Original Article

Fracture Strength of Ceramic Bracket Tie Wings Subjected to Tension

Gerald Johnson, DDS[a]; Mary P. Walker, DDS, PhD[b]; Katherine Kula, DDS, MS[c]

Abstract: One of the most common areas of ceramic bracket fracture is within the tie-wing complex. When an archwire is ligated into position, tensile forces are placed under the tie wing. However, no study, to date, has focused specifically on the fracture resistance of the tie-wing complex. The aim of this study is to compare the tensile fracture strength of seven currently available ceramic brackets (Inspire, Fascination, Mystique, InVu, Clarity, Virage, and Luxi) as a function of bracket brand and bracket configuration, semitwin vs true-twin. Based on a power analysis of pilot data, 10 maxillary central incisor brackets per group were tested to failure with a tensile load placed directly under the distoincisal tie wing. The results ranged from a maximum mean fracture strength of 147.71 (5.87) MPa with Fascination brackets to a minimum mean fracture strength of 84.28 (7.01) MPa with Luxi brackets. The statistical analysis indicated a significant effect on fracture strength as a function of bracket brand ($P < .05$) and that semitwin brackets, Fascination, Mystique, and Virage, had significantly higher fracture strength than true-twin brackets, Clarity, InVu, and Luxi ($P < .05$). Interestingly, the only monocrystalline bracket in the study, Inspire, could not be fractured using the investigation protocol. In fact, the steel ligature fixture wire would break before tie-wing fracture at a mean fixture failure of 198.65 MPa. (*Angle Orthod* 2004;75:95–100.)

Key Words: Fracture resistance, Ceramic brackets

INTRODUCTION

The ceramic orthodontic bracket was introduced in 1986, and currently, many types are available from many orthodontic manufacturers.[1–3] Ceramic brackets have been well accepted by patients, clinicians, and the media for their ability to mask the appearance of fixed orthodontic appliances. These new appliances also spurred an increased interest in orthodontics by the adult patient who found these ‘‘white,’’ ‘‘clear,’’ or ‘‘invisible’’ braces much more appealing than the traditional, more highly visible metal brackets.

All ceramic brackets currently in production are made of aluminum oxide (Al_2O_3), also called alumina.[1–4] There are 2 types of ceramic brackets on the market, polycrystalline alumina brackets, the most common type, and single-crystal alumina or sapphire brackets.

[a] Department Head, Orthodontics, US Navy, Naples, Italy.

[b] Associate Professor, Director of Dental Biomaterials, University of Missouri-Kansas City School of Dentistry, Kansas City, Mo.

[c] Associate Professor, Chair, Department of Orthodontics and Dentofacial Orthopedics, University of Missouri-Kansas City School of Dentistry, Kansas City, Mo.

Corresponding author: Mary P. Walker, DDS, PhD, Director of Dental Biomaterials, UMKC School of Dentistry, 650 E 25th Street, Kansas City, MO 64108 (e-mail: walkermp@umkc.edu).

Accepted: March 2004. Submitted: January 2004.

Although esthetics is an obvious, inherent advantage of ceramic brackets, they have do have several disadvantages, such as high brittleness and increased susceptibility to fracture.[1–3] Therefore, important mechanical properties related to clinical function are tensile strength and fracture resistance.[3] Tensile strength is defined as the ratio of the maximum load a material can support without fracture when being stretched or elongated.[5] The elongation of a ceramic at failure is less than 1%, whereas that of stainless steel is roughly 20%.[3,4,6] The metallic bonding structure of metals permits them to be significantly distorted without fracturing, even when compositional impurities exist or when stress is concentrated at geometric interfaces.[3,5] When stress is placed on a metal, grain boundaries shift, which redistributes and relieves the stress. Shifting of atomic bonds and redistribution of stresses does not occur within the ionic bonding atomic arrangement of ceramics. Thus, ceramics are much more brittle and have much lower tensile strength than metals.[3,5,6] In addition, ceramic bulk tensile strength is also dependent on both the thickness of the material[7] and the material surface condition with associated defects.[3,5,6,8] Thus, the manufacturing process itself plays a very important role in the strength of a ceramic.[1–4,6,8–11] The presence of pores, machining damage from milling, and cracks all contribute to the reduction in fracture strength of a ceramic bracket.[4] Therefore, it is necessary to test and compare actual ceramic brackets, rather than bulk bracket materials.[3,6]

