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In vitro peel/shear bond strength evaluation of orthodontic bracket base design

G. Willems*, C. E. L. Carels* and G. Verbeke†

**Department of Orthodontics and †Biostatistical Centre, Department of Epidemiology, Faculty of Medicine, Katholieke Universiteit te Leuven, Kapucijnenvoer 7, B-3000, Leuven, Belgium*

ABSTRACT

Objectives: The adhesive capacity of 17 different bracket types was evaluated in an *in vitro* peel/shear test.
Methods: Silane-treated metal bars were used as substrates with all bonding being performed using the orthodontic adhesive Concise. The effect of aluminium oxide air abrasion on the bonding performance of recycled metal bracket bases was evaluated. Morphological examination of the bracket bases was carried out under scanning electron microscopy. Statistics analysis included one-way ANOVA with Tukey's Studentized Range Test, two-way ANOVA and Weibull analysis.
Results: Mean peel/shear bond strength values range from 13.9 MPa for Allure Accu Arch, a ceramic bracket type, to 1.6 MPa for the plastic bracket CeramaFlex Advant Edge. Allure Accu Arch performed the best of all the ceramic brackets. However, bracket wing fracture was observed. The metal brackets Mini masters and Omni Arch showed no significant difference in bond strength compared with the ceramic bracket Allure Accu Arch ($P<0.01$).
Conclusion: The type of the bracket base determines its adhesive capacity. Sandblasting the base of recycled metal brackets had no uniform effect.

KEY WORDS: Shear bond strength, Bracket base design

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INTRODUCTION

Nothing has changed the course of orthodontics as much as the ability to bond attachments directly to the enamel surfaces of teeth. By the late 1970s, only 15 years after the work of Buonocore[1], direct bonding had become an accepted clinical procedure in orthodontics.

Metal, plastic and ceramic brackets of various types are currently used in orthodontics[2]. All brackets should form bonds of sufficient strength to enamel, yet be capable of being debonded with relative ease and without damage to the underlying enamel surface. Bracket bond strength may be influenced by the mechanical retention of the bracket base and the use of chemical surface treatments. The bond strength of metal and plastic brackets is predominantly based on mechanical mechanisms. Some ceramic brackets rely on mechanical retention, some on silane coating for chemical bonding and some make use of a combination of these techniques to enhance bond strength.

One of the disadvantages of bond strength testing is the limited availability of human teeth, including premolar teeth, on which to run the tests. Variability in the quality of human enamel is another disadvantage, which may contribute to the large standard deviations found in bond strength tests. Silanated metal bars do not have these disadvantages and may be more appropriate for evaluating the bond strength of bracket bases, since no failure is expected at the interface between the adhesive and the silanated bar.

The purpose of the present study was two-fold: first, to compare the retentive capacity of the bracket bases of 12 metal, three ceramic and two plastic bracket types in an *in vitro* peel/shear bond strength test using a chemically cured adhesive system bonded to silanated metal bars; and second, to evaluate the effect of sandblasting previously used metal bracket bases on their bonding performance.

Correspondence should be addressed to: Dr Guy Willems, Department of Orthodontics-KU Leuven, Kapucijnenvoer 7, B-3000 Leuven, Belgium. Tel.: +32 16 332439. Fax: +32 16 332435.

Table I. List of investigated bracket systems with manufacturer and bracket base projected surface area as reported by the manufacturer (S-area)

Bracket system	*Manufacturer*	*S-area (mm²)*
Mini Dyna Lock St Edgewise	3M	9.36
Miniature Twin	3M	7.90
Transcend 6000	3M	11.80
20/20m Ceramic brackets	American Orthodontics	7.41
Masters	American Orthodontics	8.28
Mini Masters	American Orthodontics	8.28
Silkon	American Orthodontics	9.70
Accu Arch MP	GAC	11.49
Accu Roth	GAC	11.49
Allure Accu Arch	GAC	9.88
Micro Arch Super Mesh	GAC	9.88
Omni Arch	GAC	11.49
Standard Edgewise	GAC	11.49
Optimesh	Ormco	10.30
Ormesh	Ormco	10.30
Advant-edge	TP Orthodontics	9.68
CeramaFlex	TP Orthodontics	14.90

MATERIALS AND METHODS

Stainless steel metal bars $50 \times 5 \times 3$ mm were used to bond the 17 different bracket types listed in *Table I*. The surface of the metal bars was first sandblasted to increase surface roughness and then silane coated using the Silicoater system (Silicoup Sililink, Heraeus Külzer, Wehrheim, Germany), operated according to the manufacturer's instructions. Twelve brackets of each of the 17 different bracket types were bonded to the metal bars. Brackets were bonded using a separate composite mix for each bracket. The orthodontic bracket adhesive Concise (3M Unitek, Monrovia, CA, USA) was used for all bonding procedures. This chemical-cure adhesive was chosen based on its performance in another study[3]. After bonding, the samples were stored for 24 h at 37°C in dry conditions to prevent metal oxidation. All bonding procedures were carried out by the same operator.

