Original Article

Quantitative analysis of mechanically retentive ceramic bracket base surfaces with a three-dimensional imaging system

Da-Young Kang[a]; Sung-Hwan Choi[b]; Jung-Yul Cha[c]; Chung-Ju Hwang[d]

ABSTRACT

Objective: To investigate the three-dimensional structural features of three types of mechanically retentive ceramic bracket bases.

Materials and Methods: One type of stainless steel (MicroArch, Tomy, Tokyo, Japan) and three types of ceramic maxillary right central incisor brackets—Crystaline MB (Tomy), INVU (TP Orthodontics, La Porte, Ind), and Inspire Ice (Ormco, Glendora, Calif)—were tested to compare and quantitatively analyze differences in the surface features of each ceramic bracket base using scanning electron microscopy (SEM), a three-dimensional (3D) optical surface profiler, and microcomputed tomography (micro-CT). One-way analysis of variance was used to find differences in bracket base surface roughness values and surface areas between groups according to base designs. Tukey's honestly significant differences tests were used for post hoc comparisons.

Results: SEM revealed that each bracket exhibited a unique surface texture (MicroArch, double mesh; Crystaline MB, irregular; INVU, single mesh; Inspire Ice, bead ball). With a 3D optical surface profiler, the stainless steel bracket showed significantly higher surface roughness values. Crystaline MB had significantly higher surface roughness values than Inspire Ice. Micro-CT demonstrated that stainless steel brackets showed significantly higher whole and unit bracket base surface areas. Among ceramic brackets, INVU showed significantly higher whole bracket base surface area, and Crystaline MB showed a significantly higher unit bracket base surface area than Inspire Ice.

Conclusion: Irregular bracket surface features showed the highest surface roughness values and unit bracket base surface area among ceramic brackets, which contributes to increased mechanically retentive bracket bonding strength. (*Angle Orthod.* 2013;83:705–711.)

KEY WORDS: Ceramic bracket base; Surface roughness; Surface area; Three-dimensional optical surface profiler; Microcomputed tomography

INTRODUCTION

With the increasing esthetic demands of orthodontic patients, ceramic brackets have become popular and widely used in many patients. Based on this trend, many bracket manufacturers have developed several ceramic brackets, and many varieties are available on the market.[1]

Original ceramic brackets have exhibited significantly higher bond strengths than stainless steel brackets.[2–4] Ceramic bracket bonding mechanisms are divided into three groups: those with mechanically retentive bases, those with silane-treated chemically retentive bases, and those with both mechanically and chemically retentive bases. Various studies have shown that with silane-treated chemically retentive ceramic bracket bases, the bonding strength between the composite and ceramic can approach the strength of enamel, making enamel fractures more likely.[5]

[a] Resident, Department of Orthodontics, College of Dentistry, Yonsei University, Seoul, Korea.
[b] Postgraduate student, Department of Orthodontics, College of Dentistry, Yonsei University, Seoul, Korea.
[c] Assistant Professor, Department of Orthodontics, College of Dentistry, Yonsei University, Seoul, Korea.
[d] Professor, Department of Orthodontics, Institute of Craniofacial Deformity Center, College of Dentistry, Yonsei University, Seoul, Korea.
Corresponding author: Chung–Ju Hwang, DDS, PhD, Department of Orthodontics, Institute of Craniofacial Deformity Center, College of Dentistry, Yonsei University, 134 Shinchon-dong, Seodaemun-gu, Seoul 120-752, Korea
(e-mail: hwang@yuhs.ac)

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Table 1. Identification of Brackets Used in This Study

Name of Bracket	Manufacturer	Type	Base Design
MicroArch	Tomy, Tokyo, Japan	Stainless steel	Mesh
Crystaline MB	Tomy, Tokyo, Japan	Polycrystalline alumina	Irregular
INVU	TP Orthodontics, LaPorte, Ind	Polycrystalline alumina	Polymer mesh
Inspire Ice	Ormco, Glendora, Calif	Monocrystalline alumina	Bead ball

However, mechanically retentive ceramic brackets exhibit lower enamel fracture rates than chemically retentive ceramic brackets.[3,6,7] Therefore, mechanically retentive ceramic bracket base designs are more desirable than chemically retentive ceramic brackets.

