technologies, Danbury, CT, USA). A total of 32 scans, whose spectral range was 4,000–600 cm⁻¹ with a resolution of 4 cm⁻¹, were recorded within 1 min after the irradiation and analyzed using software (IR-Mentor Pro, Bio-Rad Japan, Tokyo, Japan) to assign the functional groups. Three specimens of individual condition were investigated.

**Statistical analysis**

The effects of surface treatments on the Ra values were analyzed with two-way ANOVA selecting denture base resin and surface treatment as main factors and Tukey’s multiple comparisons test using an open-source statistical package (EZR, version 3.01) (α=0.05). Due to relatively highly deviated results, the shear bond strength of each denture base resin was analyzed with the Kruskal-Wallis non-parametric one-way ANOVA and also with the Holm’s multiple comparisons test using open-source statistical software (α=0.05).

**RESULTS**

**Surface observation**

The original surface before treatment showed scratches due to the SiC paper. Visible changes could not be found on the surface after UV irradiation (Fig. 1). The surfaces of the SB and SBUV groups appeared dull with no obvious scratches. Moreover, no visible differences could be observed between the SB and SBUV groups regardless of the type of denture base resin.

**Surface roughness**

The Ra values of the denture base resins are summarized in Table 2. The two-way ANOVA revealed that the Ra was significantly different among the denture base resin (p<0.001), surface treatment (p<0.001), and the interaction between denture base resin and surface treatment (p<0.001). The Ra of PMMA was significantly different among the surface treatments, but those of polyamide were not. The Ra values of the SB, SBUV-60, and SBUV-180 groups of PMMA were significantly greater than those of the other groups (p<0.05). The Ras of NT groups were not significant among denture base resins. The Ra after UV-180 of BT was significantly smaller than those of BP and VP (p<0.05), but not significantly different from that of PMMA. The Ras after SB and SBUV of PMMA were significantly greater than those of polyamides (p<0.05).

**Wetting tension**

The wetting tension results are summarized in Table 3.
Fig. 1 CCD microscope images of the resins after surface treatments.

Table 2  Mean values and standard deviations of the surface roughness (μm) before and after surface treatments

| Resin | Surface treatment |
|-------|------------------|
|       | NT   | UV-30 | UV-60 | UV-90 | UV-120 | UV-180 | SB   | SBUV-60 | SBUV-180 |
| BP    | 0.28 (0.04) | 0.27 (0.07) | 0.26 (0.06) | 0.29 (0.05) | 0.28 (0.06) | 0.26 (0.04) | 0.27 (0.06) | 0.27 (0.02) |
| BT    | 0.22 (0.03) | 0.23 (0.03) | 0.24 (0.04) | 0.23 (0.04) | 0.20 (0.03) | 0.23 (0.04) | 0.26 (0.03) | 0.26 (0.04) |
| VP    | 0.30 (0.02) | 0.30 (0.03) | 0.29 (0.03) | 0.29 (0.02) | 0.30 (0.03) | 0.29 (0.03) | 0.27 (0.04) | 0.27 (0.03) |
| PMMA  | 0.25 (0.03) | 0.24 (0.03) | 0.23 (0.05) | 0.23 (0.05) | 0.23 (0.05) | 0.24 (0.03) | 0.36 (0.03) | 0.33 (0.08) |

( ): S.D.
The values with different superscript capital letters in the same denture base resin and different superscript small letter in the same surface treatment were significantly different (p<0.05).

Table 3  Changes in wetting tension (mN/m) of the polyamides and PMMA before and after surface treatments

| Resin | Surface treatment |
|-------|------------------|
|       | NT   | UV-30 | UV-60 | UV-90 | UV-120 | UV-180 | SB   | SBUV-60 | SBUV-180 |
| BP    | 41, 41, 41 | 42, 42, 42 | 42, 42, 42 | 42, 42, 42 | 42, 42, 42 | 42, 42, 42 | 73, 73, 73 | 73, 73, 73 |
| BT    | 41, 41, 41 | 42, 42, 42 | 42, 42, 42 | 42, 42, 42 | 42, 42, 42 | 43, 42, 42 | 73, 73, 73 | 73, 73, 73 |
| VP    | 42, 42, 42 | 42, 42, 43 | 42, 42, 42 | 42, 42, 42 | 42, 42, 42 | 42, 42, 43 | 73, 73, 73 | 73, 73, 73 |
| PMMA  | 41, 41, 41 | 42, 42, 42 | 42, 42, 42 | 42, 42, 42 | 42, 42, 42 | 42, 42, 42 | 73, 73, 73 | 73, 73, 73 |

The wetting tensions of NT and UV groups ranged from 41 to 43 mN/m. The wetting tensions of SB and SBUV groups were 73 mN/m regardless surface treatment and denture base resin, which was greater than those of NT and UV groups.

