Surface Roughness on the Slots and Wings of Various Ceramic Self-Ligating Brackets and their Potential Concern on Biofilm Formation

Ki-Ho Park*/ Se Jik Han**/ Samjin Choi***/ Kyung Sook Kim****/ Steven Park*****/ Jae Hyun Park******

Objective: *The surface roughness of various orthodontic materials could affect biofilm formation and friction. The purpose of this study was to examine the surface roughness and chemical composition of the slots and wings of several ceramic self-ligating brackets.* ***Study design:*** *Four types of ceramic self-ligating brackets were separated into experimental groups (DC, EC, IC, and QK) while a metal self-ligating bracket (EM) was used as the control group. Atomic force microscopy and energy-dispersive x-ray spectroscope were used to examine the surface roughness and chemical composition of each bracket slot and wing.* ***Results:*** *The control group was made of ferrum and chrome while all the experimental groups were comprised of aluminum and oxide. There was a statistically significant difference in the roughness average (Sa) among the various self-ligating brackets ($p< 0.001$ in slots and $p<0.01$ in the wing). The slots in the EC group had the lowest Sa, followed by the DC, IC, control, and QK groups. The wings in the IC group had the lowest Sa, followed by the EC, DC, control, and QK groups.* ***Conclusions:*** *There is a significant difference in the surface roughness of the slots and wings among several types of ceramic self-ligating brackets.*

Keywords*: Self-ligating bracket, atomic force microscopy, energy-dispersive x-ray spectroscope, surface roughness, biofilm*

INTRODUCTION

Ceramic brackets were introduced in the 1980s, offering many advantages over traditional aesthetic appliances. Ceramic brackets provide greater strength, more resistance to wear and deformation, better color stability, and most importantly to the patient, superior aesthetics.[1,2]

The first self-ligating bracket was introduced by Stolzenberg in the early 1930s,[3] but it was not widely used for decades until more recently. During the past twenty years, interest in self-ligating brackets has been rekindled with the introduction of various new types of self-ligating systems. In the past, the body of the self-ligating bracket was made of conventional stainless steel. Still, the use of ceramic self-ligating brackets has gained in popularity because of the increasing number of patients who want aesthetic brackets now. Self-ligating brackets can be divided into two different groups; interactive clips and passive clips, depending on their closure mechanisms. With interactive self-ligating brackets, the ligation clip exerts pressure on the archwire against the slot base. In contrast, with passive self-ligating brackets, a closing slide transforms the open slot into a tube,[4] thus exerting no active force on the archwire (Fig. 1).

The main orthodontic concerns are friction of orthodontic appliances and its various biological and mechanical adverse effects, the accumulation of bacteria around the brackets and its harmful effects on the health of the surrounding tissues, and surface roughness of appliances. [5-7]

* Ki-Ho Park, DMD, MSD, PhD, Associate Professor, Department of Orthodontics, School of Dentistry, Kyung Hee University, Seoul, Korea.
** Se Jik Han, MS, PhD candidate, Department of Medical Engineering, Graduate School, Kyung Hee University, Seoul, Korea.
*** Samjin Choi, PhD, Assistant Professor, Department of Biomedical Engineering, College of Medicine, Kyung Hee University, Seoul, Korea.
**** Kyung Sook Kim, PhD, Associate Professor, Department of Biomedical Engineering, College of Medicine, Kyung Hee University, Seoul, Korea.
***** Steven Park, BS, Postgraduate Student, Master of Science in Research Administration, Advanced Academic Programs, Krieger School of Arts and Sciences, Johns Hopkins University, Washington, DC.
****** Jae Hyun Park, DMD, MSD, MS, PhD, Professor and Chair, Postgraduate Orthodontic Program, Arizona School of Dentistry & Oral Health, A.T. Still University, Mesa, AZ, and International Scholar, Graduate School of Dentistry, Kyung Hee University, Seoul, Korea