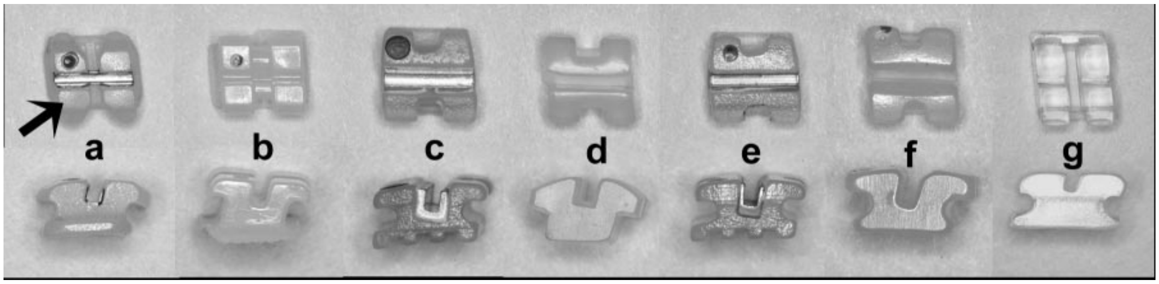

FIGURE 1. Facial and distal views of ceramic brackets. (a) Clarity, (b) InVu, (c) Luxi, (d) Fascination, (e) Virage, (f) Mystique, and (g) Inspire. Arrow in (a) indicates orientation of the distoincisal tie wing used for each bracket type mechanical testing.

TABLE 1. Brackets Tested

Brand	Manufacturer	Configuration	Crystalline Structure
Clarity	3M Unitek, St Paul, Minn	True-twin	Polycrystalline
InVu	TP Orthodontics, LaPorte, Ind	True-twin	Polycrystalline
Luxi II	Rocky Mountain Orthdontics, Denver, Colo	True-twin	Polycrystalline
Fascination	Dentaurum, Newton, Pa	Semi-twin	Polycrystalline
Virage	American Orthodontics, Sheboygan, Wis	Semi-twin	Polycrystalline
Mystique	GAC International, Bohemia, NY	Semi-twin	Polycrystalline
Inspire	Ormco, Orange, Calif	True-twin	Monocrystalline

Published research on ceramic brackets has examined fracture strength using tipping, torsion, shear, and impact forces.[4,8,10–14] However, most of the brackets tested in published studies are no longer in production, with newer, untested brackets now on the market. In addition, one of the most common areas of ceramic bracket fracture is within the tie-wing complex itself or at the interface of the tie wing and base.[15] When an archwire is ligated into position, the tie wing is subjected to tensile forces. However, no study, to date, has focused specifically on the fracture strength of the tie-wing complex. The tie-wing complex is manufactured in either of two configurations, classified as either true-twin or semitwin. Semitwin differs from twin by containing a bulk piece of ceramic connecting the mesial and distal tie wings.[3]

The aim of this study is to evaluate the most popular ceramic brackets presently on the market to compare the fracture strength of the tie-wing complex when a tensile load is placed directly under the tie wing. The hypothesis tested was that there would be a significant difference in tie-wing fracture strength as a function of bracket brand. A second hypothesis tested was that there would be a significant difference in tie-wing fracture strength between semitwin and true-twin ceramic bracket configurations.

MATERIALS AND METHODS

Seven different brands of brackets (Figure 1a through g; Table 1) were tested. All brackets were polycrystalline, except one. Maxillary right central incisor brackets with a slot size of 0.018 inches were used. Based on a pilot study and power analysis, it was determined that a sample of 10 brackets per group was needed for a 20% effect size change to represent a statistically significant difference in fracture strength. The sample size was calculated with $\alpha = .05$ and power $= .80$.

