European Journal of Orthodontics 34 (2012) 498–504
doi:10.1093/ejo/cjr034
Advance Access Publication 6 June 2011

Influence of surface conditioning on ceramic microstructure and bracket adhesion

Frank Falkensammer, Josef Freudenthaler, Bernhard Pseiner and Hans Peter Bantleon
Department of Orthodontics, Bernhard Gottlieb University Dental Clinic, Medical University of Vienna, Austria

Correspondence to: Frank Falkensammer, Department of Orthodontics, Bernhard Gottlieb University Dental Clinic, Medical University of Vienna, Währingerstrasse 25a, A-1090 Vienna, Austria. E-mail: frank.falkensammer@meduniwien.ac.at

SUMMARY The objective of this study was to investigate the influence of different conditioning procedures on various ceramic microstructures and bracket adhesion. Ceramic specimens (feldspathic, leucite, leucite-free, and fluorapatite) were mechanically conditioned ($n = 20$ per ceramic type) with conventional hydrofluoric acid (5 per cent HF; 60/30 seconds), buffered hydrofluoric acid (9.6 per cent BHF; 60/30 seconds), or sandblasting (Al_2O_3/SiO_2 particles). Silane coupling agents were added for chemical conditioning before bracket bonding. Bracket adhesion was calculated with a shear test in a universal testing machine. The bracket-composite-ceramic interface was further evaluated using the adhesive remnant index (ARI). One specimen of each ceramic/conditioning combination was subjected to qualitative electron microscopy investigation. One-way analysis of variance followed by Tukey's honestly significant difference test were applied for inferential statistics.

Conditioning with conventional 5 per cent HF or sandblasting resulted in significantly ($P < 0.001$) higher bond strengths (mean values: 34.11 and 32.86 MPa, respectively) than with 9.6 per cent BHF (mean value: 12.49 MPa). Etching time or sandblasting particles had no statistical ($P > 0.001$) influence on bond strength. Higher ARI scores were found in the conventional 5 per cent HF and sandblasted groups, when compared with the 9.6 per cent BHF group. Microscopic examination of the conditioned ceramic surfaces showed that leucite and leucite-free ceramics differed most with respect to their surface roughness, though without an influence on shear bond strength (SBS; $P < 0.001$). Bracket adhesion was mostly influenced by the conditioning procedure itself. Sandblasted ceramic surfaces showed sufficient conditioning and bracket adhesion; however, the increased bracket adhesion was associated with a risk of ceramic surface damage.

Introduction

Adequate bonding of brackets to ceramic surfaces is important due to the increasing number of adults undergoing orthodontic treatment (Pine *et al.*, 2001; Ajlouni *et al.*, 2005). The main differences among currently used silicate ceramics in restorative dentistry are in their chemical composition. Feldspathic ceramics, used for veneers, contain feldspar, silicon dioxide, and kaolin. Further development led to leucite and fluorapatite ceramics, containing leucite or fluorapatite crystals in the ceramic matrix, for enhancing cohesive strength and aesthetics. In contrast, leucite-free ceramics have no crystals integrated into the ceramic matrix and show a more homogeneous matrix (Rosenblum and Schulman, 1997; Brantley and Eliades, 2001; Pröbster, 2001; Pospiech, 2004; Barghi *et al.*, 2006).

As any ceramic surface is inert and does not adhere readily to other materials, attempts have been made to alter the ceramic surface for bracket bonding. Adhesive retention to these ceramic surfaces is achieved through a combination of mechanical and chemical retention, i.e. surface roughness and coupling agents (Calamia, 1983; Schaffer *et al.*, 1989; Ajlouni *et al.*, 2005). Surface roughness may be achieved with different procedures such as etching, sandblasting, laser irradiation, and diamond burs (Brantley and Eliades, 2001).

Hydrofluoric acid (HF) etching is a reliable procedure for bonding ceramic restorations, having a dissolving effect on the superficial layers of silicate ceramics (Calamia, 1985; Sorensen *et al.*, 1991; Thurmond *et al.*, 1994; Tylka and Stewart, 1994; Chen *et al.*, 1998; Blatz *et al.*, 2003). HF etching will result in an inhomogeneous surface configuration in leucite ceramics. Leucite crystals are more soluble than the surrounding glass matrix producing microretentive lacunae after etching (Schmid *et al.*, 1992; Blatz *et al.*, 2003; Ozcan and Vallittu, 2003; Saracoglu *et al.*, 2004; Barghi *et al.*, 2006). HF may be harmful to soft tissues in the oral cavity. As a consequence, buffered hydrofluoric acid (BHF) with reduced toxicity was introduced (Kirkpatrick and Burd, 1995; Schiettecatte *et al.*, 2003). However, the recommended application times and acid concentrations differ greatly (Chen *et al.*, 1998; Gillis and Redlich, 1998; Sant'Anna *et al.*, 2002; Saracoglu *et al.*, 2004). Thus, it remains unclear, if etching time influences bracket shear bond strength (SBS).

