Retentive strength of orthodontic brackets bonded to 3D-printed vs. milled materials after surface treatment and aging

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ABSTRACT

Objective: The purpose of this study to evaluate the shear bond strength (SBS) of orthodontic brackets bonded to 3D-printed material after various surface treatments and aging in comparison to CAD-CAM polymethyl methacrylate (PMMA) milled material.

Methods: Eighty cylindrical specimens were 3D-printed and divided into 4 subgroups (n=20 each) according to the surface treatment and ageing procedure. Group A: sandblasted with 50 µm aluminum oxide particles (SA) and aging; Group B: sandblasted with 30 µm silica-coated alumina particles (CO) and aging; Group C: SA without aging; Group D: CO without aging. For the control group, 20 CAD-CAM PMMA milled cylindrical specimens were sandblasted (SA) and aged. SBS was tested using a universal testing machine (0.25 mm/min), inspected at 2.5X magnification for failure mode classification and statistically analyzed (P = .05).

Results: The retention obtained with the 3D-printed material (groups A-D) was higher than that obtained with PMMA (Control group) however, no significant difference was found between the study and control groups except for group C (SA and no thermocycling) which was significantly higher than the control group (PMMA-SA and thermocycling) (P = .037). Study groups A-D predominantly exhibited cohesive specimen mode, meaning fracture of the specimen.

Conclusion: Orthodontic brackets bonded to 3D-printed material exhibited acceptable bonding strength. However, 3D-printed materials were more prone to cohesive failure, which may result in crown fracture.

Keywords: Prosthodontics, Retention, Bracket, Shear bond strength

Introduction

Adults make up approximately 20% of the average orthodontist's patient load and their primary motivation is to improve smile aesthetics and function.[1] Orthodontic treatment is likely to be a part of a multidisciplinary treatment approach, teeth often have temporary crowns to help maintain proper function and aesthetics. In these cases, definitive restorations prior to orthodontic treatment are not recommended because of changes in occlusal relationships and the risk of jeopardizing the surface.

Although, provisional crowns are a better option than definite restoration, a clinician is likely to face difficulties bonding orthodontic brackets to them. Placing metal bands on teeth is also an option, although this is much less esthetically acceptable compared to conventional brackets; especially on anterior teeth. Bands are also less hygienic and accumulate more plaque, which makes them a less attractive alternative.[2]

Regardless of the wide variety of materials used to fabricate temporary crowns, polymethyl methacrylate (PMMA) is the most popular choice. Milled PMMA crowns are highly cross-linked, prefabricated polymethyl methacrylate resin blocks used with the CAD-CAM technique. Furthermore, they have improved mechanical and esthetic properties, which make them more suitable for use in longer clinical applications.[3]

3D-printing has become a trend in dentistry and is a manufacturing approach that builds objects one layer at a time; adding multiple layers to form an object. CAD-CAM technology makes it easier to recreate any anatomical shape, which could be challenging if conventional methods are used. Moreover, it was also found to be more accurate and less time-consuming than milling. In addition, 3D printing gives the clinician freedom to use several materials when fabricating crowns.[4,5] 3D printable composites are used to fabricate temporary crowns that which have a comparable elastic modulus as conventional crown and bridge jet acrylic, but lower peak stress than jet acrylic self-cured resin.[5,6] A composite filling can be repaired using low pressure depositing systems. Hannig et al. reported best bond strength results using sandblasting with a Co-Jet system.[7]

Orthodontic treatment requires a strong connection between the brackets and the teeth or crowns. A weak bond will lead to a high failure rate, with adverse consequences on the cost and efficiency of the treatment, which is likely to affect the patients' overall comfort and satisfaction. Surface preparation such as etching, sandblasting, or roughening with a diamond bur are used to increase the bonding strength between a bracket and crown's surface.[8] Newman et al. investigated the combinations of different types of bonding systems, orthodontic brackets and with different methods of surface treatment.[9] However, the shear bond strength (SBS) of orthodontic brackets to 3D printed crowns with various surface treatments and artificial aging has not been tested yet.