An Instron universal testing machine (Instron 4505, Instron Corporation, Canton, MA, USA) was used to perform the peel/shear bond strength tests. The bar was

Table II. Peel/shear bond strengths (in N and MPa) for the different bracket systems tested

Bracket system		*Mean (N)*	*S.D. (N)*	*Min (N)*	*Max (N)*	*Mean (MPa)*	*S.D. (MPa)*	*Min (MPa)*	*Max (MPa)*
Metal brackets:									
Accu Arch MP		116.3	30.3	79.0	187.4	10.1	2.6	6.9	16.3
Accu Arch MP	ME	111.3	23.2	75.3	148.6	9.7	2.0	6.6	12.9
Accu Roth		112.2	19.9	87.9	143.2	9.8	1.7	7.7	12.5
Accu Roth	ME	105.3	16.3	83.5	136.1	9.1	1.4	7.3	11.9
Advant-edge		80.9	14.7	63.7	114.9	8.4	1.5	6.6	11.9
Advant-edge	ME	64.2	14.4	47.8	94.8	6.6	1.5	4.9	9.8
Masters		94.5	20.4	58.4	132.0	11.4	2.5	7.1	15.9
Masters	ME–	60.8	17.8	27.7	92.5	7.3	2.1	3.3	11.2
Micro Arch SM		108.3	8.2	92.9	121.9	11.0	0.8	9.4	12.3
Micro Arch SM	ME–	92.0	14.7	69.7	116.0	9.3	1.5	7.1	11.7
Mini Dyna Lock		36.6	7.9	28.3	52.4	3.9	0.8	3.0	5.6
Mini Dyna Lock	ME+	59.0	11.1	37.7	75.8	6.3	1.2	4.0	8.1
Mini Masters		107.4	17.1	85.8	130.3	13.0	2.1	10.4	15.7
Mini Masters	ME–	69.5	10.6	55.8	88.7	8.4	1.3	6.7	10.7
Miniature Twin		70.1	7.5	58.5	84.4	8.9	1.0	7.4	10.7
Miniature Twin	ME+	89.8	14.7	66.7	12.0	11.4	1.9	8.5	15.1
Omni Arch		136.1	15.8	108.6	166.8	11.8	1.4	9.5	14.5
Omni Arch	ME–	107.8	23.9	79.7	136.7	9.4	2.1	6.9	11.9
Optimesh		75.9	12.0	53.6	97.5	7.4	1.2	5.2	9.5
Optimesh	ME–	59.9	9.2	44.0	79.6	5.8	0.9	4.3	7.7
Ormesh		54.7	6.0	45.2	61.2	5.3	0.6	4.4	5.9
Ormesh	ME	59.5	4.2	52.4	64.9	5.8	0.4	5.1	6.3
Standard Edgewise		109.2	15.7	83.5	136.6	9.5	1.4	7.3	11.9
Standard Edgewise	ME	97.8	17.7	65.0	112.5	8.5	1.5	5.7	9.8
Ceramic/plastic brackets:									
20/20m Ceramic		50.9	6.1	43.5	61.2	6.9	0.8	5.9	8.3
Allure Accu Arch		137.4	12.7	112.6	157.2	13.9	1.3	11.4	15.9
CeramaFlex		24.1	7.2	14.6	34.4	1.6	0.5	1.0	2.3
Silkon		—	—	—	—	—	—	—	—
Transcend 6000		103.6	9.6	81.5	115	8.8	0.8	6.9	9.7

All tests were performed bonding the different systems to metal bars using Concise as bracket adhesive. Two-way analysis of variance revealed that micro-etching increased (ME+), decreased (ME–) or had no significant effect (ME) on the retentive capacity of the metal bracket base

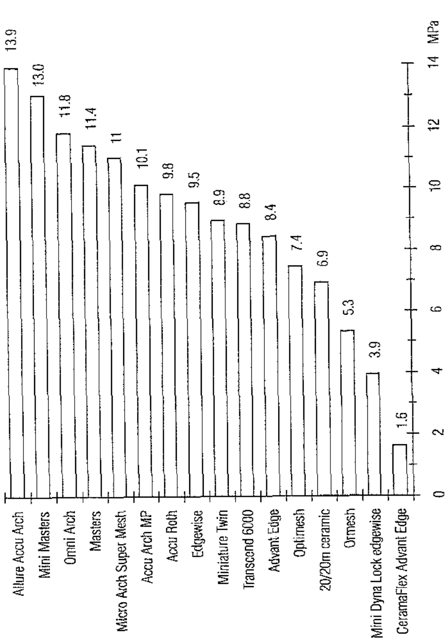

Fig. 1. Graphical presentation of *in vitro* peel/shear bond strength results of different bracket materials.

mounted so that the bracket base made an angle of 30° with the direction of the applied dislodging force. Further test conditions are specified by Willems *et al.*[3] The results of this part of the study acted as a control and provided the basis for comparison with the results of the second part of this investigation, consisting of the rebonding of previously used and sandblasted metal brackets. Indeed, after debonding, the metal bracket bases were sandblasted using a MicroEtcher (Danville Engineering Inc., Danville, CA, USA) and 0.90 µm aluminium oxide. This group of brackets (ME) was then rebonded on new silane-treated metal bars and subsequently adhesively tested. Bond strength values without and with sandblasting could then be compared.