Zachrisson *et al.* (1996) promoted sandblasting as another mechanical retention procedure. Aluminium oxide particles are blasted onto the ceramic layer at high pressure leaving a microretentive surface. Conditioning depends on particle size, application time, and angle of impact (Zachrisson *et al.*, 1996; Blatz *et al.*, 2003; Shiu *et al.*, 2007). This method homogeneously abrades the ceramic layers. Furthermore, silica-coated aluminium oxide particles should enhance adhesion tribochemically (Frankenberger *et al.*, 2000; Ozcan and Vallittu, 2003).

Chemical retention is generated by silane coupling agents (Brosh *et al.*, 1997; Cochran *et al.*, 1997; Schmage *et al.*, 2003). Their organic component binds to the silicate groups of the ceramic and their inorganic component to the methacrylate groups of the adhesive material. Previous investigations have shown a significant influence of silane coupling agents on bond strength to ceramic surfaces (Barghi, 2000; Brantley and Eliades, 2001; Blatz *et al.*, 2003).

Other conditioning methods that avoid the intraoral use of HF and sandblasting have been investigated. Diamond burs and lasers have been used for roughening the ceramic surfaces but have a destructive effect by reducing ceramic integrity (Anusavice, 1996; Nebbe and Stein, 1996; Brantley and Eliades, 2001), while laser conditioning has not yet been developed to an acceptable standard (Akova *et al.*, 2005). Phosphoric acid was found to be less successful than HF because of the absence of a dissolving effect on silicate ceramics (Bourke and Rock, 1999; Pannes *et al.*, 2003; Schmage *et al.*, 2003; Ajlouni *et al.*, 2005; Bishara *et al.*, 2005; Türk *et al.*, 2006). A combination of HF and sandblasting was found to be a more time- and material-consuming procedure (Abu Alhaija and Al-Wahadni, 2007).

This *in vitro* study aimed to evaluate the effect of different conditioning procedures on various ceramic microstructures and bracket adhesion. The null hypothesis tested was that different conditioning procedures have no effect on ceramic microstructure and bracket adhesion.

Materials and methods

Metal- and all-ceramic veneering materials frequently used in prosthodontics were tested in this *in vitro* study (Table 1). Cuboid specimens [5 mm (width) × 5 mm (height) × 25 mm (length)] were fabricated according to the manufacturer's instructions. While metal-ceramic products were sintered onto cast metal-alloy (Porta Geo Ti Wieladent, Lenzing, Austria), all-ceramic products were sintered onto CAD-CAM manufactured zirconium oxide frameworks (Zeno Zr Wieladent, Lenzing, Austria) with a ceramic layer thickness of 1 mm. The four types of ceramic were allocated to each of the six conditioning groups shown in Table 2, resulting in 24 subgroups of 40 brackets each.

Table 1 Ceramic types and manufacturers.

Ceramic type	Trade name	Manufacturer
Leucite	Kiss	Degudent, Hanau, Germany
	Initial MC	GC, Tokyo, Japan
Leucite-free	Zirox	Wieladent, Lenzing, Austria
	Initial Zr	GC
Feldspathic	Vintage	Shofu, Kyoto, Japan
	Akzent	Vita, Bad Säckingen, Germany
Fluorapatite	D.sign	Ivoclar-Vivadent, Schaan, Liechtenstein
	Emax ceram	Ivoclar-Vivadent

The HF gels were rinsed with water and air-dried for 10 seconds in the laboratory. Sandblasting was applied for 2 seconds at an air pressure of 2.5 bar (36 psi). The intraoral blaster was seated on a 10 mm spacer perpendicular to the ceramic surfaces. Silane coupling agents were applied to the pre-treated ceramic surfaces for 60 seconds. Light-cure adhesive (Transbond XT 3M Unitek, Monrovia, California, USA) was applied to each silanated ceramic surface. Nine hundred and sixty adhesive-coated upper central incisor brackets (Victory APC, 3M Unitek) were seated and positioned manually on each conditioned surface. Adhesive light polymerization (1000 mW/cm^2, 420–480 nm, Ortholux LED 3M Unitek) was initiated for 40 seconds. All specimens were stored in isotonic saline solution (NaCl 0.9 per cent Braun, Maria Enzersdorf, Austria) at 37°C for 24 hours after bonding, followed by thermocycling according to the International Organization for Standardization norm (TR 11450; 500 cycles per 5–55°C).

Shear bond testing was performed with a universal testing machine (Z010-TND Zwick, Ulm, Germany) at a crosshead speed of 1 mm/minute. The specimens were seated in the machine and manually fixed at the extension arm. The shearing wedge was positioned at the bracket base (Figure 1). SBS (MPa = Newton/mm^2) was measured at debonding and recorded automatically.

The adhesive remnant index (ARI; Årtun and Bergland, 1984; Montasser and Drummond, 2009) was used to

Table 2 Conditioning procedures and manufacturers.