The aim of this study was to test the shear bond strength (SBS) of orthodontic brackets bonded to 3D-printed provisional crowns using composite cement with various surface treatments and artificial aging in comparison to CAD-CAM PMMA milled provisional crowns. Our hypothesis was that no significant differences would be found in SBS between the two provisional crowns, nor between the various surface treatments.

Materials and Methods

In the control group, 20 PMMA (Ceramill A-temp, AmannGirrbach, Austria) cylindrical (10x8mm) specimens were milled in a CAD-CAM milling machine (Motion2, AmannGirrbach, Austria). In the study group, 80 cylindrical (10x8mm) specimens were made of a commercial 3D printing material (C&B MFH, NextDent, The Netherlands), using CAD software (Exocad Plodiv v2.4, Exocad, Germany) and a 3D printer (NextDent 5100, NextDent, The Netherlands). Specimens were printed in 0-degree angle, with printing layer thicknees of 50 µm where supports were placed on the opposite side of the testing surface. For all printed specimens supports were set to a density of 1mm, and a point size of 500 µm.

Specimens, in the control and study groups, were examined visually for cracks and irregularities. Four specimens in the study group were re-printed.

All specimens were cleaned in an ultrasonic bath (SD-120H, Mujigae Co., Seoul, Korea) containing 96% ethanol for 3 mintues, and soaked in clean 96% ethanol for 2 mintues, dried. Then lightcured for 30 minutes at 60° C (Form Cure, Formlabs Inc., MA, USA) according to manufacturer's protocol.

The chemical composition of the used materials are reported in Table 1.

The control group (20):

The specimens were sandblasted with 50 µm aluminum oxide (Zest Dental Solutions, CA, USA) (SA). 37% phosphoric acid was applied for 20 seconds on every specimen in order to clean the samples' surfaces including possible oil or debris which are possible from the CAM and cutting procedure. Then thoroughly washed for 10 seconds with water and dried. Transbond^{TM} XT Primer (3M Unitek, Monrovia, CA, USA) was applied to the dried surface and light cured for 20 seconds. Then, stainless steel (022-in Victory Series, 3M Unitek) central incisor brackets were bonded on each specimen, using light cure bis-acrylic resin composite adhesive cement (Transbond XT, 3M Unitek).

Each bracket was positioned at the center of the disc using a bracket positioning gauge (3M Unitek), and all excess composite material was removed. The specimens were light cured with a LED curing lamp (Deep Cure-S, 3M), for 20 seconds. The procedures were performed by the same clinician. After bonding, the specimens were stored at 37 ◦C under 100% humidity for 1 month, followed by thermocycling of 1000 cycles between 5° and 55° C with 30 seconds dwell time.[10,11]

The study group (n=80):

The specimens were randomly assigned to two treatment groups (2 × 40), according to the surface treatment, before bonding the brackets: Sandblasting with 50 µm Al2O3 (SA) or sandblasting with 30 µm silica-coated-alumina particles (CoJet, 3M ESPE, Seefeld, Germany) (CO). After the surface treatment with the CO, silane coupling agent (Ultradent silane, USA) was applied with a brush, left undisturbed for 60 seconds and then airdried. The sandblasting of all the specimens was done by single operator for 10 seconds at 1 bar, at a distance of 10 mm. Then, the brackets were bonded, as was described in the control group. After bonding, all specimens were stored at 37 ◦C under 100% humidity for 1 month Afterwards, the specimens from each surface treatment group were divided into two subgroups (2 × 20) based on whether or not they were subjected to aging conditions (thermocycling for 1000 cycles between 5° and 55° C, with 30-second dwell time). Therefore, there were four study groups: Group A: sandblasting with 50 µm aluminum oxide particles (SA) and aging; Group B: sandblasting with 30 µm silica-coated-alumina particles (CO) and aging; Group C: SA without aging; Group D: CO without aging (Table 1). The experiment design is presented in Figure 1.

Next, all bracket-crown assemblies were subjected to dislodgment forces using a universal testing machine (Instron, Norwood, MA). Each specimen was placed in a custom machined device and a knifed edge ram was attached (Figure 2).