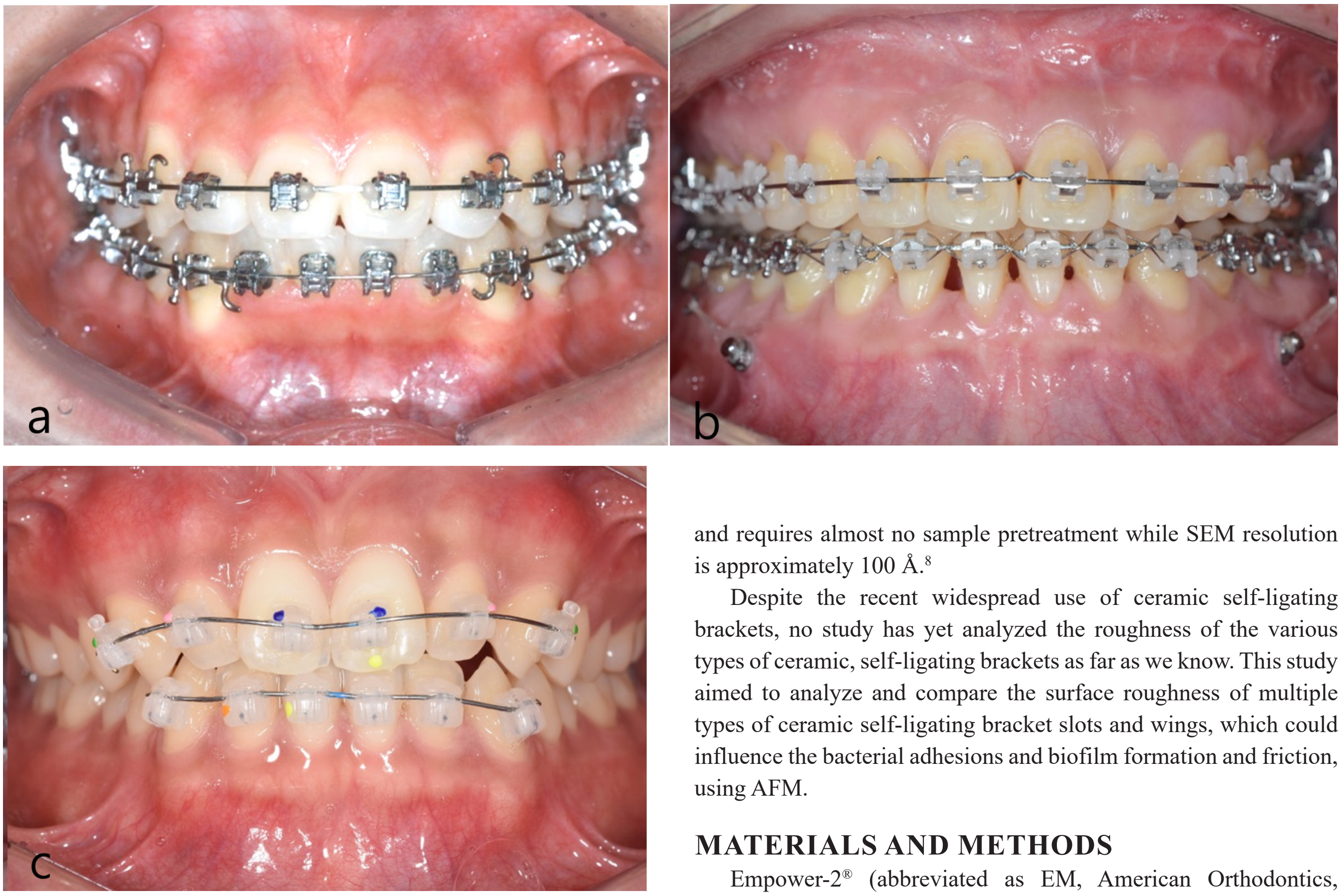
Send all correspondence to:
Jae Hyun Park, Postgraduate Orthodontic Program, Arizona School of Dentistry & Oral Health, A.T. Still University, 5835 East Still Circle, Mesa, AZ 85206;
Phone + 480-286-0455
Fax **:** +480-248-8117
E-mail : jpark@atsu.edu

Figure 1. Clinical application of various self-ligating brackets

a. Damon-MX® (Stainless steel, passive type)

b. Empower clear® (Ceramic, interactive type)

c. Damon clear® (Ceramic, passive type)



During orthodontic treatment, friction is applied between the bracket slot and the archwire. As the friction increases, the tooth movement slows.[8] Various factors influence the friction between the orthodontic bracket and the archwire, and the surface roughness of the bracket slot is one of them.[4,8-11] There is usually a positive correlation between the surface roughness of the orthodontic bracket and archwire and the amount of friction exerted against the wire.[12-14]

Bacterial adhesion has special characteristics and depends on direct biofilm interaction with the substrate surface to which it relates. Orthodontic brackets can play an essential role in enamel demineralization, because they provide additional adhesion sites for pathogenic bacteria.[15] The surface energy,[16] surface roughness,[17] and wettability[18] play critical roles in bacterial adhesion properties and biofilm formation. A rough surface generally allows bacterial colonization by increasing the adhesion areas and preventing dislodgement of bacterial colonies.[19]

Previous studies[9,20,21] reported the surface of the brackets using a scanning electron microscope (SEM) and found that ceramic brackets were rougher than their stainless steel counterparts and the monocrystalline alumina bracket was smoother than polycrystalline alumina brackets. Park et al.[8] used atomic force microscopy (AFM) to analyze the roughness of various conventional ceramic bracket slots. AFM has an excellent vertical resolution up to 0.1 Å and requires almost no sample pretreatment while SEM resolution is approximately 100 Å.[8]

Despite the recent widespread use of ceramic self-ligating brackets, no study has yet analyzed the roughness of the various types of ceramic, self-ligating brackets as far as we know. This study aimed to analyze and compare the surface roughness of multiple types of ceramic self-ligating bracket slots and wings, which could influence the bacterial adhesions and biofilm formation and friction, using AFM.

MATERIALS AND METHODS

Empower-2® (abbreviated as EM, American Orthodontics, WI), a metal self-ligating bracket, was analyzed as the control group and was compared with five types of ceramic self-ligating brackets, the experimental groups (Fig. 2): Damon clear® (DC; Ormco, CA), Empower clear® (EC; American Orthodontics, WI), In-Ovation C® (IC: GAC International, NY), and QuicKlear® (QK; Forestadent, Germany). EC, IC, and QK are interactive ceramic self-ligating brackets while DC are passive ceramic self-ligating brackets.

The sample size for this study was calculated using a significance level of 0.05 and a power of 0.9 to find statistically significant differences between the surface roughnesses of the different bracket groups. The power analysis showed that at least 21 samples would be needed in each group, so a sample size of 30 was chosen for each bracket group. To exclude prejudice against any type of bracket, bracket identity was blinded and each group was assigned a number (1. EM, 2. DC, 3. EC, 4. IC, and 5. QK), and the analysis was conducted by biomedical engineers who had no previous knowledge of brackets.