Groups	Conditioning procedure	Trade name	Manufacturer
60″ HF 5%	5% HF etching 60 seconds	Ceramics etch*	Vita, Bad Säckingen, Germany
30″ HF 5%	5% HF etching 30 seconds	Ceramics etch*	Vita
60″ HF 9.6%	9.6% BHF etching 60 seconds	Porcelain-etch**	Ultradent, South Jordan, USA
30″ HF 9.6%	9.6% BHF etching 30 seconds	Porcelain-etch**	Ultradent
Al_2O_3	50 µm Al_2O_3 sandblasting	Al_2O_3 Micron 50*	GAC, Bohemia, New York, USA
SiO_2	30 µm SiO_2 sandblasting	CoJet™ Sand*	3M Espe, Seefeld, Germany

Silane application for 60 seconds. *Monobond-S Ivoclar-Vivadent. **Silane Ultradent.

determine the mode of fracture. The ARI and the ceramic fracture rate were evaluated using a stereomicroscope (magnification ×20, Mantis FX Vision Engineering, Woking, Surrey, UK). Conditioning combinations were prepared for qualitative evaluation. They were sputter coated for scanning electron microscopy analysis (XL 30-ESEM Philips, Eindhoven, Netherlands).

Data from the shear test were automatically aggregated digitally from a computer coupled to the universal testing machine. The statistical analyses were run on Microsoft Office Excel 2003 (Microsoft Corporation, Redmond, Washington, USA). Comparisons of the different conditioning procedures were computed by one-way analysis of variance (ANOVA) followed by *post hoc* testing. Tukey's honestly significant difference test was used to determine significance among the different ceramics for each conditioning procedure. ARI and ceramic fractures were evaluated for all conditioning procedures and subjected to chi-square testing. Significance was set at $P = 0.001$.

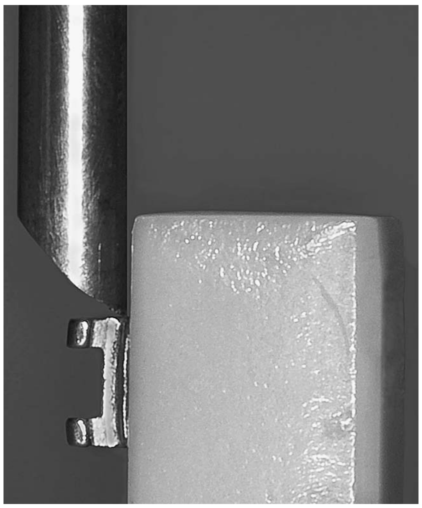

Figure 1 Photograph of the shear test representing the exact and parallel position of the shearing wedge on the bonded bracket and the ceramic specimen surface.

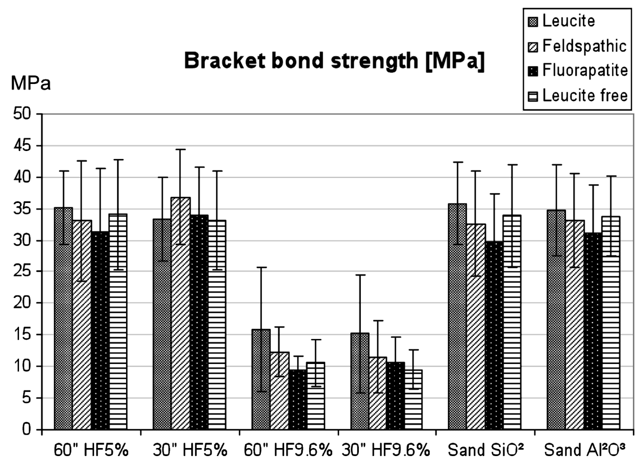

Figure 2 Diagram representing the 24 ceramic/conditioning combinations, with mean shear bond strength and standard deviations.

Table 3 Mean shear bond strengths (*X*), minimum (Min), maximum (Max) values, standard deviations (SD) and homogeneous subsets (=the same letters indicate absence of a statistical significance).

Type of ceramic	Groups	*X*	SD	Min	Max	Homogeneous subsets
Leucite	60″ HF 5%	35.13	5.86	23.68	45.00	B
	30″ HF 5%	33.36	6.59	12.88	44.73	B
	60″ HF 9.6%	15.92	9.84	4.97	35.65	A
	30″ HF 9.6%	15.19	9.37	2.47	35.33	A
	Sand SiO_2	35.80	6.52	20.97	46.33	B
	Sand Al_2O_3	34.72	7.15	17.37	45.10	B
Feldspathic	60″ HF 5%	33.08	9.57	13.40	44.62	B
	30″ HF 5%	36.80	7.48	20.53	49.61	B
	60″ HF 9.6%	12.31	3.88	4.82	23.02	A
	30″ HF 9.6%	11.51	5.73	4.65	33.70	A
	Sand SiO_2	32.57	8.35	15.61	45.23	B
	Sand Al_2O_3	33.16	7.37	14.31	43.59	B
Fluorapatite	60″ HF 5%	31.36	9.94	8.71	51.01	B
	30″ HF 5%	33.97	7.58	13.58	47.53	B
	60″ HF 9.6%	9.34	2.35	4.50	15.24	A
	30″ HF 9.6%	10.63	4.02	4.75	20.00	A
	Sand SiO_2	29.74	7.70	11.88	41.19	B
	Sand Al_2O_3	31.19	7.49	13.68	42.92	B
Leucite-free	60″ HF 5%	34.07	8.68	17.15	47.10	B
	30″ HF 5%	33.19	7.87	17.79	51.15	B
	60″ HF 9.6%	10.57	3.67	6.87	24.63	A
	30″ HF 9.6%	9.53	3.10	3.81	18.32	A
	Sand SiO_2	33.88	8.12	16.15	48.43	B
	Sand Al_2O_3	33.81	6.34	19.35	45.58	B

Results

Descriptive statistics of SBS (mean, standard deviations, minimum and maximum values including homogeneous subsets) are shown in Table 3 and for each conditioning/ceramic combination in Figure 2.

