

# EVALUATION OF BASE TREATMENT ON THE SHEAR- PEEL BOND STRENGTHS OF ORTHODONTIC BRACKETS

By

MANISH AGGARWAL, H.B.Sc., D.D.S.

A Thesis

Submitted to the Faculty of Graduate Studies

in Partial Fulfillment of the Requirements

for the Degree of

Master of Science

Faculty of Dentistry

Department of Preventive Dental Science

Section of Graduate Orthodontics

University of Manitoba

Winnipeg, Manitoba

Canada

© June, 2005

**THE UNIVERSITY OF MANITOBA**  
**FACULTY OF GRADUATE STUDIES**  
\*\*\*\*\*  
**COPYRIGHT PERMISSION**

**EVALUATION OF BASE TREATMENT ON THE SHEAR-  
PEEL BOND STRENGTHS OF ORTHODONTIC BRACKETS**

**BY**

**MANISH AGGARWAL, H.B.Sc., D.D.S.**

**A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of  
Manitoba in partial fulfillment of the requirement of the degree  
Of  
MASTER OF DENTISTRY**

**Manish Aggarwal ©2005**

**Permission has been granted to the Library of the University of Manitoba to lend or sell copies of this thesis/practicum, to the National Library of Canada to microfilm this thesis and to lend or sell copies of the film, and to University Microfilms Inc. to publish an abstract of this thesis/practicum.**

**This reproduction or copy of this thesis has been made available by authority of the copyright owner solely for the purpose of private study and research, and may only be reproduced and copied as permitted by copyright laws or with express written authorization from the copyright owner.**



## ABSTRACT

The increasing patient demand for more esthetic orthodontic appliances has motivated manufacturers to reduce the size of bracket bases. To compensate for this decrease in bondable surface area, each manufacturer has treated the base mesh by various methods with the claim of superior bond strength. Thus, one of the aims of this investigation was to compare the effect of bracket base treatments on shear-peel bond strength. Although most studies use enamel as a testing substrate, a few studies use composite resin alone as a testing substrate to isolate the base-resin interface. Thus, one of the aims of this investigation was to compare the effect of the bonding substrate on shear-peel bond strength. For the enamel substrate group, 30 specimens each of 5 bracket types were bonded with light-cured composite resin adhesive (Transbond XT, 3M Unitek) to the facial surfaces of human third molars. For the resin substrate group, 30 specimens each of 5 bracket types were bonded with Transbond XT adhesive to Transbond XT composite resin substrate. Brackets were shear-peel tested 24 hours later using a Zwick Universal Testing machine with a crosshead speed of 0.5 mm/min, employing a load cell of 10 kN. For the enamel substrate group, the Adhesive Remnant Index was used to quantify the amount of resin remaining on the enamel surface after debonding. For the resin substrate group, the Fracture Interface Score was used to describe the mode of fracture at the base-resin interface. Representative specimens were inspected under the scanning electron microscope. For the enamel substrate group, the mean shear-peel bond strengths were as follows: Victory (microetched) ( $26.80 \pm 5.73$  MPa), Primekote (polymer coated) ( $19.41 \pm 3.21$  MPa), Ormesh (untreated control) ( $18.25 \pm 3.47$  MPa), OptimeshXRT (plasma spray coating) ( $17.79 \pm 5.24$  MPa), and Ti-Orthos2 (untreated titanium) ( $14.50 \pm 3.71$  MPa).

For the resin substrate group, the mean shear-peel bond strengths were as follows: Primekote ( $22.35 \pm 3.07$  MPa), Victory ( $16.29 \pm 2.47$  MPa), Ormesh ( $14.88 \pm 2.50$  MPa), OptimeshXRT ( $13.38 \pm 2.47$  MPa), and Ti-Orthos2 ( $13.37 \pm 2.09$  MPa). Statistically significant differences ( $p < 0.05$ ) were found between brackets of different base treatments when bonded to enamel substrate. However, the large proportion of cohesive fractures within the resin adhesive suggests that enamel should not be used as a substrate when testing for differences in base treatment. Statistically significant differences ( $p < 0.05$ ) were also found between brackets of different base treatments when bonded to resin substrate alone. The large proportion of adhesive fractures at the bracket base-resin substrate interface suggests that resin substrate should be used when testing for differences in base treatment.

## Dedication

This thesis is dedicated

to

My wife, Renu. You have stood by me all the way, giving me inspiration, strength, and most of all endless love so that I can fulfill my dreams. I am truly blessed to be able to live out our dreams together with you.

My son, Rohan. You give me hope that our future will be a bright one.

and my parents, Manohar and Usha. You gave me all your love and support right from the beginning and never asked anything in return. You are the best parents a son could ever hope for. I will always be there for you.

## **ACKNOWLEDGEMENTS**

I would like to express my sincere appreciation and gratitude to all the individuals involved in making this project possible, particularly to:

My committee members, Dr. W.A. Wiltshire, Dr. R.J. Schroth and Dr. P.T. Williams for their invaluable advice, encouragement, and direction.

Dr. T. Dumore for proof-reading my thesis.

3M Unitek,Ormco, and TP Orthodontics for supplying the materials used in this study.

The University of Manitoba, Faculty of Dentistry, for use of the Zwick machine and Bencor Multi-T test device.

# TABLE OF CONTENTS

|                                      | Page |
|--------------------------------------|------|
| ABSTRACT                             | ii   |
| DEDICATION                           | iv   |
| ACKNOWLEDGEMENTS                     | v    |
| LIST OF FIGURES                      | x    |
| LIST OF TABLES                       | xii  |
| 1. INTRODUCTION                      | 1    |
| 1.1 Foreward                         | 2    |
| 1.2 Motivation for the study         | 2    |
| 1.3 Purpose of the study             | 3    |
| 1.4 Null Hypothesis                  | 4    |
| 2. LITERATURE REVIEW                 | 5    |
| 2.1 Bracket base design              | 6    |
| 2.1.1 Mesh size                      | 8    |
| 2.1.2 Weld spots                     | 9    |
| 2.1.3 Integral brackets              | 10   |
| 2.1.4 Base modifications             | 11   |
| 2.2 Composition of brackets and mesh | 11   |
| 2.3 Adhesion and bonding             | 12   |
| 2.3.1 Mechanical bonding             | 13   |
| 2.3.2 Surface tension                | 13   |
| 2.3.3 Wetting                        | 14   |

|       |                                                        |    |
|-------|--------------------------------------------------------|----|
| 2.3.4 | Contact angle                                          | 15 |
| 2.4   | Composite resin adhesives                              | 17 |
| 2.4.1 | Bond Strengths                                         | 20 |
| 2.5   | Glass ionomer and resin-modified glass ionomer cements | 23 |
| 2.5.1 | Bond strengths                                         | 25 |
| 2.6   | Effects of base treatment on bond strengths            | 27 |
| 2.6.1 | Sandblasting                                           | 27 |
| 2.6.2 | Manufacturer pretreatments                             | 28 |
| 3.    | MATERIALS AND METHODS                                  | 32 |
| 3.1   | Materials used in the study                            | 33 |
| 3.1.1 | Composite resin orthodontic adhesive system            | 33 |
| 3.1.2 | Orthodontic brackets                                   | 34 |
| 3.1.3 | Light-curing unit used in the study                    | 38 |
| 3.2   | Experimental method                                    | 39 |
| 3.2.1 | Preparation of composite resin substrate samples       | 39 |
| 3.2.2 | Preparation of enamel substrate samples                | 40 |
| 3.2.3 | Bonding Procedure                                      | 42 |
| 3.2.4 | Seating the test brackets                              | 43 |
| 3.2.5 | Light curing                                           | 43 |
| 3.2.6 | Twenty-four hour storage conditions                    | 43 |
| 3.2.7 | Shear-peel bond strength testing                       | 44 |
| 3.2.8 | Evaluation of fracture sites                           | 47 |

|       |                                                                                                                                                       |     |
|-------|-------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 3.3   | Statistical analysis                                                                                                                                  | 48  |
| 4.    | RESULTS                                                                                                                                               | 49  |
| 4.1   | Shear-peel bond strengths                                                                                                                             | 50  |
| 4.1.1 | Comparison of brackets bonded to composite resin substrate only                                                                                       | 50  |
| 4.1.2 | Comparison of brackets bonded to enamel substrate with composite resin                                                                                | 51  |
| 4.1.3 | Comparison of bracket-composite resin substrate and bracket-composite resin-enamel substrate groups                                                   | 52  |
| 4.2   | Fracture Interface Scores (FIS) and Adhesive Remnant Index (ARI) scores                                                                               | 76  |
| 4.2.1 | Comparison of brackets bonded to composite resin substrate only                                                                                       | 76  |
| 4.2.2 | Comparison of brackets bonded to enamel substrate with composite resin                                                                                | 77  |
| 5.    | DISCUSSION                                                                                                                                            | 86  |
| 5.1   | <i>In vivo</i> versus <i>in vitro</i> bond strength findings                                                                                          | 87  |
| 5.2   | Clinically acceptable bond strength                                                                                                                   | 87  |
| 5.3   | Shear-peel bond strengths of orthodontic brackets bonded with composite resin to enamel substrate                                                     | 89  |
| 5.4   | Shear-peel bond strengths of orthodontic brackets bonded to composite resin substrate alone                                                           | 97  |
| 5.5   | Comparison of shear-peel bond strengths of orthodontic brackets bonded to composite resin substrate alone or with composite resin to enamel substrate | 103 |
| 5.6   | Evaluation of the null hypothesis                                                                                                                     | 105 |
| 6.    | CONCLUSIONS AND RECOMMENDATIONS                                                                                                                       | 106 |

|     |                         |     |
|-----|-------------------------|-----|
| 6.1 | Conclusions             | 107 |
| 6.2 | Recommendations         | 108 |
| 7.  | APPENDIX                | 110 |
| 8.  | REFERENCES              | 111 |
| 9.  | ARTICLE FOR PUBLICATION | 126 |



## LIST OF FIGURES

|                                                                                                                                                                | <b>Page</b> |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| Figure 2.1. Foil-mesh strips stamped to create the bonding base to which orthodontic attachments are added                                                     | 7           |
| Figure 2.2. Contact angle between liquid adhesive and solid adherend                                                                                           | 15          |
| Figure 2.3. Air bubbles created in surface irregularities                                                                                                      | 16          |
| Figure 2.4. Potential bond failure locations                                                                                                                   | 21          |
| Figure 2.5. Cement-forming reaction of glass ionomer cement                                                                                                    | 23          |
| Figure 2.6. Scanning electron micrographs ofOrmco untreated Ormesh and metal plasma-coated OptimeshXRT bases                                                   | 30          |
| Figure 3.1. Transbond XT orthodontic composite resin                                                                                                           | 34          |
| Figure 3.2. 3M Victory Series brackets                                                                                                                         | 36          |
| Figure 3.3. TP Orthodontics Primekote brackets                                                                                                                 | 36          |
| Figure 3.4. Ormco Optimesh XRT, Ti-Orthos 2, and Mini 2000 Ormesh brackets                                                                                     | 37, 38      |
| Figure 3.5. Ortholux XT light curing unit                                                                                                                      | 38          |
| Figure 3.6. Custom fabricated cylinder with well for resin substrate                                                                                           | 40          |
| Figure 3.7. Tooth crown enamel sample with orthodontic bracket bonded to exposed facial surface, mounted in stainless steel ring filled with cold cure acrylic | 41          |
| Figure 3.8. Zwick Universal Testing Machine                                                                                                                    | 45          |
| Figure 3.9. Bracket-resin substrate sample in the Bencor Multi-T testing apparatus                                                                             | 45          |
| Figure 3.10. Shear force at the bracket base-resin substrate interface                                                                                         | 46          |
| Figure 3.11. Bracket-enamel substrate sample in the Bencor Multi-T testing apparatus                                                                           | 46          |

|              |                                                                                                                            |        |
|--------------|----------------------------------------------------------------------------------------------------------------------------|--------|
| Figure 3.12. | Shear force at the bracket base-enamel substrate interface.                                                                | 47     |
| Figure 4.1.  | Comparison of shear-peel bond strengths for all five bracket base-composite resin substrate test groups.                   | 64     |
| Figure 4.2.  | Comparison of shear-peel bond strengths for all five bracket base-composite resin-enamel substrate test groups.            | 65     |
| Figure 4.3.  | SEM ofOrmco Ormesh untreated control bracket base before bonding and after debonding.                                      | 66, 67 |
| Figure 4.4.  | SEM ofOrmco OptimeshXRT bracket base before bonding and after debonding.                                                   | 68, 69 |
| Figure 4.5.  | SEM ofOrmco Ti-Orthos2 bracket base before bonding and after debonding.                                                    | 70, 71 |
| Figure 4.6.  | SEM of3M Victory series bracket base before bonding and after debonding.                                                   | 72, 73 |
| Figure 4.7.  | SEM ofTP Primekote bracket base before bonding and after debonding.                                                        | 74, 75 |
| Figure 4.8.  | Typical total adhesive debond for the bracket base-composite resin substrate test.                                         | 79     |
| Figure 4.9.  | Typical partial adhesive, partial cohesive debond for the bracket base-composite resin substrate test.                     | 80     |
| Figure 4.10. | Typical total cohesive debond for the bracket base-composite resin substrate test.                                         | 81     |
| Figure 4.11. | Typical debond at the enamel-adhesive interface with an ARI score of 3 (All adhesive left on the tooth).                   | 82     |
| Figure 4.12. | Typical debond at the enamel-adhesive interface with an ARI score of 2 (More than half of the adhesive left on the tooth). | 83     |
| Figure 4.13. | Typical debond at the enamel-adhesive interface with an ARI score of 1 (Less than half of the adhesive left on the tooth). | 84     |
| Figure 4.14. | Typical debond at the enamel-adhesive interface with an ARI score of 0 (No adhesive left on the tooth).                    | 85     |

## LIST OF TABLES

|                                                                                                                                                                      | <b>Page</b> |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| Table 2.1. Stainless steels used in orthodontic bracket components                                                                                                   | 12          |
| Table 2.2. Composition of orthodontic bracket stainless steels                                                                                                       | 12          |
| Table 2.3. Tensile and shear bond strengths of GIC, RMGIC, and composite resin adhesives                                                                             | 27          |
| Table 3.1. Materials used in this study                                                                                                                              | 33          |
| Table 3.2. Mesh-base specifications of the five brackets compared in this study                                                                                      | 35          |
| Table 3.3. Overview of experimental method                                                                                                                           | 39          |
| Table 4.1. Shear-peel bond strengths ofOrmco Mini 2000 Ormesh untreated mesh brackets bonded to a Transbond XT composite resin substrate with Transbond XT adhesive. | 53          |
| Table 4.2. Shear-peel bond strengths ofOrmco OptimeshXRT brackets bonded to a Transbond XT composite resin substrate with Transbond XT adhesive.                     | 54          |
| Table 4.3. Shear-peel bond strengths ofOrmco Ti-Orthos 2 brackets bonded to a Transbond XT composite resin substrate with Transbond XT adhesive.                     | 55          |
| Table 4.4. Shear-peel bond strengths of3M Victory series brackets bonded to a Transbond XT composite resin substrate with Transbond XT adhesive.                     | 56          |
| Table 4.5. Shear-peel bond strengths ofTP Primekote brackets bonded to a Transbond XT composite resin substrate with Transbond XT adhesive.                          | 57          |
| Table 4.6. Shear-peel bond strengths ofOrmco Mini 2000 Ormesh untreated mesh brackets bonded to enamel substrate with Transbond XT composite resin adhesive.         | 58          |
| Table 4.7. Shear-peel bond strengths ofOrmco OptimeshXRT brackets bonded to enamel substrate with Transbond XT composite resin adhesive.                             | 59          |
| Table 4.8. Shear-peel bond strengths ofOrmco Ti-Orthos 2                                                                                                             | 60          |

brackets bonded to enamel substrate with Transbond XT composite resin adhesive.

|             |                                                                                                                                |    |
|-------------|--------------------------------------------------------------------------------------------------------------------------------|----|
| Table 4.9.  | Shear-peel bond strengths of 3M Victory series brackets bonded to enamel substrate with Transbond XT composite resin adhesive. | 61 |
| Table 4.10. | Shear-peel bond strengths of TP Primekote brackets bonded to enamel substrate with Transbond XT composite resin adhesive.      | 62 |
| Table 4.11. | Descriptive statistics of the shear-peel bond strengths                                                                        | 63 |
| Table 4.12. | Adhesive remnant index scores – bracket-composite resin substrate                                                              | 77 |
| Table 4.13. | Adhesive remnant index scores – bracket-composite resin-enamel substrate                                                       | 78 |
| Table 5.1.  | Testing parameters and values used in comparable bond strength studies.                                                        | 93 |
| Table 5.2.  | Mode of testing, type of resin used, and bond strength in comparable studies.                                                  | 97 |

# **CHAPTER 1**

## **INTRODUCTION**

|                                     | <b>Page</b> |
|-------------------------------------|-------------|
| <b>1.1 Foreward</b>                 | <b>2</b>    |
| <b>1.2 Motivation for the study</b> | <b>2</b>    |
| <b>1.3 Purpose of the study</b>     | <b>3</b>    |
| <b>1.4 Null hypothesis</b>          | <b>4</b>    |

## **1.1 Foreward**

The introduction of bondable brackets has resulted in a large decline in the use of banded attachments in the practice of orthodontics. Clinically successful bonding has been made possible through the use of resin adhesive materials that penetrate into acid-etched enamel surfaces, thus forming a micromechanical retentive interface (Buonocore, 1968). The strength of a bracket attachment to a tooth is dependent on the interface between the adhesive and the bracket base. Proper mesh design allows micromechanical penetration of the adhesive, thus retaining the bracket to the tooth. Bracket bond strength must be sufficient to withstand pressures in the minimal range of 5 to 7 MPa imposed against them in the mouth (Reynolds, 1975). The frequency of orthodontic bracket bond failures has a significant impact on the efficiency of tooth movement, length of treatment time, and office time efficiency. The reasons for bond failures may include amongst others, salivary contamination, and inadequate penetration of adhesive into retentive areas of the bracket base resulting in air bubbles between the adhesive and base. The failure of bracket bases to bond properly to adhesive is often overlooked and frequently is the weak link in bracket bond strength.

## **1.2 Motivation for the study**

Contemporary research in the field of orthodontic bonding has focused largely on enhancing the bond strength between adhesive and enamel. This has been carried out, either by utilizing different adhesive types such as composite resins and resin modified

glass ionomers, or by utilizing different methods of enamel preparation such as acid etching and self-etching primers. In addition to these methods of improving the bond strength of orthodontic brackets, several manufacturers have proposed methods of treating the bracket mesh base itself, particularly by adding mechanical (microetched mesh base, 3M Unitek, Monrovia, CA) or chemical retentive features (Primekote, TP Orthodontics Inc., LaPorte, Indiana, OptimeshXRT, sdsOrmco, Orange, CA) to the basic mesh design. Although the comparison of manufactured base treatments requires only the testing of bond strength between base and adhesive, bonding to enamel also requires evaluation in order to allow comparison with other studies and to evaluate the bond strength using more clinically relevant conditions. Intuitively, an increase in the bracket base-adhesive bond strength would result in more adhesive retained on the base than enamel. Since there is less adhesive to remove from enamel, the orthodontist can increase clinical efficiency as well as convenience to the patient.

### **1.3 Purpose of the study**

This study was undertaken to accomplish the following three objectives.

1. To compare the effectiveness of several orthodontic bracket base treatments on the shear-peel bond strength of orthodontic bracket bases bonded to composite resin alone.

2. To compare the effectiveness of several orthodontic bracket base treatments on the shear-peel bond strength of orthodontic bracket bases bonded to composite resin and human enamel.
3. To compare the influence of the substrate (i.e. composite resin alone or enamel) on the shear-peel bond strength of orthodontic bracket bases.

#### **1.4 Null hypothesis**

There are three null hypotheses for this study. The first null hypothesis states that there will be no statistically significant difference in the shear-peel bond strength of the different bracket base treatment groups when bonded to composite resin adhesive alone.

The second null hypothesis states that there will be no statistical difference in the shear-peel bond strength of the different bracket base treatment groups when bonded to composite resin adhesive and human enamel.

The third null hypothesis states that there will be no statistical difference in the shear-peel bond strength when bonding brackets to composite resin alone or composite resin and enamel together.



## CHAPTER 2

### LITERATURE REVIEW

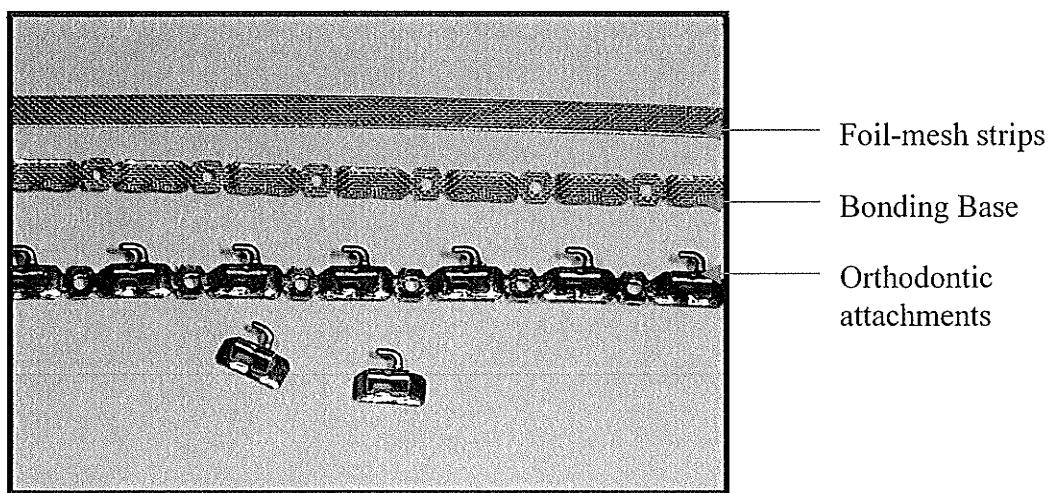
|                                                                   | Page      |
|-------------------------------------------------------------------|-----------|
| <b>2.1 Bracket base design</b>                                    | <b>6</b>  |
| 2.1.1 Mesh size                                                   | 8         |
| 2.1.2 Weld spots                                                  | 9         |
| 2.1.3 Integral brackets                                           | 10        |
| 2.1.4 Base modifications                                          | 11        |
| <b>2.2 Composition of brackets and mesh</b>                       | <b>11</b> |
| <b>2.3 Adhesion and bonding</b>                                   | <b>12</b> |
| 2.3.1 Mechanical bonding                                          | 13        |
| 2.3.2 Surface tension                                             | 13        |
| 2.3.3 Wetting                                                     | 14        |
| 2.3.4 Contact angle                                               | 15        |
| <b>2.4 Composite resin adhesives</b>                              | <b>17</b> |
| 2.4.1 Bond Strengths                                              | 20        |
| <b>2.5 Glass ionomer and resin-modified glass ionomer cements</b> | <b>23</b> |
| 2.5.1 Bond strengths                                              | 25        |
| <b>2.6 Effects of base treatment on bond strengths</b>            | <b>27</b> |
| 2.6.1 Sandblasting                                                | 27        |
| 2.6.2 Manufacturer pretreatments                                  | 28        |

## **2.1 Bracket base design**

Since their advent bracket bases have been reduced in size by manufacturers to respond to patient demands for improved appearance via smaller brackets. As a result, this has required a reduction in the bracket area available for bonding to enamel. Smith and Maijer (1983) have stated that the "effectiveness of the bonded bracket in transferring the desired forces to the teeth is dependent upon the bond strength to the tooth". In order to improve bond strengths, enhancements in bracket base design have become an area of investigation. The attachment forces between the adhesive and the enamel as well as between the adhesive and the bracket may be attributed to mechanical interlocking and/or chemical interactions (Keizer et al., 1976). While chemical bonding can be obtained between some adhesives and both enamel and stainless steel brackets, the bond strength is often too low to give a clinically satisfactory result. Therefore, mechanical retentive features in the bracket base are required (Reynolds and von Fraunhofer, 1976; Ferguson et al., 1984). The most common method is the wire mesh that is attached to the base. Mesh features that may influence the bond strength include rough and smooth wires, mesh size, wire diameter, and weld spots (Dickinson and Powers, 1980; Maijer and Smith, 1981; Smith and Maijer, 1983; Ferguson et al., 1984).

Orthodontic brackets originally had perforated metal bases. These have now been replaced by stainless steel foil-mesh bases. The foil backing is a stainless steel sheet approximately 0.005" (0.127 mm) thick. The functions of the foil backing are: 1) to confine the bonding adhesive within the bonding base for integrity, and 2) to provide a

smoother, more hygienic and therefore less plaque retentive surface (Maijer and Smith, 1981). The mesh is made of wires approximately 0.006" (0.152 mm) in diameter, resulting in an overall bracket base thickness of 0.011" (0.279 mm). The mesh is attached to the foil backing by a roll sintering process. Sheets of 12"x12" (304.8 mm x 304.8 mm) mesh and foil backing are stacked in an oven under high temperature and pressure to micro weld (sinter) the mesh to the foil and each wire to another. Flattening of the wires at the intersection of the horizontal and vertical wires occurs during the pressure welding step. The laminated mesh-foil sheets are then cut into strips of 0.5" (12.7mm) width. The strips are stamped to create the bonding base pad using matched metal stamping dies (Figure 2.1). These dies are designed to incorporate the mesio-distal and occluso-gingival curvatures of the base resulting in an anatomic shape that closely approximates the surface topography of enamel. This allows for a uniform thickness of bonding adhesive material (Personal communication Michael Swartz of sds Ormco, 2004; Deva Devanathan of TP Orthodontics, Inc., 2004).



**Figure 2.1.** Foil-mesh strips stamped to create the bonding base to which orthodontic attachments are added (sds Ormco, Orange, CA).

Reynolds and Fraunhofer (1977) showed that foil-mesh bases provided significantly higher tensile bond strengths (10 kg, 98 N) to enamel when compared to perforated bracket bases (3.5 kg, 34.3 N). This finding has been corroborated by other studies (Faust et al., 1978; Thanos et al., 1979; Lopez, 1980).