Specimen preparation

The brackets were bonded to stainless steel cylinders. The cylinder-bracket complex (Figure 2) was used with a universal testing machine (Instron 1123/5500, Canton, Mass). To enhance bond strength, so that bracket debonding would not occur before bracket fracture, the cylinders were roughened with a laboratory microabrasion system using 50-μm Al_2O_3 particles (Micro-Cab®, Danville Engineering, Danville, Calif). After cleaning with acetone, Siloc Pre® (Heraeus Kulzer, Armonk, NY) metal surface conditioner was applied to the abraded cylinder and allowed to dry for 1 minute. The cylinder was then placed in an oven for 4 minutes at 350°C. After 5 minutes of cooling at ambient room temperature, both the cylinder and bracket mesh were coated with 3M Scotchbond Ceramic Primer® (3M Unitek, St Paul, Minn) using a brush. The cylinder and bracket mesh were allowed to dry for 1 minute.

Scotchbond Multipurpose Adhesive® (3M) was then applied to both the cylinder and bracket mesh using a brush and each surface light polymerized for 40 seconds. Transbond® (3M Unitek), a composite resin cement, was applied to the bracket mesh and the bracket placed on the cylinder. To further stabilize, composite resin cement was added over the bracket base and flowed onto the cylinder. Care was taken to ensure that no composite flowed under the tie wing or into the archwire slot. The composite was light poly-

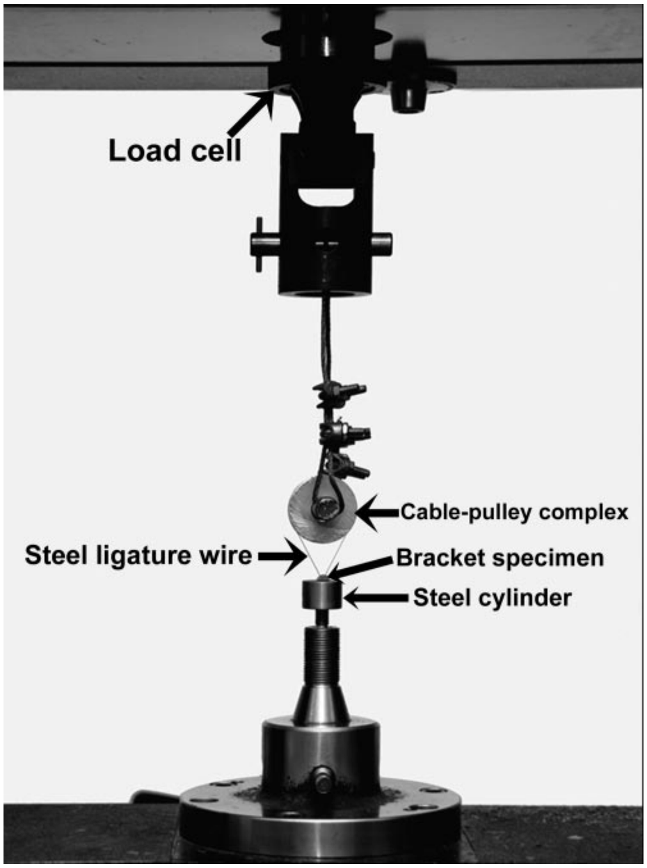

FIGURE 2. Mechanical testing apparatus.

FIGURE 3. A 0.014-inch steel ligature wire looped under the distoincisal tie wing for tensile testing.

merized from 5 directions (mesial, distal, gingival, incisal, facial) for 40 seconds each.

Mechanical testing

A 0.014-inch steel ligature tie wire (GAC International, Bohemia, NY) was looped under the distoincisal tie wing and tied around a grooved steel pulley attached to the mechanical tester load cell (Figures 2 and 3). A 0.014-inch wire was necessary because smaller diameter wires were prone to fail before bracket failure. Distoincisal tie wings were tested to failure at a crosshead speed of 10 mm/min. The tensile force/load at failure was recorded with Merlin software (v 5.43, Instron Corp). Fracture stress or strength (MPa) was calculated by dividing the force (N) by the area of contact between the ligature wire and tie wing.