SBS in the 5 per cent HF-etched groups was higher for the 60 and 30 seconds groups. No significant differences were found either between the groups or between the four ceramic types ($P > 0.001$). SBS in the 9.6 per cent BHF-etched groups was less for the 60 and 30 seconds groups. The difference between these two groups was not statistically significant ($P > 0.001$). Leucite ceramics showed significantly higher bond strength than the other tested ceramics ($P < 0.001$). SBS in the sandblasted groups was higher for the aluminium oxide and silica-coated aluminium oxide groups. There was no significant difference between the groups ($P > 0.001$). Only leucite ceramics in the silica-coated aluminium oxide sandblasting groups showed significantly higher bond strengths than fluorapatite ceramic ($P < 0.001$).

One-way ANOVA and *post hoc* testing showed significantly lower bond strengths for all 9.6 per cent BHF etched groups when compared with the 5 per cent HF etched and sandblasted groups ($P < 0.001$).

ARI scores are shown in Table 4 for each ceramic type. Qualitative analysis of the scanning electron microphotographs showed varying microretentive ceramic surface patterns especially in the HF-etched group. The surface pattern in the leucite ceramic groups are shown in the Figure 3A–3D. The 9.6 per cent BHF etching appeared to cause less leucite dissolution than 5 per cent HF etching (Figure 3A and 3B versus Figure 3C and 3D). The least significant microretentive surface pattern was found in the leucite-free ceramic group (Figure 4A, 4B, and 4C) with a cleaner surface following conditioning. Sandblasting resulted in a homogeneous conditioning effect in all ceramic groups. Sandblasting with aluminium oxide led to a rougher surface than sandblasting with silica-coated aluminium oxide (Figure 3F versus Figure 3E).

Discussion

Shear testing is a standard procedure for evaluating the SBS of brackets (Oilo, 1993). SBS in the present study was carried out using a standardized protocol as described by Major *et al.* (1995) and Klocke and Kahl-Nieke (2005a,b).

Surface conditioning of all tested ceramics with 5 per cent HF or sandblasting resulted in an adequate SBS for clinical purposes. In contrast, 9.6 per cent BHF showed

Table 4 Adhesive remnant index (ARI) scores and number of ceramic fractures.

	ARI scores				Ceramic fractures
Type of ceramic	0	1	2	3	
Leucite					
60″ HF 5%	—	5	7	20	8
30″ HF 5%	—	3	9	21	7
60″ HF 9.6%	35	—	3	—	2
30″ HF 9.6%	40	—	—	—	—
Sand SiO_2	—	2	6	23	9
Sand Al_2O_3	—	—	7	15	18
Feldspathic					
60″ HF 5%	7	6	5	8	14
30″ HF 5%	4	4	13	9	10
60″ HF 9.6%	40	—	—	—	—
30″ HF 9.6%	40	—	—	—	—
Sand SiO_2	1	3	11	12	13
Sand Al_2O_3	—	1	9	12	18
Fluorapatite					
60″ HF 5%	4	—	6	8	22
30″ HF 5%	3	6	10	13	8
60″ HF 9.6%	40	—	—	—	—
30″ HF 9.6%	40	—	—	—	—
Sand SiO_2	1	5	9	11	14
Sand Al_2O_3	—	3	7	19	11
Leucite-free					
60″ HF 5%	5	5	9	11	10
30″ HF 5%	4	6	13	9	8
60″ HF 9.6%	40	—	—	—	—
30″ HF 9.6%	40	—	—	—	—
Sand SiO_2	1	1	8	17	14
Sand Al_2O_3	—	3	5	17	15

0 = no adhesive left on ceramic surface; 1 = less than half of the adhesive left on ceramic surface; 2 = more than half of the adhesive left on ceramic surface; 3 = all adhesive left on ceramic surface.

high variability. However, the application times of both HF agents had no effect on SBS. Some authors have reported a difference following sandblasting with aluminium and silica-coated aluminium oxide particles (Vollm, 1989; Meiners *et al.*, 1990). However, the present data did not support these findings. In addition to the high SBS in the 5 per cent HF or sandblasted groups, the ARI scores (2 and 3) indicated strong adhesion between the adhesive and ceramic surfaces, with the majority of the adhesive material left on the ceramic surfaces. In all other instances, the SBS between the ceramic and adhesive exceeded the cohesive strength of the ceramic material and led to ceramic fractures, which should be avoided when debonding (Brantley and Eliades, 2001). The poorer performance in the 9.6 per cent BHF groups compared with all other groups resulted in low SBS and ARI scores (0), i.e. the adhesive remained completely on the bracket mesh base.