The crosshead speed was set at 0.025 mm/minute until failure **and** values were recorded in Newtons. The base surface area of the brackets was calculated by measuring the length and width with a digital caliper (Digimatic, Mitutoyo Co.,Tokyo, Japan) and computing the area ; bracket base area was 11.9 mm^2.[12,13] The shear bond strength value (MPa) was calculated by dividing the force (N) at dislodgment with the total surface area of each prepared sample.

The surfaces of the debonded specimens were examined under 2.5 X magnification to determine the type of failure (Table 2). A scanning electron microscope (SEM) of the study groups was used to inspect a sample of the study group specimen's surface before and after the surface treatments.

Statistical analysis

One-Sample Kolmogorov-Smirnov Test confirmed that the data follows normal distribution. Shear bond strength was evaluated using two-way analysis of variance (ANOVA); The dependent variable was SBS (MPa). Surface treatment (n = 2) and thermocycling (n = 2) were the independent variables. One way ANOVA was used to analyze the difference between study and control groups. Post hoc Dunnett t-test was applied for multiple comparisons. The level of significance was set to α=0.05.

Results

One-way ANOVA analysis showed significant statistical difference between control group and study groups (P = .043), and post hoc t-test was performed between each study group and the control (Table 3). The retentive strength (mean, SD) of the various materials, surface treatments and aging procedures combinations, are presented in Table 3.

Box plots of the minimum, maximum, interquartile range, medians, and the outliers for each group are presented in Figure 3. Two-way ANOVA for the independent variables (thermocycling, type of sandblasting and the combination) found no effect on the SBS of the study groups (Table 4).

The retention obtained with the 3D-printed material (groups A-D) was higher than that obtained with PMMA (Control group) however, no significant difference was found between the study and control groups except for group C (SA and no thermocycling) which was significantly higher than the control group (PMMA-SA and thermocycling) (P = .037).

Examination under magnification of the failure mode revealed complete adhesive cement-bracket failure for the control group (PMMA), meaning that the cement was principally on the specimen surface (classification 2). Scanning electron microscope (SEM) of specimen's surface in the control group prior to surface treatment are shown in Figures 4, a and b.

In the 3D-printed study groups, SEM images of specimen's surface prior to surface treatment are shown in Figures 4, c and d, and images of SA and CO surface treatments prior to bracket bonding groups are shown in Figures 5, a-d.

Study groups A-D predominantly exhibited cohesive specimen mode, meaning fracture of the specimen (classification 5), SEM images of surface of the fractured specimen are shown in Figure 6, a and b. Clinical image of the fractured specimen is shown in Figure 7.

Discussion

Bracket bonding to provisional crowns must support orthodontic, as well as masticatory forces during chewing cycles. Adhesive resistance of brackets bonded to temporary materials must be strong enough to resist dental movement without debonding the orthodontic accessory; yet, weak enough to be removed without damaging the surface after orthodontic treatment is finished.

The current study tested the shear bond strength (SBS) of orthodontic brackets bonded to 3D-printed material using composite cement with various surface treatments and artificial aging, in comparison to CAD-CAM PMMA milled material. Our null hypothesis was partially rejected as no significant difference in SBS was found between the study groups and between the study and the control groups, except for group C (SA and no thermocycling), which was significantly higher than in the control group (*P* = .037).

Dentists rely on several surface treatments to improve bonding. Improving the bond strength between two materials involves increasing the surface roughness to improve mechanical retention, followed by application of a bonding agent to promote a better chemical bonding It was shown that surface roughening using aluminum oxide minimizes bracket bonding failure by increasing the surface area and retentiveness. Sandblasting is a surface treatment that causes "micro" retentive features.[14]

The surface treatments used in our research were sandblasting, either with 50 µm aluminum oxide (SA) or with 30 µm silica-coated-alumina (CO). The purpose of this process was to roughen the surface and create micropores to enhance the bonding. However, a study on different composite materials with various surface treatments, found that surface treatment with 30 µm alumina particles coated with silica produced improved bond strength.[15] This fact is due to the additional chemical affect contributed by silica particles, which emphasizes that silica-coated-alumina pretreatment is not only a mechanical roughening, but also a chemical one.