### **2.1.1 Mesh Size**

Mesh size refers to the number of discrete openings per linear inch (Thanos et al., 1979). As the mesh size increases the space between intersecting wires decreases and this may affect bond strength. Reynolds and Fraunhofer (1976) investigated the effect of mesh size on base tensile bond strength. Mesh sizes ranged from 50 to 150 and were tested with three types of resin adhesives. The authors demonstrated increased tensile strength (8.4-9.1 kgf, 82.3-89.2 N) with coarser (50 to 70) mesh screen sizes. Furthermore, finer mesh-wire diameters (less than 150  $\mu\text{m}$ ) showed inadequate weld strength between the mesh and the bracket base, resulting in loss of mechanical interlocking between adhesive and mesh, and lower bond strength (3.8-6.4 kgf, 37.2-62.7 N). These findings have been corroborated by some studies and contradicted by others. Thanos et al. (1979) discovered that a 40 mesh sized base was not clinically useful because the mesh unraveled from the base. They concluded that a mesh size of 60 was ideal. Low and von Fraunhofer (1976) concluded that 50 to 70 mesh sized bases were the most clinically suitable. On the other hand, Dickinson and Powers (1980) found no relationship between mesh size and tensile bond strength. Maijer and Smith (1981) discovered that coarser meshes resulted in lower shear bond strengths (3.6-4.1 kgf, 35.3-40.2 N) than finer meshes (6.1-7.8 kgf, 59.8-76.4

N). The authors used a lower filled resin adhesive than that used by Low and von Fraunhofer (1976) and also tested in shear rather than in tension; this may explain the difference in results. Cucu et al. (2002) compared 80 and 100 mesh sized bases, as well as miniature and standard-sized bases, and found no significant differences in shear bond strength among any of the bases (9.97-10.72 versus 10.45-11.39 MPa).

### **2.1.2 Weld spots**

The location and size of weld spots between mesh wires have also been considered factors that affect bond strength (Dickinson and Powers, 1980). Weld spots obliterate areas of mesh, and therefore reduce the amount of retentive area. They also serve as areas of stress in the bond with adhesive (Maijer and Smith, 1981) which may result in a lower bond strength. Weld spots at the edge of the base may prevent an effective mesh-adhesive seal, and therefore lead to plaque retention and subsequent enamel decalcification around the bracket. The mesh backing must be welded firmly to the bracket to attain adequate bond strength. However, this may require the use of numerous welds. Reynolds and Fraunhofer (1977) found that bond failure may result if these mesh-base welds are faulty in any way. Mesh that was attached by brazing or by laser welding was found to have improved shear and tensile strengths (1.32-2.19 MPa) (Dickinson and Powers, 1980; Lopez, 1980; Maijer and Smith, 1981).

### 2.1.3 Integral Brackets

To reduce the number of welds and the probability of separation, the bracket and base were fabricated as an integral unit. This design should, in theory, reduce the possibility of air entrapment between adhesive and base, and permit excess adhesive to escape, thereby resulting in an increased bond strength (Ferguson et al., 1984; Rock and Abdullah, 1997). Investigations into two types of integral bracket-bases have been performed. The first (Dyna-lock base) contained undercuts machined into the base to provide mechanical retention, while the second (Edgeway base) was a cast integral bracket-base. Compared to foil-mesh bases, the machined integral base demonstrated lower bond strengths (19.4, 190.1 N versus 12.4 kg, 121.5 N), whereas the cast integral base showed greater bond strengths (28.8 kg, 282.2 N) (Deidrich and Dickmeiss, 1984; Regan and van Noort, 1989). The difference between the two types of integral bases may be attributed to the fact that the cast base had a rougher surface which may provide better micromechanical retention, thereby increasing retention (Regan and van Noort, 1989). Ferguson et al. (1984) compared bond strengths of integral bases with foil-mesh bases and discovered that bond strengths varied with the type of adhesive used. Integral bases demonstrated lower bond strengths (4.7 kg, 46.1 N) than foil-mesh bases (5.8 kg, 56.8 N) when a lightly filled composite resin adhesive was used, and higher bond strengths (7.4 and 6.0 kg, 72.5 and 58.8 N respectively) when a highly filled resin was used.

#### **2.1.4 Base modifications**

Another method of increasing retention was that of sintered bases. Sintering is the process of fusing ceramic or metal particles onto the base resulting in a porous surface into which the adhesive could flow. Sintered bases showed higher bond strengths (0.628-0.662 MPa) than the conventional foil-mesh bases (0.311-0.352 MPa) (Hanson et al., 1983; Smith and Majer, 1983).

Another approach to the foil-mesh base is the photo-etched base (Lopez, 1980). Retention is provided by small indentations in the base which are microscopically roughened by the photo-etching process. Bases of this design have shown lower bond strengths (5.2 kg, 51 N) than both integral bracket bases (7.4 kg, 72.5 N) and foil-mesh bases (6.0 kg, 58.8 N) (Lopez, 1980; Ferguson et al., 1984).

#### **2.2 Composition of brackets and mesh**

The stainless steels comprising each of the components of the brackets used in this study are displayed in Table 2.1. The composition of the brackets used in this study are displayed in Table 2.2. Ormco stainless steel brackets use 316 steel for the base and mesh as this steel is more corrosion resistant. Ormco Ti-Orthos 2 brackets are made of 90% titanium (Ti), 6% aluminum (Al), and 4% vanadium (V). The titanium body is not brazed to the base as titanium cannot be brazed; rather it is laser welded.

| Bracket                   | Body        | Base | Mesh |
|---------------------------|-------------|------|------|
| 3M Victory Series         | 630/17-4 PH | 304  | 304  |
| TP Orthodontics Primekote | 316L        | 316L | 316L |
| Ormco Optimesh XRT        | 305         | 316  | 316  |
| Ormco Mini 2000 Ormesh    | 305         | 316  | 316  |

**Table 2.1.** Stainless steels used in orthodontic bracket components

| Type        | Composition (%) |      |    |    |         |         |       |      |    |    |     |
|-------------|-----------------|------|----|----|---------|---------|-------|------|----|----|-----|
|             | Fe              | C    | Mn | Si | Cr      | Ni      | P     | S    | Cu | Nb | Mo  |
| 630/17-4 PH | 68.86-72.36     | 0.07 | 1  | 1  | 15.5-17 | 3-5     | 0.04  | 0.03 | 4  | 3  | 0   |
| 304         | 66.35-70.85     | 0.08 | 2  | 1  | 18-20   | 8-10.5  | 0.045 | 0.03 | 0  | 0  | 0   |
| 305         | 64.81-69.31     | 0.12 | 2  | 1  | 17-19   | 10.5-13 | 0.045 | 0.03 | 0  | 0  | 0   |
| 316         | 64.85-70.85     | 0.08 | 2  | 1  | 16-18   | 10-14   | 0.045 | 0.03 | 0  | 0  | 2-3 |

**Table 2.2.** Composition of orthodontic bracket stainless steels

### 2.3 Adhesion and bonding

When two substances are placed in intimate contact with each other, the surface molecules of one substance undergo a force of attraction to the molecules of the other substance. This force is known as adhesion when unlike molecules are attracted and cohesion when molecules of the same type are attracted (Craig, 1997; Anusavice, 2003).



### **2.3.1 Mechanical bonding**

Rigid attachment of one substance to another may also occur by mechanical bonding rather than by molecular attraction. An example of this is the penetration of a viscous adhesive into microscopic irregularities, produced by acid-etching, and located in the surface of the enamel substrate. Upon curing, the adhesive projections embedded in the substrate surface provide micromechanical retention (Craig, 1997; Anusavice, 2003).

### **2.3.2 Surface tension**

The energy at the surface of a substance is greater than that of its interior. Atoms inside the solid are equally attracted to one another. The interatomic distances are equal resulting in a minimal energy state. At the surface of the substance, the energy is greater because the outermost atoms are not equally attracted in all directions. Surface energy, or surface tension, is the increase in energy per unit area of surface. Drops of a liquid form spherical shapes by minimizing surface area because this surface tension condition represents the state of lowest energy (Craig, 1997; Anusavice, 2003).

The surface atoms of a substance tend to form bonds with other atoms in close proximity to the surface and decrease the surface energy of the substance. As mentioned above, this attraction across the interface between unlike substances is known as adhesion. For example, oxygen molecules in the air may be attracted to a silver surface and become readily adsorbed, forming a silver oxide surface layer. Adhesion that occurs by this form

of chemical bonding is stronger than physical bonding formed by van der Waals forces since the latter are intermolecular rather than intramolecular (Craig, 1997; Anusavice, 2003).

The development of van der Waals forces always precedes chemical bonding. As the distance between the two surfaces decreases, chemical bonding increases in effectiveness. The surface tension and the adhesive qualities of a given substance can be reduced by any surface impurity, such as an oxide. Surface tension may also be affected by functional chemical groups existing at the surface. As the surface tension increases, the potential for adhesion also increases (Craig, 1997; Anusavice, 2003).

### **2.3.3 Wetting**

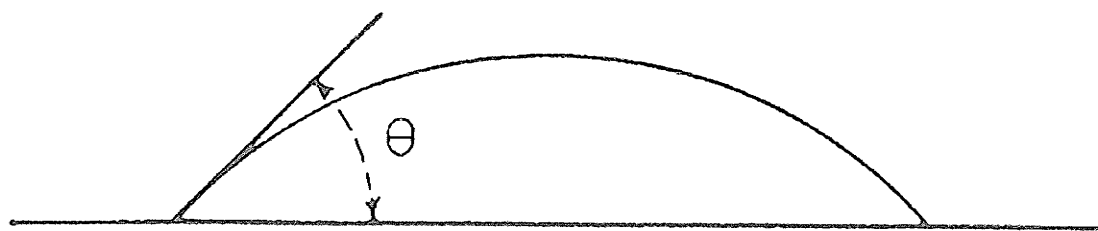
It is difficult to force two solid surfaces to adhere since only their irregularities, or asperities, are in contact over a small area. One way to overcome this difficulty is to use a fluid that flows into these irregularities, thereby providing contact over a greater part of the surface of the solid. In order for adhesion to occur, the liquid must flow readily over the entire surface and adhere to the solid. This phenomenon is known as wetting (Craig, 1997; Anusavice, 2003).

The ability of an adhesive to wet the surface of the adherend is dependent on several factors. One factor is the cleanliness of the surface. A second factor is the surface tension of the solid. If the surface tension is low, few if any liquids will wet the surface.

Teflon, for example, is designed to prevent surface adhesion. Chemically clean metals, on the other hand, have a high surface tension allowing easier wetting by relatively lower surface tension liquid adhesives. A thin film of oil on a clean metallic surface may lower surface tension enough to prevent wetting by the adhesive (Craig, 1997; Anusavice, 2003).

#### 2.3.4 Contact angle

The degree to which an adhesive wets the surface of an adherend is expressed by measuring the contact angle at their interface. The contact angle ( $\theta$ ) is defined as the angle formed between a line tangent to the droplet surface and the substrate surface. If the adhesive molecules are attracted to the adherend molecules as much as, or more than, they are attracted to themselves, then the liquid adhesive will spread readily over the surface of the solid adherend. The stronger the attraction the smaller the contact angle (Figure 2.2) (Craig, 1997; Anusavice, 2003).

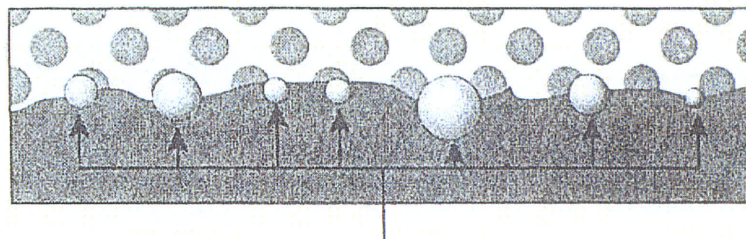


**Figure 2.2.** Contact angle between liquid adhesive and solid adherend (Craig, 1997).

If the adherend surface is contaminated, then the surface energy decreases and a measurable increase in the contact angle is observed (Craig, 1997; Anusavice, 2003).

The smaller the contact angle, the stronger the attraction between adhesive and substrate, and the better the ability of the adhesive to flow into and fill in irregularities within the adherend surface. The lower the viscosity of the adhesive the higher the degree to which these irregularities are filled (Craig, 1997; Anusavice, 2003).

Surface irregularities in solids represent an impediment to the attainment of an adhesive bond since they encourage the entrapment of air. Air bubbles may be created during flow of the adhesive that prevent complete wetting of the entire surface (Figure 2.3) (Craig, 1997; Anusavice, 2003).



Air bubbles acting  
as stress concentrators

**Figure 2.3.** Air bubbles created in surface irregularities (Anusavice, 2003).

When the interface region is subjected to thermal or mechanical stresses, stress concentrations develop around these air bubbles. The stress may increase sufficiently so that a crack is initiated in the adhesive bond adjacent to the bubble. This crack may

propagate from one bubble to the next, and adhesive failure may result (Craig, 1997; Anusavice, 2003).

## **2.4 Composite resin adhesives**

There are two types of composite resin adhesives used for orthodontic bonding: acrylic and diacrylic resins (Reynolds, 1975).

Acrylic resins are made up of a methyl methacrylate monomer and an ultrafine methyl methacrylate polymer powder which is usually activated by the tertiary amine – benzoyl peroxide curing system. They form linear polymers and have a large coefficient of thermal expansion (Reynolds, 1975).

The most widely used diacrylate resin is bisGMA (bisphenol A glycidyl dimethacrylate) which is an acrylic modified epoxy resin (Reynolds, 1975). BisGMA was patented by Bowen in 1962, and it combines the setting versatility of acrylic resin with the strength and stability of epoxy resin. Commercial products are often a variation of this material. Clinicians experienced great difficulty with the early epoxy resins because archwire placement could not be performed at the same bonding appointment due to the extremely slow set of the material. At present, composite resins attain acceptable bond strengths earlier (Proffit, 2000). Diacrylate resins form a three-dimensional cross-linked network that contribute to an increased bond strength and greater dimensional stability (less polymerization shrinkage) compared to the acrylic resins (Bishara et al., 1993).

Diacrylate resins are commonly used for bonding metal and ceramic brackets, but not for plastic polycarbonate brackets. To enhance the bond between diacrylate resins and polycarbonate brackets, a primer made of acrylic monomer or an acrylic resin is used (Bishara et al., 1993).

Manufacturers have added inert inorganic filler particles to orthodontic adhesives to increase their strength and to decrease shrinkage on setting. Polymerization shrinkage may cause stresses that lead to bond failure. Both acrylic and diacrylate resins are available as unfilled, low filled, or highly filled. Filler particles can be large (macrofilled resins) or small (microfilled resins). Most studies have found the highest bond strengths with highly filled resins with larger filler particles (3 to 20 microns) (Buzzitta et al., 1982; Ostertag et al., 1991). However, in their study of three different diacrylate resins Reynolds and von Fraunhofer (1976) stated that differences in bond strength were not primarily attributable to the viscosity of the adhesive, and thus its ability to penetrate the mesh, but rather to the diameter of the wire of the mesh base bracket.

A thick adhesive layer has been found to increase polymerization shrinkage and thermal expansion resulting in a decreased bond strength (Evans and Powers, 1985; Rock and Abdullah, 1997). A thicker adhesive layer affected shear bond strengths more than tensile bond strengths. However, Mackay (1992) found that the reduction in bond strength (36.8 to 32.4 kgf, 360.6 to 317.5 N) as a result of a thicker adhesive layer (0.03 to 0.25 mm) was not statistically significant.

Composite resin adhesives are available in autopolymerizable, light polymerizable, and dual-cure forms. The autopolymerizable (chemical cure) form includes no mix and two paste adhesive systems. The light activated adhesives include those cured by ultraviolet (UV) light (364-367 nm wavelength) and visible light (440-480 nm wavelength) (Chamda and Stein, 1996). There are two important advantages of light cured resins that contributed to their rapid acceptance by the profession. One is that they will set only when light is applied which translates to increased working time, and therefore more accurate bracket positioning and removal of excess adhesive (Smith and Shivapuja, 1993). The second is that once exposed to the curing light, the time required to achieve nearly complete polymerization was usually less than one minute which allowed the practitioner to place the archwire almost immediately (De Saeytjij et al., 1994). However, the light must be applied to each bracket individually which makes it a time consuming technique. The depth of cure depends on many factors. For example, the composition (amount of filler and particle size), viscosity of the mix, the opacity, and the wavelength of the curing light (Cook, 1987). Compared to visible light UV light is poorly transmitted through tooth structure thereby limiting the depth of cure (Newman et al., 1983; De Saeytjij et al., 1994; Sargison et al., 1995). In addition to wavelength, depth of cure is also dependent on the light source's intensity, position, and the duration of curing (Cook, 1987; McCabe and Carrick, 1989). Although UV light curing has the same advantages as visible light, the combination of its relatively poor depth of cure and the potentially harmful effect of prolonged exposure to UV radiation eventually precluded the use of UV light curing in orthodontics (De Saeytjij et al., 1994). Dual-cure resins were originally developed to overcome difficulties with inadequate depth of cure

when using light-cure only materials for restorative composite buildups and veneers (Smith and Shivapuja, 1993; Sargison et al., 1995). These resins possess both chemical and light activation capabilities (McCabe and Carrick, 1989). Complete polymerization is enhanced by the autopolymerizable component (Sargison et al., 1995).

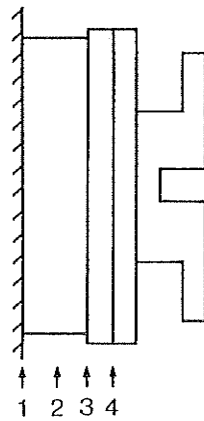
A sealant or unfilled composite resin is often used as a primer in conjunction with the filled resin adhesives. Their relatively low viscosity allows for increased penetration of resin into the etched enamel, thereby resulting in an improved micromechanical bond. Some investigators have found that with a two paste resin system the sealant does not enhance bond strength (Espinosa, 1978; Wang and Tarng, 1991). However, Gwinnett (1982) concluded that the use of a sealant did enhance bond strength.

#### **2.4.1 Bond strengths**

Bond strength is dependent on bracket base design, type of adhesive, testing method, and operator factors (Regan and van Noort, 1989; Powers et al., 1997).

Orthodontic bonding systems consist of two interfaces: bracket/adhesive and enamel/adhesive (Powers et al., 1997). Bond failures can be either adhesive or cohesive failures and can occur at the following locations: 1) enamel/adhesive interface, 2) within adhesive, 3) adhesive/base interface, and 4) base/bracket interface (Figure 2.4).





**Figure 2.4.** Potential bond failure locations (Regan and van Noort, 1989).

The site of bond failure may indicate the probable cause of failure. By recognizing where the debond occurred the bonding technique can be modified. *In-vitro* research has shown that the most common site of failure between foil-mesh brackets and resin adhesives is at the adhesive/base interface (Keizer et al., 1976; Reynolds and von Fraunhofer, 1976; Gorelick, 1977; Faust et al., 1978; Lopez, 1980; Rosenstein and Binder, 1980; Jassem et al., 1981; Fields, 1982; Hanson et al., 1983; Smith and Maijer, 1983; Ferguson et al., 1984; Odegaard and Segner, 1988; Harris et al., 1990; Willems et al., 1997b). As a result of this, the adhesive/bracket base bond has been deemed the weakest point in orthodontic bonding (Keizer et al., 1976; Faust et al., 1978; Dickinson and Powers, 1980; Wright and Powers, 1985; Knoll et al., 1986; Surmont et al., 1992). In contrast, Thanos et al. (1979) discovered failure sites to exist at the enamel/adhesive interface. One possible explanation for this difference is the fact that, in Thanos' research, the adhesives were folded over the periphery of the bracket, and this may have attached the mesh base more securely to the adhesive. Hanson et al. (1983) also found that the failure site with sintered bases occurred at the enamel/adhesive interface which implies that the sintering

process improved the bond between resin and bracket base, thereby increasing the bond strength at the adhesive/base interface. While bond strength failure at the adhesive/bracket interface may complicate enamel clean-up, it also serves as a safe failure site and may prevent enamel fracture during debonding. Stronger bond strengths are not always biologically better (Personal communication William Wiltshire, 2004).

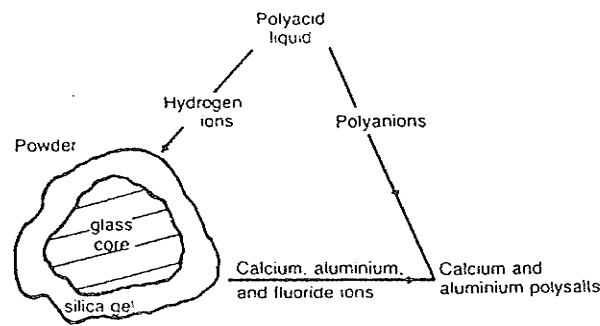
The site of failure between foil-mesh bases and resin is adhesive in nature (Millett et al., 1993), that is, at the adhesive/base interface, with most of the adhesive remaining on the enamel surface (O'Brien et al., 1988; Millett et al., 1993). Matasa (1989) stated that the strongest bond is achieved when failure was cohesive in nature, that is, within the resin itself. This translates to enamel and bracket surfaces that are entirely or mostly covered with adhesive.

The weakest link in the adhesive bonding technique is the base/adhesive interface (Keizer et al., 1976; Faust et al., 1978; Dickinson and Powers, 1980; Wright and Powers, 1985; Knoll et al., 1986; Surmont et al., 1992). Improvements in this bond is dependent upon improving 1) the mechanical interlock of the adhesive to the wire mesh and 2) the chemical forces of adhesion at the adhesive/base interface. Since stainless steel does not bond chemically to orthodontic composite resin adhesive, optimization of the mechanical retention is the most realistic unless specific processes as described later in section 2.6.2 are employed.

Bonding between a metal bracket and adhesive is usually achieved by mechanical retention. Highly filled, diacrylate composite resins give the highest bond strengths due to their high inorganic filler content (Dickinson and Powers, 1980; Buzzitta et al., 1982).

## 2.5 Glass ionomer and resin-modified glass ionomer cements

Glass ionomer cements (GIC) were first introduced to clinical restorative dentistry by Wilson and Kent (1972) and to clinical orthodontics by White (1986). The composition consists of a filler made of an alumino-calcium-silicate ( $\text{Al}_2\text{O}_3\text{-CaF}_2\text{-SiO}_2$ ) glass powder, and a liquid polyacid (polyacrylic, maleic, and tartaric) to control the rate of setting (Craig, 1997; Anusavice, 2003). The cement-forming acid-base reaction is shown in Figure 2.5.



**Figure 2.5.** Cement-forming reaction of glass ionomer cement (Anusavice, 2003).

In this reaction, glass particles are attacked by the acid. The outer layer of the glass particles is depleted of metal ions ( $\text{Ca}^{2+}$ ,  $\text{Al}^{3+}$ ) and degraded to a silica gel. These leached ions react with the polyacrylic acid to form calcium and aluminum polyacrylate salts that make up the cement matrix (Craig, 1997; Anusavice, 2003).

The mechanism by which GIC bond to enamel is not clearly understood, but may involve: 1) chelation between carboxyl groups of the GIC and calcium in the enamel apatite crystals; 2) hydrogen bonds and van der Waals forces; and 3) carboxyl/phosphate substitution (Craig, 1997; Anusavice, 2003).

Glass ionomer cements possess several unique properties that make them potentially more useful than composite resin adhesives in clinical orthodontics. Firstly, they adhere to both enamel and metal alloys (Hotz et al., 1977). Secondly, they release fluoride which is taken up by the enamel surface adjacent to the bracket, and thereby may prevent enamel decalcification (David, 1994; Hallgren et al., 1994). Finally, they can be removed more easily from enamel (Norevall et al., 1995) since the remaining adhesive can be dessicated by air drying it, thereby resulting in a more friable adhesive (White, 1986). Enamel loss from debonding brackets is therefore likely to be reduced as compared to composite resin adhesives.

Glass ionomer cements are available in a variety of forms: 1) conventional (acid-base cement forming); 2) dual-cured (acid-base cement-forming or light-activated); or 3) tri-cured (chemical or light-activated polymerization as well as acid-base cement-forming) (Craig, 1997; Anusavice, 2003). The new generation GIC's are dual- or tri-cured hybrid materials containing resin and glass ionomer components (Craig, 1997; Anusavice, 2003). One such hybrid material is resin-modified glass ionomer cements (RMGIC). RMGIC's offer the same advantages of both GIC's and resins such as adhesion to tooth

and metal, fluoride release, moisture insensitivity, rapid hardening by light, and immediate force loading (Craig, 1997; Anusavice, 2003).

### **2.5.1 Bond strengths**

In vitro studies have shown that bond strengths of GIC and RMGIC's are dependent on several factors such as: 1) method of enamel treatment prior to bonding; 2) powder/liquid ratio of cement; and 3) time from bonding to bond strength testing.

The most effective method of enamel treatment prior to bonding with GIC has been debated. Prophylaxis and cotton drying has been shown to produce a better tensile bond (60.9 N) than treatment with a 40% polyacrylic acid cleanser (55 N) (Cook and Youngson, 1988). Cook and Youngson (1988) found that phosphoric acid enamel etching significantly weakened the tensile bond (49.5 N), while Wiltshire (1994) found it to increase shear bond strength (5.5 MPa). Fischer-Brandies and Tragner-Born (1989) found that enamel treatment with polyacrylic acid or tannic acid improved GIC tensile bond strength to 60% (8.7 MPa) of the composite resin bond (14.5 MPa). For RMGIC's, enamel pre-treatment with either phosphoric acid or polyacrylic acid is required to improve their shear bond strength (10.68-74.1 N) (Carter and McCabe, 1995; Jaochakarasiri et al., 1995; Scott et al., 1995; Shin and Lee, 1995). On the other hand, Ewoldsen et al (1995) showed that the shear bond strength of RMGIC was not dependent on phosphoric acid etching (6.51 MPa) and only minimally enhanced by polyacrylic acid preconditioning (7.95 MPa). The differences in materials used and testing conditions

between the studies makes it difficult to resolve the debate over enamel pre-treatment methods.