Both HF agents produced a microretentive surface, especially in the leucite ceramic groups, by dissolving the leucite crystals in the surrounding glass matrix (Figure 3A–3D). Although the leucite-free ceramics did not show any visible microretentive surface configuration (Figure 4A–4C), high bond strengths were still achieved. It may be speculated that HF etching leads to homogeneous dissolution of the leucite-free ceramic layers, which is sufficient for bracket adhesion. Sandblasting showed a homogeneous microretentive surface in all the ceramic groups. Surface preparation with aluminium oxide particles seemed to result in a rougher surface than sandblasting with silica-coated particles (Figure 3E-3F). This is consistent with the qualitative findings of Schmage *et al.* (2003).

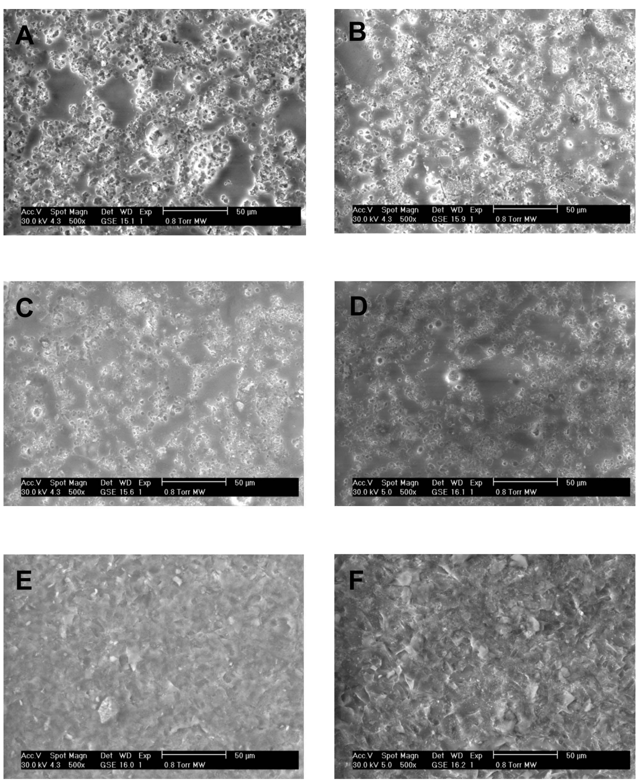

Figure 3 Scanning electron photomicrographs showing the six conditioning procedures on leucite ceramic surface (magnification ×500). A: 5 per cent hydrofluoric acid (HF) etching for 60 seconds; B: 5 per cent HF etching for 30 seconds; C: 9.6 per cent buffered hydrofluoric acid (BHF) etching for 60 seconds; D: 9.6 per cent BHF etching for 30 seconds; E: Silica-coated aluminum oxide sandblasting; F: Aluminum oxide sandblasting.

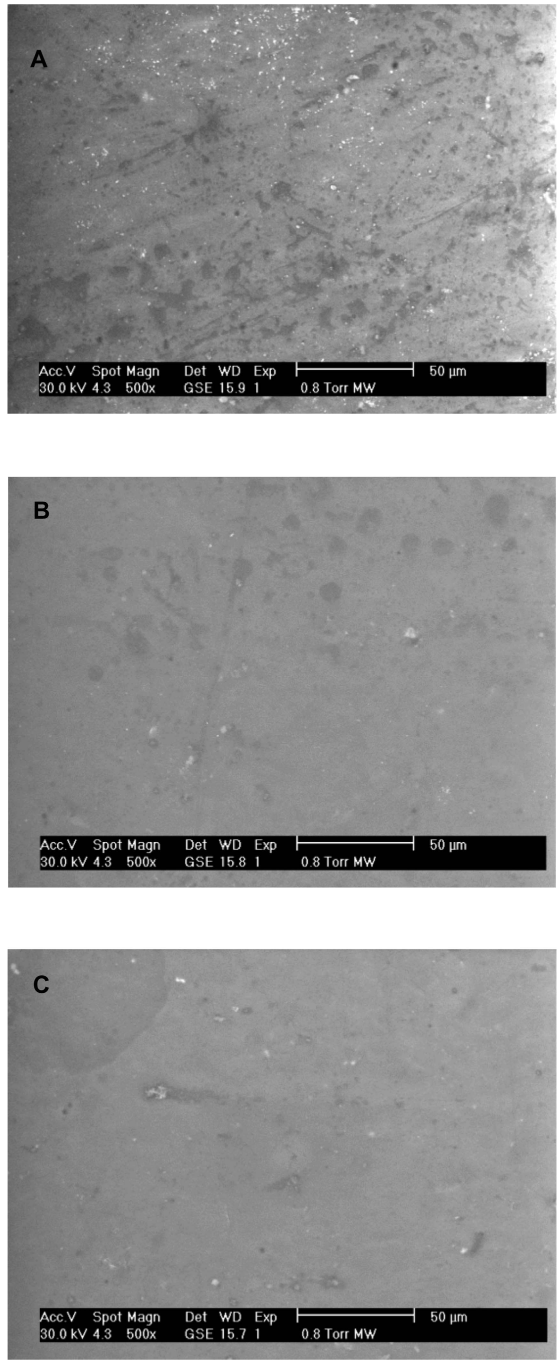

Figure 4 Scanning electron microphotographs following HF etching on leucite-free ceramic surface (magnification ×500): A: No conditioning; B: 5 per cent hydrofluoric acid (HF) etching for 60 seconds; C: 9.6 per cent buffered hydrofluoric acid (BHF) etching for 60 seconds.