An assessment of the adherent resin after bond failure was made with a light-optical stereomicroscope (Wild M5A, Wild, Heerbrugg, Switzerland). The Adhesive Remnant Index (ARI)[4] was used.

Scanning electron microscopy was performed on each type of bracket base to gather morphological evidence based on the *in vitro* behavior.

Statistical analysis included the conventional *F*-test and one-way and two-way analysis of variance with Tukey's Studentized Range Test for pairwise comparisons between test materials, as well as Weibull analysis to give an indication of the dependability of the test material[3,5,6].

RESULTS

Means, standard deviations and range of bond strength values are given in alphabetical order in *Table II* in newtons and megapascals. Mean values range from 13.9 MPa for Allure Accu Arch, a ceramic bracket that displayed the highest bond strength when expressed in load/unit area, to 1.6 MPa for the plastic bracket CeramaFlex Advant Edge. *Figure 1* gives an overview. The outcome of the one-way analysis of variance and the Tukey's Studentized Range Test performed on the data expressed in load/unit area are summarized in *Table III*. Allure Accu Arch performed best of all the

Table III. Statistical analysis: the presence of significant differences was shown with the *F*-test ($P<0.0001$)

	Allure Accu Arch	*Mini Masters*	*Omni Arch*	*Masters*	*Micro Arch SM*	*Accu Arch MP*	*Accu Roth*	*Standard Edgewise*	*Miniature Twin*	*Transcend 6000*	*Advant-edge*	*Optimesh*	*20/20m Ceramic*	*Ormesh*	*Mini Dyna Lock SE*	*CeramaFlex*
Allure Accu Arch	—			*	*	*	*	*	*	*	*	*	*	*	*	*
Mini Masters		—				*	*	*	*	*	*	*	*	*	*	*
Omni Arch			—						*	*	*	*	*	*	*	*
Masters	*			—					*	*	*	*	*	*	*	*
Micro Arch Super Mesh	*				—						*	*	*	*	*	*
Accu Arch MP	*	*				—						*	*	*	*	*
Accu Roth	*	*					—					*	*	*	*	*
Standard Edgewise	*	*						—					*	*	*	*
Miniature Twin	*	*	*	*					—					*	*	*
Transcend 6000	*	*	*	*						—				*	*	*
Advant-edge	*	*	*	*	*						—			*	*	*
Optimesh	*	*	*	*	*	*	*					—			*	*
20/20m Ceramic	*	*	*	*	*	*	*	*					—		*	*
Ormesh	*	*	*	*	*	*	*	*	*	*	*			—		*
Mini Dyna Lock SE	*	*	*	*	*	*	*	*	*	*	*	*	*		—	
CeramaFlex	*	*	*	*	*	*	*	*	*	*	*	*	*	*		—

The significant pairwise comparisons by Tukey's Studentized Range Test are marked with an asterisk

Table IV. Statistical analysis: output of the Weibull analysis (Weibull modulus, characteristic strength and its 99% confidence limits, calculated bond strength for 1% chance of failure)

Bracket system		*Weibull modulus*	*Characteristic strength (MPa)*	*99% Confidence limits (MPa)*		*Force for 1% chance of failure (MPa)*
Metal brackets:						
Accu Arch MP		4.0	11.1	9.8	13.5	4.2
Accu Arch MP	ME	6.0	10.5	9.1	12.1	3.8
Accu Roth		6.8	10.5	9.3	11.8	5.4
Accu Roth	ME	7.0	9.8	8.7	10.9	5.0
Advant-edge		5.5	9.0	7.7	10.4	3.6
Advant-edge	ME	4.7	7.2	6.0	8.7	2.9
Masters		5.3	12.4	10.6	14.5	4.4
Masters	ME–	4.0	8.1	6.6	9.9	2.9
Micro Arch SM		15.8	11.3	10.8	11.9	7.0
Micro Arch SM	ME	7.3	9.9	8.9	11.1	6.3
Mini Dyna Lock		4.8	4.3	3.6	5.0	1.9
Mini Dyna Lock	ME+	6.8	6.8	6.0	7.6	2.9
Mini Masters		7.5	13.8	12.4	15.4	7.4
Mini Masters	ME–	7.3	8.9	7.9	10.1	4.8
Miniature Twin		10.1	9.3	8.6	10.0	5.1
Miniature Twin	ME+	6.6	12.1	10.7	13.8	6.9
Omni Arch		9.3	12.4	11.4	13.5	6.7
Omni Arch	ME–	5.8	10.2	8.6	12.0	5.7
Optimesh		7.4	7.8	7.1	8.7	4.1
Optimesh	ME–	6.8	6.2	5.4	7.0	3.2
Ormesh		12.9	5.6	5.2	5.9	4.1
Ormesh	ME	18.1	5.9	5.6	6.2	4.3
Standard Edgewise		7.9	10.1	9.1	11.1	5.7
Standard Edgewise	ME	8.7	9.1	8.1	10.1	5.1
Ceramic/plastic brackets:						
20/20m Ceramic		9.5	7.2	6.7	7.9	4.5
Allure Accu Arch		12.9	14.5	13.6	15.4	10.1
CeramaFlex		4.1	1.8	1.5	2.2	0.6
Silkon		—	—	—	—	—
Transcend 6000		15.9	9.1	8.7	9.6	6.8