A bracket that provides sufficient bonding strength without damaging the enamel during debonding can be more easily obtained by modifying the bracket base design in a mechanically retentive way than through other methods. Bracket base morphology can influence the bond strength of brackets by determining the geometry (depth, size, and distribution) of the cement tags and stress distribution within the cement bracket interface.[8] However, few studies have examined the bracket base itself. Most studies examined metal brackets and only used two-dimensional analysis.[9–14]

The purpose of this study was to investigate the three-dimensional (3D) structural features of three types of mechanically retentive ceramic bracket bases by comparing and quantitatively analyzing differences in the surface features of each ceramic bracket base using scanning electron microscopy (SEM), a 3D optical surface profiler, and microcomputed tomography (micro-CT). Two null hypotheses were tested: (1) There are no differences in base surface roughness values between three types of mechanically retentive ceramic brackets; and (2) base surface roughness values do not influence base surface area.

MATERIALS AND METHODS

Brackets Used

Four types of maxillary right central incisor brackets were used in this study. A stainless steel bracket (MicroArch, Tomy, Tokyo, Japan) was compared with three different kinds of ceramic brackets. The ceramic brackets tested were as follows: Crystaline MB (Tomy), INVU (TP Orthodontics, La Porte, Ind), and Inspire Ice (Ormco, Glendora, Calif). Each of the ceramic brackets had various base designs (irregular, Crystaline MB; polymer mesh, INVU; bead ball, Inspire Ice). The characteristics of the four types of brackets used in this study are listed in Table 1.

SEM Analysis

The bracket bases were examined with a scanning electron microscope (S-3000N, Hitachi, Tokyo, Japan) to assess surface topography. The specimens were viewed and photographed at magnifications of 20× and 100× with the scanning electron microscope at an operating voltage of 20 kV.

3D Optical Profiler Analysis

The bracket bases were analyzed with a 3D optical surface profiler (NewView 6300, Zygo Corp, Middlefield, Conn) based on noncontact scanning white light interferometry to evaluate the 3D surface configuration and roughness of each bracket. Ten samples of each bracket were examined. 3D interferograms of each specimen was recorded and two surface roughness parameters were investigated; root mean square (RMS), which is the root mean square value obtained from the ordinate values of the roughness profile, and roughness average (Ra), which is the arithmetic mean value of the movement of the profile above and below the center line of the surface.

Micro-CT Analysis

Ten samples of each bracket base were examined using micro-CT (Skyscan 1076, Skyscan, Kontich, Belgium) to evaluate 3D surface areas. The whole bracket base surface areas were measured and evaluated. The unit bracket base surface areas were evaluated by measuring the bracket base surface area within a 2.0 mm × 2.0 mm square unit using micro-CT. The surface increment ratio was calculated by dividing the mean value of the unit bracket base surface areas by 4.0 mm^2.

Statistical Analysis

Means and 95% confidence intervals of base surface roughness values and surface areas were determined and statistically analyzed with the PASW Statistics 18 program (SPSS Inc, Chicago, Ill). Normality of the data was calculated using the Kolmogorov-Smirnov test. One-way analysis of variance (ANOVA) was used to find differences in bracket base surface roughness values and surface areas between groups according to base designs. Tukey's honestly significant differences tests were used for post hoc comparisons. The level of statistical significance was set at $\alpha = .05$.

