Evaluation of failure characteristics and bond strength after ceramic and polycarbonate bracket debonding: effect of bracket base silanization

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SUMMARY The objectives of this study were to evaluate the effect of silanization on the failure type and shear–peel bond strength (SBS) of ceramic and polycarbonate brackets, and to determine the type of failure when debonded with either a universal testing machine or orthodontic pliers.

Silanized and non-silanized ceramic and polycarbonate brackets (N = 48, n = 24 per bracket type) were bonded to extracted caries-free human maxillary central incisors using an alignment apparatus under a weight of 750 g. All bonded specimens were thermocycled 1000 times (5–55°C). Half of the specimens from each group were debonded with a universal testing machine (1 mm/minute) to determine the SBS and the other half by an operator using orthodontic debonding pliers. Failure types of the enamel surface and the bracket base were identified both from visual inspection and digital photographs using the adhesive remnant index (ARI) and base remnant index (BRI).

As-received ceramic brackets showed significantly higher bond strength values (11.5±4.1 MPa) than polycarbonate brackets [6.3 ± 2.7 MPa; (P = 0.0077; analysis of variance (ANOVA)]. Interaction between bracket types and silanization was not significant (P = 0.4408). Silanization did not significantly improve the mean SBS results either for the ceramic or polycarbonate brackets (12.9 ± 3.7 and 6.3 ± 2.7 MPa, respectively; P = 0.4044; two-way ANOVA, Tukey-Kramer adjustment). There was a significant difference between groups in ARI scores for ceramic (P = 0.0991) but not polycarbonate (P = 0.3916; Kruskall-Wallis) brackets. BRI values did not vary significantly for ceramic (P = 0.1476) or polycarbonate (P = 0.0227) brackets. Failure type was not significantly different when brackets were debonded with a universal testing machine or with orthodontic debonding pliers. No enamel damage was observed in any of the groups.

Introduction

In orthodontics, there is an increasing demand for relatively invisible aesthetic brackets. These brackets are generally made of polycarbonates or ceramics where the latter are either monocrystalline or polycrystalline. Since adhesion of brackets is considered semi-permanent in orthodontics, bond strength should be sufficiently high to resist accidental debonding during the entire course of treatment but low enough so that excessive force is not needed when debonding the brackets after treatment (Reynolds and von Fraunhofer, 1975). The major concern during bracket debonding is the risk of enamel damage. The iatrogenic damage risk increases when the force for debonding increases. It has previously been reported that the use of ceramic brackets results in higher mean shear-peel bond strength (SBS) than stainless steel brackets (Joseph and Rossouw, 1990; Azzeh and Feldon, 2003). Enamel damage following the use of ceramic brackets has also been reported in several other studies (Swartz, 1988; Britton et al., 1990; Winchester, 1991; Merrill et al., 1994). Due to the transparent nature of ceramic brackets, it is possible to achieve a higher degree of polymerization of the resin adhesive (Özcan et al., 2004).

The consequences of enamel damage may result in poor aesthetics and costly treatment, and could even compromise the long-term prognosis of the affected tooth (Azzeh and Feldon, 2003; Britton *et al.*, 1990).

Ceramic brackets are very rigid and brittle. Therefore as a result of debonding pressure on the bracket base, partial or complete bracket failure commonly occurs (Kusy, 1988; Flores et al., 1990; Theodorakopoulou et al., 2004). The incidence of bracket failure could also be explained by the high bond strength achieved with the ceramic brackets. On the other hand, the advantage of ceramic brackets, unlike plastic brackets, is their resistance to staining and slot distortion. For debonding ceramic brackets, Bishara and Fehr (1993) reported that pliers with narrow blades resulted in a lower mean debonding strength than pliers with wide blades. The use of pliers with narrow blades created sufficient debonding strength and led to reduced force levels on the enamel surface. Alternative ways to debond ceramic brackets are optic laser technology and ultrasonic and electrothermal debonding techniques (Krell et al., 1993; Azzeh and Feldon, 2003).