The morphologies of each sample bracket slot and wing were examined using an S-4700 field emission scanning electron microscope (FE-SEM; Hitachi, Tokyo, Japan). The chemical compositions of each bracket slots and wings were analyzed by the same investigator using a 7200-H energy-dispersive x-ray spectroscope (EDS; HORIBA, Northampton, England).

Figure 2. The control group (a) and experimental groups (b-e) used in this study.

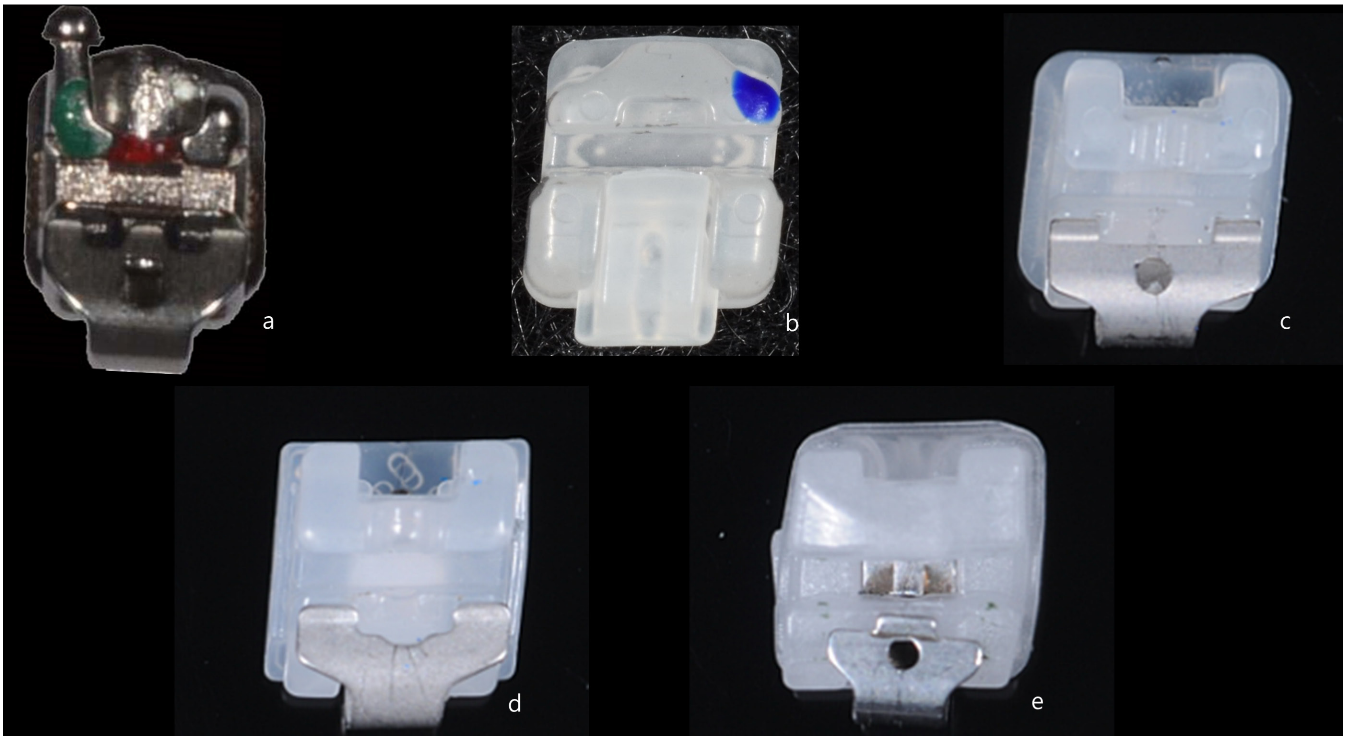
a. Empower-2® (EM)

b. Damon clear® (DC)

c. Empower clear® (EC)

d. In-Ovation C® (IC)

e. QuicKlear® (QK)



The clip was removed from each bracket, and an optical microscope (500× magnification) was used to select the area on the slot and wing of each bracket to be studied. The surface roughness of each bracket slot and wing was scanned with an AFM system (TT-AFM, Probes Inc. Korea) in contact mode to generate a high-resolution topography of the metal clips. The probe used in contact mode had a resonance frequency of 13 kHz (9-17 kHz), force constant of 0.2 N/m (0.07 – 0.4 N/m), cantilever length of 450 µm (440-460 µm), cantilever width of 50 µm (45-55 µm), cantilever thickness of 2 µm (1-3 µm), tip radius of 10 µm (<10 µm), and a tip height of 17 µm (15-19 µm). The topography of the metal clip was scanned over a lateral area of 45 × 45 µm^2 with a resolution of 256 × 256 pixels. The scanned image was analyzed using Gwyddion software (v. 2.47 for Windows, Czech Metrology Institute, Czech Republic) and the roughness measurement plane (z = 0 plane, or xy plane) was determined. Roughness average (Sa) is the parameter used to define surface roughness. Sa is the most common parameter expressing the degree of roughness with respect to the Z-axis height of the scanned area and is calculated by the following formula.[5]

$$S_a = \frac{1}{MN}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}\left|z(x_k, y_l) - \mu\right| \qquad \mu = \frac{1}{MN}\sum_{k=0}^{M-1}\sum_{i=0}^{N-1} z(x_k, y_i)$$

Statistical analysis

All statistical analyses were performed using SPSS version 12.0 (SPSS, Chicago, IL). The intraclass correlation coefficient (ICC) was used to test interexaminer and intraexaminer reliability of the roughness averages on the bracket slots and wings. The ICC values of 0.97 for interexaminer reliability and 0.98 for intraexaminer reliability indicated high levels of agreement and near-perfect reproducibility of the measurements.

