Comparison of Shear Bond Strengths and Fiction Forces Among Various Self-ligating Ceramic Brackets

Chia-Lin Wu
Institute of Oral Medicine, College of Medicine, National Cheng Kung University

Chen-Jung Chang
Institute of Oral Medicine, College of Medicine, National Cheng Kung University and Department of Stomatology, National Cheng Kung University Hospital

Tzer-Min Lee
Institute of Oral Medicine, College of Medicine, National Cheng Kung University

Jen-Bang Lo
Department of Stomatology, National Cheng Kung University Hospital

Jia-Kuang Liu
Institute of Oral Medicine, College of Medicine, National Cheng Kung University and Department of Stomatology, National Cheng Kung University Hospital

Follow this and additional works at: https://www.tjo.org.tw/tjo

Part of the Orthodontics and Orthodontology Commons

Recommended Citation
Wu, Chia-Lin; Chang, Chen-Jung; Lee, Tzer-Min; Lo, Jen-Bang; and Liu, Jia-Kuang (2020) "Comparison of Shear Bond Strengths and Fiction Forces Among Various Self-ligating Ceramic Brackets," Taiwanese Journal of Orthodontics: Vol. 32 : Iss. 4 , Article 1.
DOI: 10.38209/2708-2636.1089
Available at: https://www.tjo.org.tw/tjo/vol32/iss4/1

This Original Article is brought to you for free and open access by Taiwanese Journal of Orthodontics. It has been accepted for inclusion in Taiwanese Journal of Orthodontics by an authorized editor of Taiwanese Journal of Orthodontics.
Comparison of Shear Bond Strengths and Fiction Forces Among Various Self-ligating Ceramic Brackets

Cover Page Footnote
This investigation was supported by a grant from Taiwan Association of Orthodontists.
Comparison of Shear Bond Strengths and Fiction Forces Among Various Self-ligating Ceramic Brackets

Chia-Lin Wu a, Chen-Jung Chang a,b, Tzer-Min Lee a, Jen-Bang Lo b,**, Jia-Kuang Liu a,b,*

a Institute of Oral Medicine, National Cheng Kung University, Tainan, Taiwan
b Department of Stomatology, National Cheng Kung University Hospital, Tainan, Taiwan

ABSTRACT

Purpose: Ceramic self-ligating brackets were developed recently, however, only few comparative studies had been reported about their bond strengths and friction. The aim of the study was to compare shear bond strengths and friction forces of various self-ligating ceramic brackets.

Materials and methods: The present study is divided into two parts. In shear bond strength test, bovine teeth were used as a substitute for human teeth. Five groups of brackets (three ceramic self-ligating brackets including ClippyC), GeniusCrystal, DamonClear2, ClarityAdvanced (conventional ceramic bracket), Damon3MX (metal self-ligating bracket), were used and debonded with 12 brackets in each group. The shear bond strengths and adhesive remnant index (ARI) scores were compared. In the friction test, several parameters were investigated, including five kinds of bracket, two wire sizes (0.014" Cu–NiTi and 0.016" × 0.022" NiTi) and three angulations (0°, 5°, and 10°). Each bracket/wire/angulation combination was tested five times in 30 settings. A total of 150 runs were performed.

Results: DamonClear2 had highest bond strength among the 5 brackets with significant differences found. ClarityAdvanced and DamonClear2 had highest and lowest ARI scores, respectively. In friction behavior test, ClarityAdvanced had largest frictional force, but there was no significant difference in frictional force for 0.016" × 0.022" NiTi with an angulation of 10°. There was no significant difference in friction force between angulations of 0° and 5°, but there was a significant difference between angulations of 5° and 10° for the same brackets except ClarityAdvanced.

Conclusion: DamonClear2 had highest bond strength and ClarityAdvanced had a larger frictional force than those of self-ligating brackets, except for 0.016" × 0.022" NiTi with an angulation of 10°.