brackets. However, bracket wing fracture was seen a few times with this ceramic material. The metal brackets Mini Masters and Omni Arch showed no significant difference in bond strength compared with the ceramic bracket Allure Accu Arch. More detailed results are given in *Table III.*

Sandblasting the base of metal brackets had no consistent effect. It increased the bond strength significantly when bonding Mini Dyna Lock or Miniature Twin brackets. Sandblasting had the opposite effect on Masters, Mini Masters, Micro Arch Super Mesh, Omni Arch and Optimesh. The bond strength of Accu Arch MP, Accu Roth, Advant-edge, Ormesh and Standard Edgewise was not influenced by this technique.

The results of the Weibull analysis are shown in *Table IV.* The major difference with the analysis of variance is that according to the Weibull analysis there is no significant difference in bond strength for Micro Arch Super Mesh whether or not it is sandblasted. This is confirmed by the overlapping of the 99% confidence intervals of the characteristic strength for both material groups. The individual Weibull distributions of all materials, tested on an intercomparable scale, is displayed in *Fig. 2.*

The site of failure was evaluated according to the Adhesive Remnant Index. All but three samples of Allure Accu Arch brackets failed at the resin–bracket interface. This was due to the silanization of the metal bars which produced a perfectly clean area to which the adhesive resin could bond strongly.

The morphological screening with a scanning electron microscope is displayed in *Figs 3–16*, and is discussed hereafter.

DISCUSSION

Allure Accu Arch ceramic brackets displayed the highest bond strength values when expressed as fracture load/unit area. However, these values did not differ significantly from those for Mini Masters and Omni Arch. The Weibull distribution reveals that the Allure Accu brackets are reliable with a high characteristic strength value (*Fig. 2*). However, some precautions have to be taken when using this system in the clinical situation. Apart from some bracket wing fractures during debonding, it has also been shown that if there is a bracket fracture during treatment the fracture