To date, little is known about the bond strength of polycarbonate brackets. It has been reported that the SBS of

polycarbonate brackets is significantly lower than that of conventional metal brackets (Guan *et al.*, 2000). Polycarbonate brackets conversely present several disadvantages compared with ceramic brackets. They tend to stain under the influence of food and drinks, thereby compromising aesthetics (Aird and Durning, 1987). Moreover, all polycarbonate brackets demonstrate low resistance to torque forces and high deformation values (Feldner *et al.*, 1994). In terms of bond strength, adequate adhesion is difficult to achieve with such brackets due to their inert matrix (Özcan *et al.*, 2004).

Several attempts have been made to condition metal, ceramic, or resin-based materials using silane coupling agents (Özcan et al., 1998). Silica-modified surfaces are chemically more reactive to the resin via silane coupling agents. Silane molecules react with water to form three silanol groups (-Si-OH) from the corresponding methoxy groups (-Si-O-CH₃). The silanol groups then react further to form a siloxane (-Si-O-Si-O-) network with the silica surface. The monomeric ends of the silane molecules react with the methacrylate groups of adhesive resins in a free radical polymerization process (Matinlinna et al., 2004). Silane coupling agents are also reported to increase the bond strength of resin composite to ceramic (Pannes et al., 2003). Since adhesion has two aspects in orthodontics, namely adhesion of the resin cement to the enamel and to the bracket base surface, it could be hypothesized that silane application could affect the SBS results when it is applied on the bracket base surface.

Many bracket bond strength investigations provide information from *in vitro* studies where shear testing was employed (Powers *et al.*, 1997). Considering the fact that a combination of shear, peel, and torque forces occur during actual bracket bonding, the failure type experienced after debonding could vary from the *in vitro* set-up.

The objectives of this study, therefore, were twofold, namely to identify the effect of silane coupling agent application on the bond strength of ceramic and polycarbonate brackets as well as the failure types when debonded either by the universal testing machine or by use of pliers. The studied hypotheses were that silanization would provide a higher bond strength and there would be differences in failure types between the two debonding methods.

Materials and methods

Forty-eight caries-free human maxillary central incisors of similar size stored in distilled water with 0.1 per cent thymol solution at room temperature were selected from a pool of recently extracted teeth. To determine that the enamel was free of crack lines, all teeth were evaluated under blue light transillumination. The roots were then sectioned under cooling and the crowns were mounted in metal rings using polymethylmethacrylate (Palapress Vario, Hereaus Kulzer, Wehrheim, Germany). The specimens were stored in distilled water for up to 3 months until the experiments. The enamel surfaces were cleaned and polished using water and fluoride-free pumice (3M Espe AG, Seefeld, Germany) with a prophylaxis brush, rinsed with water, and dried using an air syringe.

Two types of brackets for mandibular central incisors were used in this study, namely monocrystalline ceramic (Inspire, Ormco, Orange, California, USA; Batch#: 443-0143) and polycarbonate (Spirit MB, Ormco; Batch#:02D31D). The base of the ceramic bracket used was flat without retentive features but coated with a silica layer, and the polycarbonate brackets had a retentive base with extruding retentive features. The average surface area of the ceramic bracket 10.06 mm² according to the information obtained from the manufacturers. This information was also verified using a digital micrometer (Mitutoyo Ltd., Kawasaki, Kanagawa, Japan).

The specimens were randomly divided into eight groups (N = 48, n = 6 per group). Classification of the experimental groups is shown in Figure 1.