The current study tested differences in SBS between surfaces treated with SA or CO. Our results revealed that there is no significant difference between groups treated with SA and CO. This result is not in agreement with other studies that found that sandblasting treatment with 50 µm aluminum oxide particles exerted a beneficial effect on shear bond strength.[16] Cardoso et al. concluded that sandblasting with aluminum oxide was the most effective mechanical treatment to increase the bond strength of brackets to PMMA material.[17] This may be explained by the fact that a cohesive failure occurred in all specimens in the study groups, without the expression of differences between the two types of surface treatment.

Subgroup C (3D-printed: SA and no thermocycling) exhibited significantly higher bonding strength than did the PMMA control group (SA and thermocycling) (P = .037). However, this difference may be related to the type of material and not only to the effect of the thermocycling procedure. Moreover, thermocycling was not a significant factor in the study groups.

Since orthodontic adhesives are routinely subjected to thermal changes in the oral cavity, it is important to determine whether such temperature variations introduce stresses in the adhesive that might affect bond strength. Therefore, thermocycling is important to simulate the conditions of temperature changes and the moist environment in a patient's mouth. These changes weaken the temporary materials in different degrees and affects some materials more than others.[18]

In our study, storage duration time was set to 1 day. Storage duration varied in different studies ranging from 30 minutes up to 12 months. However, according to previous study results, there was no significant difference between 1- and 30-days storage time in the bond strength.[19]

For this reason, the specimens in the current study were thermocycled in order to induce a mouth-like environment when measuring bond strength. We found no significant effect of thermocycling on the SBS; although, the lowest SBS was found in the PMMA control group (SA and thermocycling). This is in agreement with the results of Al Jabbari et al. and may be because PMMA materials are more prone to water softening during artificial aging.[20] Chay et al. tested the SBS of brackets bonded to PMMA restorations, and found a significant difference in bond strength was observed between treatment groups of specimens aged for 1 week or 1 month. They concluded that aging influences bond strength, as specimens aged for 1 month had a lower bond strength than those aged for 1 week.[21]

The crosshead speed was set at 0.025 mm/minute, and different studies used different crosshead speeds, varying from 0.25 up to 2 mm/minute. However, according to Klocke et al. it does not affect the debonding value but only affects the time until the debonding occurs.[22] The SBS values reported in our study are 8-times higher than those reported for polycarbonate provisional crowns.[23] This suggests that using PMMA milled or 3D-printed provisional crowns for combined orthodontic-prosthodontic treatment may allow better predictability.

The 3D printing material used in this study is classified as a micro-filled hybrid material. Previous studies have shown that when it comes to repairing a 3D-printed restoration, the material of choice should be a conventional resin.[24] This may be the reason for the higher bonding strength we found between the bracket and the 3D printed specimen, which may have caused cohesive failure due to lower mechanical properties of the material. On the other hand, PMMA has a higher flexural strength, which may mean that the material itself held up well to the pressure applied and may explain the more frequent adhesive failures observed. While the 3D printed specimens had more cohesive failures and the material broke. This indicates that the 3D printed material itself is weak and is not up to the masticatory forces in the mouth. Albahri et al. reached similar conclusions. He compared the shear bond strength of 3D printed materials with PMMA and Bis-acrylic composite resin and Bis-GMA composite, and showed that all of the failures in the 3D printed materials were due to poor cohesion, which agrees with our findings.[24]

This study had some limitations that should be considered when interpreting the results: the flat surface of the tested specimen does not resemble the normally contoured tooth bonded surface. Study settings, especially the SBS test, does not reflect the clinical settings for removing an orthodontic bracket, which may affect the failure mode. In addition, the oral cavity presents a different testing environment regarding temperature changes, saliva and different pH levels, which also may affect the outcomes.

Conclusions

Within the limitations of this in vitro study, we can conclude that orthodontic brackets bonded to 3D-printed material exhibited adequate bonding strength in comparison to the milled PMMA provisional material. However, 3D-printed material was more prone to cohesive failure, which may result in material fracture.

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Figure legends

Figure 1. Experiment design.