Keywords: Ceramic self-ligating bracket; Shear bond strength; Angulation of wire; Friction force; Resistance to sliding

INTRODUCTION

Orthodontic treatment has become increasingly popular due to esthetic and functional demand. Orthodontic tooth movement using a fixed appliance depends on adequate bond strength between the brackets and the tooth surface, and smooth tooth sliding along the archwire. Bonding brackets on tooth surfaces with a fixed appliance is a routine procedure in orthodontic treatment. For optimal mechanical retention, various base designs have been produced by manufacturers, for which good bond strength has been claimed. Excessive bond strength may lead to enamel fracture when the bracket debonds, whereas insufficient bond strength will hinder orthodontic treatment. An optimum bond strength range of 5.88–13.53 MPa was suggested in a review of bonding systems in orthodontics. Previous studies proposed the adhesive remnant index (ARI) for characterizing the resin-enamel and resin-bracket interfaces during debonding.

Received 8 January 2021; revised 20 February 2021; accepted 28 February 2021.
Available online 16 April 2021

* Corresponding author at: Department of Stomatology, National Cheng Kung University Hospital, 138 Sheng-Li Road, Tainan 704, Taiwan. Fax: 886 6 2359883.

** Corresponding author at: Department of Stomatology, National Cheng Kung University Hospital, 138 Sheng-Li Road, Tainan 704, Taiwan. Fax: 886 6 2359883.

E-mail addresses: lojenpan@yahoo.com.tw (J.-B. Lo), jklau@mail.ncku.edu.tw (J.-K. Liu).

https://doi.org/10.38209/2708-2636.1089
2708-2636/© 2021 Taiwan Association of Orthodontist. This is an open access article under the CC-BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
ARI scores can be used to assess failure site characteristics and are thus commonly used in orthodontic bonding studies.

In orthodontic treatment, tooth sliding along the archwire occurs via a tip-upright-tip-upright movement. A frictional force is generated between brackets and the archwire during sliding. Kusy and Whitley divided resistance to sliding into three components: classical friction, binding, and notching. In second-order angulation, the contact angle (\( \theta \)) is the angle between the bracket slot and the archwire. The critical contact angle (\( \theta_c \)) is the boundary angle at which the archwire first contacts the edges of the slot. It is still not fully understood how binding increasingly prevents sliding. Kusy and Whitley determined two parameters from these derivations: a bracket index (bracket width/slot) and an engagement index (archwire size/slot). Computations of the nominal values of the bracket index and engagement index were made. In the best-case scenario (larger slot, and smaller archwire and bracket width), the practitioner must align and level the brackets to within 3.7° prior to sliding. A simple, practical equation is shown as:

\[
\text{critical contact angle} = 57.32 \times \left[ 1 - \left( \frac{\text{Size}}{\text{Slot}} \right) \right] / \left( \frac{\text{Width/slot}}{} \right).
\]

In this equation, three geometric parameters define the critical contact angle. If clinicians want a sliding mechanism with more efficiency, the critical contact angle should be maximized by the decreasing wire dimension, decreasing the bracket width, or increasing the slot size.

The friction forces of metal self-ligating brackets have been previously studied.4 With developments in materials and manufacturing processes, ceramic self-ligating brackets have been developed without compromising low friction and meet the increased demand for more esthetic appliances. However, there are few comparative studies on ceramic self-ligating brackets. The aims of this study were to evaluate the effect of the base design of various self-ligating ceramic brackets on shear bond strength and to compare friction forces among brackets under various circumstances.

**MATERIALS AND METHODS**

The present study is divided into two parts: a shear bond strength test and a friction behavior test. Five groups of brackets [three ceramic self-ligating brackets: ClippyC (Tomy Inc., Tokyo, Japan), GeniusCrystal (MEM Dental Corp., Tainan, Taiwan), and DamonClear2 (Ormco Corp., California, USA); one conventional self-ligating bracket: ClarityAdvanced (3M Unitek, California, USA); one metal self-ligating bracket: Damon3MX (Ormco Corp., California, USA)] were selected in both parts (Table 1).