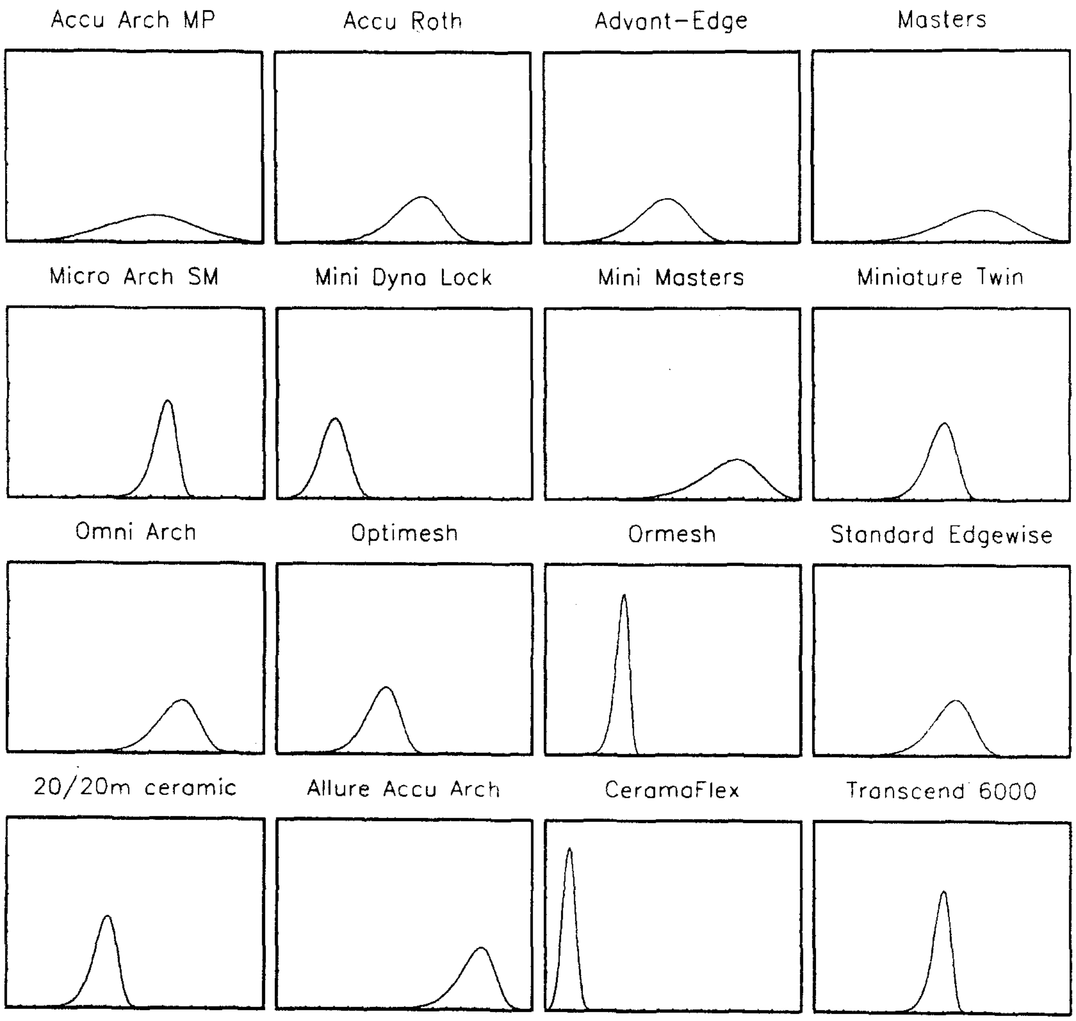

Fig. 2. Individual graphs of the Weibull distribution for each bracket system evaluated. For all graphs, *X*- and *Y*-axis have the same scale.

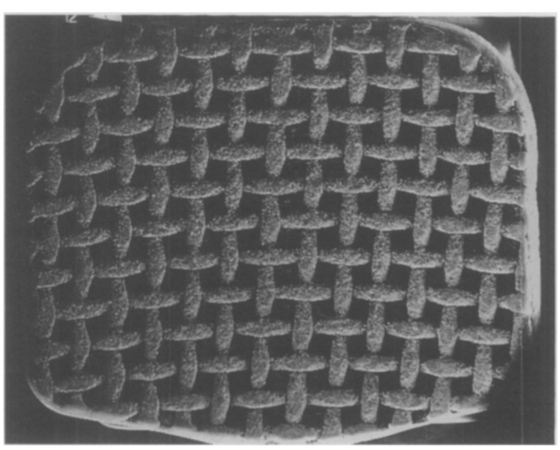

Fig. 3. The Optimesh bracket base has a monolayered mesh pattern with rough surfaces (magnification 27×).

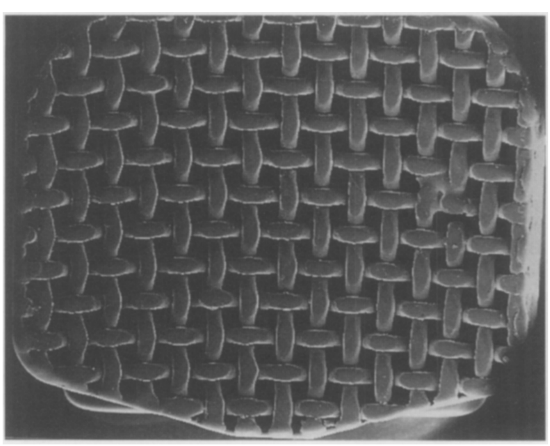

Fig. 4. Monolayered mesh pattern with smooth wires of Ormesh (magnification 27×).

surfaces can cause enormous damage to opposing teeth. Furthermore, enamel damage during debonding of ceramic brackets is well described in the clinical literature. In this respect, other ceramic brackets such as Transcend 6000 display bond strength values that facilitate debonding and thereby limit enamel damage. The Weibull distribution for Transcend 6000 indicates a reliable system with an acceptable characteristic strength (*Fig. 2*). Thus, the overall performance of Transcend 6000 is superior to that of Allure Accu Arch, especially in view of the possible enamel damage during debonding.

A chemical-cure adhesive was used for this bond strength study because of the use of metal bars as the substrate. It was found that the use of light-cure adhesives resulted in incomplete polymerization of the resin,

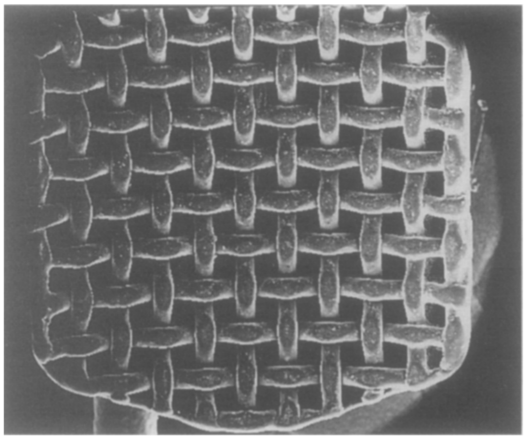

Fig. 5. Advant-edge bracket base with a monolayer of vertical and horizontal metal wires (magnification 25×).