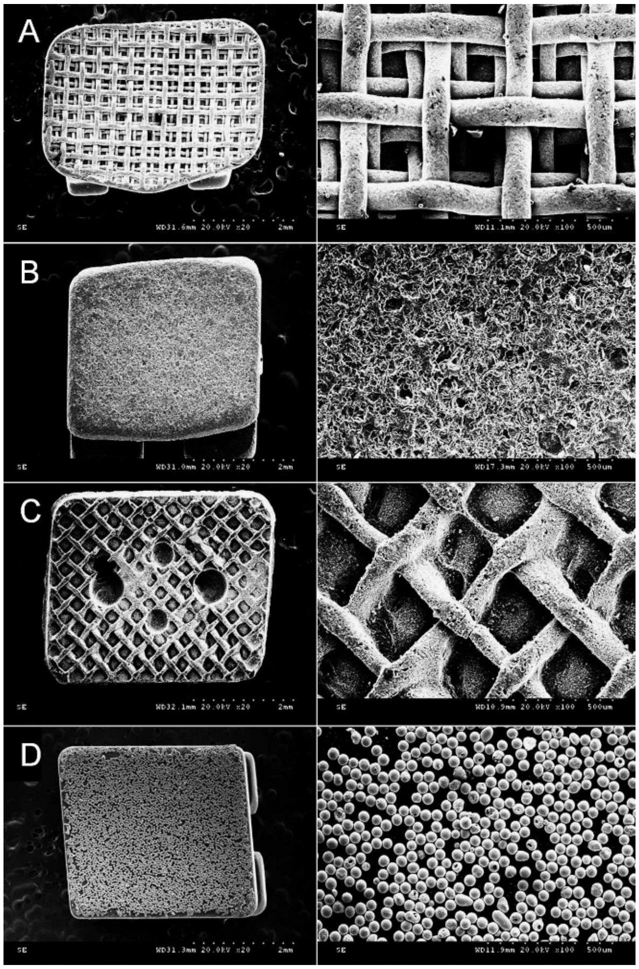

Figure 1. Scanning electron photomicrographs of each bracket base (original magnification: left, ×20; right, ×100). (A) MicroArch. (B) Crystaline MB. (C) INVU. (D) Inspire Ice.

RESULTS

SEM Analysis

Scanning electron photomicrographs of each bracket base are presented in Figure 1. Each bracket had a unique surface texture. As expected, MicroArch brackets had a double-mesh bracket base. Crystaline MB brackets displayed a rough surface with prominent irregularities, and INVU brackets portrayed a single mesh bracket base. Inspire Ice brackets had several small beads scattered over the bracket base.

3D Optical Profiler Analysis

3D interferograms of each bracket base are presented in Figure 2. Each bracket showed characteristic 3D base surface features. Whereas the MicroArch stainless steel brackets showed roughness through a double-layered mesh, ceramic brackets exhibited roughness through surface irregularities in the ceramic itself and characteristic surface features such as the

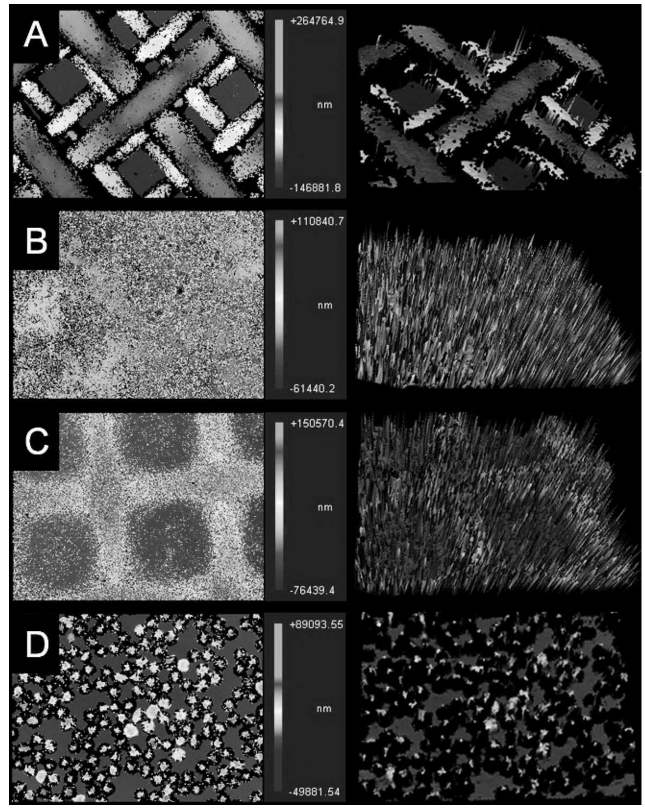

Figure 2. 3D interferograms of each bracket base (0.7 mm × 0.5mm, ×10 magnification). (A) MicroArch. (B) Crystaline MB. (C) INVU. (D) Inspire Ice. Colors indicate the surface height of the bracket bases. Left, two-dimensional plot; right, 3D oblique plot.