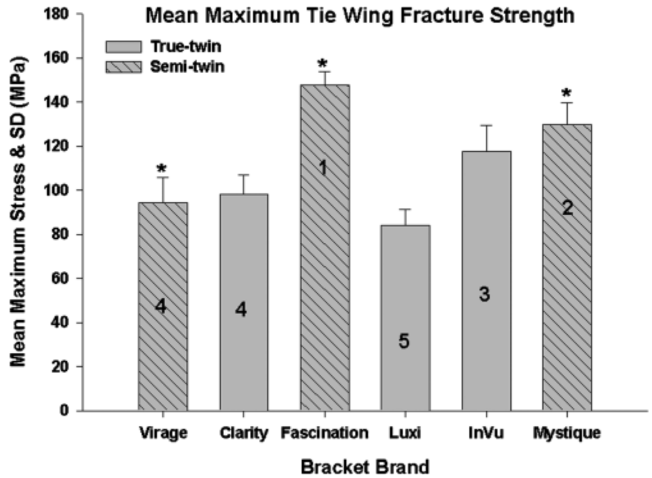

FIGURE 4. Mean fracture strength between brands is significantly different ($P < .05$). Bracket brand post hoc test subsets ($\alpha = .05$) are indicated by 1–5. *Based on bracket configuration, the mean tie-wing fracture strength of semitwin brackets was also significantly higher than the mean tie-wing fracture strength of the true-twin brackets ($P < .05$).

A 1-way analysis of variance (ANOVA) was used to determine if there was a significant difference between fracture strength as a function of both bracket brand and bracket configuration (semitwin vs true-twin). If a significant difference existed between brands, a Duncan's post hoc test was used to identify which brands were significantly different.

RESULTS

The tie-wing mean maximum fracture strength (stress) results are presented in Figure 4. The results reflect both the brand of the bracket and the bracket configuration. Although Inspire brackets (Ormco, Orange, Calif) were also part of this investigation, the tie wings of these brackets could not be fractured using the investigation protocol. Attempts were made to break the Inspire tie wings, but the steel ligature wire would fail at a mean of 198.65 MPa before tie-wing fracture. Thus, results from these brackets were not included in the statistical analysis.

Mean maximum fracture strength and SDs because of brands varied from 84.28 (7.01) to 147.71 (5.87) MPa. The statistical analysis (Table 2) indicated that there was a significant effect on maximum bracket tie-wing fracture strength because of bracket brand ($P < .05$). A Duncan's post hoc test (Table 3) indicated that the fracture strength of Fascination (Dentaurum, Newton, Pa) was significantly higher than all other brands, whereas Mystique (GAC) and

TABLE 2. One-Way Analysis of Variance of Bracket Brand Results, Fracture Strength (MPa) Tests of Between-Subjects Effects

Source	Type III Sum of Squares	Degrees of Freedom	Mean Square	*F*	Significance	Partial Eta Squared	Observed Power[a]
Corrected model	289.41	5	5782.68	66.16	.000	.860	1.000
Intercept	753,545.23	1	753,545.23	8621.16	.000	.994	1.000
Brand	28,913.41	5	5782.68	66.16	.000	.860	1.000
Error	4719.58	54	87.40				
Total	787,178.22	60					
Corrected total	33,632.99	59					

[a] Computed using $\alpha = .05$.

TABLE 3. Duncan's Post Hoc Test[a] of Mean Fracture Strength (MPa) as a Function of Bracket Brand

		Subset				
Brand	N	1	2	3	4	5
Fascination	10	147.71				
Mystique	10		129.93			
InVu	10			117.67		
Clarity	10				98.36	
Virage	10				94.46	
Luxi	10					84.28
Significance	10	1.000	.355	1.000	1.000	1.000

[a] $\alpha = .05$. Means for groups in homogeneous subsets are displayed. Based on Type III sum of squares.

TABLE 4. One-Way Analysis of Variance of Bracket Configuration Results, Fracture Strength (MPa). Tests of Between-Subjects Effects

Source	Type III Sum of Squares	Degrees of Freedom	Mean Square	*F*	Significance	Partial Eta Squared	Observed Power[a]
Corrected model	8591.11	1	8591.11	19.90	.000	.255	.992
Intercept	753,545.23	1	753,545.23	1745.30	.000	.968	1.000
Configuration	8591.101	1	8591.11	19.90	.000	.255	.992
Error	25,041.88	58	431.76				
Total	787,178.22	60					
Corrected total	33,632.99	59					

[a] Computed using $\alpha = .05$.