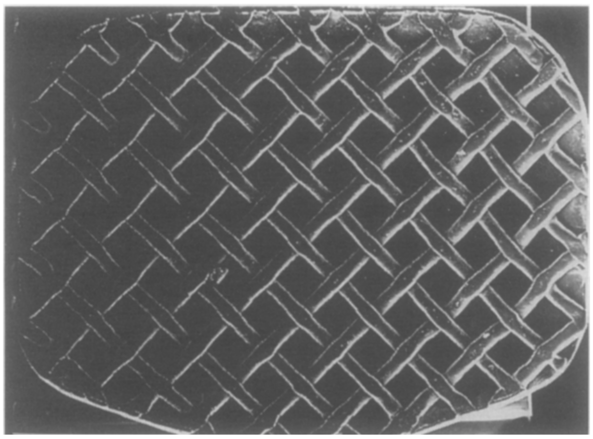

Fig. 6. Diagonal mesh pattern of Masters (magnification 30×).

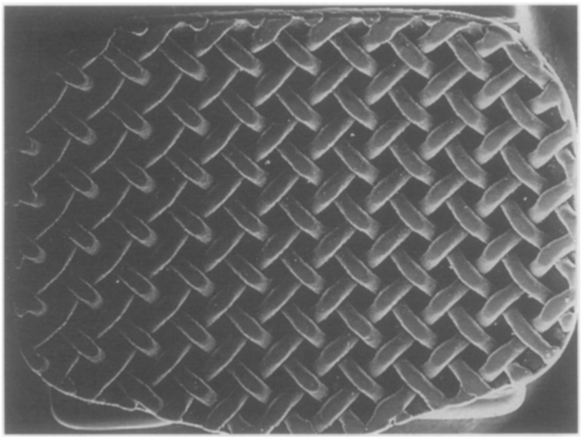

Fig. 7. The mesh pattern of Mini Masters consists of more densely packed thicker metal wires (magnification 30×).

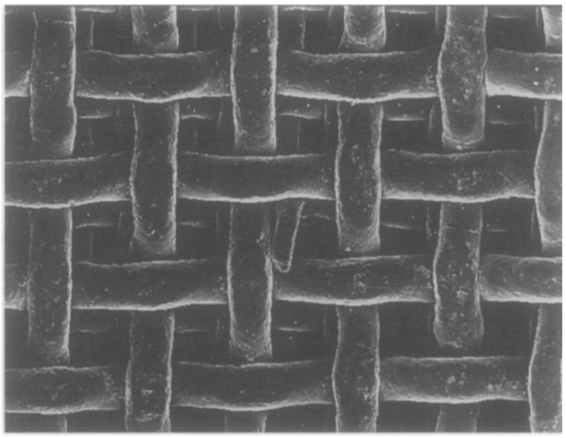

Fig. 8. Micro Arch Super Mesh has a bilayered mesh pattern (magnification 80×).

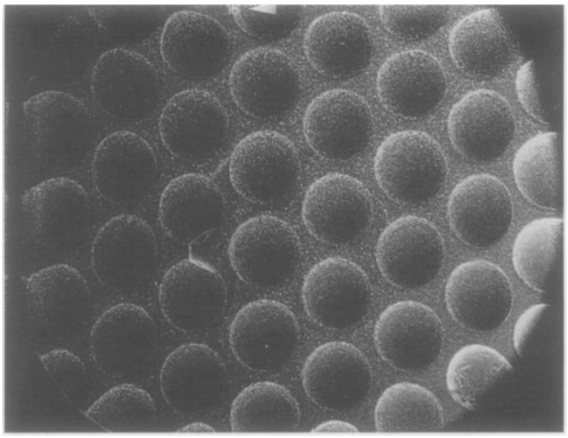

Fig. 9. Photo-etched bracket base of Accu Roth displaying spherical indentations (magnification 27×).

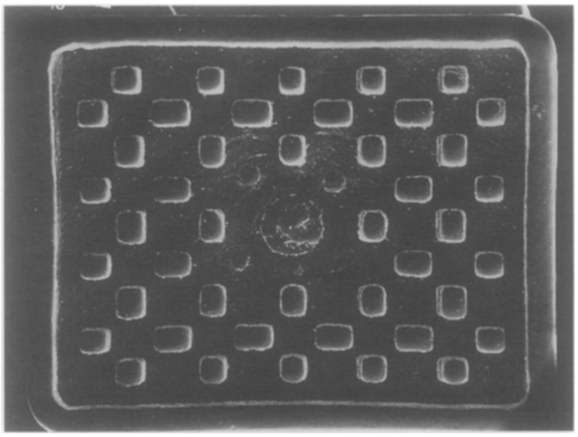

Fig. 10. Miniature Twin bracket base (magnification 40×).

even when a 4 × 30 s light-cure was carried out. This can be explained by the lack of transillumination through the metal bars.