mesh and ball (Figure 2). The surface roughness parameters that were measured are presented in Table 2. The surface roughness values (μm) were ranked from the highest to the lowest as follows: MicroArch (RMS, 73.73; Ra, 64.15), Crystaline MB (RMS, 39.74; Ra, 30.32), INVU (RMS, 33.67; Ra, 28.10), and Inspire Ice (RMS, 16.39; Ra, 14.14). ANOVA indicated the presence of significant differences among the various groups ($P < .001$), and post hoc testing showed that each bracket had significantly different roughness ($P < .001$), except for the Ra values of Crystaline MB and INVU brackets ($P = .441$).

Micro-CT Analysis

Micro-CT images of each bracket base are presented in Figure 3. The bracket base area measurements are presented in Table 3. The whole bracket base surface areas were ranked (white area in Figure 3) from highest to the lowest as follows: MicroArch (50.04 ± 1.07 mm^2), INVU (45.46 ± 0.87 mm^2), Cystaline MB (35.02 ± 0.75 mm^2), and Inspire Ice (33.73 ± 0.60 mm^2). Both the unit bracket base surface area (black area in Figure 3) and surface increment ratio were ranked from highest to lowest as follows:

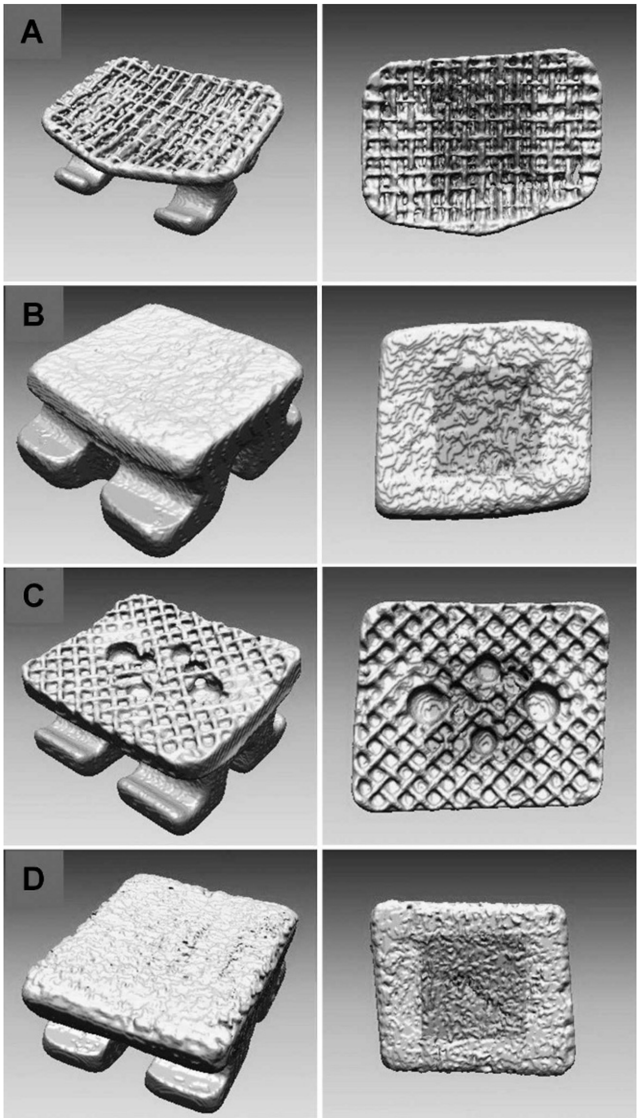

Figure 3. Micro-CT images of each bracket base. (A) MicroArch. (B) Crystaline MB. (C) INVU. (D) Inspire Ice. White areas indicate the whole bracket base surface area measured. Black areas indicate the 2 mm × 2 mm square unit bracket base surface area measured.