**Shear bond strength**
The shear bond strengths are summarized in Fig. 2;
Fig. 2 Shear bond strengths for all groups displayed in a box and whisker plot. The white circle (O) is an outlier. The horizontal lines in the box represent the medians, the boxes represent the 50% quartile, and the whiskers the 25% quartiles. Bars with the same letter were not significantly different ($p > 0.05$).

those of BP, BT, VP, and PMMA ranged from 4.1 to 17.8 MPa, 4.9 to 18.3 MPa, 5.7 to 16.6 MPa, and 28.3 to 37.5 MPa, respectively. The one-way ANOVA revealed that the shear bond strengths were significantly different, regardless types of denture base resins ($p < 0.001$). The shear bond strengths of NT group of polyamides, from 4.1 to 5.7 MPa were smaller than that of PMMA 28.3 MPa. The shear bond strengths of polyamides generally increased after UV irradiation, but still smaller than that of PMMA. The shear bond strengths of SBUV groups of polyamides, from 15.2 to 18.3 MPa were significantly greater than those of NT group ($p < 0.05$), but still smaller than that of PMMA.

Concerning BP, the shear bond strengths of the UV-120, UV-180, SB, SBUV-60, and SBUV-180 groups were significantly greater than that of the NT group ($p < 0.05$); the shear bond strengths of the UV irradiation groups, except for the UV-30 group, were not significantly different from that of SB group; the shear bond strengths of the SBUV-60 and SBUV-180 groups were significantly greater than those of the other groups ($p < 0.05$). The shear bond strength of the SBUV-60 group was not significantly different from that of SBUV-180 group. Concerning BT, the shear bond strengths of the UV-60, UV-90, UV-120, SB, SBUV-60, and SBUV-180 groups were significantly greater than that of the NT group ($p < 0.05$). The shear bond strengths for the UV-120, and UV-180 groups were not significantly different from that of the SB group; that of the SBUV-60 group was not significantly different from those of the UV-120, UV-180, SB, and SBUV-180 groups. Concerning VP, the shear bond strengths of the SB, SBUV-60, and SBUV-180 groups were significantly greater than that of the NT group ($p < 0.05$), whereas those of all the UV irradiation groups were not. The shear bond strengths of all the UV irradiation groups were not significantly different from that of the SB group; those of the SBUV-60 and SBUV-180 groups were significantly greater than that of the NT group ($p < 0.05$); the shear bond strengths of all the UV irradiation groups were not significantly different from that of the SB group. The shear bond strength of SBUV-180 group was significantly greater than that of SBUV-60 group ($p < 0.05$). The shear bond strengths of all
the polyamides after SBUV treatment were significantly greater than those of the NT groups \((p<0.05)\). The changes of the shear bond strengths between the UV-60 and UV-180 groups were similar to those between the SBUV-60 and SBUV-180 groups regardless types of denture base resin.

Fracture modes
The fracture modes are classified in Table 4. Only interfacial fracture was observed for BP, BT, and VP. Mixed fracture was mainly observed for PMMA; cohesive fracture of the PMMA was observed in the UV-90, UV-120, UV-180, SBUV-60, and SBUV-180 groups, while the cohesive fracture of the chemical-cured resin was observed in the NT, UV-30, UV-60, and SB groups.