The Shapiro–Wilks and Levene's tests were used to examine the normality of the distributions and the equality of variances between groups, respectively. We used one-way ANOVAs to compare the roughness average of the six types of brackets, followed by Scheffe analysis. Statistical significance was considered as a p-value of less than 0.05.

RESULTS

Tables 1 and 2 show the results of the chemical composition of each bracket obtained using SEM-EDS. The main components of the slot base and wing of the EM control were ferrum (59.92% in the slot and 65.00% in the wing) and chrome (14.28% in the slot and 15.40% in the wing). The main component in the slot base and wings of all ceramic self-ligating brackets was aluminum oxide (Tables 1 and 2). In the experimental group, the aluminum content in the QK slots was the smallest (37.12%), followed by EC (44.34%), DC (67.12%), and IC (82.11%). The aluminum content in the IC wings was the smallest (50.58%), followed by DC (51.13%), EC (53.97%), and QK (58.28%).

 doi 10.17796/1053-4625-44.6.10

Table 1. EDS component analysis for as-received ceramic self-ligating bracket slots (unit: Wt%)

Bracket	Al	C	Cr	Cu	Fe	Ni	O
Control (EM)	2.75	4.72	14.28	6.88	59.92	4.91	6.54
DC	67.12	0.00	0.00	0.00	0.00	0.00	32.88
EC	44.34	0.00	0.00	0.00	0.00	0.00	55.66
IC	82.11	0.00	0.00	0.00	0.00	0.00	17.89
QK	37.12	0.00	0.00	0.00	0.00	0.00	62.88

Energy-dispersive x-ray spectroscope (EDS); Empower-2® (EM); Damon clear® (DC); Empower clear® (EC); In-Ovation C® (IC); QuicKlear® (QK).

Table 2. EDS component analysis for as-received ceramic self-ligating bracket wings (unit: Wt%)

Bracket	Al	C	Cr	Cu	Fe	Ni	O
Control (EM)	0.00	0.00	15.40	7.61	65.00	5.43	6.56
DC	51.13	0.00	0.00	0.00	0.00	0.00	48.87
EC	53.97	0.00	0.00	0.00	0.00	0.00	46.03
IC	50.58	5.98	0.00	0.00	0.00	0.00	43.44
QK	58.28	3.82	0.00	0.00	0.00	0.00	37.90

Energy-dispersive x-ray spectroscope (EDS); Empower-2® (EM); Damon clear® (DC); Empower clear® (EC); In-Ovation C® (IC); QuicKlear® (QK).

Table 3. Quantitative analysis of surface roughness of each bracket using AFM-Sa (nm)

Bracket	Slot	Wing
Control (EM)	84.50 ± 32.15^{B}	71.90 ± 29.95^{c}
DC	28.82 ± 12.01^{A}	45.61 ± 13.29^{b}
EC	28.23 ± 5.25^{A}	43.10 ± 28.70^{b}
IC	74.81 ± 31.97^{B}	24.14 ± 11.39^{a}
QK	134.13 ± 63.83^{C}	104.37 ± 70.23^{d}
p-value	$< 0.001^{***}$	$< 0.01^{**}$

Atomic force microscopy (AFM); Roughness average (Sa); Empower-2® (EM); Damon clear® (DC); Empower clear® (EC); In-Ovation C® (IC); QuicKlear® (QK).

Values are presented as mean ± standard deviation.

An one-way ANOVA was performed and the results were verified with Scheffe's *post hoc* test.

$p<0.01^{**}$, $p<0.001^{***}$ considered statistically significant difference among bracket groups.

A < B < C considered statistically significant difference among slots of bracket groups.

a < b < c < d considered statistically significant difference among wings of bracket groups.

Figure 3 shows an optical microscope image (500×, left), and a 3D AFM image (right) of each bracket slot. The DC and EC slots appear to be smooth, whereas the QK slots seem to be rough. The Sa for each bracket slot obtained from the AFM image is shown in Table 3. There were statistically significant differences in the Sa of the slots in the various ceramic self-ligating groups ($p<0.001$). The slots of DC (28.82 ± 12.01 nm) and EC (28.23 ± 5.25 nm) were significantly smoother than those of the control group (84.50± 32.15 nm) ($p<0.001$) but there was no significant difference in the Sa of the slots in the DC and EC groups. Likewise, there was no significant difference in the Sa of the slots in the IC (74.81 ± 31.97 nm) and control groups. The slots in the QK group (134.13 ± 63.83 nm) were significantly rougher than those in the control group ($p<0.001$).

Figure 4 shows an optical microscope image (500×) of each bracket wing (left) and a 3D AFM image (right) of each bracket slot. The IC, DC, and EC wings appear to be smooth, whereas those of the QK group appear to be rough. Results of the Sa from each bracket wing obtained from the AFM image are shown in Table 3. There were statistically significant differences in the Sa between the various groups of ceramic, self-ligating bracket wings ($p<0.01$). The Sa of the brackets in the IC group (24.14 ± 11.39 nm) was significantly lower than that of all the other groups ($p<0.01$). The slots in the DC (45.61 ± 13.29 nm) and EC (43.10 ± 28.70 nm) groups were significantly smoother than those in the control group (71.90 ± 29.95 nm) ($p<0.01$) and there was no significant difference in the Sa of the DC and EC slots. The slots in the QK group (104.37 ± 70.23 nm) were rougher than those of the control group.