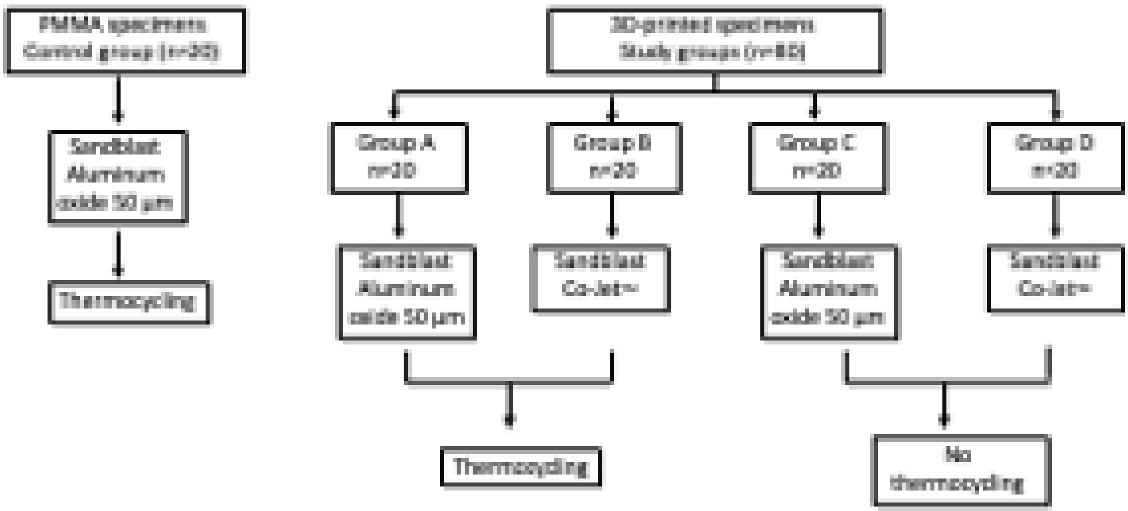


Figure 2. Specimen positioned in the universal testing machine for shear bond strength test.

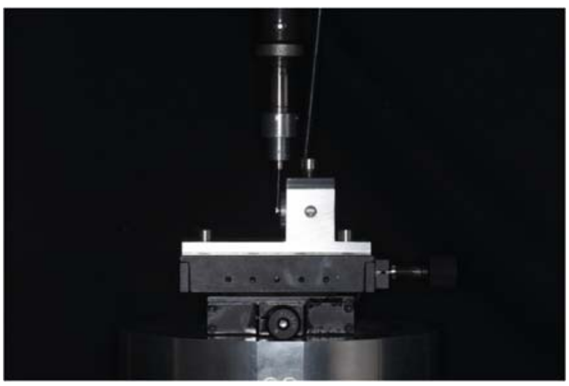
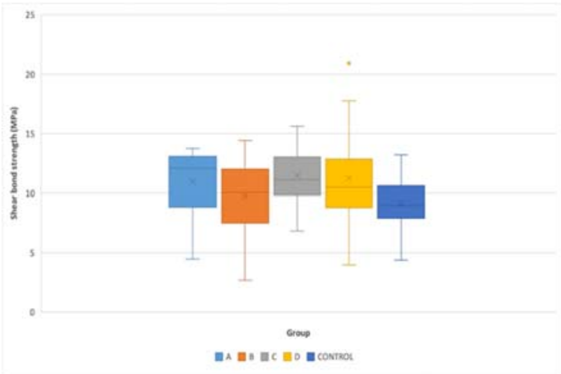
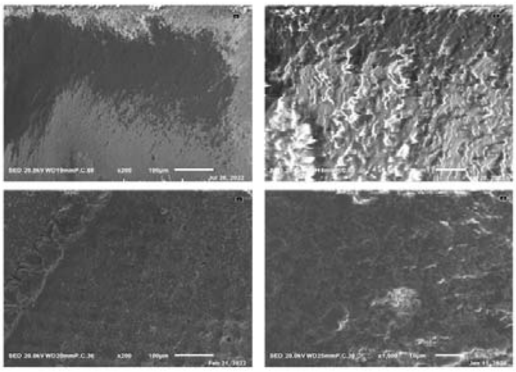