Scanning electron microscopy enabled the following classification of bracket bases according to the type of retention. For metal brackets, retention may be provided by soldering or welding a mesh pattern to the bracket base. This mesh pattern consists of one or two layers. Optimesh, Ormesh and Advant-edge have mono-layered mesh patterns with horizontal and vertical metal wires (*Figs 3–5*). This is in contrast to the mono-layered mesh pattern with diagonal metal wires found on Masters and Mini Masters (*Figs 6 and 7*). The thickness of the metal wires is different for Masters (90 μm) compared with Mini Masters (110 μm). The bi-layered mesh pattern incorporates horizontal and vertical metal wires of 50 μm thick underneath a similarly aligned second layer of 100 μm thick metal wires.

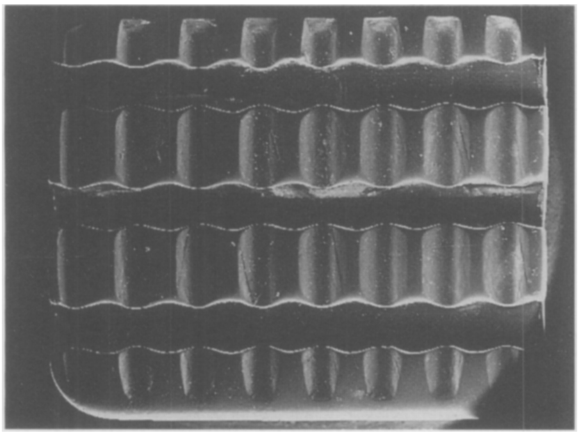

Fig. 11. Integral grooves in the bracket base of Mini Dyna Lock (magnification 27×).

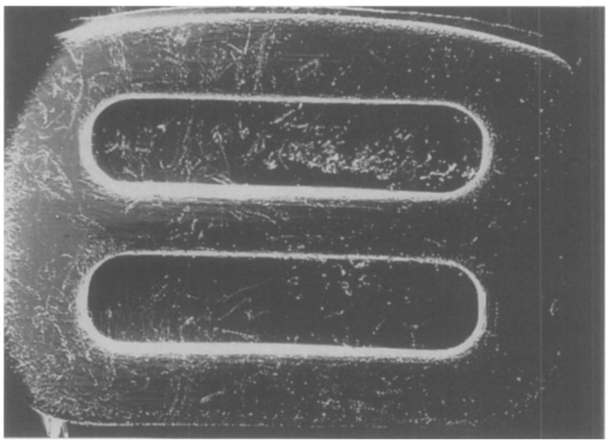

Fig. 12. Bracket base of the plastic bracket Silkon with its macro-mechanical retention slots (magnification 40×).

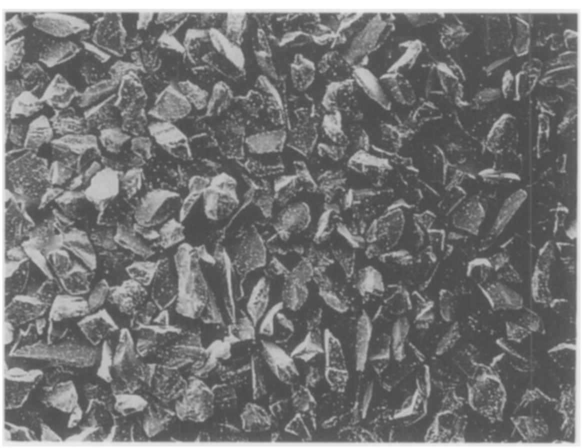

Fig. 13. 20/20m Ceramic: ceramic particles at the bracket base ensure mechanical interlocking of the adhesive resin (magnification 80×).

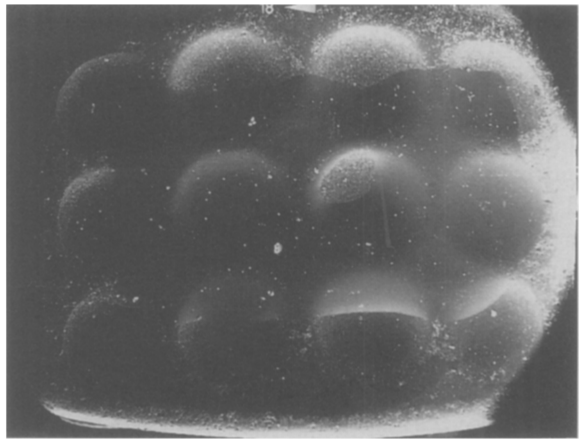

Fig. 14. Allure Accu Arch brackets mainly rely on chemical bonding mechanisms for their bond strength to enamel (magnification 27×).

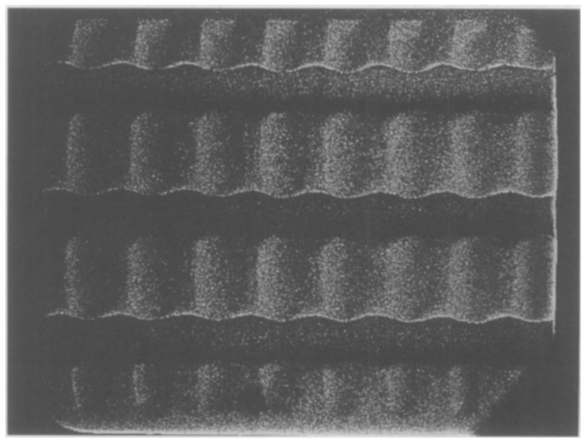

Fig. 15. Mini Dyna Lock sandblasted bracket base showing a clean roughened surface for mechanical adhesion of the orthodontic resin (magnification 27×).