DISCUSSION

In recent decades, the use of self-ligating brackets has increased rapidly and some studies have analyzed the chemical makeup of the brackets using SEM-EDS. For instance, Huang et al.[22] showed that the main components of various metal self-ligating bracket such as Axis®, mini-Clippy® (In-Ovation R®), Smart Clip®, Carriere LX® were Fe and Cr, while Liu et al.[23] found that the main components BioQuick®, a type of metal self-ligating bracket, were also Fe (62.91%) and Cr (16.78%).

Our study showed that the main components in the slot base and wing of the control EM metal self-ligating brackets were Fe (slot 59.92%, wing 65.00%) and Cr (slot 14.28 %, wing 15.40%) which was similar to the results from Huang's study [22]. This study found that the main components in the slot base and wings of all of the ceramic self-ligating brackets used in the study were aluminum oxide, similar to the results from the previous studies[1,12] and that the aluminum content of the ceramic self-ligating bracket slots used in this study ranged from 37.12% (QK) to 82.11% (IC). In comparison, those of the ceramic self-ligating bracket wings ranged from 50.58% (IC) to 58.28% (QK).

The surface roughness of orthodontic appliances is an important characteristic that can be associated with numerous clinical factors such as bacterial aggregation, friction, biocompatibility, color stability, hygiene, or esthetics.[5,7] Thus, studies of bracket surface roughness are of great clinical interest, and several studies have been conducted on the surface roughness of various types of brackets.[9,20,21]

In the past, SEM was widely used to observe bracket surface roughness,[9,20,21] but while it showed the surface morphology in two dimensions, surface changes could not be studied in real-time, thus allowing for simultaneously quantitative and qualitative analysis.[24-26] Sample preparation for SEM analysis requires a metallization step and vacuum exposure, both of which could potentially induce modifications to the surface details. By contrast, AFM is a suitable technique to evaluate any effect resulting from sample manipulation because it can be applied without any specific treatment.[27] AFM is a

Figure 3. Optical microscopic image (left, 500x) and AFM image (right) of the slot base of each self-ligating bracket.

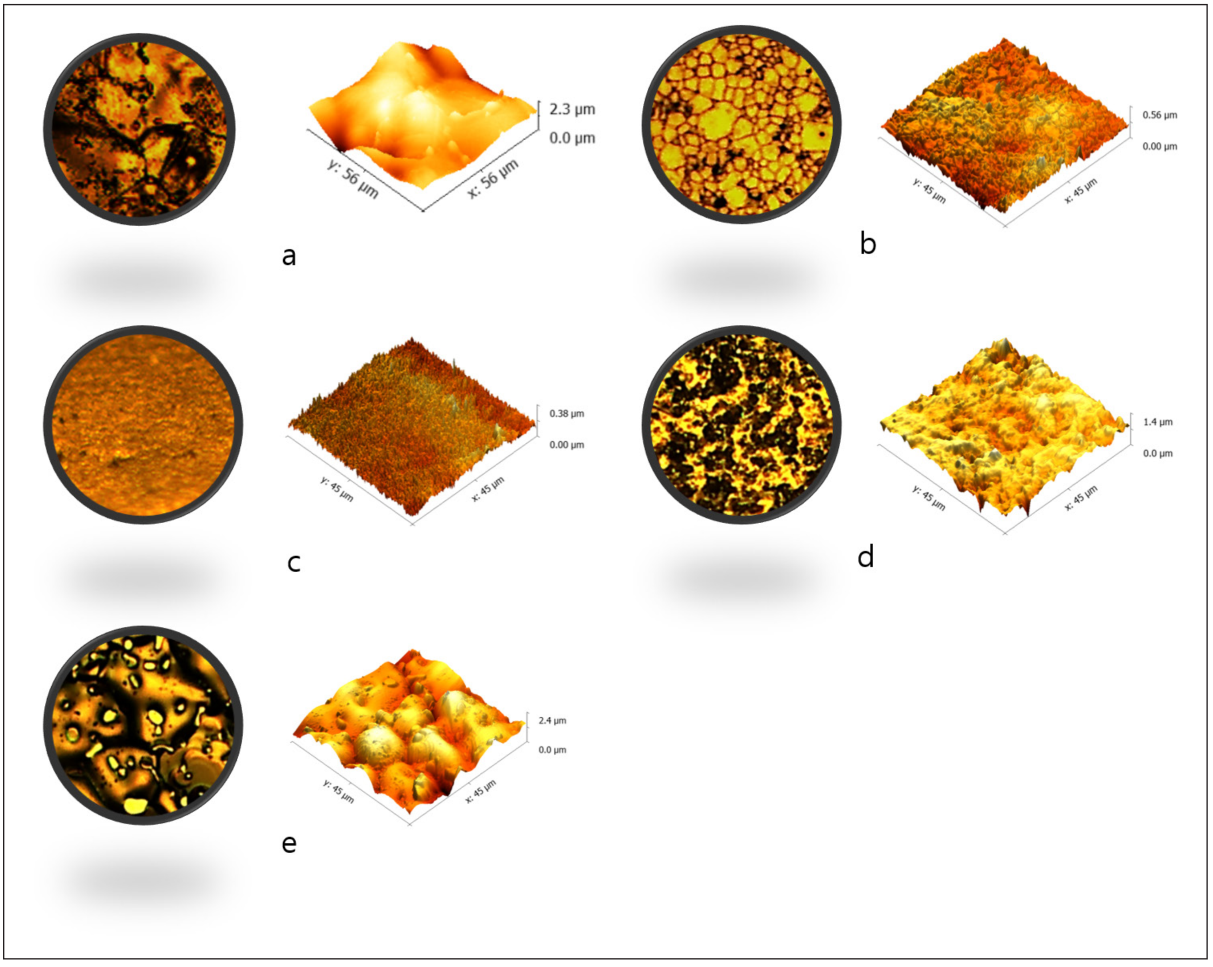
a. EM

b. DC

c. EC

d. IC

e. QK



 doi 10.17796/1053-4625-44.6.10

Figure 4. Optical microscopic image (left, 500x) and AFM image (right) of the wing of each self-ligating bracket.