FTIR observation
Representative FTIR spectra before and after UV irradiation are shown in Fig. 3. Obvious differences in the FTIR spectra by UV irradiation could not be detected in the 180-s time period. After 48-h UV irradiation, shifts and intensity changes of several peaks were detected. Regarding BP, increased peak intensities of 1720 and 910 cm\(^{-1}\) were considered to be C=O and O–H, respectively. For BT, the increased peak intensity at 1720 cm\(^{-1}\) and the decreased peak intensity at 1050 cm\(^{-1}\) were considered to be C=O and C-O, respectively. For VP, the increased peak intensity at 1720 cm\(^{-1}\) was determined to be C=O. Regarding PMMA, the peak at 1730 cm\(^{-1}\) of C=O became broad. The peaks of C-H at 1490 and 1435 cm\(^{-1}\) and those at 990 and 960 cm\(^{-1}\) combined into one

Table 4  Classification of fracture mode of flexible denture resin before and after surface treatments

| Resin | Fracture mode | Irradiation period |
|-------|---------------|-------------------|
|       |               | NT | UV-30 | UV-60 | UV-90 | UV-120 | UV-180 | SB | SBUV-60 | SBUV-180 |
| BP    | 1)            | 8  | 8    | 8    | 8    | 8     | 8     | 8  | 8       | 8         |
|       | 2)            | 0  | 0    | 0    | 0    | 0     | 0     | 0  | 0       | 0         |
|       | 3)            | 0  | 0    | 0    | 0    | 0     | 0     | 0  | 0       | 0         |
| BT    | 1)            | 8  | 8    | 8    | 8    | 8     | 8     | 8  | 8       | 8         |
|       | 2)            | 0  | 0    | 0    | 0    | 0     | 0     | 0  | 0       | 0         |
|       | 3)            | 0  | 0    | 0    | 0    | 0     | 0     | 0  | 0       | 0         |
| VP    | 1)            | 8  | 8    | 8    | 8    | 8     | 8     | 8  | 8       | 8         |
|       | 2)            | 0  | 0    | 0    | 0    | 0     | 0     | 0  | 0       | 0         |
|       | 3)            | 0  | 0    | 0    | 0    | 0     | 0     | 0  | 0       | 0         |
| PMMA  | 1)            | 0  | 0    | 0    | 0    | 0     | 0     | 0  | 0       | 0         |
|       | 2)            | 8(0)| 8(0)| 8(0)| 6(1)| 6(1)| 5(1)| 8(0)| 5(1)| 3(1) |
|       | 3)            | 0  | 0    | 0    | 0    | 0     | 0     | 0  | 0       | 0         |

1) interfacial fracture, 2) cohesive fracture; denture base resin, 3) mixed fracture; interfacial fracture and cohesive fracture of the chemical-cured resin; number in parentheses indicates mixed fracture of interfacial fracture and cohesive fracture of denture base resin.

Fig. 3  Change of ATR-FTIR spectrum after UV irradiation.
Lines from the top to bottom are 0-s, 180-s, and 48-h UV irradiation.
DISCUSSION

The null hypothesis of this in vitro study that UV irradiation and sandblasting treatment would not influence the bonding between the polyamide and the chemical-cured resin, regardless of the type of commercial polyamide, was partially rejected.

Three types of commercial polyamides used for flexible dentures were tested for bonding with the chemical-cured resin. The structure of VP was reported to be polyamide-12\(^7\); the main structure of BP and BT was polyamide polymer, although detailed structures were not clearly identified. The spectra of BP, BT, and VP showed similar peak patterns except for a low wave number region. The physical and mechanical properties of polyamide depend on the molecule structure\(^8\). The effects of surface treatments varied among the polyamides examined, probably due to their mechanical properties, which will be evaluated in a future study. The changes in the FTIR spectra of the polyamides after 48-h UV irradiation were mainly identified as C=O, C–O, and O–H peaks, which indicated the degradation of the alkylene unit in the side chain and creation of oxidized materials\(^16\,17\). Therefore, the main structure of the polyamides was not strongly influenced after longer irradiation, which will not degrade the mechanical properties. As a result, the observed fracture mode of the polyamides was interfacial. The changes in the FTIR spectrum of the PMMA after 48-h UV irradiation was mainly the presence of C=O, C–O, and C–H peaks, which indicated the degradation of the ester unit in the side chain and creation of oxidized materials\(^16\,17\).