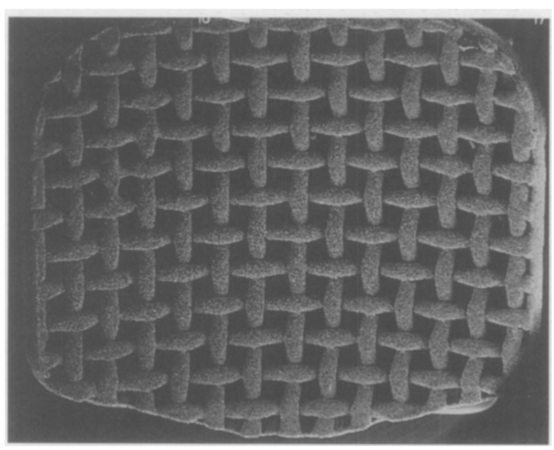

Fig. 16. The sandblasted Optimesh bracket base shows a relatively smoother surface compared with the non-sandblasted base shown in *Fig. 3* (magnification 27×).

This mesh pattern is characteristic for Micro Arch Super Mesh, Omni Arch and Accu Arch MP (*Fig. 8*). A second method of mechanically increasing the bonding capacity of metal bracket bases is by photo-etching. The retention of Accu Roth and Standard Edgewise brackets is established through the mechanical interlocking of resin and bracket base at spherical indentations in the surface of the base (*Fig. 9*). A third form of retention is created by adding structures to the surface of the bracket base, resulting in bracket bases with integral grooves as seen in the Miniature Twin (*Fig. 10*) and Mini Dyna Lock (*Fig. 11*) systems.

The bond strength of the plastic brackets Silkon and CeramaFlex is related to the macro-mechanical interlocking of resin at macro-indentations in the bracket base (*Fig. 12*). In the present study, it was not possible to obtain any acceptable bond for Silkon brackets despite using four methods of bonding: Concise, Concise and a plastic primer (3M Unitek, Monrovia, CA, USA), No Mix:30 and plastic primer, and No Mix:30 specially designed for use in combination with Silkon brackets. As a consequence, Silkon was excluded from statistical analysis.

Ceramic brackets (*Fig. 13*) obtain their retentive capacity from the inclusion of ceramic particles at the bracket base, as is shown for 20/20m Ceramic and Transcend 6000, or from a combination of macro-mechanical interlocking and chemical treatment of part of the bracket surface (*Fig. 14*). The surface texture of Allure Accu Arch (*Fig. 14*) clearly displays a difference between the centre and the periphery of the bracket base. Whether or not this results from chemical treatment is unclear.

Sandblasting metal brackets improves retention by causing microroughness with an increase in surface area for bonding. This may be true when sandblasting unused metal brackets. However, when utilizing this technique for rebonding of debonded brackets, it may suffer limitations. Conventional statistical analysis showed that five out of 12 metal bracket types tested showed no statistical difference with respect to their bonding capacity when sandblasted and another five of the bracket types suffering a significant drop in bond strength values with such treatment. Sandblasting produced a significant increase in the bond strength values of two bracket types, Mini Dyna Lock and Miniature Twin. The design of the bracket base of both brackets is such that sandblasting allows for an increase in surface roughness and complete removal of the cured resin. As can be seen from *Fig. 15*, the bracket bases may be cleaned by aluminium oxide air abrasion. For the other 10 materials, a possible explanation could be that the particle size of the abrasive was too large to completely remove all adhesive remnants from underneath the mesh patterns, thus creating a less retentive surface for adhesion. The amount of remaining adhesive is likely to negatively influence bond strength.

According to the manufacturers, Optimesh is the improved form of Ormesh with Optimesh having been surface treated such that bond strength has been increased by about 35%. This is confirmed by our results. From a morphological standpoint, it seems that the Optimesh base (*Fig. 16*) is sandblasted to a greater extent by the manufacturer, than the Optimesh bracket base (*Fig. 3*). In the present study, aluminium oxide air abrasion of the Optimesh bracket base did significantly influence the bond strength of this system (*Table II*).

CONCLUSION

The ceramic bracket Allure Accu Arch was found to have the highest bond strength. The metal bracket types Mini Masters and Omni Arch displayed bond strength values that did not differ significantly from Allure Accu Arch. However the use of Transcend 6000 is advocated because of its relatively lower bond strength and thus limited risk for enamel damage during debonding. The plastic brackets systems tested had poor bond strength values.

The effect of sandblasting debonded metal brackets depends on bracket type: a significant effect on bracket bases with integral grooves was reported.

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