**Shear bond strength test**

In the shear bond strength test, bovine teeth were used as a substitute for human teeth. Five groups of brackets were used and debonded with 12 brackets in each group. The labial surfaces of the bovine teeth were cleaned with pumice powder (Korox 50, Bego, Germany), etched with 37% phosphoric acid gel (Ultra-Etch; 3M Unitek, California, USA) for 20 s, rinsed with water spray, and then thoroughly air-dried. For adhesive bonding, a thin coat of primer was applied to the tooth surface and resin paste was applied to the bracket base. Then, the bracket was placed on the tooth surface and pressure was applied. Excess paste was removed and the resin was light-cured using an LED light curing machine (Ultra-Lite 1800E, Rolence Enterprise Inc., Taoyuan, Taiwan). Then, all samples were embedded in epoxy resin using 0.021” × 0.025” stainless steel guide wire and stored in a distilled water bath at 37 °C for 24 h. All the samples were stored in a moisture-proof box with 40% humidity at 23 °C. Then, the samples were tested on a universal testing machine (AG-1, Shimadzu, Kyoto, Japan) at a crosshead speed of 0.5 mm/min with a 1-kN load cell for bond strength. A shear force was delivered from occlusal plane to the gingival plane by a blade parallel to the bracket bonded surfaces using a compression force (Figure 1). The bracket bases and bovine teeth after debonding were subsequently evaluated using low/variable vacuum scanning electron microscopy (LV-SEM; JEOL JSM-939OLV; Jeol Ltd., Tokyo, Japan) to observe the mode of failure and enamel surfaces. The interfaces after debonding were analyzed and the adhesive remnant index (ARI) scores were compared (Table 2).

**Friction test**

In friction test, an experimental model was designed on an X–Y table with an outer stainless-steel block that could move and rotate to various angles. A temperature-controlled chamber was built using an acrylic sheet with heating tape adhered around the chamber box (Figure 2). To monitor the temperature, a temperature controller (HT-720; NEWLAB Co. LTD., Taipei, Taiwan) with a thermometer was used. A temperature of 37 °C was set to simulate human oral conditions. For sample preparation, brackets were bonded with the adhesive Transbond XT on the stainless-steel block using a custom-made bracket mounting apparatus with
0.021” × 0.025” stainless steel guide wire, which enabled accurate placement of all brackets. Metal Primer (Reliance Orthodontics, Illinois, USA) was painted onto the block prior to the application of resin to enhance bonding strength between the brackets and the metal plate. A 30-mm section of wire was cut from the distal part of an archwire and bonded to a customized stainless-steel jig. The jig was then connected to a universal testing machine (AGS-X, Shimadzu, Kyoto, Japan) with a 50-N load cell. The outer stainless-steel block could move and rotate to various angles. The wire was pulled out through the bracket with a tension force at a cross-head speed of 0.5 mm/min (Figure 3).

Several parameters were investigated, including five kinds of bracket, two wire sizes (0.014” Cu–NiTi and 0.016” × 0.022” NiTi) (Ormco Corp., California, USA) and three angulations (0°, 5°, and 10°) (Figure 3). Each bracket/wire/angulation combination was tested five times in 30 settings. A total of 150 runs were performed.

**SEM observation**

To verify the integrity of the various brackets, LV-SEM was used to observe the front design and bracket base before the test. The bracket bases and bovine tooth surfaces were evaluated after the shear bond strength test to observe the mode of failure and enamel surfaces. The front and lateral slot surfaces and archwires were also evaluated before and after the friction test to observe the effect of binding on the angles and roughness of the bracket slots. ARI scores and bracket slots widths were calculated using ImageJ. ImageJ is a software and an open source image processing program designed for scientific multidimensional images.