The sandblasting treatment was expected to increase the surface roughness and surface energy. However, the surface roughness of the polyamide did not change after the sandblasting treatment, which coincided with the results of a previous study\(^7\). Compared to PMMA, polyamide polymer is very tough\(^3\,5\,20\), but the polishability is poor\(^6\). As a result, PMMA displayed a rough surface after the sandblasting treatment, while the polyamide did not. The UV irradiation periods of SBUV groups were selected 60 and 180 s, because the shear bond strength generally increased after 60-s irradiation. According to the CCD images of the polyamide surfaces, the surface morphologies before and after sandblasting treatment were different, but the surface roughness values were not.

In the present study, the wetting tension value of the PMMA after polishing was greater than that of PMMA in a previous study (38 mN/m)\(^10\). This discrepancy was due to differences in surface roughness. The wetting tension after UV irradiation slightly increased, which was similar to the previous study. The reason the wetting tension of polymer surface increased might be attributed to the removal of the organic contamination by UV irradiation\(^12\). The wetting tensions of the resins examined dramatically increased after sandblasting treatment. The retention capacity of the aqueous solution may have increased due to changes in the surface morphology\(^21,22\). As a result, the wetting tensions of the denture base resins after the sandblasting treatment indicated high wetting tension values.

The shear bond strength between chemical-cured resin and polyamides except for VP has not been reported. The shear bond strengths of VP before surface treatment were previously reported to be approximately 3 to 5 MPa\(^5\,7\), which was similar to the present results. The shear bond strength of VP after the sandblasting treatment was reported to be 3.6 MPa, which was not significantly greater than that of the control group (without surface treatment) in the previous study\(^6\). However, the shear bond strengths of the polyamides significantly increased after sandblasting. The reasons for these discrepancies might be the blasting conditions, such as the distance and blasting time\(^6\). The shear bond strength of the polyamides slightly increased after the longer irradiation in the present study. Moreover, the shear bond strengths of the UV-irradiated polyamides were not significantly different from those of the sandblasting-treated polyamides. Improvements in the bond strengths of the polyamides by UV irradiation were influenced by the amount of UV-irradiated energy; a longer period of UV irradiation would proceed more surface modification.

The shear bond strength of the chemical-cured resin to VP after the combined tribochemical silica coating and 4-META/HEMA-TBB application was reported 16.5 MPa\(^6\), which was comparable to the bond strength obtained by SBUV, regardless of the type of polyamide. The combining sandblasting treatment and UV irradiation was more effective on the shear bond strength, probably because of the interaction between the mechanical interlocking increased by sandblasting and the molecular structural change by UV irradiation.

Regarding PMMA, the shear bond strengths after UV irradiation, except for 180 s, did not significantly increase, compared to the NT group. A previous study reported that the bond strength of the fiber-reinforced composite post using PMMA increased after UV irradiation, regardless of the irradiation period\(^13\). The present study examined the bond strength between PMMA and chemical-cured MMA resin, but the previous study examined that between PMMA and composite resin. PMMA is easily dissolved by MMA compared to composite resin. As a result, the shear bond strength of the NT group was sufficient. Therefore, the UV irradiation did not dramatically increase. UV irradiation potentially degrades the superficial area of PMMA. As a result, the UV-90, UV-120, UV-180, SBUV-60, and SBUV-180 groups showed cohesive fracture of the PMMA.

This in vitro study evaluated bonding after 24-h storage in water. The bonding durability between the surface-treated polyamide and the chemical-cured resin has not been examined. Moreover, the UV irradiation
mechanisms improving the shear bond strength have not been clearly elucidated. Future research is necessary to evaluate the long-term stability of the bond strength between UV-irradiated polyamide and chemical-cured resin and the improved mechanisms caused by UV irradiation.

CONCLUSIONS

Within the limitations of the present study, the following conclusions can be made:

1. UV irradiation significantly increased the shear bond strength of polyamides, except for Valplast.
2. Sandblasting treatments significantly increased the shear bond strength of all the polyamides.
3. The combining sandblasting treatment and UV irradiation significantly increased the shear bond strength of all the polyamides. This combined treatment was the most effective at improving the shear bond strength between polyamide and chemical-cured resin.