The powder/liquid ratio is an important contributor to successful bonding, but has varied between studies. Some authors followed manufacturer's instructions (2.9-47 N) (Klockowski et al., 1989; Norevall et al., 1990; Oen et al., 1991), others used a thicker mix (6-60.9 N) (Cook and Youngson, 1988; Rezk-Lega and Ogaard, 1991), while others have tested encapsulated cements (18.7-153 N) (Evans and Oliver, 1991; Oen et al., 1991; Rezk-Lega and Ogaard, 1991).

The time from bonding to bond strength testing has varied from 15 minutes to 4 weeks. The bond strength of GIC and RMGIC's has been shown to increase more than 50% between 10 (31.4 N) and 20 minutes (49.1 N) after the setting time (Oen et al., 1991), but achieves its optimal bond strength at 24 hours (60.4 N) (Oen et al., 1991).

Many studies have compared bond strengths accomplished with conventional glass ionomer cements to those achieved with composite resins. The conclusion of most of these studies is that the composite resins yield significantly higher bond strengths than the glass ionomer cements or the resin-modified glass ionomer materials (RMGIC) (Table 2.3). RMGIC's demonstrate bond strengths between GIC's and composite resins (Table 2.3). The large range in bond strength values in Table 2.3 may be attributable to the use of different cement compositions and study designs (Cook and Youngson, 1988; Rezik et al., 1988; Fischer-Brandies and Tragner-Born, 1989; Klockowski et al., 1989;

Miller et al., 1989; Fajen et al., 1990; Evans and Oliver, 1991; Fox et al., 1991; McCourt et al., 1991; Oen et al., 1991; Rezk-Lega and Ogaard, 1991; Compton et al., 1992; Dasch et al., 1993; Fischer-Brandies et al., 1993; Joseph et al., 1994; Wiltshire, 1994; Ewoldsen et al., 1995; Silverman et al., 1995; Miller et al., 1996; McCabe, 1998).

| Adhesive                     | Bond strength |             |
|------------------------------|---------------|-------------|
|                              | Tensile (MPa) | Shear (MPa) |
| Glass ionomer                | 2.7 - 6.4     | 1 - 5.5     |
| Resin-modified glass ionomer | 2.2 - 10      | 4.5 - 14.2  |
| Composite resin              | 6.9 - 24.5    | 6 - 26      |

**Table 2.3.** Tensile and shear bond strengths of GIC, RMGIC, and composite resin adhesives.

The fracture pattern observed most commonly in enamel specimens bonded with GIC is adhesive between bracket and cement (Cook and Youngson, 1988; Davis et al., 1988).

The fracture pattern for RMGIC's has been shown to vary between bracket-adhesive and adhesive-enamel interfaces (Scott et al., 1995).

## **2.6 Effects of base treatment on bond strengths**

### **2.6.1 Sandblasting**

The interface between resin adhesive and bracket is the weak link in the overall bonding system (Keizer et al., 1976). Sandblasting metal brackets causes microscopic roughness with a resulting increase in surface area available for bonding which appears to lead to an

increase in retention (Willems et al., 1997). Mizrahi and Smith (1971) found that sandblasting increased bond strength when used with zinc polycarboxylate cement. Diedrich and Dickmeiss (1983) reported that sandblasting increased bond strength by 34% (10.32 MPa) compared to untreated bracket bases (7.70 MPa). Millett et al. (1993) used 60 micron alumina to sandblast foil-mesh bases prior to bonding with glass ionomer cements. They found sandblasting for three seconds led to a significant increase in bond strength whereas sandblasting for nine seconds led to damage and distortion of the mesh wire. Newman et al. (1995) also discovered that sandblasting increased bond strengths by approximately 20% (10.8 MPa) compared to untreated bracket bases (9.0 MPa) when used with an autopolymerizing adhesive system.

## **2.6.2 Manufacturer pretreatments**

Bracket pretreatments such as microetching and chemical coatings are available to enhance the bond between composite resin adhesives and metal brackets (Siomka and Powers, 1985). Microetching is a grit-blasting procedure performed by the manufacturer, however, details of this technique are not readily available from the manufacturers (Personal communication Enrique Nikutowski of 3M/Unitek, 2004). This procedure is the manufacturer's version of sandblasting and removes unfavourable oxides, contaminants, and increases surface roughness, thereby increasing surface energy and bonding surface area (Newman et al., 1995). MacColl et al. (1998) found that both sandblasting and microetching of foil-mesh bases resulted in a statistically significant increase in bond strengths (14.44 versus 15.34 kgf, 141.5 versus 150.3 N) as compared to

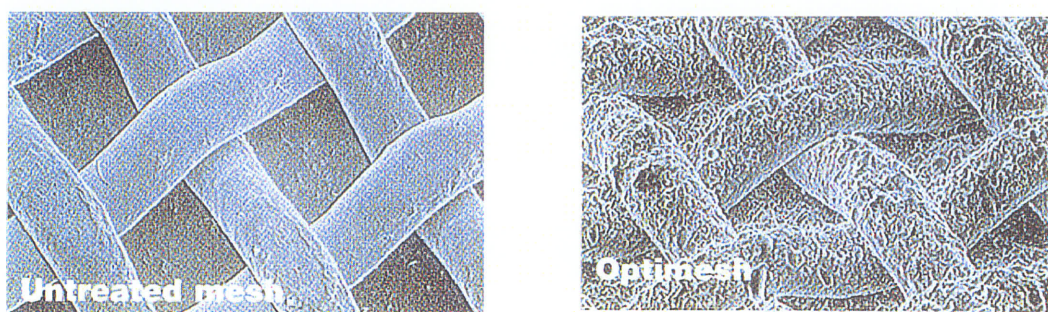


an untreated foil-mesh base (11.97 kgf, 117.3 N). Siomka and Powers (1985) found that microetching increased the bond strength of an integral grooved base by 56% (1.50 MPa) whereas the bond strength of a foil-mesh base was unaffected.

In order to overcome the inability of orthodontic adhesives to bond to stainless steel, several solutions have been developed. Polymer coating is applied by the manufacturer to increase bond strength between bracket base and adhesive (Personal communication Deva Devanathan of TP Orthodontics, Inc., 2004). Currently, TP bases undergo a high-energy plasma cleaning process to remove surface contamination, and are subsequently coated with a thin layer of their proprietary polymer (Primekote). The coating is then cured to achieve its final properties. TP bases coated with Primekote claim not only mechanical retention of adhesive to the mesh, but also a chemical bond to both the metal mesh and the orthodontic resin adhesive. The polymer coating reduces mesh surface tension, reducing entrapped air between adhesive and mesh and increasing wettability of the mesh surface with adhesive. This decreases the incidence of voids at the adhesive/mesh interface that may contribute to bond failure. The chemical bond between polymer coating and adhesive translates to increased adhesive retention on the mesh surface, and therefore less cleanup time for the clinician. This chemical bond also lends itself to increased tolerance against moisture/saliva contamination without a reduction in bond strength.

Metal plasma-coating is another bond enhancing technique. With this technique, 316 stainless steel alloy is thermally sprayed onto the mesh base by the manufacturer with the

intent to augment mesh surface roughness, to increase surface area available for adhesive to bond micromechanically, and therefore enhance bond strengths (Personal communication Michael Swartz of Ormco, 2004) (Figure 2.6).



**Figure 2.6.** Scanning electron micrographs of Ormco untreated Ormesh and metal plasma-coated OptimeshXRT bases (sds Ormco, Orange, CA).

Stainless steel was chosen by Ormco as it is the same material as the mesh base itself, and it is highly corrosive resistant. Currently, Ormco has replaced propylene with hydrogen as the fuel for the thermal spraying process in order to avoid potential carbon contamination which may occur with propylene as it is a hydrocarbon. The coatings are sintered after the thermal spraying process to eliminate any increase in oxygen and carbon content of the alloy as well as to enhance the adhesion of the coating to the base. The sintering process is performed by elevating the temperature of the coating in an inert atmosphere or vacuum to approximately the melting point of the materials (Personal communication Michael Swartz of sds Ormco, 2004).

There are few studies that examine the effect of plasma-coatings on bond strengths. Willems et al. (1997b) found that Ormco's Optimesh plasma-coated mesh base demonstrated a 40% increase in tensile and shear bond strength (7.42 MPa) over Ormco's

Ormesh uncoated mesh base (5.3 MPa). In addition, significantly less adhesive remained on enamel after debonding the plasma-coated brackets. Droese and Diedrich (1992) compared metal mesh bracket bases (uncoated and coated with metal plasma), as well as metal bases without mesh (coated with metal plasma). They found that metal bracket bases with mesh that had been coated with metal plasma, showed two to four times higher mean tensile bond strengths (20.03 MPa) in relation to uncoated mesh bases (5.31-10.76 MPa), depending on adhesive used. They also found that metal bracket bases without mesh, but coated with metal plasma, showed mean tensile bond strengths comparable to uncoated mesh bases (8.21-8.74 MPa). The authors attributed this significant enhancement of adhesion to the profound increase of the retentive active surface created by the metal plasma.

## **CHAPTER 3**

### **MATERIALS AND METHODS**

|                                                                                                                         | <b>Page</b> |
|-------------------------------------------------------------------------------------------------------------------------|-------------|
| <b>3.1 Materials used in the study</b>                                                                                  | <b>33</b>   |
| <b>3.1.1 Composite resin orthodontic adhesive system<br/>            (Transbond Orthodontic Bonding Kit, 3M/Unitek)</b> | <b>33</b>   |
| <b>3.1.2 Orthodontic brackets</b>                                                                                       | <b>34</b>   |
| <b>3.1.3 Light-curing unit used in the study</b>                                                                        | <b>38</b>   |
| <b>3.2 Experimental method</b>                                                                                          | <b>39</b>   |
| <b>3.2.1 Preparation of composite resin substrate samples</b>                                                           | <b>39</b>   |
| <b>3.2.2 Preparation of enamel substrate samples</b>                                                                    | <b>40</b>   |
| <b>3.2.3 Bonding procedure</b>                                                                                          | <b>42</b>   |
| <b>3.2.4 Seating the test brackets</b>                                                                                  | <b>43</b>   |
| <b>3.2.5 Light curing</b>                                                                                               | <b>43</b>   |
| <b>3.2.6 Twenty-four hour storage conditions</b>                                                                        | <b>43</b>   |
| <b>3.2.7 Shear-peel bond strength testing</b>                                                                           | <b>44</b>   |
| <b>3.2.8 Evaluation of fracture sites</b>                                                                               | <b>47</b>   |
| <b>3.3 Statistical analysis</b>                                                                                         | <b>48</b>   |

### 3.1 Materials used in the study

The materials used in this study are listed in Table 3.1.

| Material                                    | Manufacturer                               | Batch Number |
|---------------------------------------------|--------------------------------------------|--------------|
| Transbond XT Adhesive Paste                 | 3M Unitek                                  | 712-031      |
| Transbond XT Primer                         | Monrovia, CA, USA                          | 712-032      |
| 34% Tooth Conditioning Gel                  |                                            | 712-039      |
| 3M Victory Series stainless steel brackets  | 3M Unitek<br>Monrovia, CA, USA             | 017-757      |
| PrimeKote stainless steel brackets          | TP Orthodontics, Inc.<br>LaPorte, IN, USA. | 293-370      |
| Orthos OptimeshXRT stainless steel brackets | sdsOrmco<br>Orange, CA, USA.               | 454-0411     |
| Ti-Orthos 2 titanium brackets               | sdsOrmco<br>Orange, CA, USA.               | 448-6411     |
| Mini 2000 Ormesh stainless steel brackets   | sdsOrmco<br>Orange, CA, USA.               | 303-0515     |

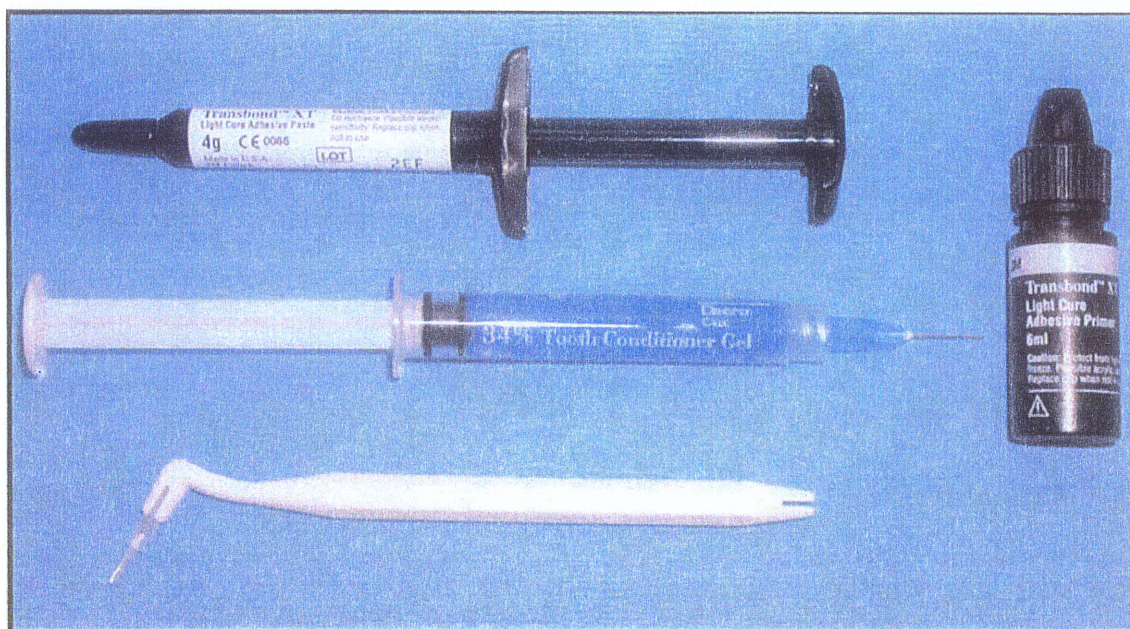
**Table 3.1.** Materials used in this study.

#### 3.1.1. Composite resin orthodontic adhesive system (Transbond Orthodontic Bonding Kit, 3M/Unitek)

Transbond XT adhesive paste is a light-cured, hybrid composite resin. The resin base is Bis-GMA and TEGDMA in a 1:1 ratio and the filler particles are a hybrid of silica with an average size of 3  $\mu\text{m}$ . Filler loading is approximately 82% by weight. A diketone and an organic amine are added as photoinitiators. Transbond XT light-cured primer is an unfilled resin composed of 50% Bis-GMA and 50% TEGDMA. The tooth conditioning gel is 34% phosphoric acid in an amorphous silicate gel. (Material Safety Data Sheets a



and b, 2000 and 2001 respectively). Transbond XT adhesive paste, primer and conditioning gel are shown in Figure 3.1.



**Figure 3.1.** Transbond XT adhesive paste, primer and tooth conditioning gel

### 3.1.2. Orthodontic brackets

Gingivally offset brackets were selected for all samples in order to facilitate contact between the shearing blade of the testing device and the bracket base rather than the attachment. Lower first bicuspid brackets were used for all samples because they are supplied in the gingivally offset variety and because they have a curved base which adequately adapts to the rounded topography of the human third molar enamel samples. The diameter ( $d$ ) of the orthodontic bracket base was obtained from the manufacturer. The base area ( $A$ ) was calculated using the formula  $A = \pi(d/2)^2$ . This base area was used to calculate the stress in MPa at shear-peel bond failure.

Mesh-base specifications for the brackets used in this study are displayed in Table 3.2.

The open area is defined as the total area available for the adhesive to penetrate.

3M Victory Series stainless steel bracket bases consist of a basic wire mesh design roughened mechanically by sandblasting with 50  $\mu\text{m}$  particle size grit (Figure 3.2).

TP Orthodontics Primekote stainless steel bracket bases are similar to the 3M Victory series brackets except that they are sandblasted with 150-200  $\mu\text{m}$  aluminum grit and treated chemically with a proprietary polymer coating (Figure 3.3).

Ormco Mini 2000 Ormesh stainless steel bracket bases consist only of an untreated basic mesh design (Figure 3.4).

Ormco Optimesh XRT stainless steel bracket bases are the same as the Ormco Mini 2000 Ormesh brackets except that they are treated chemically with a thermal spray coating as previously discussed in section 2.6.2 (Figure 3.4).

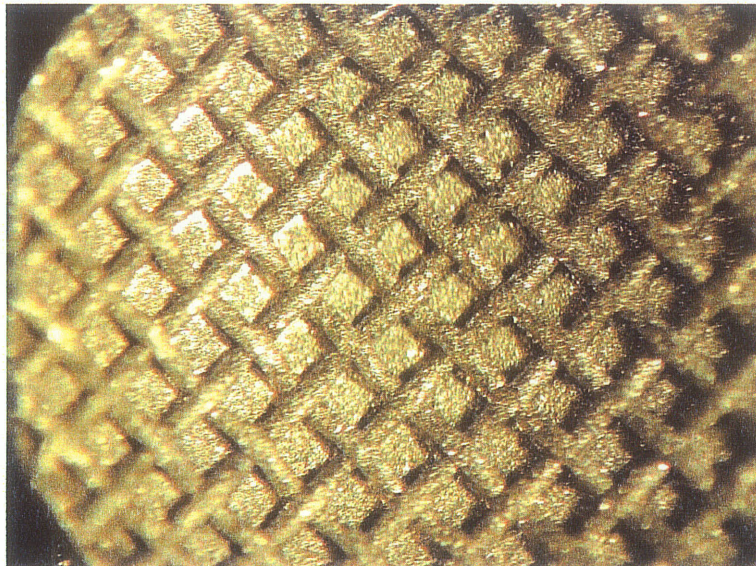
Ormco Ti-Orthos 2 titanium bracket bases consist only of an untreated basic mesh design (Figure 3.4).

| Bracket                   | Mesh size | Mesh wire diameter (inches, mm) | Open area (%)* | Mean bondable base surface area ( $\text{mm}^2$ ) |
|---------------------------|-----------|---------------------------------|----------------|---------------------------------------------------|
| 3M Victory Series         | 80        | .0055, 0.140                    | 31.5           | 9.81                                              |
| TP Orthodontics Primekote | 80        | .0055, 0.140                    | 31.5           | 12.9                                              |
| Ormco Optimesh XRT        | 100       | .0050, 0.127                    | 30             | 14                                                |
| Ormco Ti-Orthos 2         | 80        | .0040, 0.102                    | 35             | 14                                                |
| Ormco Mini 2000 Ormesh    | 100       | .0050, 0.127                    | 30             | 14                                                |

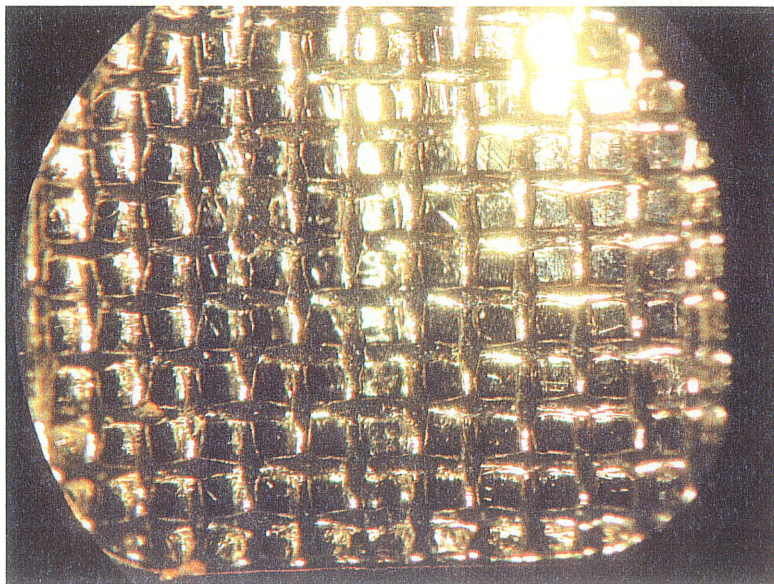
\* Determined by the manufacturer

**Table 3.2.** Mesh-base specifications of the five brackets compared in this study.



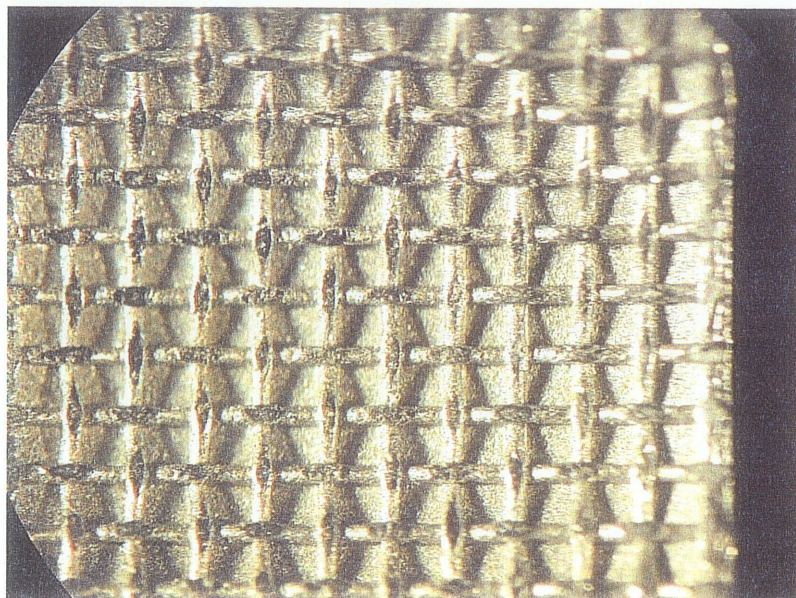


**Figure 3.2.** 3M Victory Series bracket base (400x magnification)

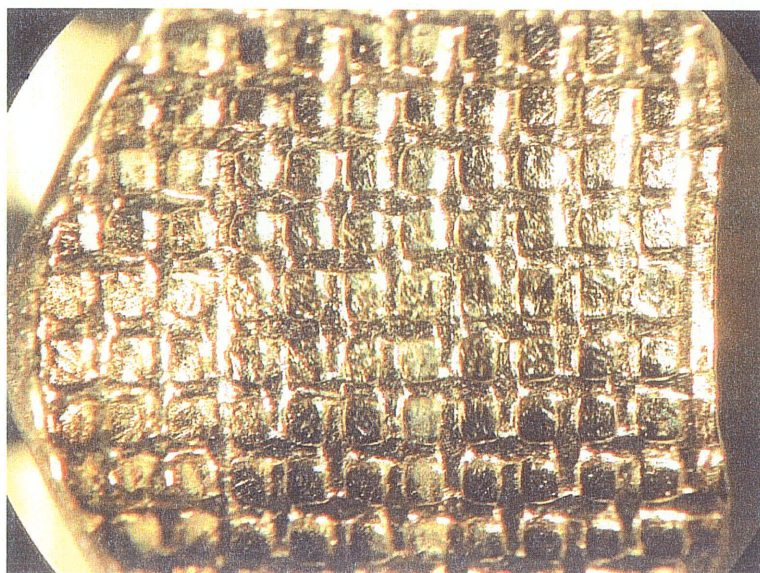


**Figure 3.3.** TP Orthodontics Primekote bracket base (400x magnification)





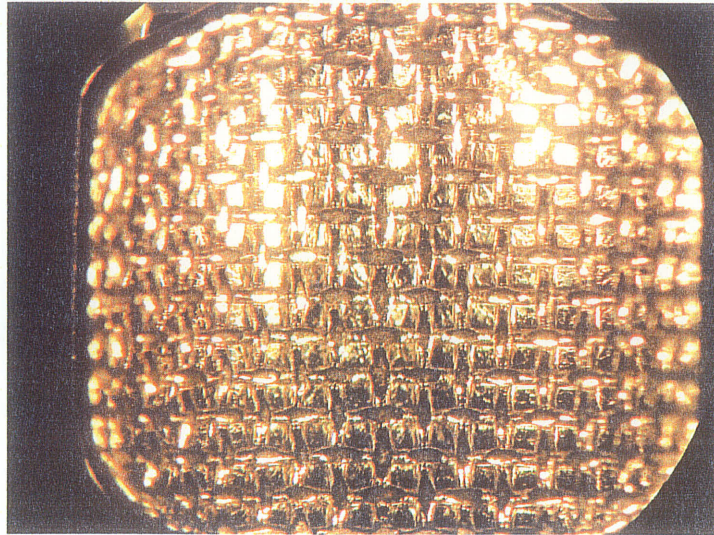
(A)



(B)



(C)



**Figure 3.4.** Ormco Optimesh XRT (A), Ti-Orthos 2 (B), and Mini 2000 Ormesh (C) bracket bases (400x magnification)

### 3.1.3 Light-curing unit used in the study

The Ortholux XT light curing unit (SN 116094) (3M/Unitek, Monrovia, CA) (Figure 3.5) used in the study has a quartz-tungsten-halogen bulb with a filter to produce light in the range of 430-480 nm. The power density is 550 mW/cm<sup>2</sup> (Manufacturer manual). The power density of the light curing unit was tested before the study with a Demetron Radiometer (Demetron Research Corporation, Danbury, CT, USA).