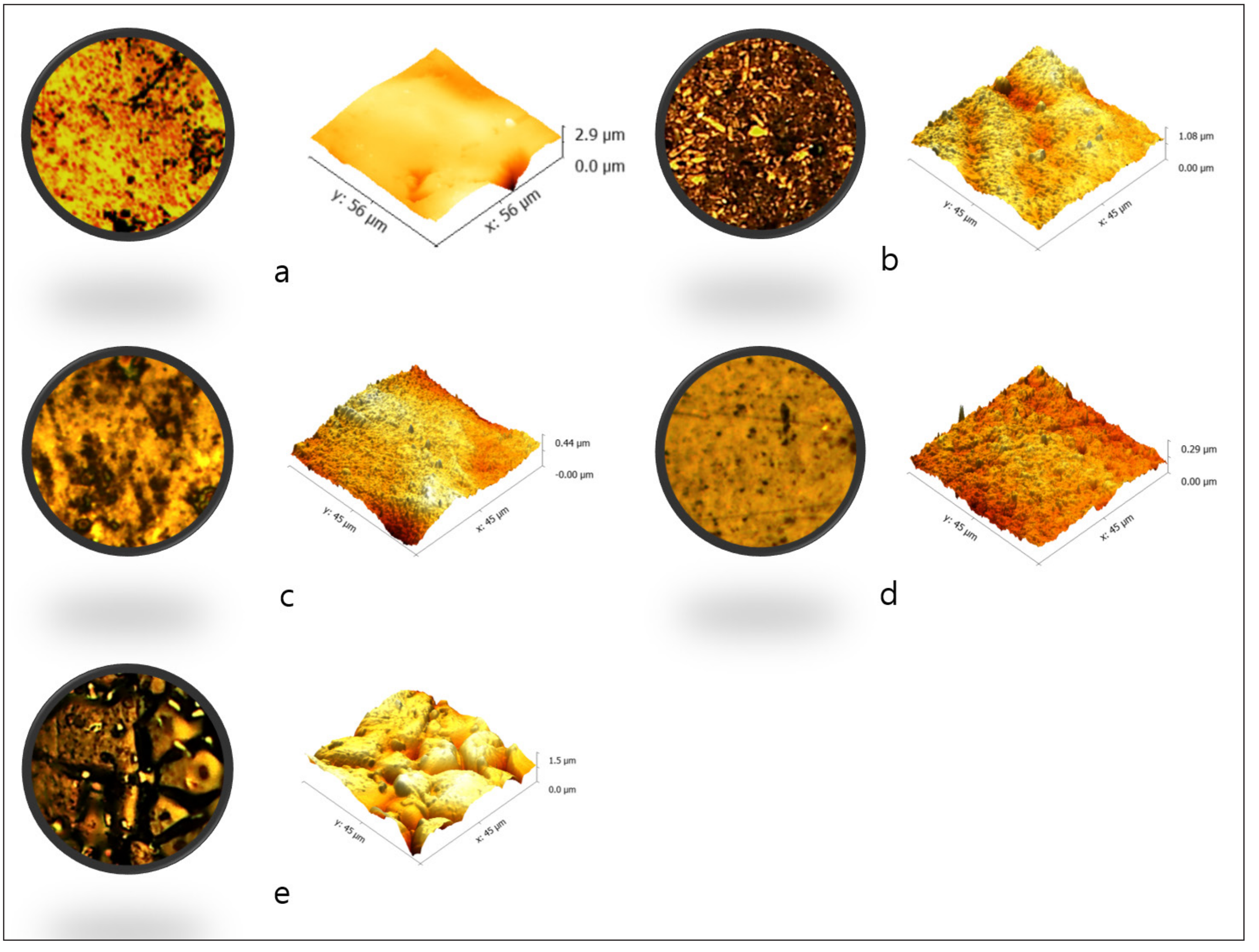
a. EM

b. DC

c. EC

d. IC

e. QK



spring deflection system with a tip (SiN) (length of 100–200µm and diameter of 100 Å or less) at the end of a spring cantilever. When the tip scans the specimen, there is a Vander Waal force between the tip and the surface of the specimen, which causes the cantilever to bend. A photodetector detects the bending of the laser that is incident to the backside of the cantilever. Thus the surface structure of the material is formed into three dimensions in terms of the atomic unit size so that surface changes can be observed in real-time. Furthermore, quantifying surface roughness is advantageous for quantitative and qualitative analysis. AFM has an excellent vertical resolution up to 0.1 Å and requires almost no sample pretreatment while a general optical microscope has about 200 nm of resolution. The resolution of a SEM is approximately 100 Å.[8]

From the best of our knowledge, no studies have been done to evaluate the surface roughness of various ceramic self-ligating brackets; the present study is the first to observe and compare the surface roughness of various ceramic, self-ligating brackets using AFM. The present study showed that some ceramic self-ligating bracket slots (DC and EC) were significantly smoother than the control group which was metal self-ligating bracket slots, and other ceramic self-ligating bracket slots (QK) were significantly rougher than the control group. This study also showed that some ceramic self-ligating bracket wings (DC, EC, and IC) were significantly smoother than the control group which was metal self-ligating bracket wings, and other ceramic self-ligating bracket wings (QK) were significantly rougher than the control group.