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REFERENCES

1) Yavuz T, Aykent F. Temporary flexible removable partial denture: a clinical report. Clin Dent Res 2012; 36: 41-44.
2) Ito M, Wee AG, Miyamoto T, Kawai Y. The combination of a nylon and traditional partial removable dental prosthesis for improved esthetics: a clinical report. J Prosthodont Dent 2013; 109: 5-8.
3) Takahashi Y, Hamanaka I, Shimizu H. Effect of thermal shock on mechanical properties of injection-molded thermoplastic denture base resins. Acta Odontol Scand 2012; 70: 297-302.
4) Abuzar MA, Bellur S, Duong N, Kim BB, Lu P, Palfreyman N, Surendran D, Tran VT. Evaluating surface roughness of a polyamide denture base material in comparison with poly (methyl methacrylate). J Oral Sci 2010; 52: 577-581.
5) Takahashi H, Kawata E, Tamaki Y, Teraoka F, Hosoi T, Yoshida T. Basic properties of thermoplastic resins for denture base material referred to "non clasp denture". J Dent Mater 2009; 28: 161-167.
6) Hamanaka I, Shimizu H, Takahashi Y. Shear bond strength of an autopolymerizing repair resin to injection-molded thermoplastic denture base resins. Acta Odontol Scand 2013; 71: 1250-1254.
7) Katsumata Y, Hojo S, Hamano N, Watanabe T, Yamaguchi H, Okada S, Teranaka T, Ino S. Bonding strength of autopolymerizing resin to nylon denture base polymer. Dent Mater J 2009; 28: 409-418.
8) Krevelen VDW, Nijenhuis TK. Properties of polymers. 4th ed. Amsterdam: Elsevier; 2009. p. 925-929.
9) Miura E, Takayama Y, Mizuno Y, Abe M, Kawai Y, Ohkubo C. Effect of surface treatment agents on bond strength of auto-polymerized acrylic resin to poly(ethylene terephthalate). Int J Dent Res 2010; 10: 57-62.
10) Lovaga-Rendon PG, Takahashi H, Iwasaki N, Reza F. Effect of ultraviolet light irradiation on bonding of experimental composite resin artificial teeth. Dent Mater J 2007; 26: 805-813.
11) Asakawa Y, Takahashi H, Iwasaki N, Kobayashi M. Effect of ultraviolet light irradiation period on bond strength between fiber-reinforced composite post and core build-up composite resin. Dent Mater J 2014; 33: 133-140.
12) Teare DOH, Ton C, Bradley RH. Surface characterization and ageing of ultraviolet-ozone-treated polymers using atomic force microscopy and x-ray photoelectron spectroscopy. Surf Interface Anal 2000; 29: 276-283.
13) Mai YW, Head DR, Cotterell B, Roberts BW. Mechanical properties of nylon 6 subjected to photodegradation. J Mater Sci 1980; 15: 3057-3065.
14) Kazmarek H, Kamińska A, Herk VA. Photooxidative degradation of poly(alkyl methacrylate). Eur Polym J 2000; 36: 767-777.
15) Çaykaraa T, Güvenb O. UV degradation of poly(methyl methacrylate) and its vinyltriethoxysilane containing copolymers. Polym Degradat Stabil 1999; 65: 225-229.
16) Cerruti P, Lavorgna M, Carfagna C, Nicolais L. Comparison of photo-oxidative degradation of polyamide 6,6 films stabilized with HALS and CuCl2+KI mixtures. Polym 2005; 46: 4571-4583.
17) Cerruti P, Carfagna C. Thermal-oxidative degradation of polyamide 6,6 containing metal salts. Polym Degradat Stabil 2010; 95: 2405-2412.
18) JIS K 6768: 1999, Plastics-Film and sheeting-Determination of wetting tension.
19) Kanda Y. Investigation of the freely available easy-to-use software ‘EZR’ for medical statistics. Bone Marrow Transplants 2013; 48: 452-458.
20) Takabayashi Y. Characteristics of denture thermoplastic resins for non-metal clasp dentures. Dent Mater J 2010; 29: 553-561.
21) Spori DM, Drobek T, Zürcher S, Ochsner M, Sprecher C, Mühlebach A, Spencer ND. Beyond the lotus effect: roughness influences on wetting over a wide surface-energy range. Langmuir 2008; 24: 5411-5417.
22) Sharma S, Pakhan AJ, Thombare RU, Godbole SR, Gupta VK, Gupta N. Effect of surface texture of intaglio surface on denture retention—An in vivo analysis—. Chhattisgarh J Health Sci 2013; 1: 35-39.