Enamel conditioning and bracket bonding

In all groups the enamel surfaces were etched with 37 per cent orthophosphoric acid (SDS Ormco) for 30 seconds and then rinsed thoroughly using an air-water spray for 20 seconds. The enamel surfaces were air-dried until they appeared dull and frosty. In groups 3, 4, 7, and 8, silane coupling agent (Espe-Sil, 3M Espe AG) was applied on the ceramic and polycarbonate brackets using a clean brush. After waiting 3 minutes for silane reaction, the bonding procedure was started. Bonding agent was applied on the enamel surfaces (Ortho Solo Sealant, Ormco), air-thinned and the adhesive resin (Enlight Light Cure Adhesive, Ormco) was then applied to the enamel. The bracket was then placed on the adhesive resin using an alignment apparatus under a load of 750 g to ensure an even film thickness of the adhesive resin at the enamel-bracket interface (Figure 2). The excess resin was removed first using the tip of the probe followed by a microbrush (Kerr, Orange, California, USA). The adhesive resin was light polymerized for 10 seconds from the mesial, distal, cervical and occlusal directions with a conventional halogen light polymerization device (Demetron LC, SDS Kerr; light output: 400 mW/cm²). The irradiation distance between the exit window and the resin surface was maintained at 2 mm to obtain adequate polymerization. The specimens were stored in distilled water for 1 week and then thermocycled 1000 times between 5°C and 55°C (dwell time: 30 seconds, transfer time from one bath to the other: 2 seconds; Willytec, Gräfelfing, Germany).

Bracket debonding

The specimens in groups 1, 3, 5, and 7 were mounted in the jig of the universal testing machine (Zwick Roell Z2.5



Figure 1 Schematic representation of the experimental groups depending on bracket type, silanization, and debonding technique.

MA 18-1-3/7, Ulm, Germany) where the force was applied at the bracket–enamel interface from an occluso-cervical direction. The shearing blade had a 45 degree inclined cutting blade. The specimens were loaded at a crosshead speed of 1.0 mm/minute until failure occurred. The stress– strain curve was analysed with the software program (Zwick Roell). The force required to shear–peel the bracket was recorded and converted into MPa using the known bracket surface areas. In groups 2, 4, 6, and 8, the brackets were debonded by an experienced orthodontist using a bracket debonding plier (SDS Ormco). Subsequently, digital photographs (Canon Ixus 40, Canon Inc., Tokyo, Japan) were taken of the substrate and bracket surfaces.

Failure analysis

After debonding, the failure sites were examined by two calibrated operators (AY, MÖ) both visually and from digital photographs at ×20 magnification using a software program (CorelDraw 9.0, Corel Corporation, Ottowa, Ontario, Canada). Classification of the enamel failures was made according to the adhesive remnant index (ARI; Årtun and Bergland, 1984).

A base remnant index (BRI) scoring system was created for evaluation of the failure type on the bracket surfaces. Tooth surfaces and bracket bases were further examined from representative failure types under scanning electron microscopy (SEM; JSM-5500, Jeol Instruments, Tokyo, Japan) after debonding at ×20 magnification.



Figure 2 Bonding of the brackets using an alignment apparatus under a constant force of 750 g in order to achieve an even film thickness of the adhesive at the bracket–enamel interface.

Statistical analysis

Statistical analysis was performed using the SAS System for Windows, release 8.02/2001 (Cary, North the Carolina, USA). The means for each group were analysed by one-way analysis of variance (ANOVA). Because of the significant group factor (P = 0.0388), multiple comparisons were made using a Tukey-Kramer adjustment to determine the effect of bracket silanization. A Kruskall-Wallis non-parametric test was used to analyse the differences in ARI and BRI scores between groups. P values less than 0.05 were considered to be statistically significant in all tests.

Results

Shear-peel bond strength

As-received ceramic brackets showed significantly higher SBS values (11.5 ± 4.1 MPa) than polycarbonate brackets (6.3 ± 2.7 MPa; P = 0.0077; ANOVA). Interaction between bracket types and silanization was not significant (P = 0.4408). Silanization did not significantly improve the mean SBS results either for the ceramic or polycarbonate brackets (12.9± 3.7 and 6.3 ± 2.7 MPa, respectively; P = 0.4044; two-way ANOVA, Tukey-Kramer adjustment; Figure 3).