MicroArch (20.48 ± 0.86 mm^2; 5.12), Crystaline MB (15.28 ± 0.72 mm^2; 3.82), INVU (14.64 ± 0.50 mm^2; 3.66), and Inspire Ice (14.48 ± 0.35 mm^2; 3.62). ANOVA identified the presence of significant differences among the various groups ($P < .001$), whereas post hoc testing showed that each bracket had significantly different whole bracket base surface areas ($P < .01$). Significant differences in unit bracket surface areas were also found between the stainless steel and all three ceramic brackets ($P < .001$) and between the ceramic brackets Crystaline MB and Inspire Ice ($P = .028$). No significant difference in unit bracket surface area was found between the Crystaline MB and INVU ($P = .975$) or the INVU and Inspire Ice ($P = .112$).

DISCUSSION

The present study assessed the structure of different ceramic bracket base surfaces using SEM, 3D optical profiler, and micro-CT.

Scanning electron microscopic analysis of the ceramic bracket bases confirmed the differences in bracket base configurations among the bracket samples. Each manufacturer had applied unique surface characteristics to the bracket bases to increase the surface area for adequate bonding, such as the use of undercuts in various designs for mechanical retention of adhesive resin.

3D optical profilers are interference microscopes that are used to measure height variations on surfaces using the wavelength of light. Optical profiling uses the wave properties of light to compare the optical path difference between a test surface and a reference surface by splitting the incoming light and producing a light and dark fringe pattern.[15,16] Together, a vertical scanning transducer and camera generate a 3D interferogram of the surface, which is processed by a computer and transformed by frequency domain analysis to give a quantitative, noncontact, 3D image.[15,16] After a profile is made, the computer analyzes each pixel for height data, and the results are

Table 2. Surface Roughness Values Measured by Three-Dimensional Optical Profiler (μm) Expressed as the Root Mean Square (RMS) and Roughness Average (Ra)[a]

	RMS			Ra		
		95% CI[b]			95% CI	
Bracket	Mean	Minimum	Maximum	Mean	Minimum	Maximum
MircoArch	73.73D	71.55	75.90	64.15C	61.84	66.46
Crystaline MB	39.74C	35.88	43.59	30.32B	26.75	33.90
INVU	33.67B	31.74	35.60	28.10B	26.23	29.97
Inspire Ice	16.39A	16.03	16.75	14.14A	13.71	14.57

[a] The same uppercase letters indicate no statistically significant difference between the groups ($P > .05$). Increasing group mean values were expressed in ascending alphabetical order.

[b] CI indicates confidence interval.

Table 3. Bracket Base Surface Area Measured by Microcomputed Tomography (mm^2)[a]

Bracket	Whole Area			Unit Area			
		95% CI[b]			95% CI		Surface
	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Increment Ratios
MicroArch	50.04D	49.27	50.80	20.48C	19.87	21.10	5.12
Crystaline MB	35.02B	34.48	35.56	15.28B	14.77	15.79	3.82
INVU	45.46C	44.84	46.09	14.64AB	14.28	14.99	3.66
Inspire Ice	33.73A	33.30	34.15	14.48A	14.23	14.73	3.62

[a] The same uppercase letters indicate no statistically significant difference between the groups ($P > .05$). Increasing group mean values were expressed in ascending alphabetical order. Total area, measured whole bracket base surface area (white area in Figure 3); unit area, measured bracket base surface area in 2 mm × 2 mm square unit area (black area in Figure 3); Surface increment ratios, calculated by dividing mean unit bracket base surface area by 4 mm^2.

[b] CI indicates confidence interval.

calculated based on the equation for each surface roughness parameter.[17] Surface profilometry can induce sample damage, and it is difficult to use when overall surface roughness is measured because it analyzes the topography of a single line in a preselected area.[18] In contrast, an optical profiler is noninvasive and provides 3D information regarding surface morphology and mechanical properties; quantification of surface roughness can be useful for quantitative analysis.[17,19] In this study, a 3D optical surface profiler was used to study ceramic bracket base surfaces. Surface roughness parameters such as RMS and Ra were measured.

Micro-CT has been widely used in recent studies.[20–24] A micro-CT system using microfocal spot X-ray sources and high-resolution detectors allows projections to be rotated through multiple viewing directions to produce 3D reconstructed images of samples.[23] With the micro-CT, we obtained 3D reconstructed images of each bracket and evaluated the 3D bracket base surface areas.