**Statistical analysis**

In the shear bond test, the data were analyzed using the Analysis ToolPak in Excel and the Statistical Package for Social Sciences (version 8.0 for Windows; SPSS Japan Inc, Japan). In the friction behavior test, the mean of the kinetic frictional force was determined by averaging the data for 1- to 2-mm displacement. The mean and standard deviation of the frictional force were calculated using the Analysis ToolPak in Excel.
deviations of each combination of brackets, archwires, and angulations were calculated. Statistics analysis comparing groups was performed using one-way analysis of variance (ANOVA). Thereafter, Tukey’s honestly significant difference (HSD) test was performed for multiple comparisons of means. A p value of less than 0.05 was considered statistically significant.

RESULTS

Shear bond strength test

Shear bond strength (SBS) (MPa) was calculated as the force (N) divided by the bracket surface area (mm²). The means and standard deviations of the SBSs of the five types of bracket are shown in Table 3. The results showed that DamonClear2 had the highest bond strength among the 5 brackets, with significant differences found. GeniusCrystal had the lowest bond strength; however, it was not significantly different from those for the other brackets.

The means and standard deviations of ARI scores are shown in Table 4. The distribution of ARI scores for each group is shown in Figure 4. ClarityAdvanced and DamonClear2 had the highest and lowest ARI scores, respectively. An analysis of ARI scores revealed that the ARI score for ClarityAdvanced was significantly higher than those for GeniusCrystal and DamonClear2.

Friction behavior test

The means and standard deviations of frictional force values of various combinations of brackets and wire angulations for the 0.014” Cu–NiTi archwire and 0.016” × 0.022” NiTi archwire are shown in Table 5 and Table 6, respectively. In general, the friction force of ClarityAdvanced was the highest among five types of brackets. All brackets had higher friction forces when coupling with rectangular wires than those coupling with round wires. Although the frictional force value increased with angulation, there are some differences between these two wire types. For the rectangular wire, the increasing rate was greater and the slope was steeper than those for the round wire (Figure 5).

In statistical analysis, when the bracket type as a parameter was used, a comparison of frictional forces with two different wires and three angulations is shown in Table 7. When coupled with 0.014” Cu–NiTi, the friction force of ClarityAdvanced, which had the highest friction level with statistically

<table>
<thead>
<tr>
<th>Bracket brand</th>
<th>Bracket base area (mm²)</th>
<th>Shear bond strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>ClippyC</td>
<td>16.50</td>
<td>6.74</td>
</tr>
<tr>
<td>GeniusCrystal</td>
<td>12.65</td>
<td>4.32</td>
</tr>
<tr>
<td>DamonClear2</td>
<td>16.00</td>
<td>11.14*</td>
</tr>
<tr>
<td>ClarityAdvanced</td>
<td>15.60</td>
<td>7.19</td>
</tr>
<tr>
<td>Damon3MX</td>
<td>11.90</td>
<td>5.56</td>
</tr>
</tbody>
</table>

*: p < 0.05.
significant differences from those of the other brackets except that of ClippyC bracket at an angulation of 10°. When coupled with 0.016" × 0.022" NiTi, ClarityAdvanced had a significantly higher friction force than those of the other brackets at an angulation of 0°. Damon3MX had a significant lower friction force than those of ClarityAdvanced and ClippyC at an angulation of 0° and that of ClarityAdvanced at an angulation of 5°. There were no significant differences in friction forces among groups at an angulation of 10°.

Then, angulation as a parameter was analyzed. Statistical analysis showed that there was no significant difference in friction force between angulations of 0° and 5°, but there was a significant difference between angulations of 0° and 10° for the same brackets (Table 8). Regarding the change of force when angulation was changed from 5° to 10°, most wire-bracket groups showed significant differences except ClarityAdvanced for 0.016" × 0.022" NiTi.

### Table 4. Means and standard deviations of ARI scores.

<table>
<thead>
<tr>
<th>Bracket brand</th>
<th>ARI score</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard deviation</td>
<td></td>
</tr>
<tr>
<td>ClippyC</td>
<td>3.25</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td>GeniusCrystal</td>
<td>3.00</td>
<td>1.76</td>
<td></td>
</tr>
<tr>
<td>DamonClear2</td>
<td>2.92</td>
<td>*</td>
<td>1.38</td>
</tr>
<tr>
<td>ClarityAdvanced</td>
<td>4.75</td>
<td></td>
<td>0.97</td>
</tr>
<tr>
<td>Damon3MX</td>
<td>3.33</td>
<td></td>
<td>1.92</td>
</tr>
</tbody>
</table>

*: p < 0.05.