Failure sites

Tables 1 and 2 show the tabulation of the modes of failure for the enamel and the bracket bases for both the ceramic and polycarbonate brackets after debonding either with a universal testing machine or by the operator. There was a significant difference between groups in ARI scores for ceramic (P = 0.0991) but not for polycarbonate (P = 0.3916; Kruskall-Wallis) brackets.

For almost all specimens (22 out of 24) in the ceramic bracket groups, the adhesive resin was left on the enamel surface (ARI score 3) and no enamel fractures were recorded. The BRI scores with this bracket type showed mainly (14 out of 24) score 0 where the silica layer was fully intact indicating that the adhesive resin was detached from the bracket base leaving the silica layer attached on the bracket base. BRI values did not vary significantly for ceramic brackets (P = 0.1476). For the brackets debonded using the orthodontic pliers, the incidence of bracket base silica layer damage (scores 1–3) was found more often (8 out of 12) than in specimens



Figure 3 Mean shear bond strengths after thermocycling for the ceramic (groups 1 and 3) and polycarbonate (groups 5 and 7) brackets with and without silanization. Vertical lines represent the standard deviations.

debonded with the universal testing machine (4 out of 12). Only one fracture was experienced in the body of the bracket.

All polycarbonate brackets were almost exclusively debonded leaving the adhesive resin on the enamel surfaces (23 out of 24, ARI–score 3). In this group, one bracket was dislodged prior to debonding. There was no significant difference in ARI scores for this bracket type (P = 0.3916) or in BRI values (P = 0.0227). No enamel fractures were recorded in this group. In five of the specimens debonded by the universal testing machine, some of the retentive features of the bracket base were found to be detached and were retained in the adhesive resin on the enamel. However, when debonded by the orthodontic pliers, the site of failure was exclusively at the bracket–adhesive interface without bracket base damage. No fracture in the body of the bracket was observed in this group. Representative SEM photographs

 Table 1
 Adhesive Remnant Index (ART) scores for enamel surfaces of as-received or silanized ceramic/polycarbonate brackets debonded either with the universal testing machine or orthodontic pliers (see Figure 1 for group details).

	ARI								
	Dislodged*	0	1	2	3	Enamel fracture			
Group 1	0/0	0/0	0/0	0/1	6/5	0/0			
Group 2	2/1	0/0	0/0	0/0	6/6	0/0			
Group 3	0/0	0/0	0/0	2/0	4/6	0/0			
Group 4	0/0	0/0	0/0	0/0	6/6	0/0			

Score 0 = no composite left on the enamel surface. Score 1 = less than half of the composite left. Score 2 = more than half of the composite left. Score 3 = all composite left on the enamel surface, with a distinct impression of the bracket mesh.

*During thermocycling or testing.

Table 2 Base Remnant Index (BRI) scores for bracket base surfaces of as-received or silanized ceramic/polycarbonate brackets debonded either with the universal testing machine or orthodontic pliers (see Figure 1 for group details).

	BRI								
	Dislodged*	0	1	2	3	Bracket fracture			
Group 1	0/0	4/2	1/3	1/1	0/0	0/0			
Group 2	0/0	2/6	0/0	2/0	2/0	0/0			
Group 3	0/0	4/4	2/2	0/0	0/0	0/0			
Group 4	0/0	2/6	1/0	2/0	1/0	1/0			

Score 0=bracket base coating completely intact. Score 1=coating debonded less than half of the bracket. Score 2=coating debonded more than half of the bracket base. Score 3=coating completely debonded. *During thermocycling or testing.

from the enamel and bracket base surfaces are presented in Figures 4a-c.

Discussion

In this study, the debonding characteristics of two aesthetic ceramic and polycarbonate brackets were tested. The mean SBS results obtained for the ceramic brackets demonstrated a significantly higher bond strength than polycarbonate brackets.