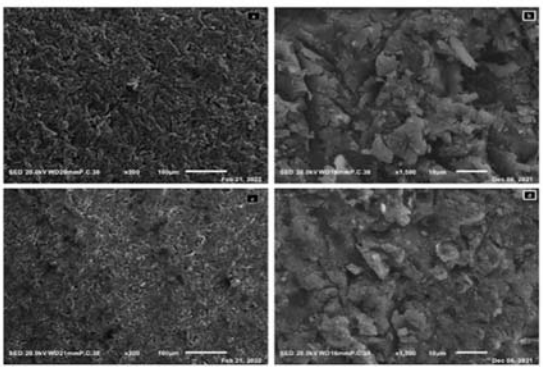
Figure 3. Minimum, maximum, interquartile range, medians, and the outliers of measurements for the control and study groups.



Figures 4, (a-d). Scanning electron images of the specimen surfaces prior to surface treatment in the control group; (a). Surface scanning at x200 magnification; (b). Surface scanning at x1500 magnification. In the 3D-printed groups; (c). Surface scanning at X200 magnification; (d). Surface scanning at X1500 magnification. Some irregularities and porosities can be seen at the specimen’s surface at X1500 magnification.



Figures 5, (a-d). Scanning electron images of the specimen surfaces prior to bracket bonding in the 3D-printed groups; (a,b). Surface after treatment with 50 µm aluminum oxide particles (x200 a and x1500 b); (c,d). Surface after treatment with 30 µm silica-coated-aluminum particles (x200 c and x1500 d). Specimen surfaces after surface treatment showed more irregularities and porosities while with the 50 µm aluminum oxide particles treatment it was more pronounced than with the 30 µm silica-coated-aluminum particles treatment.



Figures 6, (a-b). Scanning electron image of a fractured specimen in the study group, cohesive type; (x200 and x1500 b).

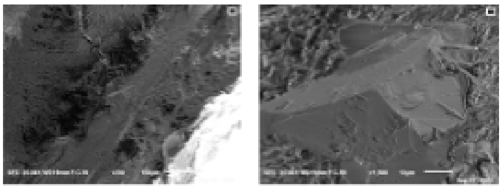


Figure 7. Clinical image of a fractured specimen showing cohesive fracture.

Tables:

Table 1. The various control and study groups.

Group	N	Material	Surface Treatment	Aging	Chemical composition
Control	20	PMMA	SA	+	Polymethyl methacrylate, methyl methacrylate
Study					
A	20	3D printed	SA	+	Methacrylic oligomers, methacrylate monmer, inorganic filler, phsphine oxide, pigment
B	20	3D printed.	CO	+	
C	20	3D printed	SA	-	
D	20	3D printed	CO	-	

PMMA- polymethyl methacrylate; SA- Sandblasting with 50 µm Al_2O_3; CO- sandblasting with 30 µm silica-coated-alumina particles

Table 2. Classification of failures.

Classification	Failure description	Criteria
1	Cement principally on bracket surface	Adhesive cement-specimen
2	Cement principally on specimen surface	Adhesive cement-bracket
3	Cement equally distributed on specimen & bracket	Cohesive cement
4	Mixed mode	Adhesive and cohesive cement
5	Fracture of the specimen	Cohesive specimen

Table 3. Mean and standard deviation of retentive strength (MPa) of the shear bond strength for the control and the study groups.

Group	Mean Retentive Value (MPa)	Standard Deviation	*p**
Control	9.11	2.21	
Study			
A	10.95	2.42	.136
B	9.75	3.06	.887
C	11.46	2.21	.037
D	11.24	3.68	.067

Group A: sandblasted with 50 µm aluminum oxide particles (SA) and aging; Group B: sandblasted with 30 µm silica-coated alumina particles (CO) and aging; Group C: SA without aging; Group D: CO without aging. * Post hoc t-tests between each study group and the control.

Table 4. Two-way ANOVA analysis among the study groups.

Source	Sum of Squares	df	Mean Square	F	Sig.
Thermo	19.809	1	19.809	2.220	.140
SA_Cojet	10.068	1	10.068	1.128	.292
Thermo*SA_Cojet	4.845	1	4.845	0.543	.463
Error	678.211	76	8.924		
Total	10147.005	80			
Corrected Total	712.933				

a R Squared=.049 (Adjusted R Squared= .011)