**Figure 3.5.** Ortholux XT light curing unit.

### 3.2 Experimental method

Table 3.3 provides a summary of the experimental method, displaying the specific bonding substrate, substrate preparation, and bracket bases used for each test group.

| Method 1                                                                                                                                               | Method 2                                                                                                                                                                                                |
|--------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Bonding Bracket to Transbond XT Composite Resin Substrate                                                                                              | Bonding Bracket with Transbond XT Adhesive to Enamel Substrate                                                                                                                                          |
| 3M Victory Series brackets<br>TP Primekote brackets<br>Ormco OptimeshXRT brackets<br>Ormco Ti-Orthos 2 brackets<br>Ormco Mini 2000 Ormesh brackets*    | 3M Victory Series brackets<br>TP Primekote brackets<br>Ormco OptimeshXRT brackets<br>Ormco Ti-Orthos 2 brackets<br>Ormco Mini 2000 Ormesh brackets*                                                     |
| Fill well with adhesive - light cure 20s<br>Apply adhesive to bracket and place on<br>cured adhesive surface - light cure 20s<br>Sample size: 30/group | Enamel preparation 37% phosphoric acid<br>for 30s, rinse 20s and dry 20s<br>Apply primer – light cure 10s<br>Apply adhesive to bracket and place on<br>enamel - light cure 20s<br>Sample size: 30/group |

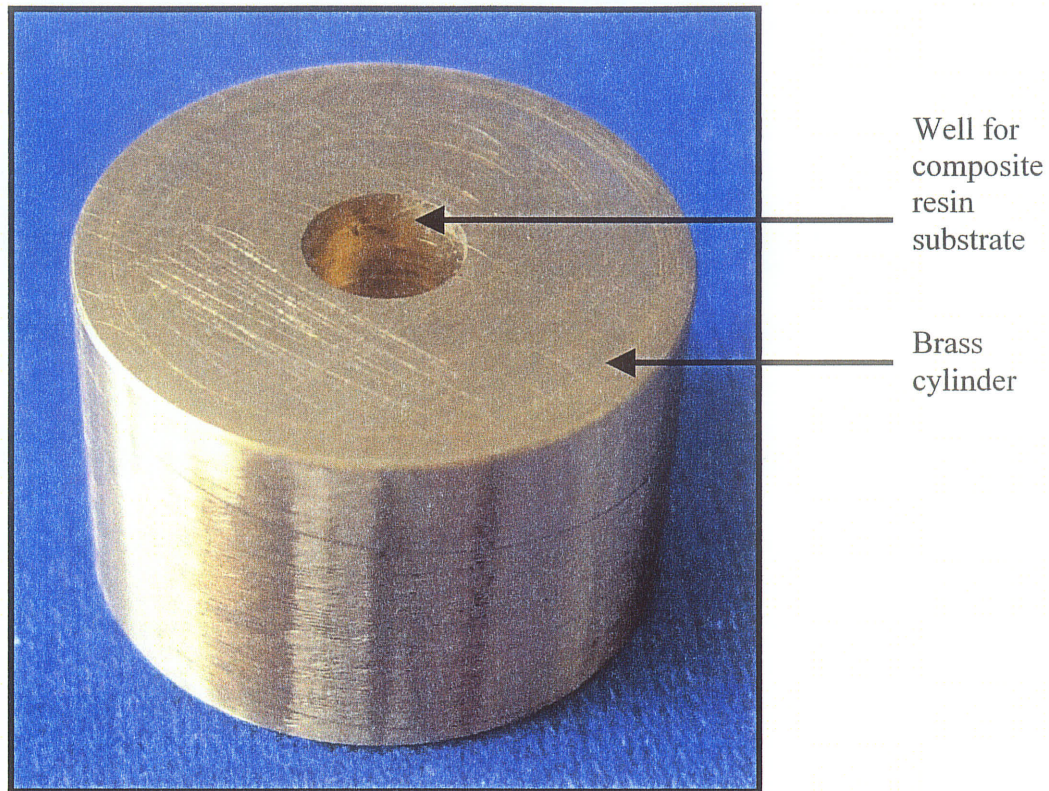
\* Control group

**Table 3.3.** Overview of experimental method

#### 3.2.1 Preparation of composite resin substrate samples

One hundred and fifty solid brass mounting cylinders with a diameter of 20 mm and a height of 13 mm were custom fabricated. A well with a diameter of 5mm and a depth of 5mm to accept composite resin substrate was created in the center of one face of each cylinder (Figure 3.6). Transbond XT composite resin was injected into the well, manually packed with a composite resin plugger and trimmed flush with the top of the well with a cement spatula. The resin substrate was then cured for 20 seconds with the light-curing unit.





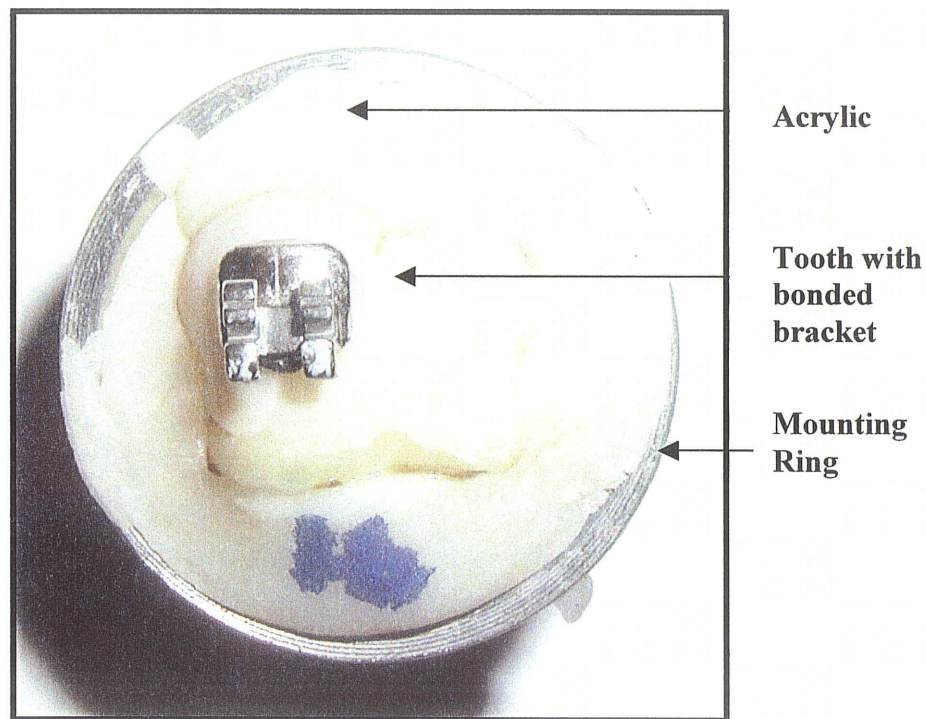
**Figure 3.6** Custom fabricated cylinder with well for composite resin substrate.

### **3.2.2 Preparation of enamel substrate samples**

One hundred and fifty extracted human third molar teeth were selected based on the following criteria: intact buccal and lingual enamel, no visible cracks, caries or fluorosis, and an enamel topography that was suitable for intimate bonding with the curved base of the orthodontic brackets as determined by visual inspection with a binocular microscope at 20X magnification (Nikon SM2-10, Tokyo, Japan) according to Bishara et al (1998). Once the appropriate teeth were selected, the roots were removed using a high speed hand piece and a cross cut bur (Midwest Dental Products Corp. Des Plaines, IL, USA;



Bur No: FG 556) under a running spray of water. The crowns were then individually fixed in stainless steel mounting rings with cold cure acrylic (Self-curing orthodontic resin, Dentsply Limited, England) so that the facial surface was exposed (Figure 3.7). A surveyor was used to ensure the crowns were mounted so that the facial surface (height of contour) was parallel to the base of the mounting ring. The mounted crowns were rinsed and placed in a covered glass container filled with distilled deionized water and stored for 24 hours at 37°C and 100% relative humidity in an incubator (Thelco, Precision Scientific Co., Chicago, IL) until the brackets were bonded (ISO, 1994; Wiltshire, 1994).



**Figure 3.7** Tooth crown enamel sample with orthodontic bracket bonded to exposed facial surface, mounted in stainless steel ring filled with cold cure acrylic.

### **3.2.3 Bonding procedure**

The one hundred and fifty mounted composite resin and enamel substrate samples were each randomly divided into five test groups of thirty samples each as listed in Table 3.2.

The test groups were as follows:

1. 3M Victory Series brackets
2. TP Primekote brackets
- 3.Ormco OptimeshXRT brackets
4. Ormco Ti-Orthos 2 brackets
5. Ormco Mini 2000 Ormesh brackets

All of the enamel facial surfaces were cleaned and polished with residue free, non-fluoridated, non-flavoured pumice and water slurry for 10 seconds with a slow speed dental hand piece and rubber prophylactic cup (Bishara, 1998b). The samples were then thoroughly rinsed with tap water and dried with oil free compressed air for 30 seconds. For the composite resin substrate samples, Transbond XT adhesive paste was applied and worked into the base of the bracket. The bracket base was placed on the resin substrate without primer. For the enamel substrate samples, the enamel surface was etched for 30 seconds with phosphoric acid gel, rinsed for 20 seconds with a water spray and dried with an oil free air source for 20 seconds. The enamel surface was inspected to assure it appeared chalky white in colour. Transbond XT primer was applied to the enamel surface in a thin layer and the adhesive paste was applied and worked into the base of the bracket.

#### **3.2.4 Seating the test brackets**

A force of 500 gm was applied to each bracket using the Bencor Multi-T testing apparatus to assure complete seating of the bracket base against the substrate. Excess bonding material was carefully removed with an explorer to prevent disturbing any initial set of the material which may have occurred by ambient light, while providing a clean junction between the bracket base and substrate for the shearing blade (Delpont and Grobler, 1988; Driessen et al., 1989).

#### **3.2.5 Light curing**

Each bonded bracket was light cured separately with an Ortholux XT light curing unit for 20s (10s mesial and 10s distal) as per manufacturer's instructions. The light tip was positioned parallel to the bracket base/substrate interface and as close as possible without disturbing the position of the bracket during curing. The light-guide end was kept clean of debris throughout curing.

#### **3.2.6 Twenty-four hour storage conditions**

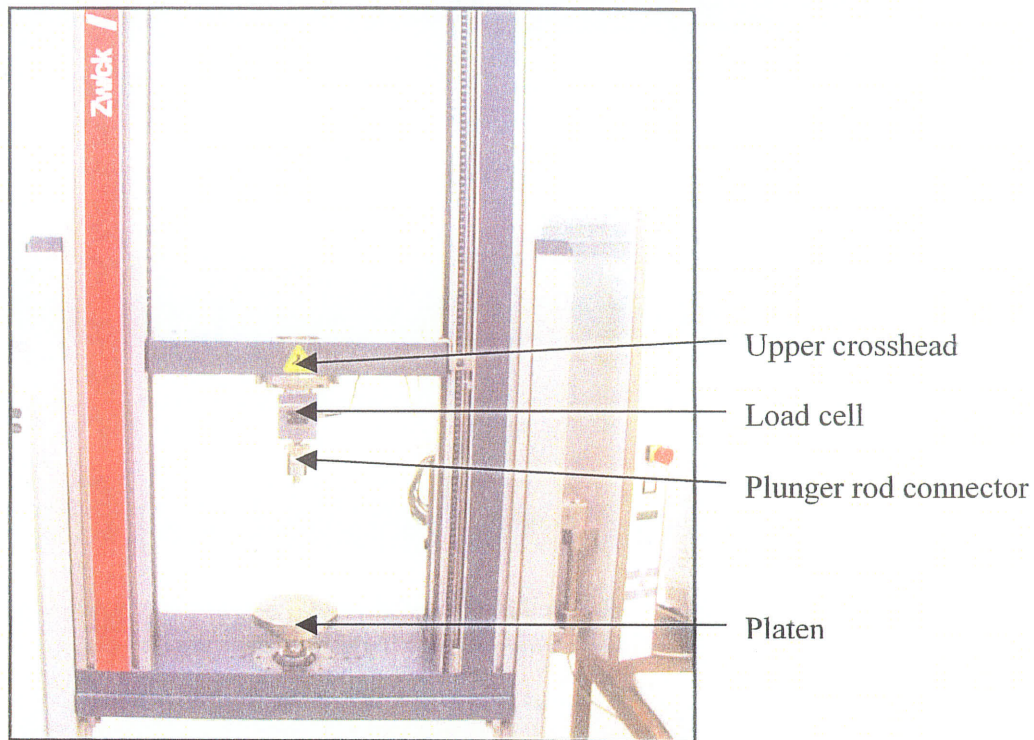
Immediately after bonding, the samples were stored in distilled deionized water for 24 hours at 37 °C and 100% relative humidity in an incubator (Thelco, Precision Scientific Co., Chicago, IL) according to guidelines of the international standards organization

(ISO, 1994; Wiltshire, 1994). Upon completion of the 24 hour period, shear-peel bond strength measurements were taken.

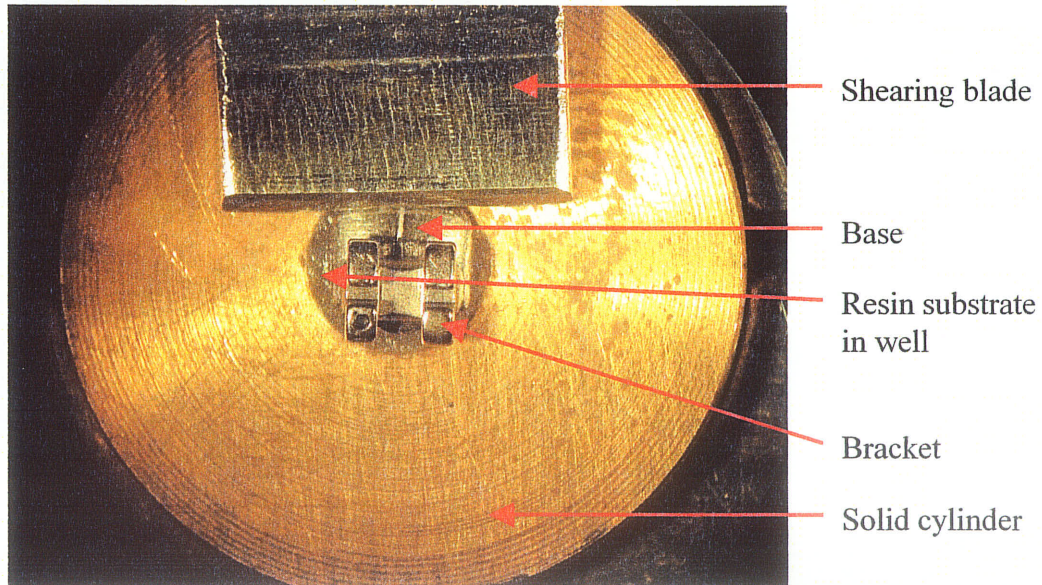
### **3.2.7 Shear-peel bond strength testing**

The samples were mounted into the shear-peel testing device (Bencor<sup>TM</sup> Multi-T, Danville Engineering, San Ramon, CA, USA) and tested in a Zwick Universal Testing Machine (#1445, Zwick GmbH & Co. Ulm, Germany) (Figure 3.8). The debond load was applied occlusogingivally, with a crosshead speed of 0.5 mm/minute using a 10 kN load cell. The load was applied as close as possible to the bracket-substrate interface using a custom straight edge shearing blade aligned parallel to the adhesive (Figures 3.9 and 3.10) or enamel height of contour (Figures 3.11 and 3.12) and the bracket base. The samples were loaded until bond failure. The Zwick computer requires the input of the surface area of the bracket base. With this information, and the load upon failure, the shear-peel bond strength in MPa (megapascals) was recorded. The debonding procedures were carried out by one operator to ensure consistency.



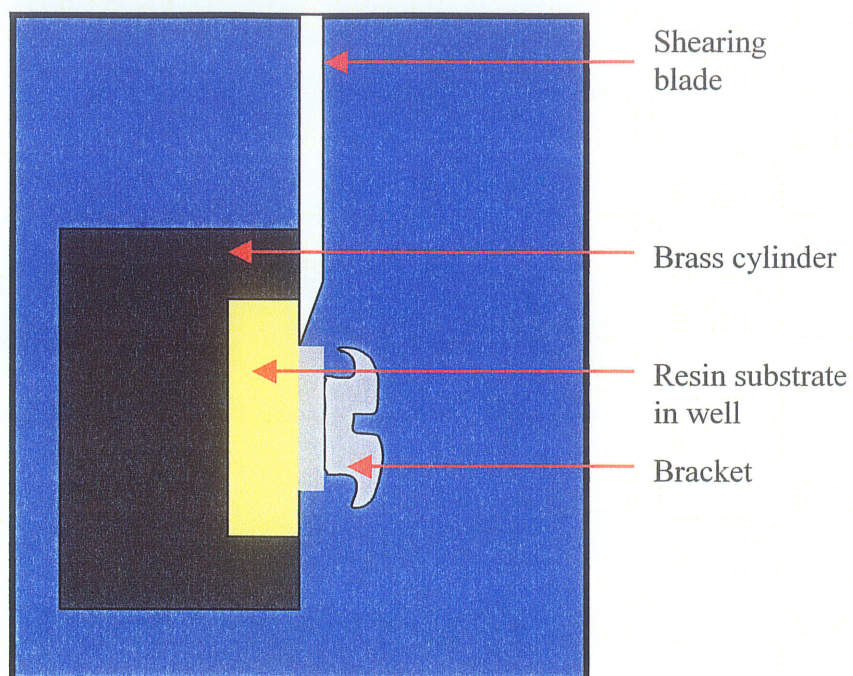


**Figure 3.8** Zwick Universal Testing Machine

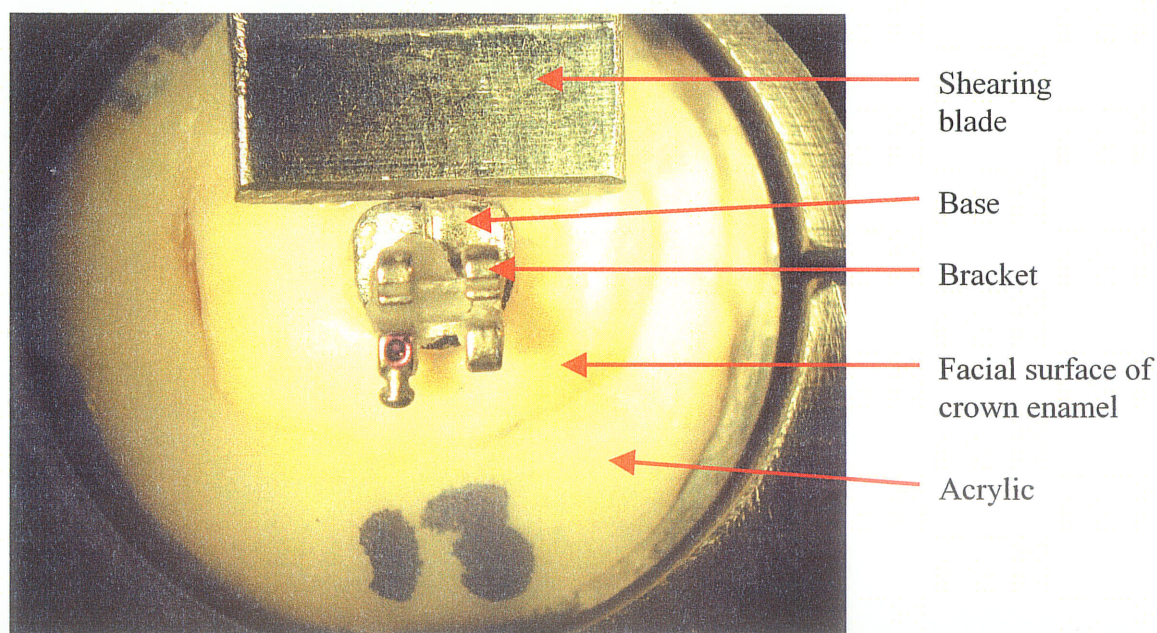


**Figure 3.9** Bracket bonded to resin substrate in the well of the brass ring is shown mounted in the Bencor Multi-T testing apparatus (Danville Engineering, San Ramon, CA, USA).



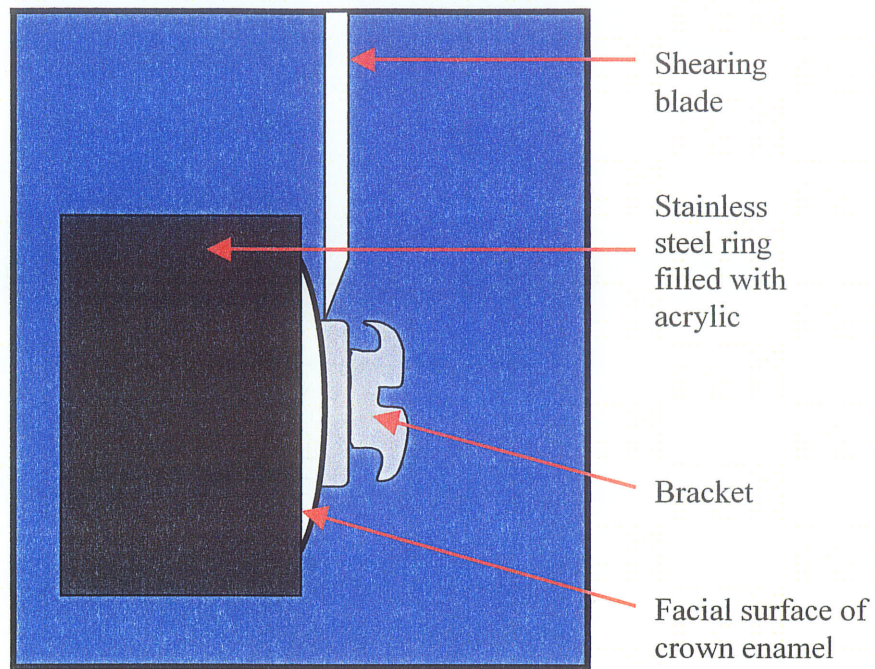


**Figure 3.10** Diagrammatic representation of the knife-edged shearing blade positioned parallel to the bracket base-resin substrate interface.



**Figure 3.11** Bracket bonded to the tooth, embedded in the stainless steel ring is shown mounted in the Bencor Multi-T testing apparatus (Danville Engineering, San Ramon, CA, USA).





**Figure 3.12** Diagrammatic representation of the knife-edged shearing blade positioned parallel to the enamel-bracket base interface.

### 3.2.8 Evaluation of fracture sites

The Adhesive Remnant Index (ARI) employed by Artun and Bergland (1984) was used to evaluate the amount of adhesive remaining on the enamel surface of each sample after debonding. For the bracket-enamel substrate test, the ARI was evaluated with a light-optical stereomicroscope at 20X magnification (Nikon SM-2, Tokyo, Japan). When using Artun and Bergland's method, the index numbers for each enamel sample range from zero to three as follows:

Score 0 = No adhesive left on the tooth.

Score 1 = Less than half of the adhesive left on the tooth.

Score 2 = More than half of the adhesive left on the tooth.

Score 3 = All adhesive left on the tooth, with distinct impression of the bracket mesh

The ARI scores were also used as a method of defining the general site of bond failure between enamel, adhesive and bracket base. For the bracket-resin substrate test since an enamel surface was not involved a traditional ARI could not be employed. Instead, bond failures were categorized using the Fracture Interface Score (FIS). The index numbers for each type of fracture range from one to three as follows:

Score 1 = Total adhesive fracture between bracket base and composite resin substrate.

Score 2 = Partial adhesive-cohesive fracture.

Score 3 = Total cohesive fracture within composite resin substrate.

Three months later 10% of the sample was randomly selected and the FIS and ARI reevaluated by the same operator in order to assess intra-evaluator discrepancies.

### **3.3 Statistical analysis**

Descriptive statistics, including the mean, standard deviation, minimum and maximum values, and coefficient of variation for each of the groups were recorded. A one-way analysis of variance was used to determine whether significant differences in mean bond strengths existed among the test groups. If significant differences were present, Tukey's post-hoc test was used to identify which of the means were significantly different from each other. A chi-square test was used to determine significant differences in the ARI and FIS scores among the different test groups. Significance for all statistical tests was predetermined at a probability value of .05 or less.

## **CHAPTER 4**

### **RESULTS**

|                                                                                                                  | <b>Page</b> |
|------------------------------------------------------------------------------------------------------------------|-------------|
| <b>4.1 Shear-peel bond strengths</b>                                                                             | <b>50</b>   |
| <b>4.1.1 Comparison of brackets bonded to composite resin substrate only</b>                                     | <b>50</b>   |
| <b>4.1.2 Comparison of brackets bonded to enamel substrate with composite resin</b>                              | <b>51</b>   |
| <b>4.1.3 Comparison of bracket-composite resin substrate and bracket-composite resin-enamel substrate groups</b> | <b>52</b>   |
| <b>4.2 Fracture Interface Scores (FIS) and Adhesive Remnant Index (ARI) scores</b>                               | <b>76</b>   |
| <b>4.2.1 Comparison of brackets bonded to composite resin substrate only</b>                                     | <b>76</b>   |
| <b>4.2.2 Comparison of brackets bonded to enamel substrate with composite resin</b>                              | <b>77</b>   |

## **4.1 Shear-peel bond strengths**

The individual shear-peel bond strengths of each sample, as well as mean shear-peel bond strengths, standard deviations, coefficients of variation, maximums, and minimums for each group are listed in Tables 4.1-4.10. The comparative data for the mean shear-peel bond strengths of the groups tested is listed in Table 4.11. The analysis of variance indicated that there was a significant difference in mean shear-peel bond strengths among the test groups ( $p < .05$ ) which is represented graphically in Figures 4.1-4.2. Tukey's multiple range test was then used to identify which of the means were significantly different from each other. Any statistically significant differences in the mean bond strengths between the different groups discussed below was predetermined at a probability value of .05 or less. Scanning electron micrographs (SEM) of each of the bracket bases before bonding and after debonding are displayed in Figures 4.3 – 4.7.

### **4.1.1 Comparison of brackets bonded to composite resin substrate only**

The shear-peel bond strength of the TP Primekote bracket group ( $22.35 \pm 3.07$  MPa) was significantly higher than all the groups tested ( $p < .05$ ). The shear-peel bond strength of the 3M Victory series bracket group ( $16.29 \pm 2.47$  MPa) was higher than the Ormco Ormesh control group ( $14.88 \pm 2.50$  MPa), but not significantly ( $p > 0.05$ ). However, it was significantly higher than both the Ormco OptimeshXRT bracket group ( $13.38 \pm 2.47$  MPa) and the Ormco Ti-Orthos2 bracket group ( $13.37 \pm 2.09$  MPa). There was no

statistically significant difference in the shear-peel bond strengths of the threeOrmco bracket groups.