Figure 4 Representative scanning electrone photomicrographs ($\times 20$ original magnification) from (a) the enamel surface following debonding of a silanized ceramic bracket. Note that all adhesive resin is left adhering to the enamel with a distinct impression of the bracket base. (b) The base of the ceramic bracket after debonding. Note that the bracket base is devoid of adhesive resin and the coating is partially removed (*). (c) The base surface of a polycarbonate bracket following debonding with the universal testing machine. Note that the retentive features are distorted (\mathcal{P}).

Weinberger et al. (1997) investigated the adhesive strength of poly- and monocrystalline ceramic brackets with an argon laser, light, and chemically polymerized adhesive resins. In their study, the highest average bond strength of 29.58 MPa was found with monocrystalline brackets with the argon laser. However, Retief (1974) reported enamel fractures with bond strengths as low as 9.7 MPa. Despite the results of the present study, the findings are comparable with those of Retief (1974), i.e. no enamel fractures were observed. Klocke et al. (2003) also used monocrystalline ceramic (Inspire) brackets but a different type of adhesive than that used in this study. The specimens were not thermocycled but stored in water for 24 hours. They found mean SBS values ranging between 19.85 MPa (plasma arc curing light, 1 second curing interval) and 22.94 MPa (plasma arc curing light, 3 second curing interval). Arici and Minors (2000) used chemically coated ceramic brackets (Transcend) with a chemically polymerized adhesive resin (Concise). The specimens were again not thermocycled but only stored in water. They found a mean SBS of 14.51 MPa. It can be anticipated that the temperature elevations and water uptake of the adhesive resin at the enamel-bracket interface might have resulted in the relatively lower results in that research.

Reynolds and von Fraunhofer (1975) reported that a minimum bond strength of 6–8 MPa could provide a satisfactory clinical performance and successful clinical bonding. Although the SBS of both silanized and non-silanized polycarbonate brackets was within this range, this advised bond strength value should be evaluated with caution because thermal or other types of ageing procedures are not taken into consideration. Temperature change, humidity, acidity (pH), and chewing stresses placed on a bracket in the oral cavity may all have an effect on adhesive strength and it is impossible to simulate all these factors *ex vivo* (Øilo, 1993; Pickett, 2001). Considering these factors, it is conceivable that clinical debonding values could be lower than those reported in the study of Reynolds and von Fraunhofer (1975).

It is, however, interesting to note that although the ceramic brackets had flat surfaces and the adhesion relies completely on chemical adhesion principles, significantly higher bond strength results were obtained when compared with mechanically retentive polycarbonate brackets. Although due to their transparent nature improved polymerization of the adhesive resin should be expected with aesthetic brackets, when compared with their metallic counterparts, the results were more favorable for ceramic brackets. In contrast to the general belief on mechanical retention of orthodontic brackets, this finding underlines the importance of chemical adhesion more than mechanical retention (Özcan et al., 1998). It is also possible that when the adhesive resin does not wet in and around the retentive mesh of the polycarbonate brackets, water penetration to these areas could result in early

detachment of the mechanically retentive brackets (Özcan *et al.*, 2004).

In this study, mandibular incisor brackets were used due to their flat bases in order to ensure optimal adaptation to the tooth surface. It should also be noted that when brackets are more curved, there is a possible mismatch between the curvature of the bracket base and tooth surface. This mismatch will affect the stress distribution between the adhesive cement-tooth complex. Water uptake during thermocycling could also be affected depending on the thickness of the adhesive between the bracket base and the enamel surface. For this reason, in order to keep the film thickness standard, adhesion of the brackets was performed under a load of 750 g.

The manufacturer of the ceramic brackets used in this study claim that the silanized as-received bracket bases would improve adhesion. This was verified, although the specimens were thermocycled 1000 times. A rapid increase in the amount of water absorbed by the resin-based materials causes hydrolysis and degradation of the silane (Reuter and Brose, 1984). However, even after at 1 week period of water storage and 1000 thermal cycles, the bond strength of ceramic brackets varied between 11 and 12 MPa without any enamel damage.