5 per cent HF etching

Studies using 5 per cent HF showed SBSs between 12 and 23 MPa (Major *et al.*, 1995; Shahverdi *et al.*, 1998; Bourke and Rock, 1999; Schmage *et al.*, 2003). A short etching time (10–40 seconds) was only investigated in two studies with contradictory outcomes (6/27 MPa; Ozcan and Vallittu, 2003; Saracoglu *et al.*, 2004). Conditioning different ceramics with 5 per cent HF was tested by Ferri *et al.* (2006). In agreement with their results, the present findings are that ceramic type may not have an influence on SBS. Other studies that used the ARI showed similar scores of 3 and ceramic fractures as observed in the present study, but lower SBSs (Major *et al.*, 1995; Bourke and Rock, 1999; Schmage *et al.*, 2003). The high SBS of leucite crystal-free ceramics lacking microretentive surfaces (Figure 4B and 4C) is contrary to reports claiming that SBS is dependent on the presence of leucite crystals in the ceramic surface (Kamada *et al.*, 1998; Estafan *et al.*, 2000; Barghi *et al.*, 2006).

9.6 per cent BHF etching

The influence of 9.6 per cent BHF etching has been investigated by several authors (Pameijer *et al.*, 1996; Gillis and Redlich, 1998; Leibrock *et al.*, 1999; Sant'Anna *et al.*, 2002; Ozcan and Vallittu, 2003; Saracoglu *et al.*, 2004; Barghi *et al.*, 2006; Türk *et al.*, 2006; Shiu *et al.*, 2007). In contrast to the present findings, they found that longer etching leads to higher SBS. Conditioning different ceramics with 9.6 per cent BHF was tested by Türk *et al.* (2006). The findings of the present study are in agreement with their results that ceramic type may not have an influence on SBS. Some disparity is found in the literature regarding ARI scores in SBS testing (Cochran *et al.*, 1997; Gillis and Redlich, 1998; Sant'Anna *et al.*, 2002; Larmour *et al.*, 2006).

Sandblasting

The effect of sandblasting has been tested by numerous investigators (Kao *et al.*, 1988; Smith *et al.*, 1988; Kao and Johnston, 1991; Wolf *et al.*, 1993; Cochran *et al.*, 1997; Gillis and Redlich, 1998; Bourke and Rock, 1999; Sant'Anna *et al.*, 2002; Schmage *et al.*, 2003). SBS ranging from 7 to 41 MPa were found. Sandblasting with silica-coated aluminium oxide showed no significant difference in SBS compared with conventional aluminium oxide sandblasting as also seen in the present study. The same was also observed for the effect of sandblasting different ceramics (Karan *et al.*, 2007). Sandblasted surface preparation led to a high SBS between the ceramic surface and the adhesive material with an ARI score of 3 and ceramic fractures on debonding for all ceramic surface types (Cochran *et al.*, 1997; Gillis and Redlich, 1998; Sant'Anna *et al.*, 2002; Schmage *et al.*, 2003; Türk *et al.*, 2006; Karan *et al.*, 2007).

Conclusions

The following conclusions can be drawn from this investigation:

1. The null hypothesis was rejected. Different conditioning procedures have an effect on ceramic microstructures and bracket adhesion.
2. High SBS (29.74–36.80 MPa) were found for all ceramic surfaces when conditioned with 5 per cent HF or sandblasted, indicating a higher risk of ceramic fracture.
3. The 9.6 per cent BHF appeared to have a minor conditioning effect, resulting in a lower SBS (9.34–15.92 MPa), but fewer ceramic fractures.
4. A short etching time (30 seconds) was as effective as standard etching (60 seconds).
5. Silica coating of ceramic surfaces showed no advantage as compared with conventional sandblasting.

Acknowledgements

The veneering ceramics, framework materials, the different conditioning materials and accessories as well as the brackets were donated by the various manufacturers. The authors are indebted to Irene Mischak, Department of Statistics, Medical University of Graz, for assistance with the statistical analyses and to Professor Johann Wernisch, Department of Solid State Physics, Technical University of Vienna, for assistance with the scanning electron microscopy.