The standard deviations for all the tested groups were low, with coefficients of variation ranging from 13.7 to 18.5%. The OptimeshXRT group had the highest coefficient of variation (18.5%) out of all the groups with shear-peel bond strengths ranging from 9.33 to 19.33 MPa.

#### **4.1.2 Comparison of brackets bonded with composite resin to enamel substrate**

The shear-peel bond strength of the 3M Victory series bracket group ( $26.80 \pm 5.73$  MPa) was significantly higher than all the groups tested ( $p < .05$ ). The shear-peel bond strength of the TP Primekote bracket group ( $19.41 \pm 3.21$  MPa) was not significantly higher than theOrmco Ormesh control group ( $18.25 \pm 3.47$  MPa) or theOrmco OptimeshXRT group ( $17.79 \pm 5.24$  MPa). The shear-peel bond strength of the Ti-Orthos2 bracket group ( $14.50 \pm 3.71$  MPa) was significantly lower than all the groups tested.

The standard deviations for all the tested groups were low, with coefficients of variation ranging from 16.5 to 29.5%. The OptimeshXRT group had the highest coefficient of variation (29.5%) out of all the groups with shear-peel bond strengths ranging from 10.10 to 30.92 MPa.

#### **4.1.3 Comparison of bracket-composite resin substrate and bracket-composite resin-enamel substrate groups**

The shear-peel bond strengths of theOrmco Ormesh control brackets bonded to the composite resin substrate alone ( $14.88 \pm 2.50$  MPa) were significantly lower than when bonded with the composite resin to enamel substrate ( $18.25 \pm 3.47$  MPa) ( $p < 0.05$ ). The shear-peel bond strengths of Ormco OptimeshXRT brackets bonded to the composite resin substrate alone ( $13.38 \pm 2.47$  MPa) were significantly lower than when bonded with the composite resin to enamel substrate ( $17.79 \pm 5.24$  MPa) ( $p < 0.001$ ). The Ormco Ti-Orthos2 bracket-adhesive group ( $13.37 \pm 2.09$  MPa) was the only group whose shear-peel bond strength was not significantly greater than when bonded with the composite resin to enamel substrate ( $14.50 \pm 3.71$  MPa) ( $p > 0.05$ ). The shear-peel bond strengths of 3M Victory series brackets bonded to the composite resin substrate alone ( $16.29 \pm 2.47$  MPa) were significantly lower than when bonded with the composite resin to enamel substrate ( $26.80 \pm 5.73$  MPa) ( $p < 0.001$ ). The TP Primekote bracket-adhesive group ( $22.35 \pm 3.07$  MPa) was the only group where the shear-peel bond strength was significantly greater than when bonded with the composite resin to enamel substrate ( $19.41 \pm 3.21$  MPa) ( $p < 0.05$ ).



| Ormesh untreated mesh-adhesive only<br>Sample # | Shear-peel bond strength (MPa) |
|-------------------------------------------------|--------------------------------|
| 1                                               | 11.74                          |
| 2                                               | 17.68                          |
| 3                                               | 15.34                          |
| 4                                               | 16.77                          |
| 5                                               | 11.65                          |
| 6                                               | 15.17                          |
| 7                                               | 15.66                          |
| 8                                               | 16.88                          |
| 9                                               | 16.79                          |
| 10                                              | 15.66                          |
| 11                                              | 19.49                          |
| 12                                              | 11.12                          |
| 13                                              | 11.93                          |
| 14                                              | 14.29                          |
| 15                                              | 13.90                          |
| 16                                              | 17.91                          |
| 17                                              | 10.83                          |
| 18                                              | 15.46                          |
| 19                                              | 14.53                          |
| 20                                              | 10.32                          |
| 21                                              | 11.91                          |
| 22                                              | 17.08                          |
| 23                                              | 17.51                          |
| 24                                              | 15.69                          |
| 25                                              | 16.60                          |
| 26                                              | 14.87                          |
| 27                                              | 18.97                          |
| 28                                              | 14.48                          |
| 29                                              | 13.25                          |
| 30                                              | 12.85                          |
| Minimum                                         | 10.32                          |
| Maximum                                         | 19.49                          |
| Mean                                            | 14.88                          |
| Standard deviation                              | 2.50                           |
| Coefficient of Variation (%)                    | 16.80                          |

**Table 4.1.** Twenty-four hour shear-peel bond strengths ofOrmco Mini 2000 Ormesh untreated mesh brackets (control) bonded to a Transbond XT composite resin substrate with Transbond XT adhesive.

| OptimeshXRT-adhesive only<br>Sample # | Shear-peel bond strength (MPa) |
|---------------------------------------|--------------------------------|
| 1                                     | 10.41                          |
| 2                                     | 9.89                           |
| 3                                     | 13.35                          |
| 4                                     | 13.38                          |
| 5                                     | 13.55                          |
| 6                                     | 11.47                          |
| 7                                     | 12.62                          |
| 8                                     | 9.33                           |
| 9                                     | 13.66                          |
| 10                                    | 10.78                          |
| 11                                    | 14.41                          |
| 12                                    | 16.07                          |
| 13                                    | 10.53                          |
| 14                                    | 13.14                          |
| 15                                    | 14.60                          |
| 16                                    | 11.49                          |
| 17                                    | 13.86                          |
| 18                                    | 16.51                          |
| 19                                    | 13.30                          |
| 20                                    | 11.37                          |
| 21                                    | 11.79                          |
| 22                                    | 10.55                          |
| 23                                    | 14.83                          |
| 24                                    | 14.84                          |
| 25                                    | 14.08                          |
| 26                                    | 16.04                          |
| 27                                    | 14.95                          |
| 28                                    | 18.98                          |
| 29                                    | 19.33                          |
| 30                                    | 12.37                          |
| Minimum                               | 9.33                           |
| Maximum                               | 19.33                          |
| Mean                                  | 13.38                          |
| Standard deviation                    | 2.47                           |
| Coefficient of Variation (%)          | 18.50                          |

**Table 4.2.** Twenty-four hour shear-peel bond strengths of Ormco OptimeshXRT brackets bonded to a Transbond XT composite resin substrate with Transbond XT adhesive.

| Ti-Orthos 2-adhesive only<br>Sample # | Shear-peel bond strength (MPa) |
|---------------------------------------|--------------------------------|
| 1                                     | 13.64                          |
| 2                                     | 17.75                          |
| 3                                     | 14.12                          |
| 4                                     | 10.40                          |
| 5                                     | 15.19                          |
| 6                                     | 12.37                          |
| 7                                     | 11.05                          |
| 8                                     | 14.16                          |
| 9                                     | 13.36                          |
| 10                                    | 11.34                          |
| 11                                    | 15.38                          |
| 12                                    | 12.15                          |
| 13                                    | 13.45                          |
| 14                                    | 14.64                          |
| 15                                    | 11.01                          |
| 16                                    | 9.79                           |
| 17                                    | 14.92                          |
| 18                                    | 14.47                          |
| 19                                    | 16.94                          |
| 20                                    | 10.48                          |
| 21                                    | 11.95                          |
| 22                                    | 11.55                          |
| 23                                    | 15.83                          |
| 24                                    | 11.60                          |
| 25                                    | 15.36                          |
| 26                                    | 16.58                          |
| 27                                    | 13.26                          |
| 28                                    | 13.23                          |
| 29                                    | 11.20                          |
| 30                                    | 13.96                          |
| Minimum                               | 9.79                           |
| Maximum                               | 17.75                          |
| Mean                                  | 13.37                          |
| Standard deviation                    | 2.09                           |
| Coefficient of Variation (%)          | 15.60                          |

**Table 4.3.** Twenty-four hour shear-peel bond strengths ofOrmco Ti-Orthos 2 brackets bonded to a Transbond XT composite resin substrate with Transbond XT adhesive.



| Victory-adhesive only<br>Sample # | Shear-peel bond strength (MPa) |
|-----------------------------------|--------------------------------|
| 1                                 | 14.93                          |
| 2                                 | 12.58                          |
| 3                                 | 18.99                          |
| 4                                 | 11.67                          |
| 5                                 | 13.03                          |
| 6                                 | 18.09                          |
| 7                                 | 20.83                          |
| 8                                 | 14.57                          |
| 9                                 | 14.93                          |
| 10                                | 12.73                          |
| 11                                | 18.52                          |
| 12                                | 15.71                          |
| 13                                | 15.63                          |
| 14                                | 17.08                          |
| 15                                | 20.06                          |
| 16                                | 15.14                          |
| 17                                | 16.69                          |
| 18                                | 18.52                          |
| 19                                | 14.21                          |
| 20                                | 17.42                          |
| 21                                | 19.60                          |
| 22                                | 16.87                          |
| 23                                | 14.16                          |
| 24                                | 18.49                          |
| 25                                | 13.82                          |
| 26                                | 18.20                          |
| 27                                | 19.54                          |
| 28                                | 15.04                          |
| 29                                | 14.09                          |
| 30                                | 17.44                          |
| Minimum                           | 11.67                          |
| Maximum                           | 20.83                          |
| Mean                              | 16.29                          |
| Standard deviation                | 2.47                           |
| Coefficient of Variation (%)      | 15.20                          |

**Table 4.4.** Twenty-four hour shear-peel bond strengths of 3M Victory series brackets bonded to a Transbond XT composite resin substrate with Transbond XT adhesive.

| Primekote-adhesive only<br>Sample # | Shear-peel bond strength (MPa) |
|-------------------------------------|--------------------------------|
| 1                                   | 20.79                          |
| 2                                   | 14.56                          |
| 3                                   | 21.09                          |
| 4                                   | 21.00                          |
| 5                                   | 21.77                          |
| 6                                   | 15.71                          |
| 7                                   | 22.15                          |
| 8                                   | 19.21                          |
| 9                                   | 21.12                          |
| 10                                  | 23.59                          |
| 11                                  | 22.57                          |
| 12                                  | 20.62                          |
| 13                                  | 27.29                          |
| 14                                  | 22.72                          |
| 15                                  | 24.32                          |
| 16                                  | 25.24                          |
| 17                                  | 20.37                          |
| 18                                  | 20.49                          |
| 19                                  | 21.35                          |
| 20                                  | 23.93                          |
| 21                                  | 24.68                          |
| 22                                  | 21.21                          |
| 23                                  | 23.72                          |
| 24                                  | 22.43                          |
| 25                                  | 28.50                          |
| 26                                  | 28.60                          |
| 27                                  | 21.51                          |
| 28                                  | 24.20                          |
| 29                                  | 20.90                          |
| 30                                  | 24.98                          |
| Minimum                             | 14.56                          |
| Maximum                             | 28.60                          |
| Mean                                | 22.35                          |
| Standard deviation                  | 3.07                           |
| Coefficient of Variation (%)        | 13.70                          |

**Table 4.5.** Twenty-four hour shear-peel bond strengths of TP Primekote brackets bonded to a Transbond XT composite resin substrate with Transbond XT adhesive.

| Ormesh untreated mesh-adhesive-enamel<br>Sample # | Shear-peel bond strength (MPa) |
|---------------------------------------------------|--------------------------------|
| 1                                                 | 18.17                          |
| 2                                                 | 19.59                          |
| 3                                                 | 12.54                          |
| 4                                                 | 14.54                          |
| 5                                                 | 11.64                          |
| 6                                                 | 23.19                          |
| 7                                                 | 17.07                          |
| 8                                                 | 22.06                          |
| 9                                                 | 16.61                          |
| 10                                                | 15.48                          |
| 11                                                | 18.03                          |
| 12                                                | 21.28                          |
| 13                                                | 21.99                          |
| 14                                                | 14.37                          |
| 15                                                | 11.96                          |
| 16                                                | 18.19                          |
| 17                                                | 16.92                          |
| 18                                                | 22.69                          |
| 19                                                | 19.76                          |
| 20                                                | 18.96                          |
| 21                                                | 21.50                          |
| 22                                                | 21.70                          |
| 23                                                | 23.06                          |
| 24                                                | 22.48                          |
| 25                                                | 17.15                          |
| 26                                                | 20.24                          |
| 27                                                | 14.56                          |
| 28                                                | 17.74                          |
| 29                                                | 20.12                          |
| 30                                                | 14.00                          |
| Minimum                                           | 11.64                          |
| Maximum                                           | 23.19                          |
| Mean                                              | 18.25                          |
| Standard deviation                                | 3.47                           |
| Coefficient of Variation (%)                      | 19.00                          |

**Table 4.6.** Twenty-four hour shear-peel bond strengths ofOrmco Mini 2000 Ormesh untreated mesh brackets (control) bonded to enamel substrate with Transbond XT composite resin adhesive.



| OptimeshXRT-adhesive-enamel<br>Sample # | Shear-peel bond strength (MPa) |
|-----------------------------------------|--------------------------------|
| 1                                       | 14.52                          |
| 2                                       | 17.31                          |
| 3                                       | 23.77                          |
| 4                                       | 21.92                          |
| 5                                       | 11.37                          |
| 6                                       | 17.03                          |
| 7                                       | 14.33                          |
| 8                                       | 17.29                          |
| 9                                       | 27.31                          |
| 10                                      | 11.59                          |
| 11                                      | 21.10                          |
| 12                                      | 15.35                          |
| 13                                      | 11.41                          |
| 14                                      | 17.99                          |
| 15                                      | 15.53                          |
| 16                                      | 25.02                          |
| 17                                      | 28.66                          |
| 18                                      | 15.67                          |
| 19                                      | 30.92                          |
| 20                                      | 15.50                          |
| 21                                      | 10.10                          |
| 22                                      | 23.62                          |
| 23                                      | 13.88                          |
| 24                                      | 16.17                          |
| 25                                      | 15.36                          |
| 26                                      | 16.63                          |
| 27                                      | 14.69                          |
| 28                                      | 16.00                          |
| 29                                      | 15.67                          |
| 30                                      | 17.87                          |
| Minimum                                 | 10.10                          |
| Maximum                                 | 30.92                          |
| Mean                                    | 17.79                          |
| Standard deviation                      | 5.24                           |
| Coefficient of Variation (%)            | 29.50                          |

**Table 4.7.** Twenty-four hour shear-peel bond strengths ofOrmco OptimeshXRT brackets bonded to enamel substrate with Transbond XT composite resin adhesive.



| Ti-Orthos 2-adhesive-enamel<br>Sample # | Shear-peel bond strength (MPa) |
|-----------------------------------------|--------------------------------|
| 1                                       | 25.77                          |
| 2                                       | 13.53                          |
| 3                                       | 8.67                           |
| 4                                       | 16.36                          |
| 5                                       | 13.32                          |
| 6                                       | 9.91                           |
| 7                                       | 18.16                          |
| 8                                       | 14.24                          |
| 9                                       | 19.57                          |
| 10                                      | 15.54                          |
| 11                                      | 22.14                          |
| 12                                      | 14.22                          |
| 13                                      | 14.46                          |
| 14                                      | 16.57                          |
| 15                                      | 10.30                          |
| 16                                      | 16.36                          |
| 17                                      | 12.46                          |
| 18                                      | 11.79                          |
| 19                                      | 17.96                          |
| 20                                      | 11.73                          |
| 21                                      | 11.96                          |
| 22                                      | 11.61                          |
| 23                                      | 11.68                          |
| 24                                      | 12.09                          |
| 25                                      | 12.80                          |
| 26                                      | 12.80                          |
| 27                                      | 12.11                          |
| 28                                      | 15.81                          |
| 29                                      | 13.06                          |
| 30                                      | 18.05                          |
| Minimum                                 | 8.67                           |
| Maximum                                 | 25.77                          |
| Mean                                    | 14.50                          |
| Standard deviation                      | 3.71                           |
| Coefficient of Variation (%)            | 25.60                          |

**Table 4.8.** Twenty-four hour shear-peel bond strengths ofOrmco Ti-Orthos 2 brackets bonded to enamel substrate with Transbond XT composite resin adhesive.

| Victory-adhesive-enamel<br>Sample # | Shear-peel bond strength (MPa) |
|-------------------------------------|--------------------------------|
| 1                                   | 17.44                          |
| 2                                   | 31.97                          |
| 3                                   | 28.65                          |
| 4                                   | 28.64                          |
| 5                                   | 23.99                          |
| 6                                   | 29.61                          |
| 7                                   | 30.68                          |
| 8                                   | 26.76                          |
| 9                                   | 22.86                          |
| 10                                  | 27.05                          |
| 11                                  | 21.91                          |
| 12                                  | 38.28                          |
| 13                                  | 17.49                          |
| 14                                  | 40.11                          |
| 15                                  | 34.30                          |
| 16                                  | 30.73                          |
| 17                                  | 21.71                          |
| 18                                  | 26.20                          |
| 19                                  | 20.53                          |
| 20                                  | 22.59                          |
| 21                                  | 27.88                          |
| 22                                  | 21.93                          |
| 23                                  | 17.46                          |
| 24                                  | 34.65                          |
| 25                                  | 24.79                          |
| 26                                  | 23.34                          |
| 27                                  | 28.92                          |
| 28                                  | 25.86                          |
| 29                                  | 30.49                          |
| 30                                  | 27.18                          |
| Minimum                             | 17.44                          |
| Maximum                             | 40.11                          |
| Mean                                | 26.80                          |
| Standard deviation                  | 5.73                           |
| Coefficient of Variation (%)        | 21.40                          |

**Table 4.9.** Twenty-four hour shear-peel bond strengths of 3M Victory series sandblasted brackets bonded to enamel substrate with Transbond XT composite resin adhesive.

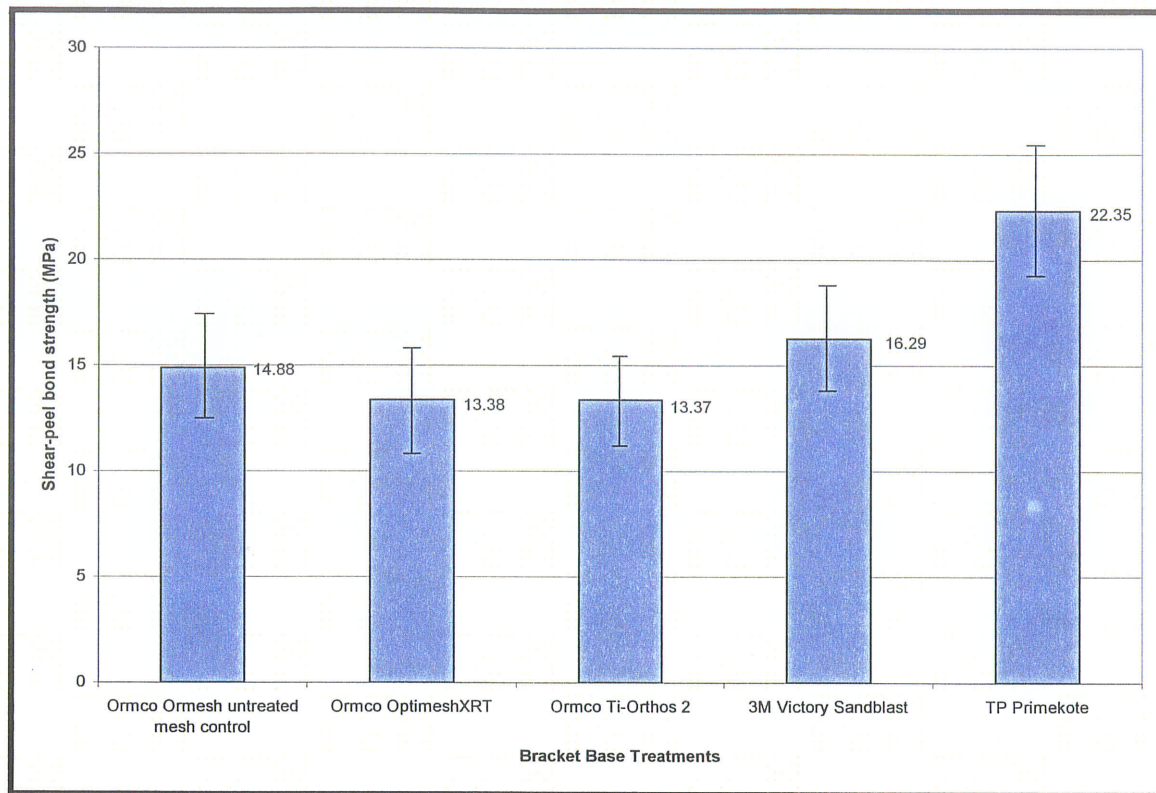
| Primekote-adhesive-enamel<br>Sample # | Shear-peel bond strength (MPa) |
|---------------------------------------|--------------------------------|
| 1                                     | 22.81                          |
| 2                                     | 18.45                          |
| 3                                     | 18.55                          |
| 4                                     | 23.42                          |
| 5                                     | 21.31                          |
| 6                                     | 19.03                          |
| 7                                     | 22.54                          |
| 8                                     | 19.91                          |
| 9                                     | 16.40                          |
| 10                                    | 20.49                          |
| 11                                    | 17.62                          |
| 12                                    | 18.69                          |
| 13                                    | 19.89                          |
| 14                                    | 18.23                          |
| 15                                    | 27.65                          |
| 16                                    | 26.08                          |
| 17                                    | 19.82                          |
| 18                                    | 17.44                          |
| 19                                    | 17.74                          |
| 20                                    | 21.04                          |
| 21                                    | 15.60                          |
| 22                                    | 15.34                          |
| 23                                    | 21.19                          |
| 24                                    | 12.76                          |
| 25                                    | 18.53                          |
| 26                                    | 18.23                          |
| 27                                    | 18.96                          |
| 28                                    | 15.34                          |
| 29                                    | 22.88                          |
| 30                                    | 16.36                          |
| Minimum                               | 12.76                          |
| Maximum                               | 27.65                          |
| Mean                                  | 19.41                          |
| Standard deviation                    | 3.21                           |
| Coefficient of Variation (%)          | 16.50                          |

**Table 4.10.** Twenty-four hour shear-peel bond strengths of TP Primekote brackets bonded to enamel substrate with Transbond XT composite resin adhesive.

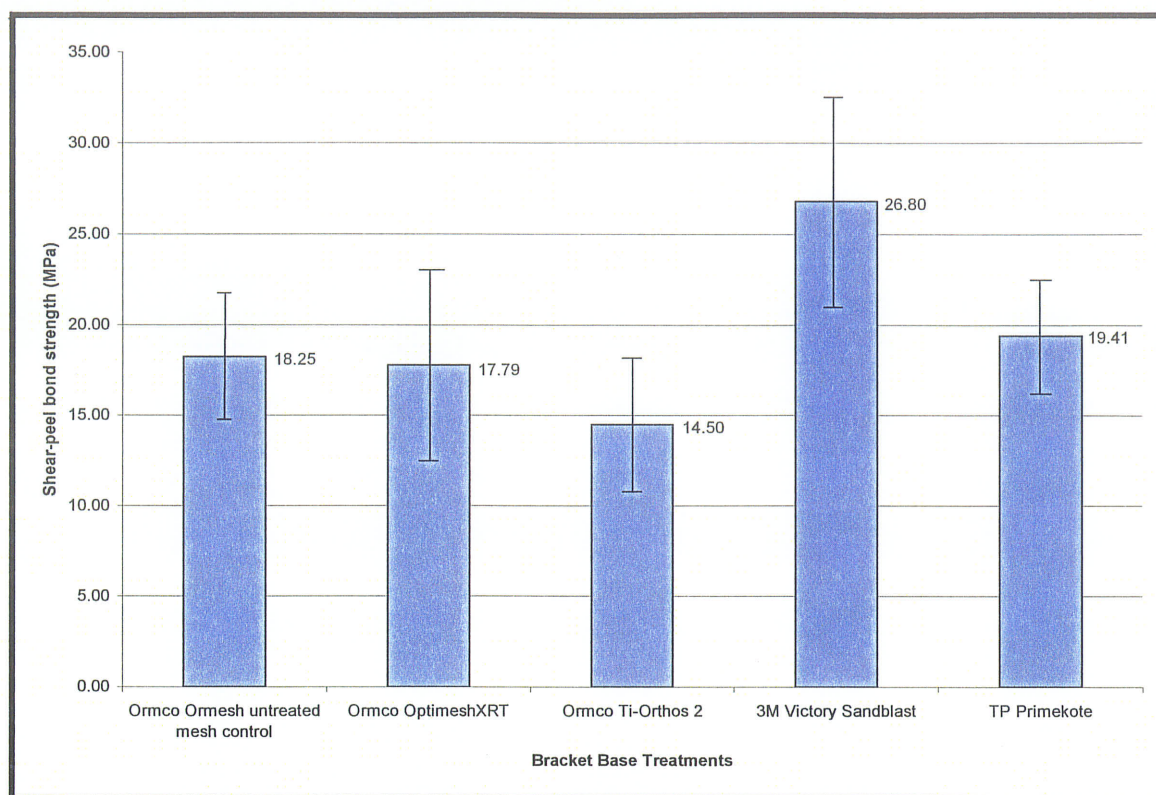
| Test Groups<br>each N=30                       | Mean<br>SPBS<br>(MPa) | Std.<br>Dev<br>(MPa) | Coefficient of<br>Variation<br>(%) | Maximum<br>(MPa) | Minimum<br>(MPa) |
|------------------------------------------------|-----------------------|----------------------|------------------------------------|------------------|------------------|
| <b>Bonded to composite<br/>resin substrate</b> |                       |                      |                                    |                  |                  |
| Ormesh                                         | 14.88                 | 2.50                 | 16.80                              | 19.49            | 10.32            |
| OptimeshXRT                                    | 13.38                 | 2.47                 | 18.50                              | 19.33            | 9.33             |
| Ti-Orthos2                                     | 13.37                 | 2.09                 | 15.60                              | 17.75            | 9.79             |
| Victory                                        | 16.29                 | 2.47                 | 15.20                              | 20.83            | 11.67            |
| Primekote                                      | 22.35                 | 3.07                 | 13.70                              | 28.60            | 14.56            |
| <b>Bonded to enamel<br/>substrate</b>          |                       |                      |                                    |                  |                  |
| Ormesh                                         | 18.25                 | 3.47                 | 19.00                              | 23.19            | 11.64            |
| OptimeshXRT                                    | 17.79                 | 5.24                 | 29.50                              | 30.92            | 10.10            |
| Ti-Orthos 2                                    | 14.50                 | 3.71                 | 25.60                              | 25.77            | 8.67             |
| Victory                                        | 26.80                 | 5.73                 | 21.40                              | 40.11            | 17.44            |
| Primekote                                      | 19.41                 | 3.21                 | 16.50                              | 27.65            | 12.76            |

**Table 4.11.** Descriptive statistics of the shear-peel bond strengths (SPBS) in megapascals (MPa) for all groups tested. Groups with a dot joined by a vertical line showed no statistical differences in their mean bond strengths at a 95% confidence level (ANOVA with Tukey's post hoc test).