![Figure 4. Bar graph of ARI score distribution for various brackets.](image)
Table 5. Mean frictional forces and standard deviations of 0.014” Cu–NiTi with various angles for five types of bracket.

<table>
<thead>
<tr>
<th>Brackets</th>
<th>Mean frictional force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°</td>
</tr>
<tr>
<td>ClippyC</td>
<td>0.02 ± 0.02</td>
</tr>
<tr>
<td>GeniusCrystal</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>DamonClear2</td>
<td>0.01 ± 0.00</td>
</tr>
<tr>
<td>ClarityAdvanced</td>
<td>1.00 ± 0.27</td>
</tr>
<tr>
<td>Damon3MX</td>
<td>0.00 ± 0.00</td>
</tr>
</tbody>
</table>

Table 6. Mean frictional forces and standard deviations of 0.016” × 0.022” NiTi with various angles for five types of bracket.

<table>
<thead>
<tr>
<th>Brackets</th>
<th>Mean frictional force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°</td>
</tr>
<tr>
<td>ClippyC</td>
<td>1.05 ± 0.38</td>
</tr>
<tr>
<td>GeniusCrystal</td>
<td>0.74 ± 0.59</td>
</tr>
<tr>
<td>DamonClear2</td>
<td>0.64 ± 0.44</td>
</tr>
<tr>
<td>ClarityAdvanced</td>
<td>2.06 ± 0.43</td>
</tr>
<tr>
<td>Damon3MX</td>
<td>0.18 ± 0.10</td>
</tr>
</tbody>
</table>

SEM observation

Under 20X magnification with LV-SEM, the front view, lateral view, and bracket base were shown in Figure 6. Different bases of brackets were found as followings: rivet lock on ClippyC, small mesh and bead on GeniusCrystal, large mesh and laser-etched base on DamonClear2, microcrystalline with central stress concentrator on ClarityAdvanced, and small mesh on Damon3MX.

From the front view of the five types of bracket slot at 100X magnification before the friction test under SEM, it is noticed that ClippyC had a small bevel angle (Figure 7). GeniusCrystal had a medium rounded angle, and DamonClear2 and Damon3MX had large rounded angles. ClarityAdvanced had the smallest rounded angle. From the lateral view, images were taken when the bracket clips were open and closed at 65X magnification. Then, to evaluate the self-ligating bracket slot dimensions in the clip closed images, the narrowest depths of the slots were calculated. ClippyC had the smallest depth (0.42 mm) among the self-ligating brackets. DamonClear2 (0.67 mm) and Damon3MX had similar slot depths (0.64 mm), and GeniusCrystal had the largest slot depth (0.77 mm) among the four self-ligating brackets.

Table 7. Statistical analysis with bracket type used as parameter.

<table>
<thead>
<tr>
<th>Bracket brand comparison</th>
<th>Difference of mean frictional force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ClippyC vs.</td>
<td></td>
</tr>
<tr>
<td>GeniusCrystal</td>
<td>0.01 ± 0.00 0.01 ± 0.01 0.16 ± 0.06 0.82 ± 0.62</td>
</tr>
<tr>
<td>DamonClear2</td>
<td>0.00 ± 0.00 0.01 ± 0.01 0.01 ± 0.01 0.69 ± 0.56</td>
</tr>
<tr>
<td>ClarityAdvanced</td>
<td>0.00 ± 0.00 0.00 ± 0.00 0.00 ± 0.00 0.82 ± 0.62</td>
</tr>
<tr>
<td>Damon3MX</td>
<td>0.00 ± 0.00 0.00 ± 0.00 0.00 ± 0.00 0.82 ± 0.62</td>
</tr>
</tbody>
</table>

Table 8. Statistical analysis with angulation used as a parameter.