InVu (TP Orthodontics, LaPorte, Ind) were ranked second and third, respectively. Both Clarity (3M Unitek) and Virage (American Orthodontics, Sheboygan, Wis) were ranked fourth, and Luxi (Rocky Mountain Orthodontics, Denver, Colo) had the lowest fracture strength. Based on configuration, the mean maximum tie-wing fracture strength and SDs were 100.10 (16.60) and 124.03 (24.25) MPa for true-twin and semitwin, respectively. A 1-way ANOVA (Table 4) indicated that the fracture strength difference related to bracket configuration was also statistically significant ($P < .05$).

Based on these results, the hypothesis that bracket tie-wing fracture strength would vary because of bracket brand was accepted, and the hypothesis that tie-wing fracture strength would vary because of bracket configuration was also accepted. However, although both hypotheses were accepted, it is important to note that the partial Eta-squared values were .255 and .860, for configuration and brand, respectively. Based on Cohen's criteria,[16] this suggests that only approximately 25% of the fracture strength variance was related to configuration, whereas approximately 86% of the tie-wing fracture strength variance was related to bracket brand.

DISCUSSION

This experiment was designed to study tie-wing tensile fracture strength of commercially available ceramic brackets as a function of brand and tie-wing configuration. Among the polycrystalline alumina brackets tested, semitwin brackets (Fascination, Mystique, Virage) had statistically significant higher fracture strength, mean 124.03 (24.25) MPa, as compared with true-twin brackets (Clarity, InVu, Luxi), mean 100.10 (16.60) MPa. This difference in tie-wing fracture strength as function of configuration can be explained on the basis of morphological characteristics because, with the semitwin design, the mesial and distal tie wings can be thought of as 1 unit. There is a bulk piece of ceramic connecting the mesial and distal tie wings that, in turn, has a cross-stabilizing effect.[3] The mesial and distal tie wings are not independent projections from the bracket base as is the case in a true-twin design.

Based on brand, Fascination (Figure 1d) had the statistically highest mean maximum tie-wing fracture strength, 147.71 (5.87) MPa, of all polycrystalline, semitwin brackets in the study. According to the manufacturer,[17] Fascination brackets are subjected to a specialized hardening process, which may explain the high tie-wing fracture strength found in this study. The results of this investigation would also support previous reports of Fascination brackets exhibiting high fracture strength from impact forces and moments related to second-order bends.[10,13]

Mystique brackets (Figure 1f), also semitwin, followed Fascination with a mean fracture value of 129.93 (9.69) MPa. Mystique's manufacturer claims that its rare gas resintering process helps strengthen the polycrystalline alumina.[18]

Virage, although a semitwin, did not perform nearly as well as Fascination or Mystique. In fact, it had the second lowest mean fracture strength value at 94.46 (11.54) MPa. One reason this semitwin may not have performed as well as the other semitwins may simply be related to its proportions (Figure 1e). Both the ceramic component connecting the mesial and distal tie wings and the tie wings themselves were thinner labiolingually than Fascination and Mystique. In addition, the base of the Virage tie wings was thinner occlusogingivally. Another plausible reason for Virage's performance may be related to its surface characteristics. Looking at Figure 1e, it is apparent that the Virage surface is rough as compared with the surface of the other semitwins, Mystique and Fascination. Ceramic surface defects and roughness can significantly reduce the fracture strength of ceramics.[3,5,6]

InVu proved to be the most resistant polycrystalline true-twin, with mean tie-wing fracture occurring at 117.76 (11.82) MPa. Among the polycrystalline brackets tested, it ranked third behind Fascination and Mystique. Statistically, InVu performed significantly better than the other polycrystalline true-twin brackets (Clarity and Luxi), as well as the semitwin Virage. InVu brackets (Figure 1b) are manufactured using an injection molding process, which the manufacturer claims will produce a much smoother, less irregular surface than a machined ceramic bracket.[19] This may explain InVu's higher tie-wing tensile fracture strength when compared with other machined true-twins because machining damage and associated surface defects can serve as foci for fracture.[6]

Clarity, a true-twin, had a mean fracture of the tie wing at 98.36 (8.61) MPa. Of the polycrystalline brackets tested, Clarity ranked fourth overall and again, the lower fracture strength is probably related to the true-twin design (Figure 1a).