References

Abu Alhaija E S, Al-Wahadni A M 2007 Shear bond strength of orthodontic brackets bonded to different ceramic surfaces. European Journal of Orthodontics 29: 386–389

Ajlouni R, Bishara S E, Oonsombat C, Soliman M, Laffoon J 2005 The effect of porcelain surface conditioning on bonding orthodontic brackets. Angle Orthodontist 75: 858–864

Akova T, Yoldas O, Toroglu M S, Uysal H 2005 Porcelain surface treatment by laser for bracket-porcelain bonding. American Journal of Orthodontics and Dentofacial Orthopedics 128: 630–637

Anusavice K J 1996 Reducing the failure potential of ceramic-based restorations. Part 1: metal-ceramic crowns and bridges. General Dentistry 44: 492–494

Årtun J, Bergland S 1984 Clinical trials with crystal growth conditioning as an alternative to acid-etch enamel pretreatment. American Journal of Orthodontics 85: 333–340

Barghi N 2000 To silanate or not to silanate: making a clinical decision. Compendium of Continuing Education in Dentistry 21: 659–662, 664

Barghi N, Fischer D E, Vatani L 2006 Effects of porcelain leucite content, types of etchants, and etching time on porcelain-composite bond. Journal of Esthetic and Restorative Dentistry 18: 47–52

Bishara S E, Ajlouni R, Oonsombat C, Laffoon J 2005 Bonding orthodontic brackets to porcelain using different adhesives/enamel conditioners: a comparative study. World Journal of Orthodontics 6: 17–24

Blatz M B, Sadan A, Kern M 2003 Resin-ceramic bonding: a review of the literature. Journal of Prosthetic Dentistry 89: 268–274

Bourke B M, Rock W P 1999 Factors affecting the shear bond strength of orthodontic brackets to porcelain. British Journal of Orthodontics 26: 285–290

Brantley W, Eliades T 2001 Orthodontic materials—scientific and clinical aspects. Georg Thieme Verlag, Stuttgart

Brosh T, Pilo R, Bichacho N, Blutstein R 1997 Effect of combinations of surface treatments and bonding agents on the bond strength of repaired composites. Journal of Prosthetic Dentistry 77: 122–126

Calamia J R 1983 Etched porcelain facial veneers: a new treatment modality based on scientific and clinical evidence. New York Journal of Dentistry 53: 255–259

Calamia J R 1985 Etched porcelain veneers: the current state of the art. Quintessence International 16: 5–12

Chen J H, Matsumura H, Atsuta M 1998 Effect of etchant, etching period, and silane priming on bond strength to porcelain of composite resin. Operative Dentistry 23: 250–257

Cochran D, O'Keefe K L, Turner D T, Powers J M 1997 Bond strength of orthodontic composite cement to treated porcelain. American Journal of Orthodontics and Dentofacial Orthopedics 111: 297–300

Estafan D, Dussetschleger F, Estafan A, Jia W 2000 Effect of prebonding procedures on shear bond strength of resin composite to pressable ceramic. General Dentistry 48: 412–416

Ferri N P, Eliades T, Zinelis S, Bradley T G 2006 Force to debond brackets from high-fusing and low-fusing porcelain systems. Angle Orthodontist 76: 278–281

Frankenberger R, Kramer N, Sindel J 2000 Repair strength of etched vs silica-coated metal-ceramic and all-ceramic restorations. Operative Dentistry 25: 209–215

Gillis I, Redlich M 1998 The effect of different porcelain conditioning techniques on shear bond strength of stainless steel brackets. American Journal of Orthodontics and Dentofacial Orthopedics 114: 387–392

Kamada K, Yoshida K, Atsuta M 1998 Effect of ceramic surface treatments on the bond of four resin luting agents to a ceramic material. Journal of Prosthetic Dentistry 79: 508–513

Kao E C, Johnston W M 1991 Fracture incidence on debonding of orthodontic brackets from porcelain veneer laminates. Journal of Prosthetic Dentistry 66: 631–637

Kao E C, Boltz K C, Johnston W M 1988 Direct bonding of orthodontic brackets to porcelain veneer laminates. American Journal of Orthodontics and Dentofacial Orthopedics 94: 458–468

Karan S, Büyükyilmaz T, Toroglu M S 2007 Orthodontic bonding to several ceramic surfaces: are there acceptable alternatives to conventional methods? American Journal of Orthodontics and Dentofacial Orthopedics 132: 144. e7–e14

Kirkpatrick J J, Burd D A 1995 An algorithmic approach to the treatment of hydrofluoric acid burns. Burns 21: 495–499

Klocke A, Kahl-Nieke B 2005a Influence of cross-head speed in orthodontic bond strength testing. Dental Materials 21: 139–144

Klocke A, Kahl-Nieke B 2005b Influence of force location in orthodontic shear bond strength testing. Dental Materials 21: 391–396

Larmour C J, Bateman G, Stirrups D R 2006 An investigation into the bonding of orthodontic attachments to porcelain. European Journal of Orthodontics 28: 74–77

Leibrock A, Degenhart M, Behr M, Rosentritt M, Handel G 1999 *In-vitro* study of the effect of thermo- and load-cycling on the bond strength of porcelain repair systems. Journal of Oral Rehabilitation 26: 130–137