Retief (1974) reported enamel fractures with bond strengths of 13.73 MPa. Bowen and Rodriguez (1962) found that the mean linear tensile strength of enamel is 14.51 MPa. Based on these studies, Bishara and Fehr (1993) suggested that bond strengths lower than 12.75 MPa would be safer in order not to damage the enamel. The mean SBS of the ceramic brackets, silanized (12 MPa) and non-silanized (10 MPa), were indeed lower than these suggested values, and because no enamel damage was recorded, these values could be considered clinically optimal.

In this study, an attempt was made to evaluate the failure types occurring on the bracket surface (BRI). After debonding, when bracket bases were evaluated in the ceramic bracket group, the silica layer was found to be predominantly intact indicating that the coating was well attached to the bracket base. Bond strength results should always be associated with failure type. When the failure site is at the bracket–adhesive interface, this indicates safe debonding and a reduced chance of enamel loss. However, this then requires meticulous removal of the resin remnants from the enamel surface.

A further aim of this study was to compare the differences in failure type created by the blade of the universal testing machine and the orthodontic pliers supplied by the manufacturer of the ceramic brackets. Fox *et al.* (1994) compared the results from published bond strength studies, presenting differences in test configurations and experimental methodologies. They noted that the bending moment generated during bond strength testing was associated with the force application site in relation to the bracket base surface. Variability in the location of the force application site and the relative positions of the components of the bonded assembly could result in substantial differences in the measured force that causes bond failure. The crosshead speed of the testing machine and the configuration of the testing jig could also affect the results (Eliades and Brantley, 2000). Those authors also claimed that the universal testing machine applies a unilateral load at the bracket-adhesive interface contrary to the pliers. Since there was no significant difference between the failure types caused by the blade of the universal testing machine and the orthodontic pliers, the hypothesis is rejected. Interestingly, the cutting blade was placed between the bracket base and the tooth surface in such a manner that the cutting edge was as close to the enamel surface as possible but the cutting ends of the pliers were at the tie wings according to the manufacturer's instructions. Further research is necessary to investigate the effect of the location on debonding force.

Bishara *et al.* (1994) attempted to measure the actual force applied by the pliers during debonding and found that this method transmits 30 per cent less force to the enamel compared with *in vitro* shear force. This is a very significant reduction in debonding force. Therefore, the enamel fractures reported with the use of ceramic brackets from *in vitro* bond strength data where the specimens are tested under non-aged conditions should be evaluated with caution.

One drawback of this study was the low sample size. The strict selection of teeth free of existing cracks and/or crack lines led to elimination of a large number of teeth prior to the experiment. Although the orthodontic literature contains studies with a similar sample size due to similar reasons (Özcan et al., 2004), the results needs to be verified in a larger sample. Furthermore, as an alternative to the polycarbonate brackets used, recently polyoxymethylene copolymer (POM) brackets have been introduced. POM, also known as acetal or polyacetal, is a highly crystalline, high-performance engineering polymer that displays a low coefficient of friction, excellent wear resistance, high modulus, low moisture absorption, and resistance to many solvents. Information on the performance of this bracket type are limited (Whitley and Kusy, 2007) but brackets made of such materials may perform differently than those tested in this study.

Conclusions

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

- 1. Ceramic brackets showed significantly higher bond strength results than those of polycarbonate brackets after water storage for 1 week and thermal cycling 1000 times.
- 2. Silanization did not significantly improve the mean bond strength results either for the ceramic or polycarbonate brackets.

3. Failure type was not significantly different when brackets were debonded with a universal testing machine or with orthodontic debonding pliers, and no enamel damage was observed in any of the groups.

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- Winchester L J 1991 Bond strength of five different ceramic brackets: an in vitro study. European Journal of Orthodontics 13: 293–305EFFECT OF BRACKET SILANIZATION ON BOND STRENGTH

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