Pratten *et al* [9] and Bednar *et al* [20] found that the ceramic brackets were rougher than the stainless steel brackets, which was not consistent with this study. The reason for this seemed that only one or two kinds of stainless steel brackets and ceramic brackets were compared in those studies[9,20]. However, Park *et al* [8] observed the surface roughness of various bracket slots using AFM, and they found that some ceramic bracket slots were significantly rougher than steel bracket slots and that other ceramic bracket slots weren't rougher than steel bracket slots. The study concluded that not only the material of the bracket but also the manufacturing method of each company affects the roughness of the bracket slot.

Ceramic brackets were divided into monocrystalline and polycrystalline,[28,29] and monocrystalline brackets are machined from extrusions of synthetic sapphire, on the other hand, polycrystalline alumina brackets are made by injection molding submicron-sized particles of alumina suspended in resin, sintering them to fuse the alumina.[1,30] All the ceramic self-ligating brackets used in the present study were polycrystalline alumina made by ceramic injection molding (CIM) method.

Despite the similarities in bracket materials and manufacturing methods for all the brackets used in this study, there was a significant difference in their surface roughness, consistent with the results of Park *et al* [8] Possible sources of difference in the roughness of the CIM brackets may have been due to the roughness of the mold for a given bracket and the post-curing phase where the green body is fired in a furnace.[30]

Surface roughness is the primary determinant of bacterial adhesion.[16,31] Previous studies showed that a positive correlation was observed between surface roughness and the vital Streptococcus mutans adhesion.[32,33] Lee *et al* [15] showed that rough surfaces on orthodontic materials such as orthodontic adhesives and bracket materials create an opportunity for bacteria to adhere to them by increasing the surface area and providing suitable niches. However, some previous studies reported that minor variations of less than 0.2μm in surface roughness have no significant effect on bacterial adhesion.[15,19] Therefore, further study is needed to investigate how the difference in surface roughness of various ceramic self-ligating brackets revealed in this study affect bacterial adhesion.

The roughness of the bracket slot could also affect the friction between the bracket and the archwire,[34,35] and the slot surfaces of the ceramic bracket should be smooth to prevent wire damage by the bracket.[12] However, since many other factors can affect the friction, further research is needed to determine the relationship between these factors and the roughness of the bracket slots. The clinical performance of brackets also depends on diverse synergistic effects such as corrosion from saliva, mouth-washing solutions, and galvanic reactions between two dissimilar materials. The effects of an oral environment cannot be simulated in an in vitro investigation, so further studies on changes to the bracket slot surface roughness during orthodontic treatment will be needed in the future as well.

Clinical implications

The surface roughness of orthodontic appliances plays an important role in clinical factors such as bacterial aggregation, friction, hygiene, or esthetics. Therefore, several studies have been conducted on the surface roughness of various types of brackets.[8,9,20,21] Previous studies showed that there is a positive correlation between the surface roughness of the orthodontic bracket and archwire and the amount of friction exerted against the wire,[12-14] and there is usually a positive correlation between the surface roughness and the vital Streptococcus mutans adhesion.[32,33] This is the first study to analyze the surface roughness of various ceramic self-ligating bracket bodies and it would be better to try to reduce the surface roughness of the brackets, based on the results of this study.

CONCLUSIONS

There was a statistically significant difference in the surface roughness of the various ceramic self-ligating bracket slots and wings, which could affect bacterial adhesion, biofilm formation, and friction.

The Sa of the slots in the EC group was the smallest, followed by DC, IC, the control group, and QK.

The Sa of the wings of the IC group was the smallest, followed by EC, DC, the control group, and QK.