<table>
<thead>
<tr>
<th>Angulation comparison</th>
<th>Difference of mean frictional force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ClippyC</td>
<td>0.016” × 0.022” NiTi</td>
</tr>
<tr>
<td>0° – 5°</td>
<td>1.48 ± 0.71 1.48 ± 0.71 1.48 ± 0.71 1.48 ± 0.71</td>
</tr>
<tr>
<td>0° – 10°</td>
<td>4.64 ± 2.67 4.64 ± 2.67 4.64 ± 2.67 4.64 ± 2.67</td>
</tr>
<tr>
<td>5° – 10°</td>
<td>3.16 ± 1.88 3.16 ± 1.88 3.16 ± 1.88 3.16 ± 1.88</td>
</tr>
</tbody>
</table>

*: p < 0.05; **: p < 0.01.
The bracket slots were observed after the friction test under SEM. There was little or no effect to the ceramic and metal slot surfaces for both round and rectangular wires when angulations of NiTi wire within 10° degrees (Figs. 8 and 9). However, wire scratches were noted for round wires except coupled with DamonClear2 and ClarityAdvanced brackets and nicks on the archwires were observed for rectangular wires coupled with all kinds of brackets (Figure 10).

DISCUSSION

Effect of parameters on bond strength

Multiple factors, such as tooth cleaning, enamel conditioning, primer application, substrate type, bonding material, bracket materials, bracket design, polymerization lamp, and bracket reuse, are known to affect bond strength.7 In the present study, we used the same adhesive system, polymerization machine, and bonding conditions, and so the discussion focuses on the substrate, base design, and bracket material.

Bovine teeth have been used as substitutes for human teeth due to their similarity in histochemical composition and mineralization degree to those of human teeth. In 1998, a study found that bond strengths to primary and permanent bovine enamel were 21% and 44% weaker than those to permanent human enamel.6 In a review, four studies reported that the bonding strength of bovine teeth is less than that of human teeth. Seven studies reported that there was no significant difference between the bond strengths of bovine and human teeth, and no studies reported that the bonding strength of bovine teeth was stronger than that of human teeth. An optimum bond strength range of 5.88–13.53 MPa was suggested in another review article on bonding systems in orthodontics.1 In the present study, we used bovine teeth as substrates in the bonding test. The bond strength range was between 4.32 and 11.14 MPa, which is lower than those in previous studies. This may be due to different preparation
methods of bovine tooth surfaces in the various studies. All brackets in this study except GeniusCrystal (4.32 MPa) were in this range. However, concerning the substrate of bovine tooth, underestimation of the bonding strength should be taken into consideration.

About bracket design, six types of metal bracket base were evaluated in vitro in one study. Among the metal brackets with mesh-type bases, larger base and mesh spacing led to greater bond strength. The authors speculated that the free volume between the mesh and base allows the penetration of resin and escape of air, enhancing bonding. Metal bracket bases and bovine teeth were used as substrates in another study. The results revealed that a non-homogenous base shape with a pronounced tip had the lowest bond strength. A rectangular base shape had the highest bond strength, which was significantly different from those of other shapes. The geometrical shapes might allow for uniform force distribution within the enamel-resin-base system. A pronounced tip at the base might lead to peak stress concentration and initiate a crack, resulting in bond failure. In the present study, DamonClear2 had a homogenous base design with a large mesh and without a pronounced tip, and thus was expected to have good bond strength. ClarityAdvanced, with its microcrystalline mechanical lock design and stress concentrator, had good bond strength but still had the highest ARI. GeniusCrystal and Damon3MX had a pronounced tip base and a smaller base area compared to those of the other ceramic brackets, and had lower bond strength.