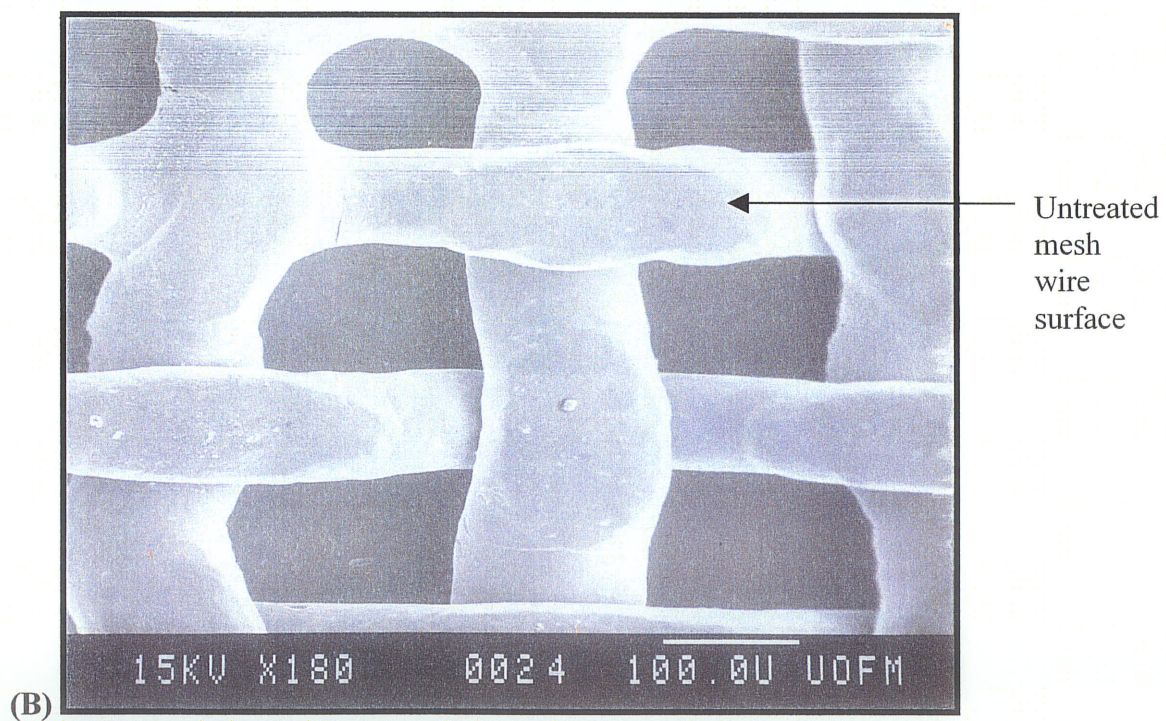
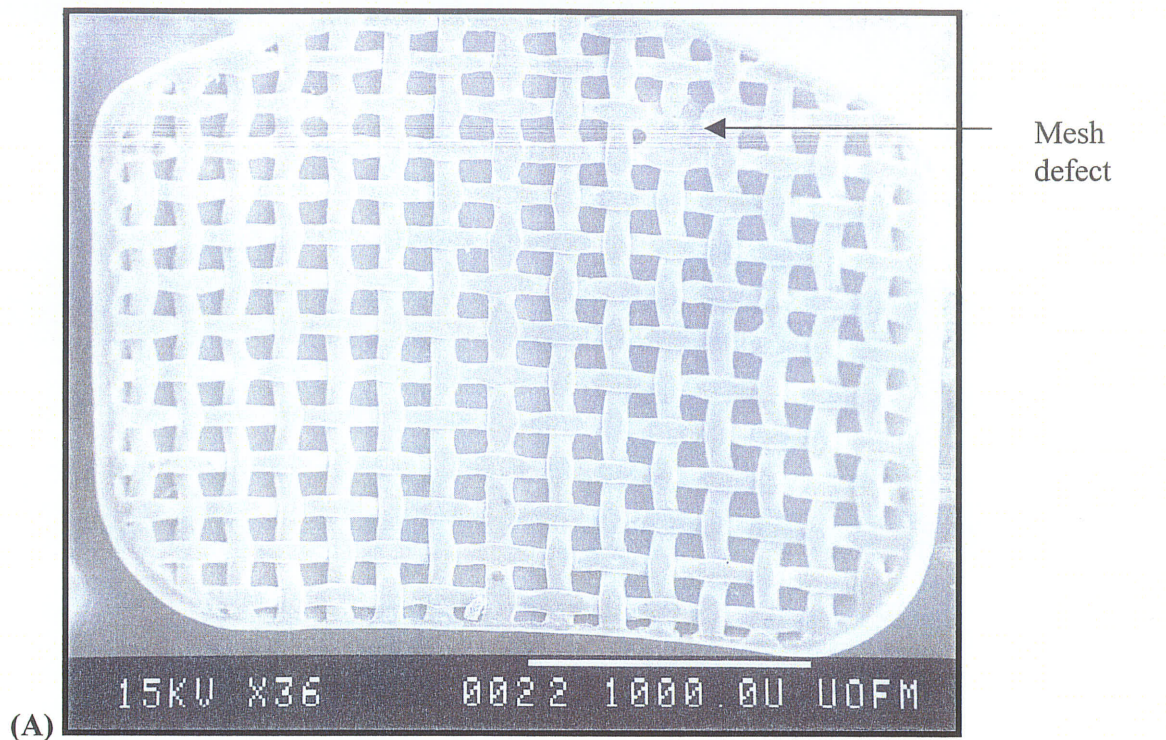


**Figure 4.1.** Comparison of shear-peel bond strengths in megapascals (MPa) for all five bracket base-composite resin substrate test groups (standard deviations shown with error bars).

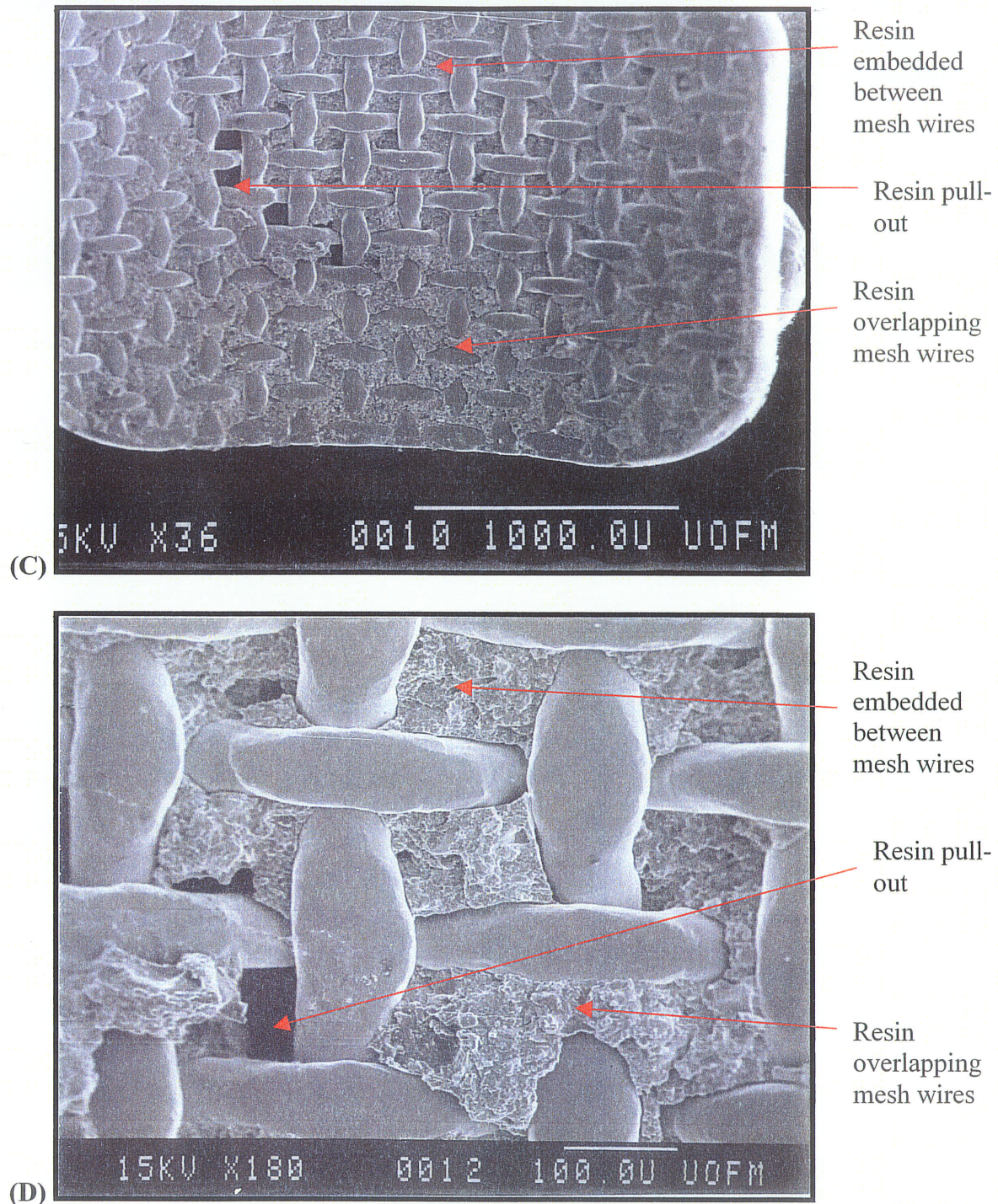


**Figure 4.2.** Comparison of shear-peel bond strengths in megapascals (MPa) for all five bracket base-composite resin-enamel substrate test groups (standard deviations shown with error bars).



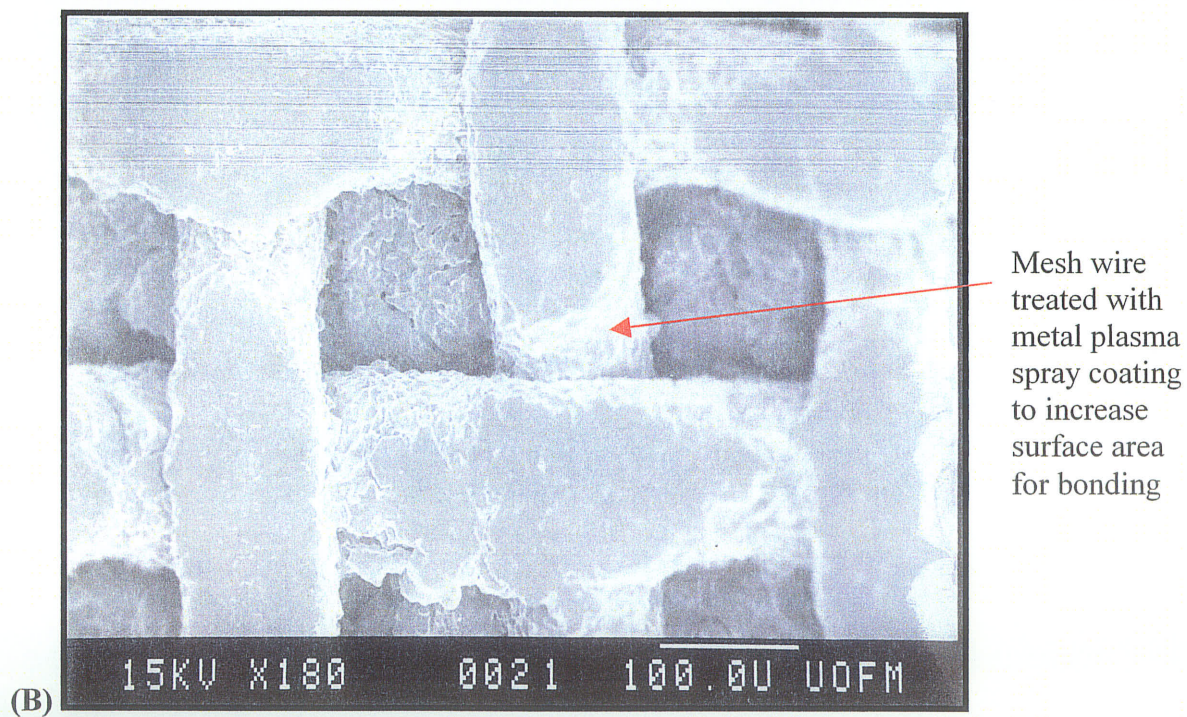
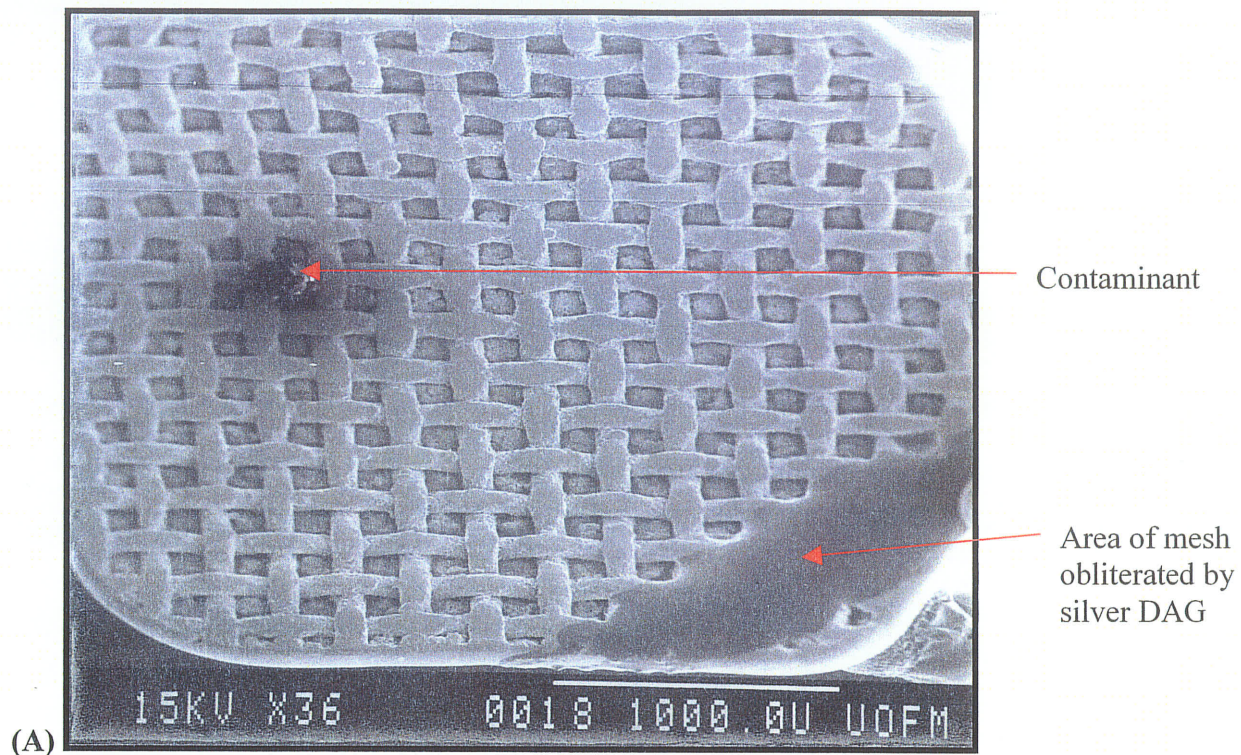




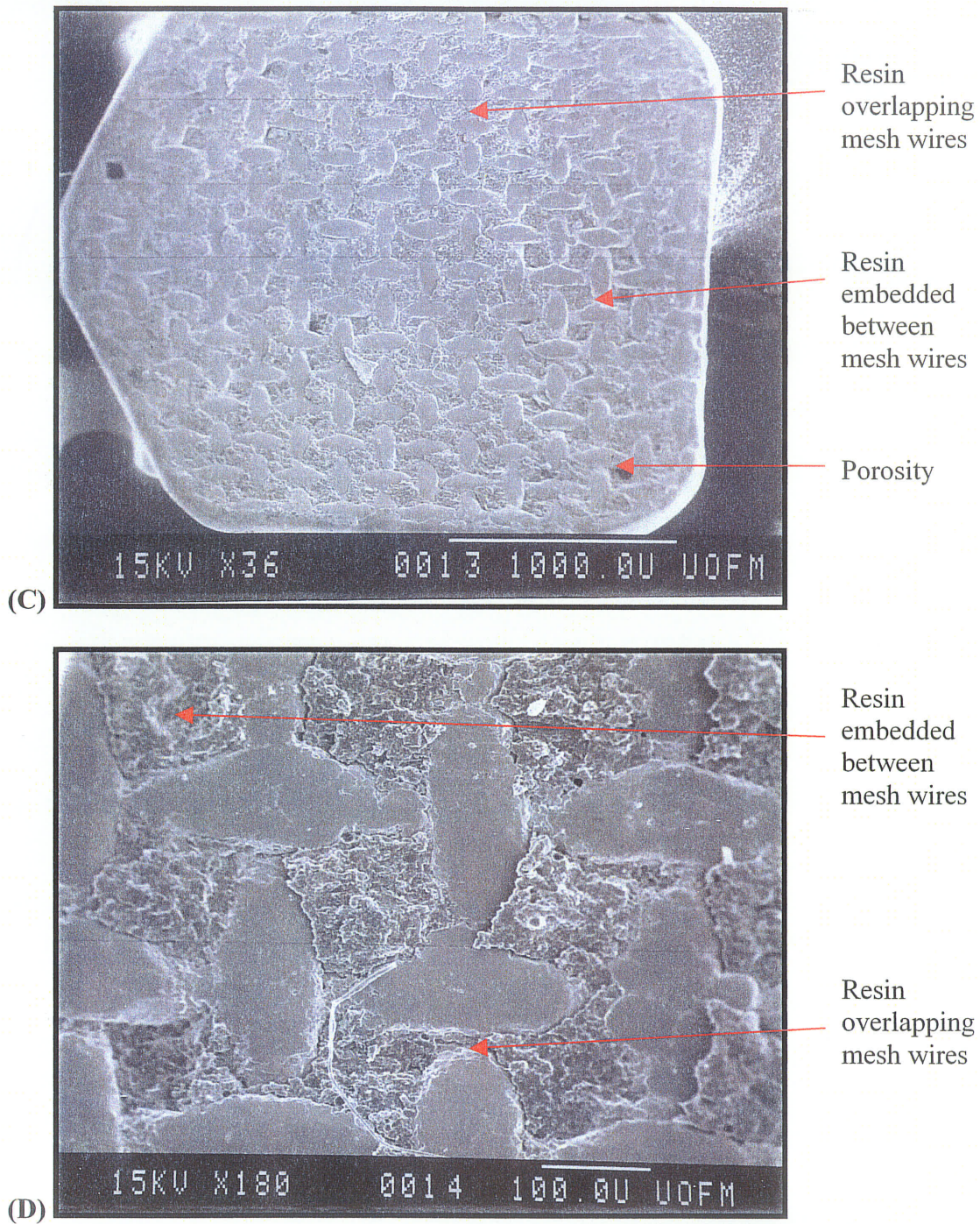


**Figure 4.3.** SEM of Ormco Ormesh untreated control bracket base (A) before bonding 36x magnification, note mesh defect (B) before bonding 180x magnification, (C) after debonding 36x magnification, and (D) after debonding 180x magnification. Note regions of resin pull-out, resin embedded between mesh wires, and resin overlapping mesh wires.



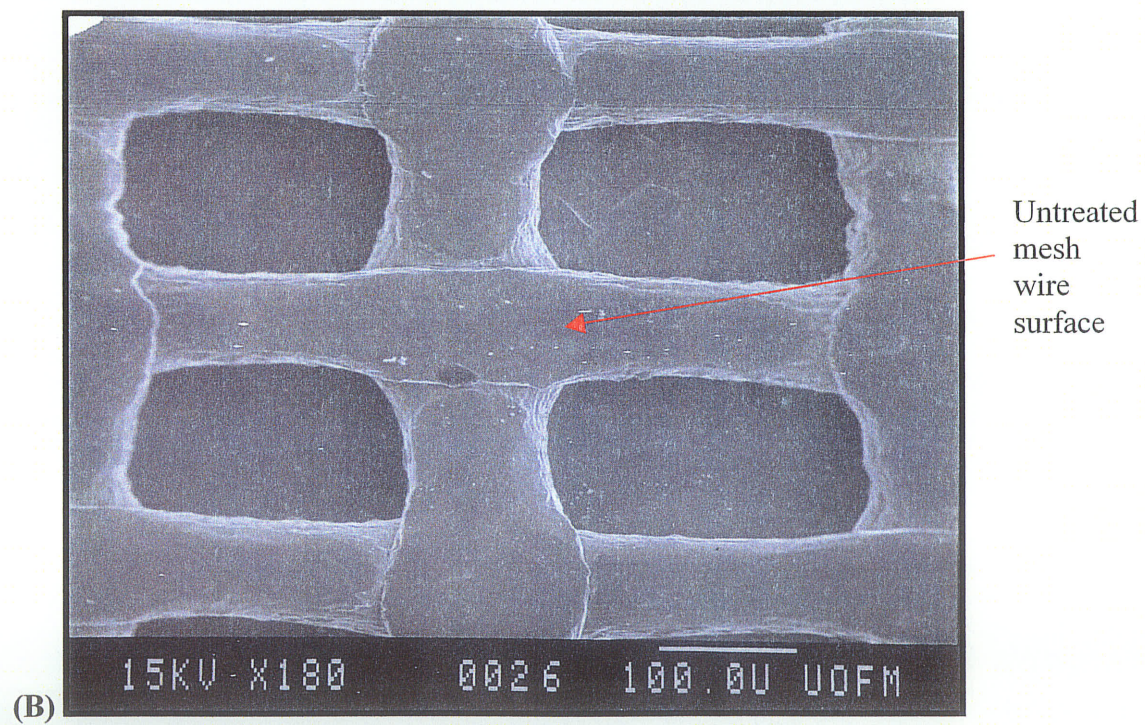
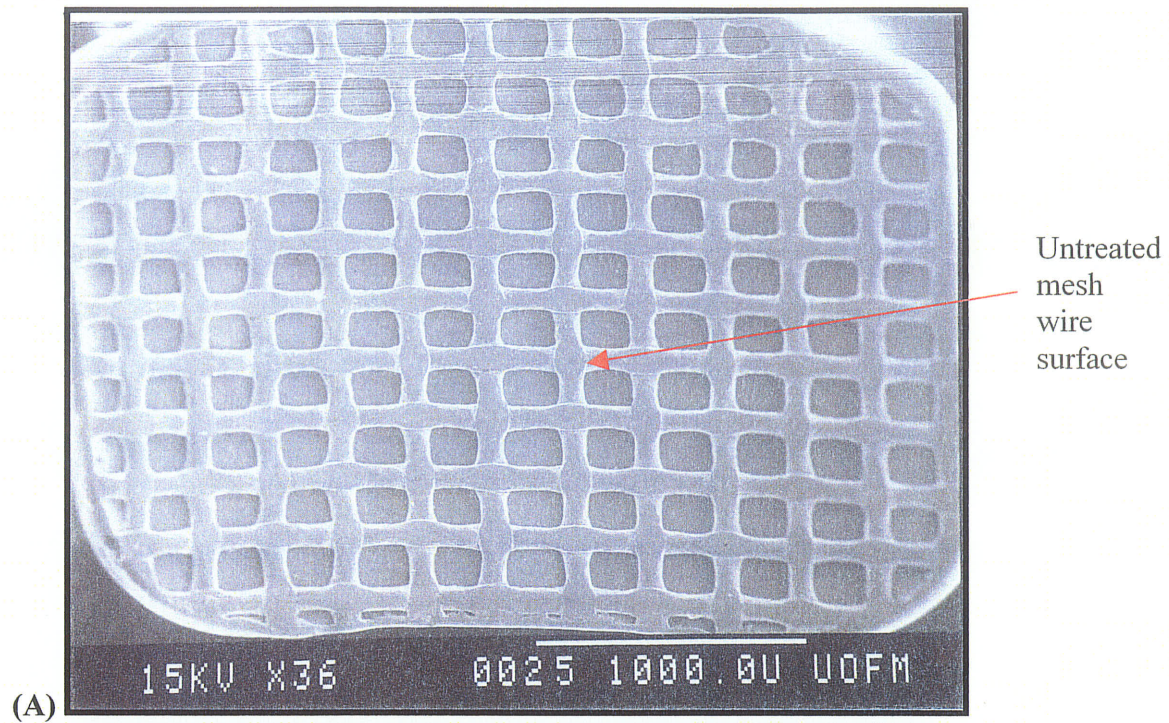




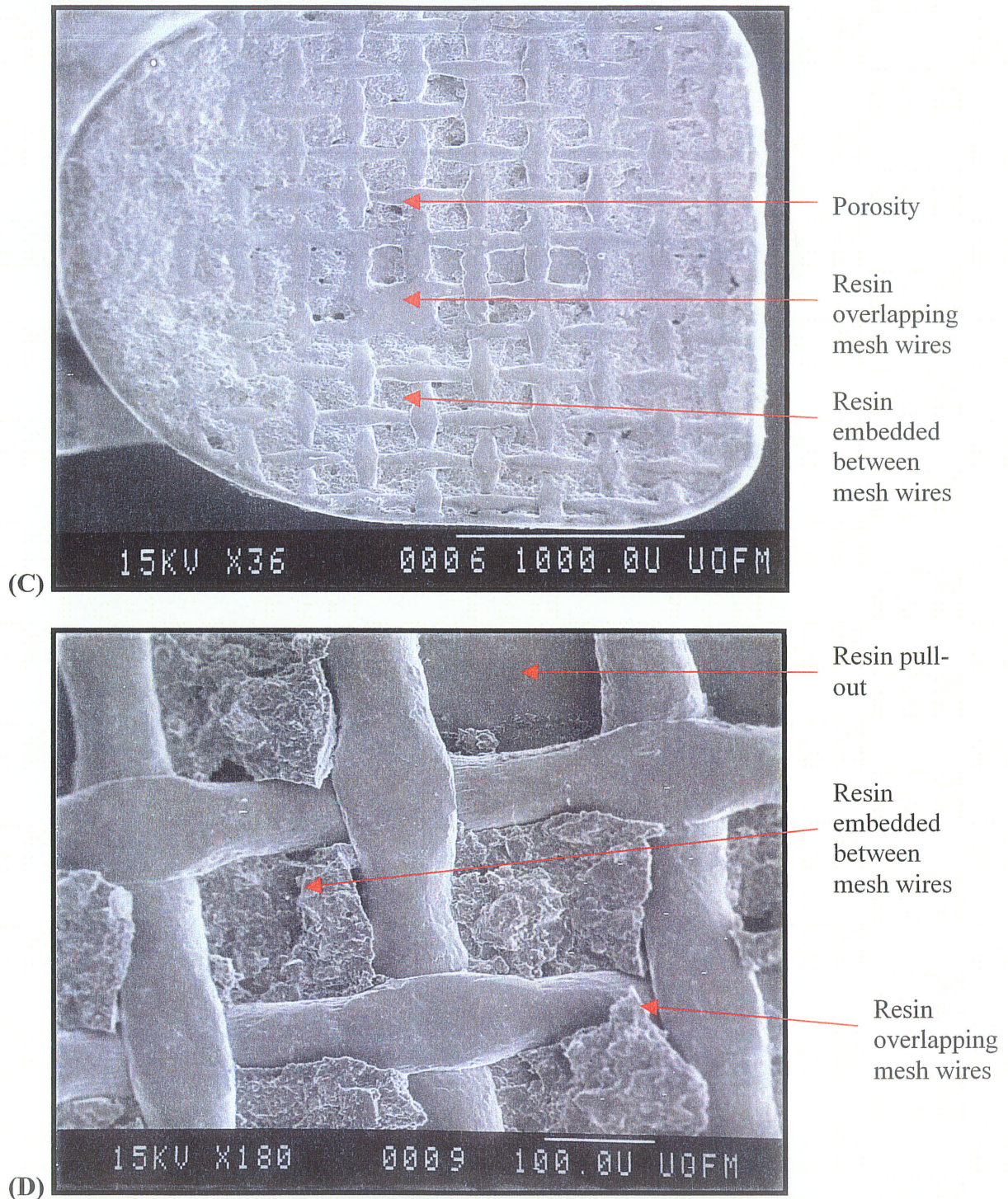


**Figure 4.4.** SEM of Ormco OptimeshXRT bracket base (A) before bonding 36x magnification, note contaminant and area of mesh obliterated by silver DAG (B) before bonding 180x magnification, note increase in surface area of mesh wire due to metal plasma spray coating (C) after debonding 36x magnification, and (D) after debonding 180x magnification. Note regions of porosity, resin embedded between mesh wires, and resin overlapping mesh wires.