Whereas results indicated that Luxi had the lowest mean tie-wing fracture strength at 84.28 (7.01) MPa, for clarification purposes, it should be pointed out that although the gingival wings of the Luxi bracket are of the semitwin design, the incisal wings have only a very small ceramic connection (Figure 1c). Therefore, for the purposes of this experiment Luxi was classified as a true-twin design because only the distoincisal wing was tested. Luxi's low fracture stress levels may be explained in the same manner as that of Virage. Like Virage, both Luxi's tie-wing base and tie wing were thin occlusogingivally and labiolingually, when compared with the other brackets tested. Moreover, Luxi has a rough surface very similar to that of Virage. This combined with the true-twin design characteristics of the incisal wings may explain its low tie-wing tensile fracture strength.

As stated in the ''Results'' section, the tie wing of the monocrystalline Inspire bracket could not be fractured using the experimental protocol used in this investigation. Several attempts were made to break the distoincisal tie wing of the Inspire brackets (Figure 1g). Each time, however, the steel ligature tie would break before tie-wing fracture (mean steel ligature failure at 198.65 MPa).

From a materials standpoint, the high fracture strength of the monocrystalline Inspire bracket can be explained by the fact that monocrystalline alumina has a much higher tensile strength than polycrystalline alumina.[1,2,6] Monocrystalline alumina has been reported to have a tensile strength of roughly 1800 Mpa, whereas that of polycrystalline alumina is 380 MPa. Monocrystalline ceramics are also not susceptible to ceramic grain pluck-out or pull-out at the ceramic surface as is true of polycrystalline ceramics.[9] A missing grain fragment can drastically reduce fracture strength of polycrystalline ceramics.

Although the high fracture strength results of the monocrystalline bracket tested in this investigation would suggest that only monocrystalline brackets should be selected for clinical use, there are other factors that must be considered. Even though all ceramics are hard, the synthetic sapphire used for monocrystalline brackets is the third hardest substance known to man, roughly nine times harder than stainless steel or enamel.[2] Thus, severe enamel abrasion can occur very quickly when monocrystalline brackets occlude with enamel.[3] In addition, the brackets tested in this study were new and thus had no surface damage from clinical application. However, ceramic brackets will probably not remain scratch-free for long with clinical function. Although polycrystalline brackets, which contain more initial surface flaws,[1,6,11] are weaker than monocrystalline brackets, a previous investigation reported that there was no significant decrease in polycrystalline fracture strength after purposeful scratching of the bracket slot base to simulate potential clinical damage.[20] In contrast, after using the same scratch protocol, monocrystalline bracket fracture strength was significantly reduced, and the resultant monocrystalline strength was similar to polycrystalline bracket fracture strength.[20] Therefore, the additional treatment cost associated with the more expensive monocrystalline brackets may not be justified, leaving polycrystalline brackets as a more realistic and economical option.

The results of this in vitro investigation should be viewed cautiously because laboratory testing cannot exactly model clinical situations. The brackets tested in this study were new, and thus had no potential surface damage from hemostats or ligature tie removers. A future investigation could include placement of a uniform scratch within the tie-wing complex before analysis of the stress levels necessary for tie-wing fracture. In addition, the brackets were tested dry at ambient temperature, which does not resemble the oral environment. Both moisture and body temperature would likely also decrease bracket fracture strength.

The fundamental focus of this investigation was a comparison of tie-wing fracture strength related to bracket brand and bracket configuration. Based on the results of this investigation, both brand and the tie-wing configuration of polycrystalline brackets appear to be significant factors of tie-wing fracture strength.

The evidence would suggest that semitwin polycrystalline brackets will have higher fracture strength; however, the results also suggest that selecting a semitwin bracket with a smoothly processed surface might also improve fracture strength. Although tie-wing thickness was not a variable in this investigation, just as ceramic thickness contributes substantially to the fracture strength of all-ceramic crowns,[7] ceramic thickness also appears to be an important factor of tie-wing fracture strength. A future investigation could more specifically address this issue.

With tie-wing fracture continuing to be a significant problem associated with ceramic brackets, there is still room for improvement in design and manufacturing processes. Ceramics by nature are brittle entities, and fracture will always be a complication. However, further refinements and innovations in fabrication, as well as finishing techniques such as glazing, controlled heat treatment, and sintering to help reduce surface roughness and defect size could potentially reduce fracture susceptibility.