Mentioned about material, ceramic brackets have several advantages, such as high rigidity, high abrasion resistance, stable properties, and good esthetics. In the early stage, ceramic brackets were bonded using a silane coupling agent with adhesives. However, silane coupling was so strong that debonding frequently caused enamel peeling or cracking. An in vitro study of ceramic brackets showed significantly higher bond strength (24.25 MPa) than that of stainless-steel brackets (17.8 MPa). The possibility of enamel fracture was higher in the ceramic bracket, especially for nonvital teeth. In recent years, mechanical retention base design using light-polymerized resin has been used to limit adhesion strength and reduce the problem of debonding. In the present study, DamonClear2 showed a significantly higher shear bond strength compared to those of ClarityAdvanced, ClippyC, Damon3MX, and GeniusCrystal. The SBS of most ceramic brackets is thus higher than that of metal brackets, but the differences between these two materials are gradually decreasing.

Possible failure types after bracket debonding are adhesion between the enamel and the adhesive resin, partial adhesion and cohesion in the adhesive resin (mixed), and adhesion between the bracket base and the adhesive resin. The ARI scores enable the clinician to determine the bracket–failure interface. A low score is interpretable as a failure between the enamel and the adhesive interface, and a high score indicates a failure between the bracket base and the adhesive interface. Most groups except ClarityAdvanced were shown 25–50% adhesive remained on the tooth, which suggests a risk of enamel fracture when the bracket debonded. A previous study stated that damage to the enamel is inevitable in orthodontic applications. The results of the study also revealed that there was no correlation between the enamel surface index and ARI tooth scores. Another study found enamel loss after bracket debonding and found no association between shear bond strength and resin area. Our finding is consistent with previous results that showed that SBS is not associated with remnant resin area.

Effect of parameters on friction behavior

Frictional resistance of orthodontic appliances is recognized by most clinicians to be detrimental to tooth movement. Several parameters must be considered for friction, including material, roughness, hardness, wire stiffness, geometry, fluid media, and surface chemistry. Some parameters are discussed below.

A comparison of friction between stainless steel and ceramic brackets is given below. The results of one study demonstrated that under experimental conditions, ceramic brackets, nitinol arch wires, and saliva all increased static frictional resistance. Another study selected one conventional ceramic bracket, one conventional ceramic bracket with stainless steel slot, and one conventional stainless steel bracket coupled with three orthodontic wire alloys: stainless steel, nickel-titanium, and beta-titanium. This study demonstrated that metal-insert ceramic brackets generated significantly lower frictional forces than those of conventional ceramic brackets, but they still had higher forces than those of stainless-steel brackets. Beta-titanium archwires showed higher frictional resistances than those of stainless steel and nickel-titanium archwires.

Five types of brackets were chosen in this study. Four kinds of brackets were polycrystalline ceramic brackets and one was metal bracket. Regarding bracket type, the frictional resistance for the conventional ceramic bracket (ClarityAdvanced) was

---


C.-L. WU ET AL

BOND STRENGTH AND FRICTION OF SELF-LIGATING CERAMIC BRACKET
larger than that for the active ceramic self-ligating bracket (ClippyC), followed by those for the passive ceramic self-ligating bracket (GeniusCrystal & DamonClear2) and metal self-ligating bracket (Damon3MX). Another study selected Damon3MX (metal PSLB), Quick (metal ASLB), ClippyC (ceramic ASLB), and Micro-arch (conventional metal brackets) brackets coupled with 0.018" and 0.019" × 0.025" stainless steel wires. The results revealed that the metal PSLB showed the lowest frictional force, conventional brackets had the highest frictional force, which is consistent with the results of our study. It is indicated that ligation for conventional brackets contributed to friction resistance.