REFERENCES

1. Birnie D. Ceramic brackets. Br J Orthod 17:71-74, 1990.
2. Russell JS. Aesthetic orthodontic brackets. J Orthod 32:146-163, 2005.
3. Stolzenberg J. The Russell attachment and its improved advantages. Int J Orthod Dent Child 21:837-840, 1935.
4. Harradine NWT. Self-ligating brackets: where are we now? J Orthod 30:262-273, 2003.
5. Ghasemi T, Arash V, Rabiee SM, Rajabnia R, Pourzare A, Rakhshan V. Antimicrobial effect, frictional resistance, and surface roughness of stainless steel orthodontic brackets coated with nanofilms of silver and titanium oxide: a preliminary study. Microsc Res Tech 80:599-607, 2017.
6. Ahn SJ, Lim BS, Lee SJ. Prevalence of cariogenic streptococci on incisor brackets detected by polymerase chain reaction. Am J Orthod Dentofacial Orthop 131:736–741, 2007.
7. Amini F, Rakhshan V, Pousti M, Rahimi H, Shariati M, Aghamohamadi B. Variations in surface roughness of seven orthodontic archwires: An SEM-profilometry study. Korean J Orthod 42:129–137, 2012.
8. Park KH, Yoon HJ, Kim SJ, Lee GJ, Park HK, Park YG. Surface roughness analysis of ceramic bracket slots using atomic force microscope. Korean J Orthod 40:294-303, 2010.
9. Pratten DH, Popli K, Germane N, Gunsolley JC. Frictional resistance of ceramic and stainless steel orthodontic brackets. Am J Orthod Dentofacial Orthop 98:398-403, 1990.
10. Sung HM, Park YC. Comparison of the frictional resistance between orthodontic bracket & archwire. Korean J Orthod 21:543-559, 1991.
11. Drescher D, Bourauel C, Schumacher HA. Frictional forces between bracket and arch wire. Am J Orthod Dentofacial Orthop 96:397-404, 1989.
12. Tanne K, Matsubara S, Hotei Y, Sakuda M, Yoshida M. Frictional forces and surface topography of a new ceramic bracket. Am J Orthod Dentofacial Orthop 106:273-278, 1994.
13. Choi S, Hwang EY, Park HK, Park YG. Correlation between frictional force and surface roughness of orthodontic archwires. Scanning 37:399-405, 2015.
14. Kim KS, Han SJ, Lee TH, Park TJ, Choi S, Kang YG, Park KH. Surface analysis of metal clips of ceramic self-ligating brackets. Korean J Orthod. 49:12-20, 2019.
15. Lee SP, Lee SJ, Lim BS, Ahn SJ. Surface characteristics of orthodontic materials and their effects on adhesion of mutans streptococci. Angle Orthod 79:353-360, 2009.
16. Quirynen M, Bollen CM. The influence of surface roughness and surface-free energy on supra- and subgingival plaque formation in man. A review of the literature. J Clin Periodontol 22:1-14, 1995.
17. Teughels W, Van Assche N, Sliepen I, Quirynen M. Effect of material characteristics and/or surface topography on biofilm development. Clin Oral Implants Res 17:68-81, 2006.
18. Jansen B, Kohnen W. Prevention of biofilm formation by polymer modification. J Ind Microbiol 15:391-396, 1995.
19. Ahn HB, Ahn SJ, Lee SJ, Kim TW, Nahm DS. Analysis of surface roughness and surface free energy characteristics of various orthodontic materials. Am J Orthod Dentofacial Orthop 136:668-674, 2009.
20. Bednar JR, Gruendeman GW, Sandrik JL. A comparative study of frictional forces between orthodontic brackets and arch wires. Am J Orthod Dentofacial Orthop 100:513-522, 1991.
21. Saunders CR, Kusy RP. Surface topography and frictional characteristics of ceramic brackets. Am J Orthod Dentofacial Orthop 106:76-87, 1994.
22. Huang TH, Luk HS, Hsu YC, Kao CT. An in vitro comparison of the frictional forces between archwires and self-ligating brackets of passive and active types. Eur J Orthod 34:625-632, 2012.
23. Liu X, Lin J, Ding P. Changes in the surface roughness and friction coefficient of orthodontic bracket slots before and after treatment. Scanning 35:265-272, 2013.
24. Cassinelli C, Morra M. Atomic force microscopy studies of the interaction of a dentin adhesive with tooth hard tissue. J Biomed Mater Res 28:1427-1431, 1994.
25. Marshall GW Jr, Balooch M, Tench RJ, Kinney JH, Marshall SJ. Atomic force microscopy of acid effects on dentin. Dent Mater 9:265-268, 1993.
26. Marshall GW Jr, Balooch M, Kinney JH, Marshall SJ. Atomic force microscopy of conditioning agents on dentin. J Biomed Mater Res 29:1381-1387, 1995.
27. Poletti G, Orsini F, Lenardi C, Barborini E. A comparative study between AFM and SEM imaging on human scalp hair. J Microsc 211:249-255, 2003.
28. Swartz ML. Ceramic brackets. J Clin Orthod 22:82-88, 1988.
29. Gwinnett AJ. A comparison of shear bond strengths of metal and ceramic brackets. Am J Orthod Dentofacial Orthop 93:346-348, 1988.
30. Silver M, Griffin AC Jr, Azzopardi L, Masoud MI, Tokede O, Griffin AC 3rd. Novel methods reveal that parallelism contributes to the functional vertical slot dimension in ceramic and metal brackets. Angle Orthod 88:812-818, 2018.
31. Sardin S, Morrier JJ, Benay G, Barsotti O. In vitro streptococcal adherence on prosthetic and implant materials. Interactions with physicochemical surface properties. J Oral Rehabil 31:140-148, 2004.
32. Contreras-Guerrero P, Ortiz-Magdaleno M, Urcuyo-Alvarado MS, Cepeda-Bravo JA, Leyva-Del Rio D, Pérez-López JE, Romo-Ramírez GF, Sánchez-Vargas LO. Effect of dental restorative materials surface roughness on the in vitro biofilm formation of Streptococcus mutans biofilm. Am J Dent 33:59-63, 2020.
33. Aykent F, Yondem I, Ozyesil AG, Gunal SK, Avunduk MC, Ozkan S. Effect of different finishing techniques for restorative materials on surface roughness and bacterial adhesion. J Prosthet Dent 103:221-227, 2010.
34. Kusy RP, Whitley JQ, de Araujo Gurgel J. Comparisons of surface roughnesses and sliding resistances of 6 titanium-based or TMA-type archwires. Am J Orthod Dentofacial Orthop 126:589–603, 2004.
35. Angolkar PV, Kapila S, Duncanson MG Jr, Nanda RS. Evaluation of friction between ceramic brackets and orthodontic wires of four alloys. Am J Orthod Dentofacial Orthop 98:499–506, 1990.