CONCLUSIONS

Based on the results of this in vitro investigation, the following ceramic brackets are listed in order, from most to least resistant to tensile fracture of the distoincisal tie wing: Ormco Inspire (monocrystalline alumina), Dentaurum Fascination, GAC Mystique, TP InVu, 3M/Unitek Clarity, American Orthodontics Virage, and Rocky Mountain Luxi. The six polycrystalline brackets tested fell into five statistically significant and different subsets ($\alpha = .05$); Clarity and Virage were statistically equivalent. Furthermore, as a group, the tie wings of the polycrystalline semitwin ceramic orthodontic brackets had a statistically significant, higher tensile fracture strength than their true-twin counterparts ($P < .05$). Other noteworthy findings include: (1) tie wings with thicker dimensions tend to offer more fracture strength than those with thinner dimensions and (2) brackets with smoother surfaces also tend to have tie wings with higher tensile fracture strength than brackets with rough surface topography.

REFERENCES

1. Birnie D. Ceramic brackets. *Br J Orthod.* 1990;17:71–74.
2. Swartz ML. Ceramic brackets. *J Clin Orthod.* 1988;22:82–88.
3. Karamouzos A, Athanasiou AE, Papadopoulos MA. Clinical characteristics and properties of ceramic brackets: a comprehensive review. *Am J Orthod Dentofacial Orthop.* 1997;112:34–40.
4. Viazis AD, Chabot KA, Kucheria CS. Scanning electron microscope (SEM) evaluation of clinical failures of single crystal ceramic brackets. *Am J Orthod Dentofacial Orthop.* 1993;103:537–544.
5. Anusavice KJ. *Phillips' Science of Dental Materials.* Philadelphia, Penn: WB Saunders Co; 2003:85–86.
6. Scott GE Jr. Fracture toughness and surface cracks—the key to understanding ceramic brackets. *Angle Orthod.* 1988;58:5–8.
7. Lawn BR, Deng Y, Lloyd IK, Janal MN, Rekow ED, Thompson VP. Materials design of ceramic-based layer structures for crowns. *J Dent Res.* 2002;81:433–438.
8. Holt MH, Nanda RS, Duncanson MG Jr. Fracture resistance of ceramic brackets during arch wire torsion. *Am J Orthod Dentofacial Orthop.* 1991;99:287–293.
9. Kusy RP. Morphology of polycrystalline alumina brackets and its relationship to fracture toughness and strength. *Angle Orthod.* 1988;58:197–203.
10. Matasa CG. Impact resistance of ceramic brackets according to ophthalmic lenses standards. *Am J Orthod Dentofacial Orthop.* 1999;115:158–165.
11. Rhodes RK, Duncanson MG Jr, Nanda RS, Currier GF. Fracture strengths of ceramic brackets subjected to mesial-distal archwire tipping forces. *Angle Orthod.* 1992;62:67–76.
12. Gunn S, Powers JM. Strength of ceramic brackets in shear and torsion tests. *J Clin Orthod.* 1991;25:355–358.
13. Lindauer SJ, Macon CR, Browning H, Rubenstein LK, Isaacson RJ. Ceramic bracket fracture resistance to second order arch wire activations. *Am J Orthod Dentofacial Orthop.* 1994;106:481–486.
14. Aknin PC, Nanda RS, Duncanson MG Jr, Currier GF, Sinha PK. Fracture strength of ceramic brackets during arch wire torsion. *Am J Orthod Dentofacial Orthop.* 1996;109:22–27.
15. Gibbs SL. Clinical performance of ceramic brackets: a survey of British orthodontists' experience. *Br J Orthod.* 1992;19:191–197.
16. Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* Hillsdale, NJ: Lawrence Erlbaum Associates, Inc; 1988:280–287.
17. Dentaurum. Available at: http://www.dentaurum.com/eng/orthodontie/orthodontie.htm. Accessed 12/29/03
18. GAC International. Available at: http://www.gacmystique.com. Accessed 12/29/03
19. TP Orthodontics. Available at: http://www.invubrackets.com. Accessed 12/29/03
20. Flores DA, Caruso JM, Scott GE, Jeiroudi MT. The fracture strength of ceramic brackets: a comparative study. *Angle Orthod.* 1990;60:269–276.