Bond strengths between 6 MPa and 8 MPa are clinically sufficient to successfully bond brackets to enamel because these values are considered able to withstand masticatory and orthodontic forces.[25] The bracket bonding strength should be sufficiently high enough to resist accidental debonding during treatment. Adequate bracket adhesion to the teeth requires that the orthodontic forces be applied without bond failure during treatment, and it also enables easy removal of the brackets without excessive force and with minimal damage to the tooth surface during debonding. The original ceramic brackets used a chemical form of retention. The bases of these ceramic brackets were coated with silane. Unfortunately, enamel fractures occurred when debonding these brackets. In an effort to prevent enamel fracture, mechanically retentive ceramic brackets that get their retention ability from mechanical undercuts were developed; however, these have significantly less bond strength than the chemically bonded (silane) ceramic brackets.[26,27]

The double-mesh base design of the stainless steel brackets used as a control showed significantly higher roughness values, whole and unit base surface area, and surface increment ratio than the ceramic brackets. A highly complex arrangement of undercuts is provided in this base design, with a more widely spaced outer mesh and a finer deeper mesh. Also, adhesion at the bracket cement interface is achieved by the provision of mechanical undercuts into which the orthodontic adhesive extends before polymerization.[8]

In contrast, three kinds of mechanically retentive ceramic brackets used in this study have base surface textures (irregular texture, single mesh, and small beads) that are different from that of the metal bracket. As a result, the surface roughness value, whole and unit bracket base surface area, and surface increment ratio of ceramic brackets are lower than those of the metal bracket. This result supports the notion that the bond strength of these mechanically retentive ceramic brackets is similar to or less than the bonding strength of metal (mechanically retentive) brackets evaluated in previous studies.[27,28]

Among ceramic brackets, Crystaline MB showed significantly higher roughness values and a larger unit base surface area than Inspire Ice and INVU. The bracket base surface feature of Crystaline MB has a prominent irregular pattern with numerous spikes in 3D interferograms (Figure 2B), and this pattern seems to contribute to the increase in the unit bracket surface area with micro-CT (Figure 3B).

The base surface of Inspire Ice has many round monocrystalline beads as completely distributed over the base surface as possible. These small beads have undercuts for mechanical interlocking of the adhesive resin. In this study, this bracket had the lowest surface roughness value and the smallest base surface area, but in previous studies, bond strength values between bead base ceramic brackets and glazed feldspathic porcelains were the statistically highest values among all groups.[29] Although bracket bonding strengths relate to base surface roughness values or surface area, several researchers have evaluated the bond strength of ceramic brackets and found that several factors can modify bond strength, including bracket base design, choice of adhesive, different types of enamel conditioning, and different etch times.[30,31] However, the highest surface roughness values and unit surface areas of mechanically retentive bracket bases with irregular patterns can help maintain adequate bracket bonding strength.

INVU brackets showed the largest whole bracket base surface area because of the larger bracket size compared with the other ceramic brackets. In contrast, Crystaline MB showed the largest unit bracket base surface and surface increment ratio. According to a previous study using finite element analysis, bond strength tends to increase with smaller bonding areas because the larger the bonding area, the higher the probability that a flaw of critical size is present and, consequently, the lower the specimen's bond strength.[30] This indicates that a specific base design that gives favorable stress distribution at the bond interface is preferred over increasing bracket dimensions. Irregular surface features like those of Crystaline MB used in this study may decrease bracket base dimension while maintaining bracket bonding strength.

Although the results of this research seem encouraging and statistically valid, a possible limitation of the present study is that there was not a large sample size in each group. Further studies using a wide variety of base designs of mechanically retentive ceramic brackets and a larger sample size in each group will be needed.

CONCLUSION

- Ceramic brackets from different manufacturers had significantly different base surface roughness values, base surface areas, and surface increment ratio ranges depending on the 3D base surface features.
- Irregular bracket surface features showed the highest surface roughness values and unit bracket base surface area among ceramic brackets, which helps increase mechanically retentive bracket bonding strength.

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