When angulation as a parameter to compare resistance to sliding, a previous study showed that the frictional force values were proportional to the angulation between the bracket and wire. In our research, all the bracket–wire combinations had no significant differences between 0° and 5°, whereas significant differences were found between 5° and 10° in all groups except the conventional ceramic brackets. The reason may be due to a critical contact angle. In the present study, the critical contact angles of the five kinds of bracket were calculated according to a theoretical equation for two archwire sizes. Most of the angles were within 4°, which is consistent with the previous study, which suggested that clinicians align and level brackets to within 4° prior to sliding. The frictional force differs when binding occurs, and changes with the relative dimensions of the wire size, slot size, and bracket width. Generally, the trends revealed that the frictional force increases as the rotational angle increases when less clearance exists. Most brackets in

---

Figure 7. Front view of slots of five types of bracket slot at 100X magnification and lateral view (clips open and closed) at 65X magnification before friction test except bracket of ClarityAdvanced.
the present study had rounded or beveled slot design, which may help expand the contact angle range. The edge-off structure of the Tip-Edge Plus bracket and Transmission Straight Archwire bracket help to expand the passive configuration range.\textsuperscript{18} This finding is consistent with another study, which found that a larger bevel angle of the self-ligating brackets resulted in lower friction.\textsuperscript{19} The critical contact angle may be not influenced by slot size and width only, but also by ligation, material, and bracket design. So the theoretical equation indicates that the critical contact angle is 4°, the clinical critical contact angle may be between 5° and 10°.

Moreover, no significantly different friction force was found among the five types of brackets in the 0.016\textsuperscript{00} × 0.022\textsuperscript{00} NiTi 10° group in the present study. The results suggest that there binding happened and that friction becomes small, which dominates resistance to sliding. In the active configuration and with low clearance, self-ligating brackets and

---

**Figure 8.** Front view of five types of bracket at 100X magnification and lateral view at 65X magnification after 0.014° Cu–NiTi test.
conventional brackets have no significant differences. The clinical advantage of reduced resistance to sliding should be a reduction in the amount of time required to align the teeth and close the spaces. However, a limited number of clinical studies have compared self-ligating brackets and conventional brackets in either non-extraction or extraction cases, and the results showed that treatment time was not significantly different, which is consistent with the present study.

**SEM observation**

No obvious scratches or wear were observed on the bracket slots after the friction test in either the 0.014" Cu–NiTi or 0.016" × 0.022" NiTi wire group. This indicates that NiTi wire did not cause wear on the ceramic bracket slot surface within 10" in this experimental design. However, nicks in archwires were noticed in every group, particularly in the rectangular archwires. Furthermore, it was noticed
that the slot dimension affected the frictional force. Although all manufacturers claim that the slot sizes of these brackets are $0.022'' \times 0.028''$, the slot dimensions had minor variations in our observations. ClippyC had the smallest depth (0.42 mm) among the self-ligating bracket, and GeniusCrystal had the largest slot depth (0.77 mm) among the four self-ligating brackets. This may explain why ClippyC had the largest frictional force among the self-ligating brackets, and GeniusCrystal had the lowest frictional force at an angulation of $10^\circ$.

**Limitation of study**

The limitations of this study are as follows. Due to the limited sample size, statistical bias may exist in some groups. Moreover, the SBSs may be underestimated due to the substrate, which may not coincide with the clinical situation. The present study measured kinetic frictional force as the average data for 1- to 2-mm displacements. However, in orthodontic treatment, tooth sliding along the archwire via tip-upright-tip-upright movement combines both static and kinetic frictional forces. In
addition, the friction experiments were conducted with angulations of 0°, 5°, and 10°, which cannot provide detailed information about the turning points of frictional forces. Moreover, the friction test was conducted in a constant-temperature environment. The complicated oral environment and biomechanics in orthodontic treatment are difficult to simulate accurately and consistently. Still, this in vitro study provides valuable information on the bond strengths and resistance to sliding for current ceramic self-ligating brackets.

CONCLUSION

It is found that DamonClear2 had the highest bond strength. The ARI score of ClarityAdvanced as significantly higher than those of GeniusCrystal and DamonClear2. In friction behavior test, ClarityAdvanced generally had a larger frictional force than those of the self-ligating brackets, except for 0.016" × 0.022" NiTi with an angulation of 10°.

ACKNOWLEDGMENTS

This investigation was supported by a grant from Taiwan Association of Orthodontists.

Conflicts of interest statement

The authors declare that there is no conflict of interest.

REFERENCES