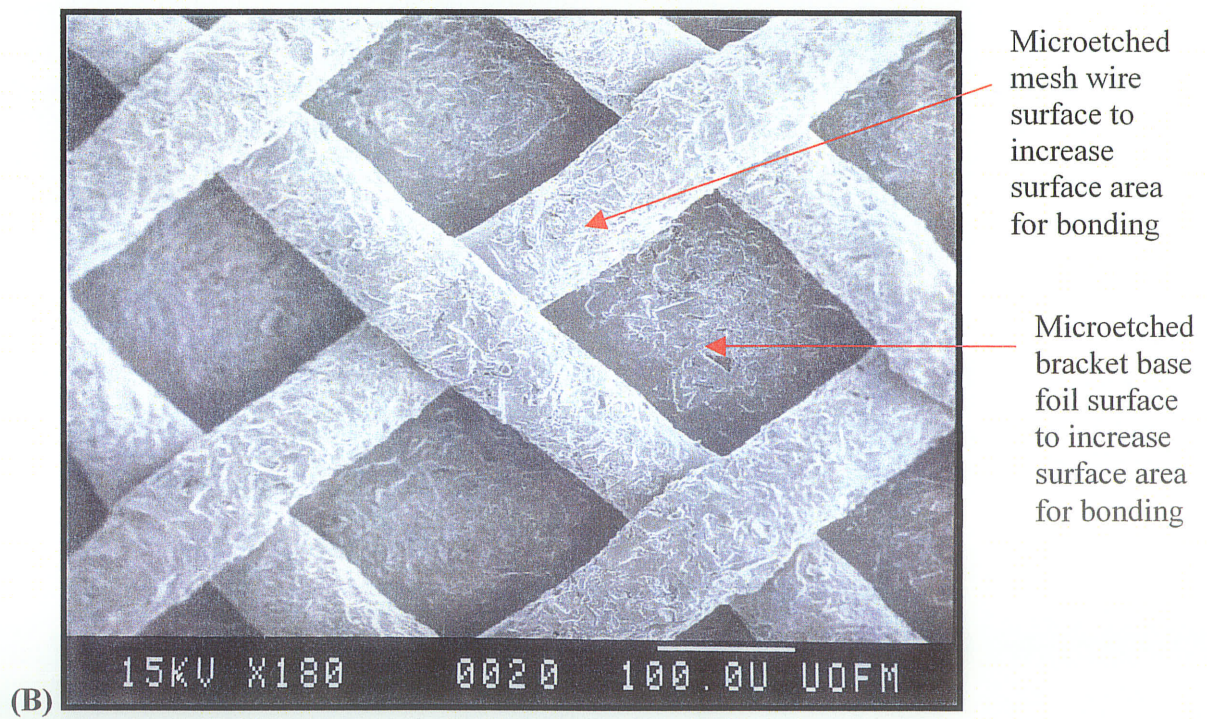
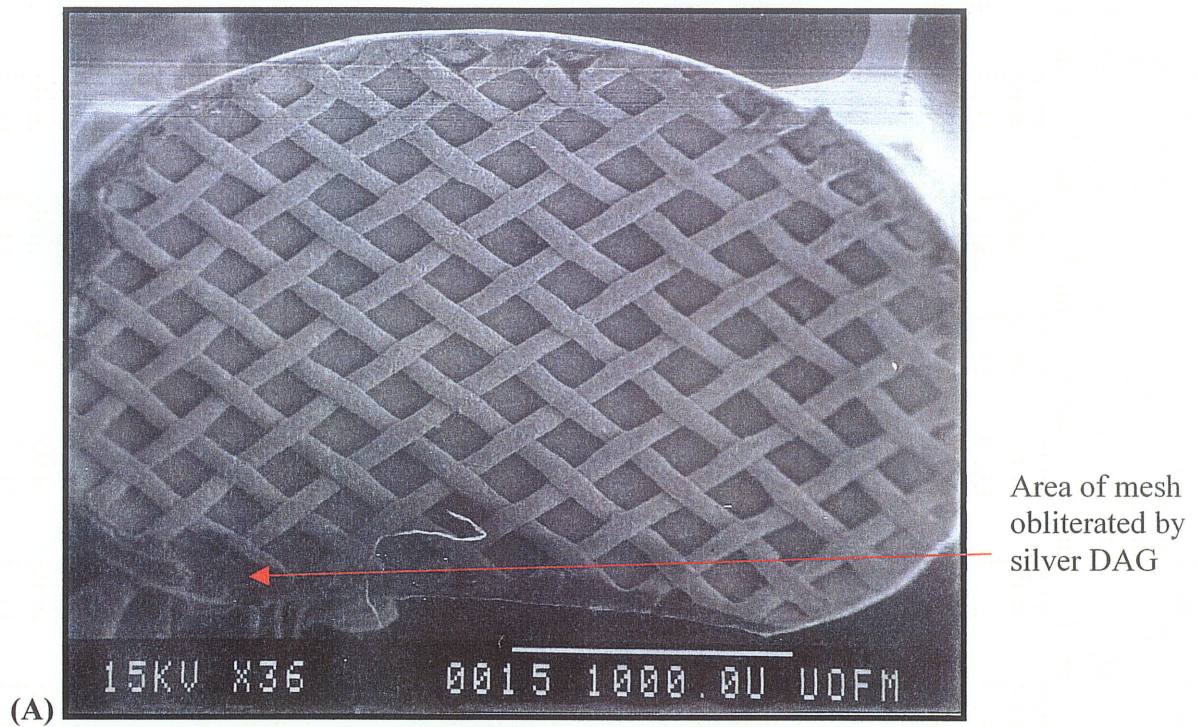




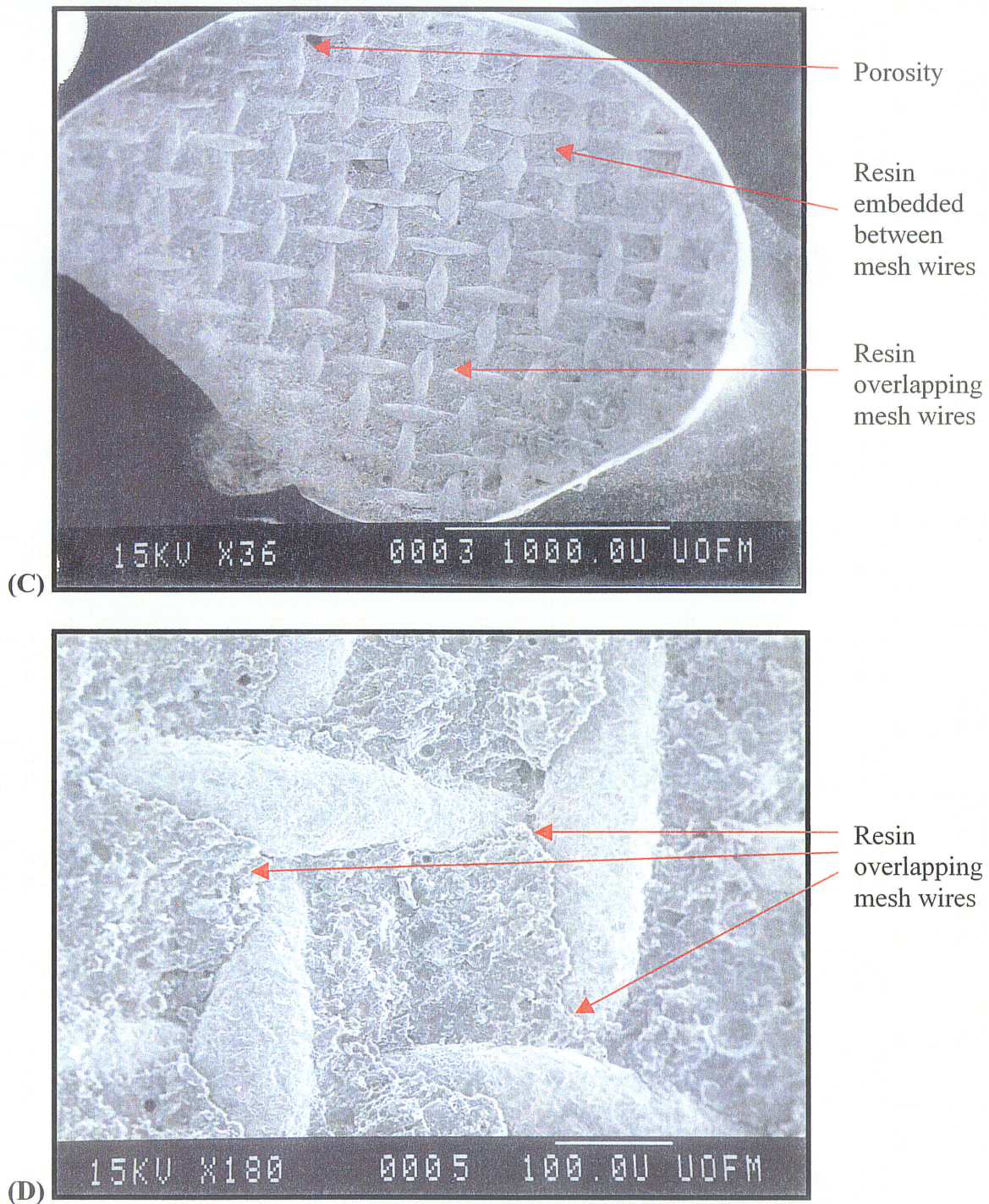


**Figure 4.5.** SEM of Ormco Ti-Orthos2 bracket base (A) before bonding 36x magnification, (B) before bonding 180x magnification, (C) after debonding 36x magnification, and (D) after debonding 180x magnification. Note regions of porosity, resin pull-out, resin embedded between mesh wires, and resin overlapping mesh wires.



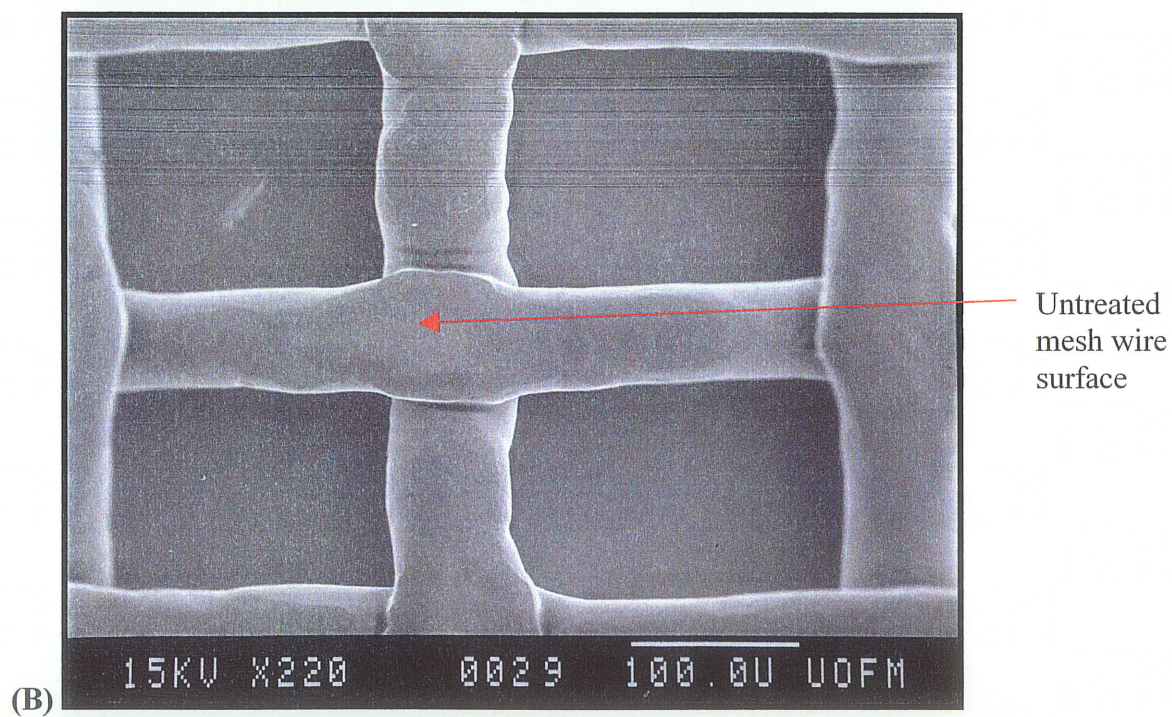
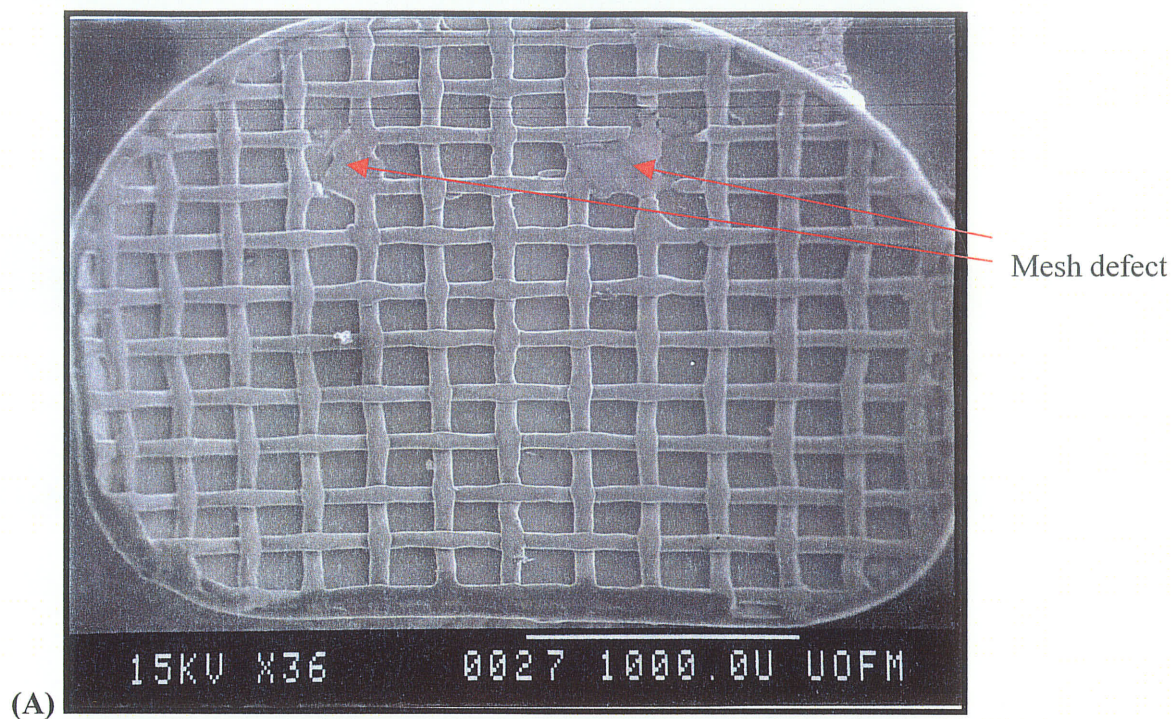




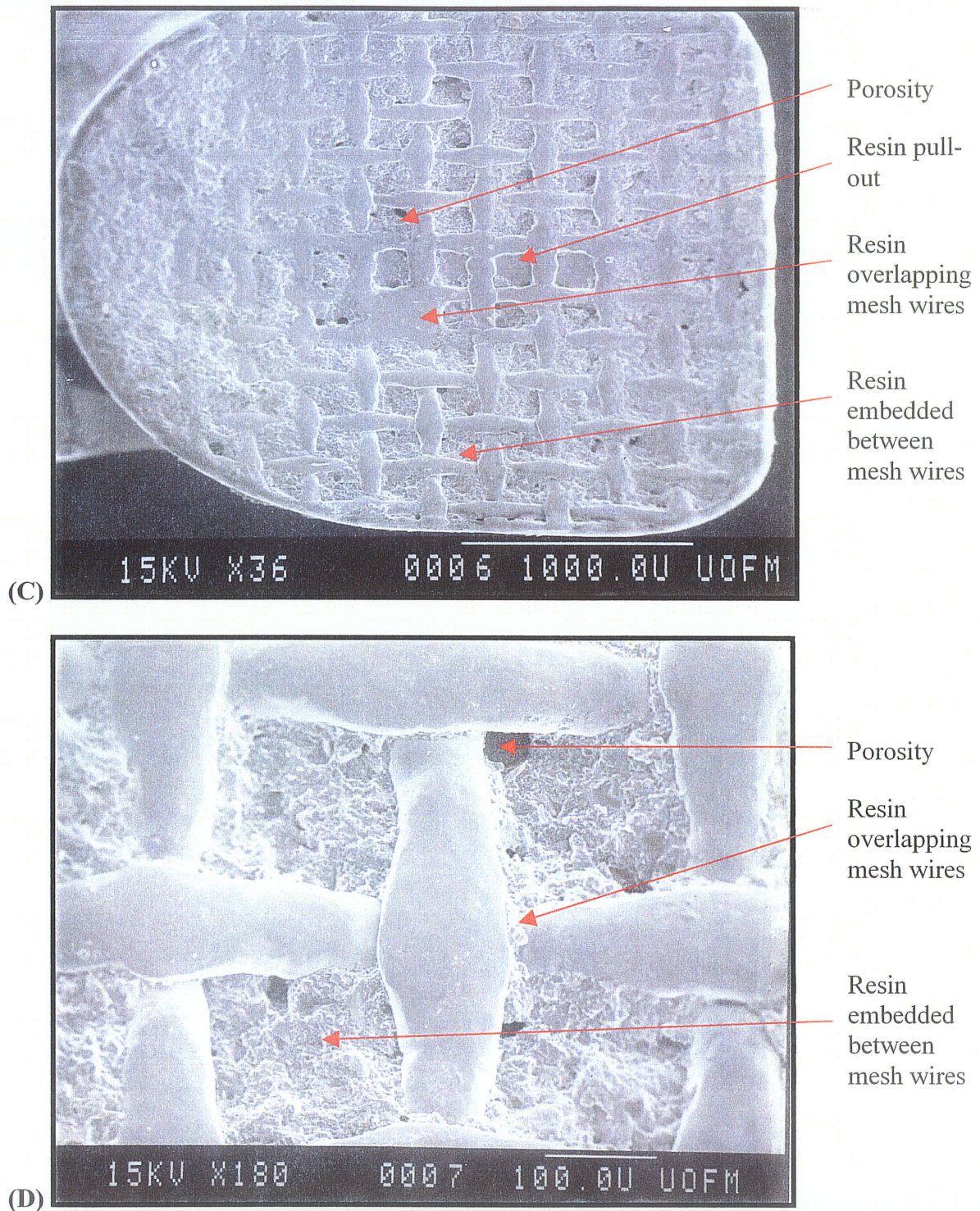


**Figure 4.6.** SEM of 3M Victory series bracket base (A) before bonding 36x magnification, note area of mesh obliterated by silver DAG (B) before bonding 180x magnification, note microetched foil and mesh wire surface (C) after debonding 36x magnification, and (D) after debonding 180x magnification. Note regions of porosity, resin embedded between mesh wires, and resin overlapping mesh wires.









**Figure 4.7.** SEM of TP Primekote bracket base (A) before bonding 36x magnification, note mesh defects (B) before bonding 180x magnification, (C) after debonding 36x magnification, and (D) after debonding 180x magnification. Note regions of porosity, resin pull-out, resin embedded between mesh wires, and resin overlapping mesh wires.



## **4.2 Fracture Interface Scores (FIS) and Adhesive remnant index (ARI) scores**

The Fracture Interface Scores (FIS) for the bracket-composite resin substrate and the ARI scores for the bracket-composite resin-enamel substrate groups are listed in Tables 4.12-4.13. There was greater than 90% intraoperator agreement. Photomicrographs and scanning electron micrographs (SEM) representing the different FIS and ARI scoring categories are shown in Figures 4.8 - 4.14. The chi-square test indicated that there were significant differences in the FIS and ARI scores among the test groups in both the bracket-composite resin substrate and bracket-composite resin-enamel substrate groups, respectively ( $p < 0.001$  and  $p < 0.0001$ , respectively). Any statistically significant differences in the FIS and ARI scores between the different groups discussed below was predetermined at a probability value of .05 or less.

### **4.2.1 Comparison of brackets bonded to composite resin substrate only**

All bracket groups bonded to composite resin substrate demonstrated fractures between bracket and adhesive that were largely adhesive (Figure 4.8) rather than cohesive in nature (Figure 4.10). More partial adhesive-cohesive fractures (Figure 4.9) occurred with Primekote brackets than with Ti-Orthos2 brackets, which tended to have more total adhesive fractures.

| Test Groups (N=30)                                | Fracture Interface Score (FIS) |                                        |                             |
|---------------------------------------------------|--------------------------------|----------------------------------------|-----------------------------|
|                                                   | 1 = Total adhesive fracture    | 2 = Partial adhesive-cohesive fracture | 3 = Total cohesive fracture |
| Ormco Mini 2000 Ormesh untreated mesh control (%) | 27 (90.0)                      | 0 (0.0)                                | 3 (10.0)                    |
| Ormco OptimeshXRT (%)                             | 26 (86.7)                      | 0 (0.0)                                | 4 (13.3)                    |
| Ormco Ti-Orthos2 (%)                              | 28 (93.3)                      | 0 (0.0)                                | 2 (6.7)                     |
| 3M Victory series (%)                             | 24 (80.0)                      | 0 (0.0)                                | 6 (20.0)                    |
| TP Primekote (%)                                  | 18 (60.0)                      | 5 (16.7)                               | 7 (23.3)                    |

**Table 4.12.** Fracture Interface Scores – bracket-composite resin substrate

Score 1 = total adhesive fracture (Figure 4.8).

Score 2 = partial adhesive-cohesive fracture (Figure 4.9).

Score 3 = total cohesive fracture (Figure 4.10).