Major P W, Koehler J R, Manning K E 1995 24-hour shear bond strength of metal orthodontic brackets bonded to porcelain using various adhesion promoters. American Journal of Orthodontics and Dentofacial Orthopedics 108: 322–329

Meiners H, Herrmann R, Spitzbarth S 1990 Bond strength of Rocatec systems. Dental Labor (Munch) 38: 185–188

Montasser M A, Drummond J L 2009 Reliability of the adhesive remnant index score system with different magnifications. Angle Orthodontist 79: 773–776

Nebbe B, Stein E 1996 Orthodontic brackets bonded to glazed and deglazed porcelain surfaces. American Journal of Orthodontics and Dentofacial Orthopedics 109: 431–436

Oilo G 1993 Bond strength testing—what does it mean? International Dental Journal 43: 492–498

Ozcan M, Vallittu P K 2003 Effect of surface conditioning methods on the bond strength of luting cement to ceramics. Dental Materials 19: 725–731

Pameijer C H, Louw N P, Fischer D 1996 Repairing fractured porcelain: how surface preparation affects shear force resistance. Journal of the American Dental Association 127: 203–209

Pannes D D, Bailey D K, Thompson J Y, Pietz D M 2003 Orthodontic bonding to porcelain: a comparison of bonding systems. Journal of Prosthetic Dentistry 89: 66–69

Pine C M, Pitts N B, Steele J G, Nunn J N, Treasure E 2001 Dental restorations in adults in the UK in 1998 and implications for the future. British Dental Journal 190: 4–8

Pospiech P 2004 Keramik-Vollkeramik. Ein Kompendium für die keramikgerechte Anwendung vollkeramischer Systeme in der Zahnmedizin. 3M Espe AG, Seefeld, Germany

Pröbster L 2001 Sind vollkeramische Kronen und Brücken wissenschaftlich anerkannt? Deutsche Zahnärztliche Zeitung 56: 575–576

Rosenblum M A, Schulman A 1997 A review of all-ceramic restorations. Journal of the American Dental Association 128: 297–307

Sant'Anna E F, Monnerat M E, Chevitarese O, Stuani M B 2002 Bonding brackets to porcelain—*in vitro* study. Brazilian Dental Journal 13: 191–196

Saracoglu A, Cura C, Cötert H S 2004 Effect of various surface treatment methods on the bond strength of the heat-pressed ceramic samples. Journal of Oral Rehabilitation 31: 790–797

Schaffer H, Dumfahrt H, Gausch K 1989 [Surface structures and substance loss during the etching of ceramic materials]. Schweizer Monatsschrift für Zahnmedizin 99: 530–543

Schiettecatte D, Mullie G, Depoorter M 2003 Treatment of hydrofluoric acid burns. Acta Chirurgica Belgica 103: 375–378

Schmage P, Nergiz I, Herrmann W, Ozcan M 2003 Influence of various surface-conditioning methods on the bond strength of metal brackets to ceramic surfaces. American Journal of Orthodontics and Dentofacial Orthopedics 123: 540–546

Schmid M, Fischer J, Salk M, Strub J 1992 [The microstructure of leucite-reinforced glass ceramics]. Schweizer Monatsschrift für Zahnmedizin 102: 1046–1053

Shahverdi S, Canay S, Sahin E, Bilge A 1998 Effects of different surface treatment methods on the bond strength of composite resin to porcelain. Journal of Oral Rehabilitation 25: 699–705

Shiu P, De Souza-Zaroni W C, Eduardo Cde P, Youssef M N 2007 Effect of feldspathic ceramic surface treatments on bond strength to resin cement. Photomedicine and Laser Surgery 25: 291–296

Smith G A, McInnes-Ledoux P, Ledoux W R, Weinberg R 1988 Orthodontic bonding to porcelain–bond strength and refinishing. American Journal of Orthodontics and Dentofacial Orthopedics 94: 245–252

Sorensen J A, Engelman M J, Torres T J, Avera S P 1991 Shear bond strength of composite resin to porcelain. International Journal of Prosthodontics 4: 17–23

Thurmond J W, Barkmeier W W, Wilwerding T M 1994 Effect of porcelain surface treatments on bond strengths of composite resin bonded to porcelain. Journal of Prosthetic Dentistry 72: 355–359

Türk T, Saraç D, Saraç Y S, Elekdağ-Türk S 2006 Effects of surface conditioning on bond strength of metal brackets to all-ceramic surfaces. European Journal of Orthodontics 28: 450–456

Tylka D F, Stewart G P 1994 Comparison of acidulated phosphate fluoride gel and hydrofluoric acid etchants for porcelain-composite repair. Journal of Prosthetic Dentistry 72: 121–127

Vollm L 1989 Rocatec—new bonding system for synthetic resin technic. Dental Labor (Munch) 37: 527–530, 533–535

Wolf D M, Powers J M, O'Keefe K L 1993 Bond strength of composite to etched and sandblasted porcelain. American Journal of Dentistry 6: 155–158

Zachrisson Y O, Zachrisson B U, Büyükyilmaz T 1996 Surface preparation for orthodontic bonding to porcelain. American Journal of Orthodontics and Dentofacial Orthopedics 109: 420–430