#### 4.2.2 Comparison of brackets bonded to enamel substrate with composite resin

3M Victory series and TP Primekote brackets both demonstrated bond failures largely between the bracket and adhesive with less than half of the adhesive remaining on the enamel surface (Figure 4.13). Ormesh, OptimeshXRT, and Ti-Orthos2 brackets demonstrated bond failures largely between the bracket and adhesive with more than half of the adhesive remaining on the enamel surface (Figure 4.12). These results suggest that less adhesive remains on the tooth surface when Victory and Primekote brackets are used.

| Test Groups (N=30)                                | Adhesive Remnant Index (ARI) |              |              |             |
|---------------------------------------------------|------------------------------|--------------|--------------|-------------|
|                                                   | 3                            | 2            | 1            | 0           |
| Ormco Mini 2000 Ormesh untreated mesh control (%) | 6<br>(20.0)                  | 14<br>(46.7) | 10<br>(33.3) | 0<br>(0.0)  |
| Ormco OptimeshXRT (%)                             | 4<br>(13.3)                  | 13<br>(43.3) | 10<br>(33.3) | 3<br>(10.0) |
| Ormco Ti-Orthos2 (%)                              | 2<br>(6.7)                   | 15<br>(50.0) | 13<br>(43.3) | 0<br>(0.0)  |
| 3M Victory series (%)                             | 1<br>(3.3)                   | 5<br>(16.7)  | 17<br>(56.7) | 7<br>(23.3) |
| TP Primekote (%)                                  | 0<br>(0.0)                   | 7<br>(23.3)  | 16<br>(53.3) | 7<br>(23.3) |

**Table 4.13.** Adhesive remnant index scores – bracket-composite resin-enamel substrate

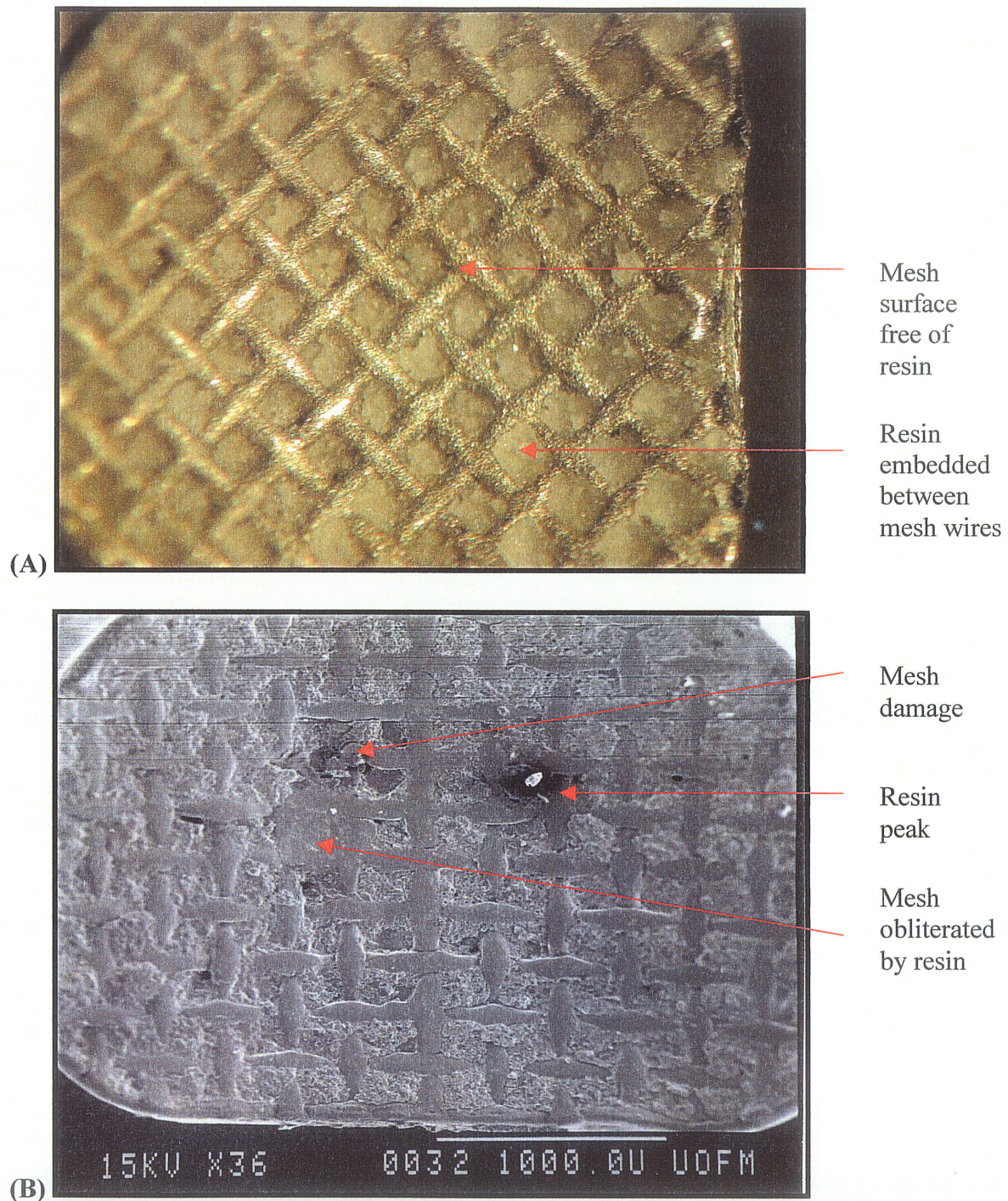
Score 3 = All adhesive left on the tooth (Figure 4.11).

Score 2 = More than half of the adhesive left on the tooth (Figure 4.12).

Score 1 = Less than half of the adhesive left on the tooth (Figure 4.13).

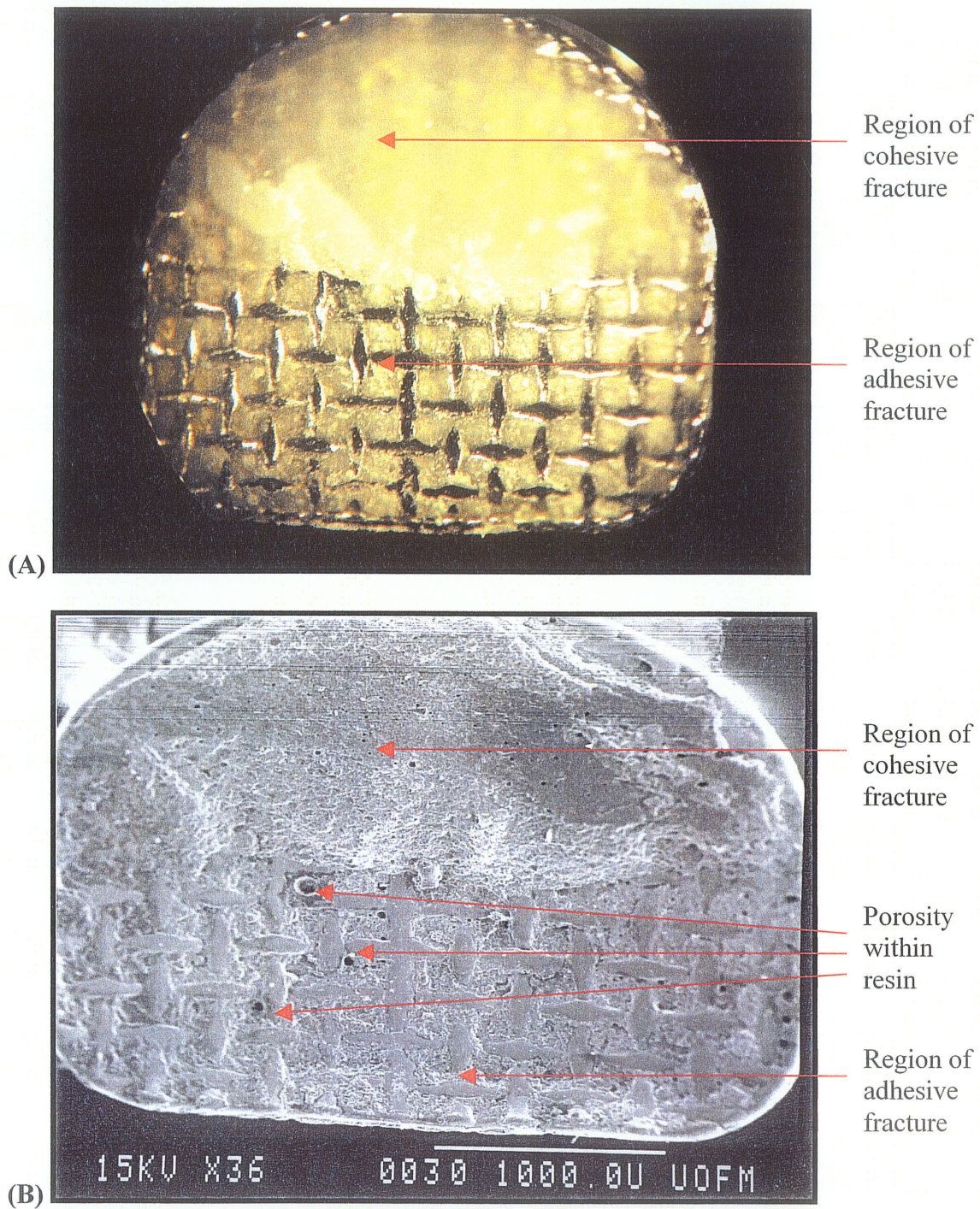
Score 0 = No adhesive left on the tooth (Figure 4.14).





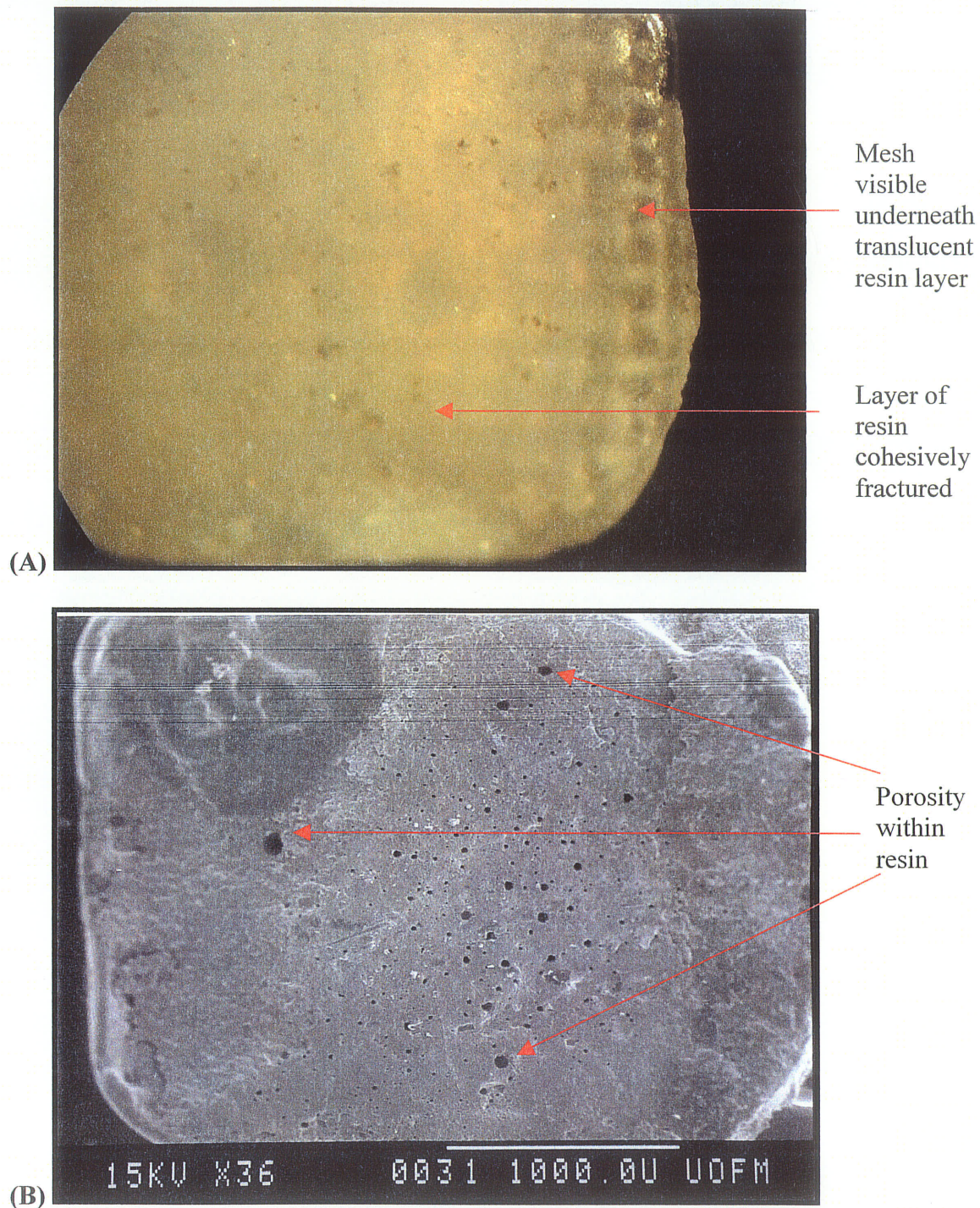
**Figure 4.8.** Typical total adhesive debond for the bracket base-composite resin substrate test (A) Photomicrograph (B) SEM. Note region of apparent mesh damage, resin peak, and mesh obliterated by resin.





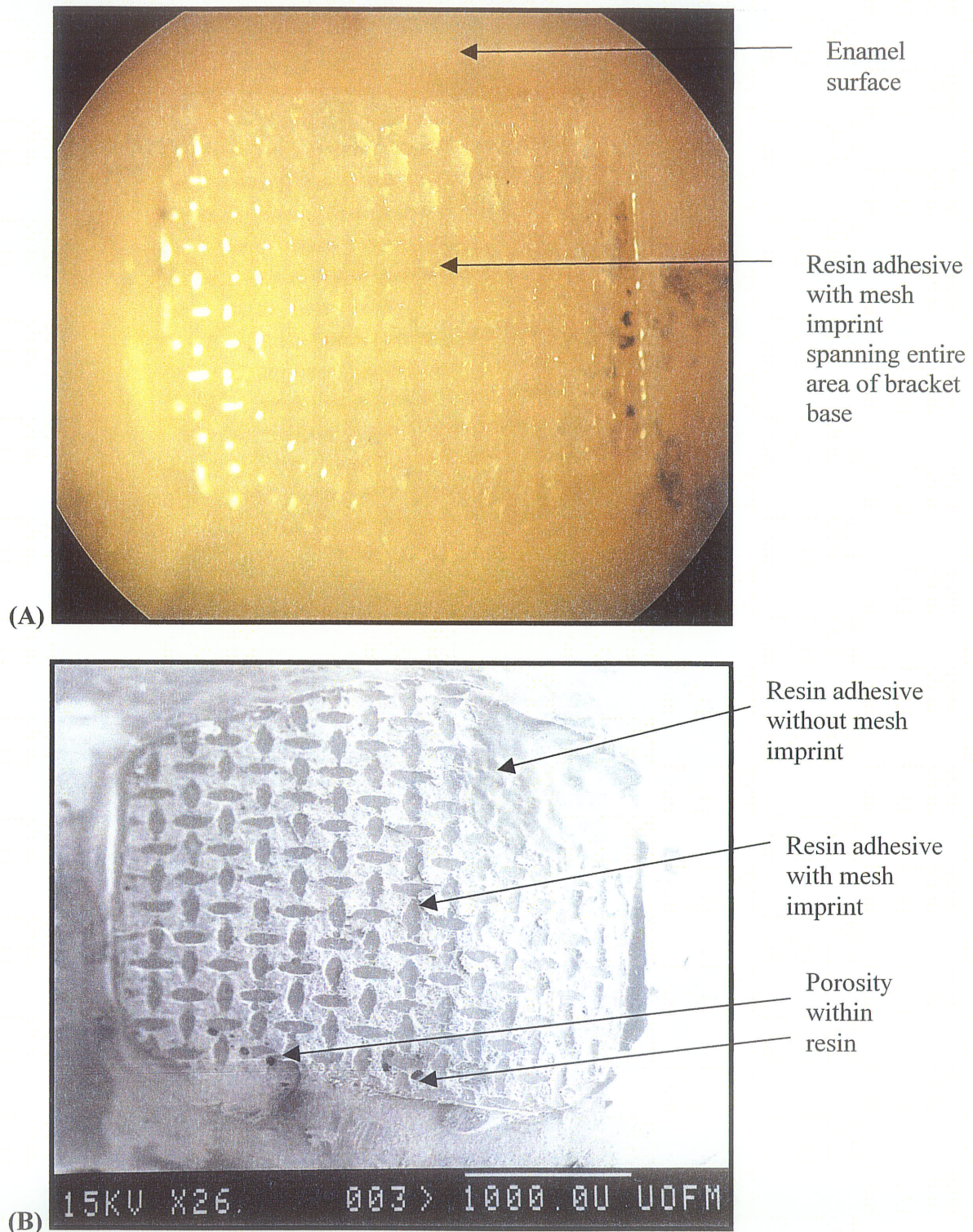
**Figure 4.9.** Typical partial adhesive, partial cohesive debond for the bracket base-composite resin substrate test (A) Photomicrograph (B) SEM. Note regions of porosity within resin.





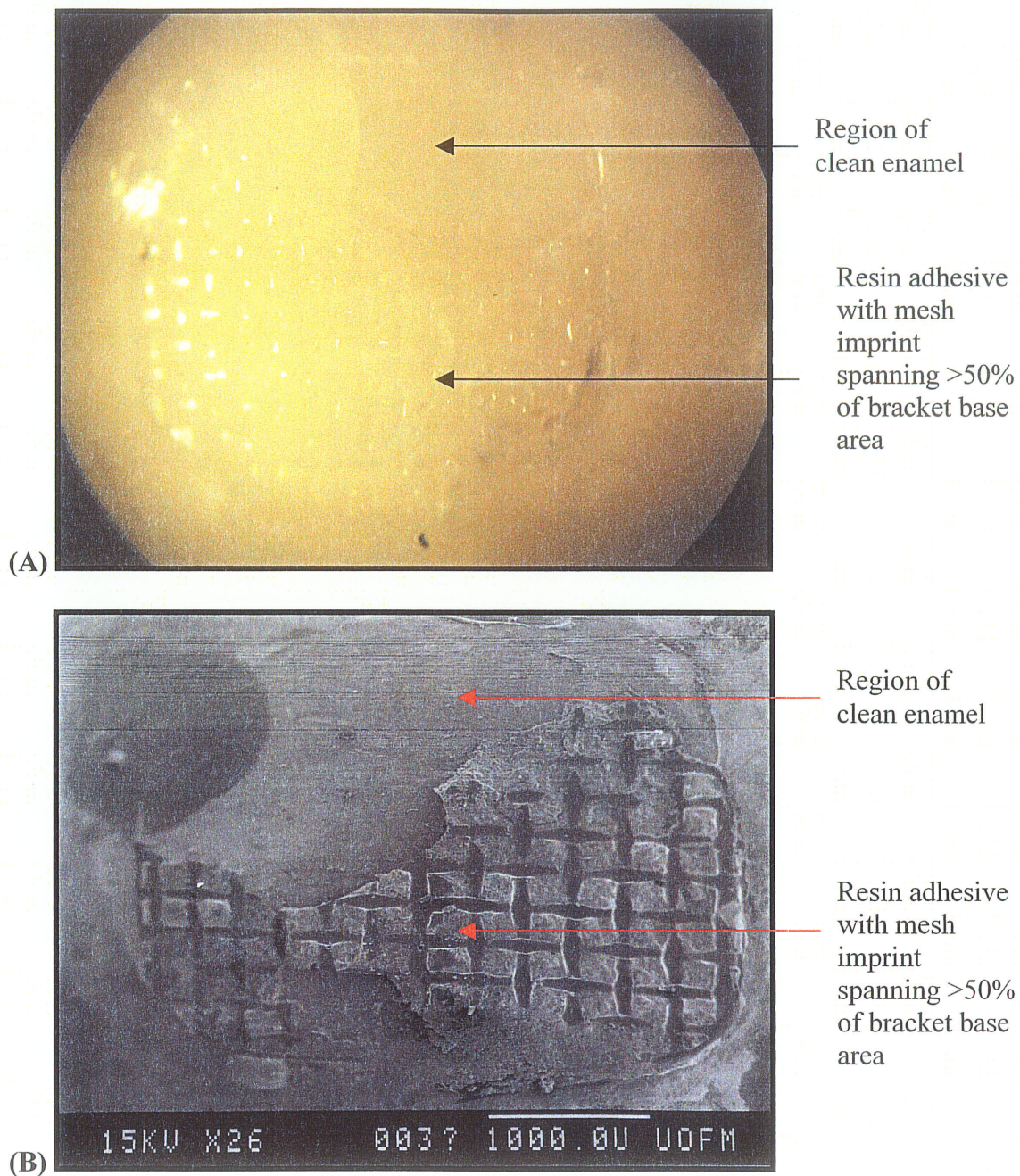
**Figure 4.10.** Typical total cohesive debond for the bracket base-composite resin substrate test (A) Photomicrograph (B) SEM. Note regions of porosity within resin.





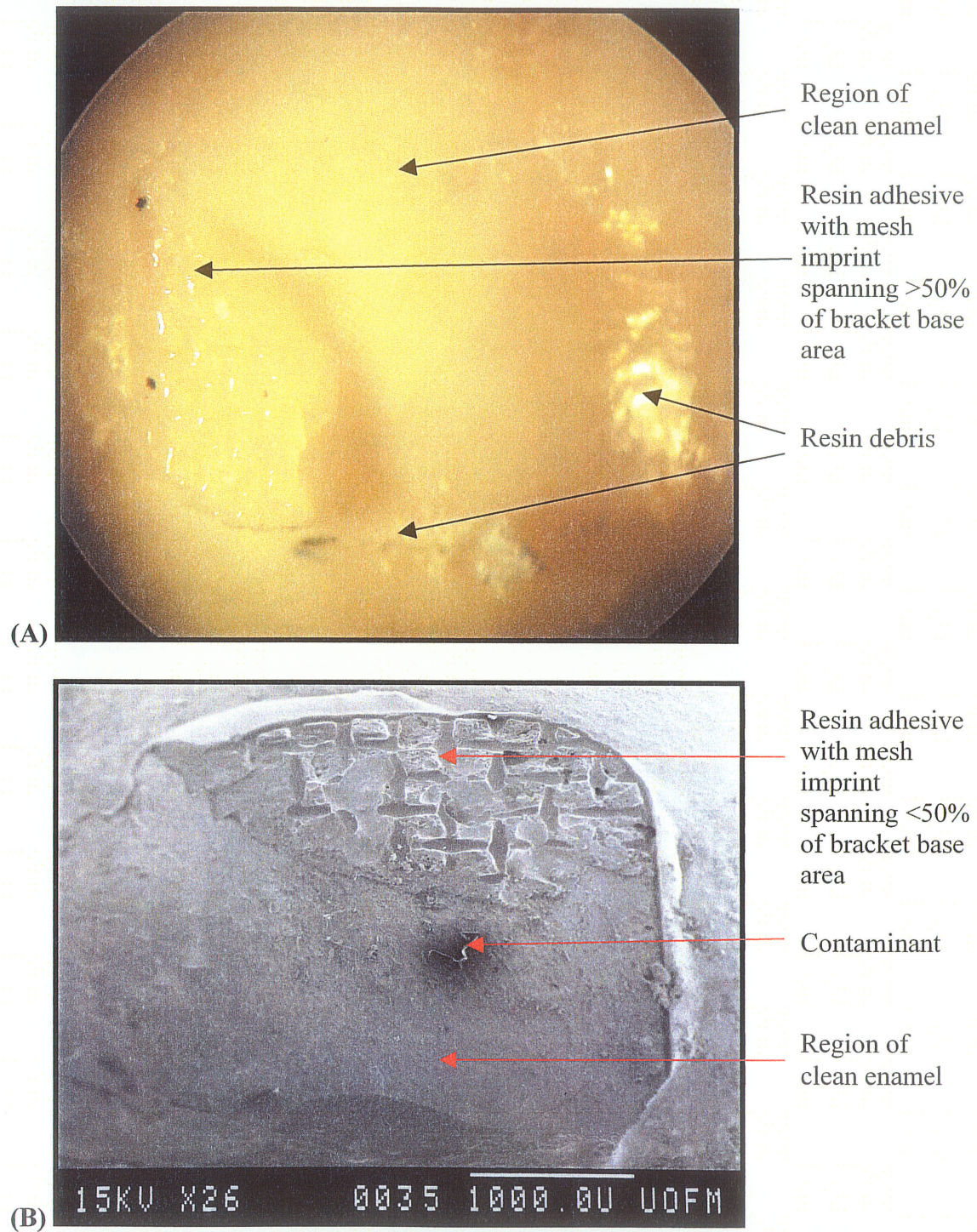
**Figure 4.11.** Typical debond at the bracket base-enamel interface with an ARI score of 3 (All adhesive left on the tooth) (A) Photomicrograph (B) SEM. Note regions of porosity within resin adhesive.





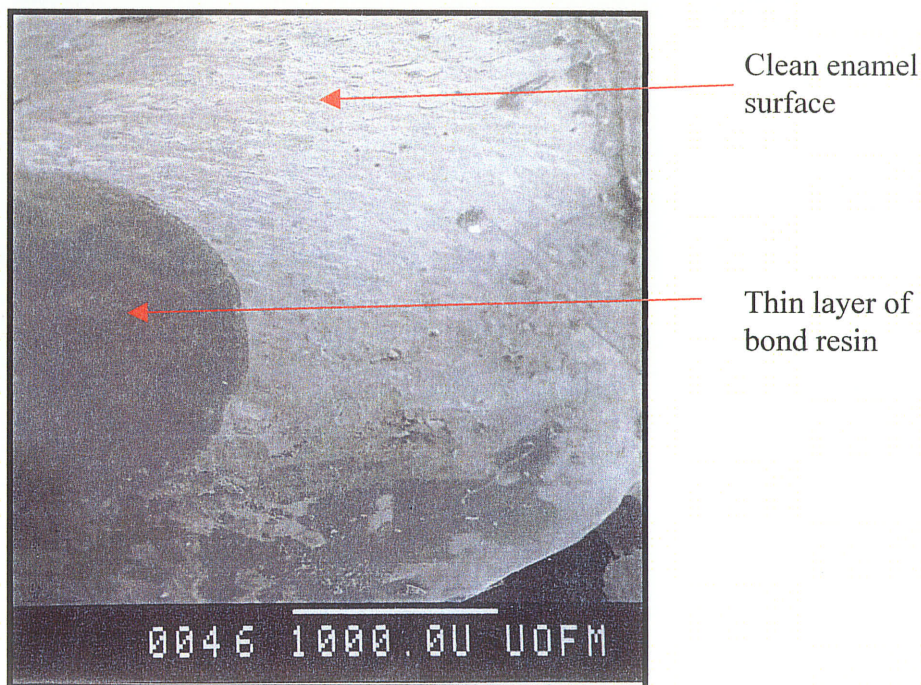
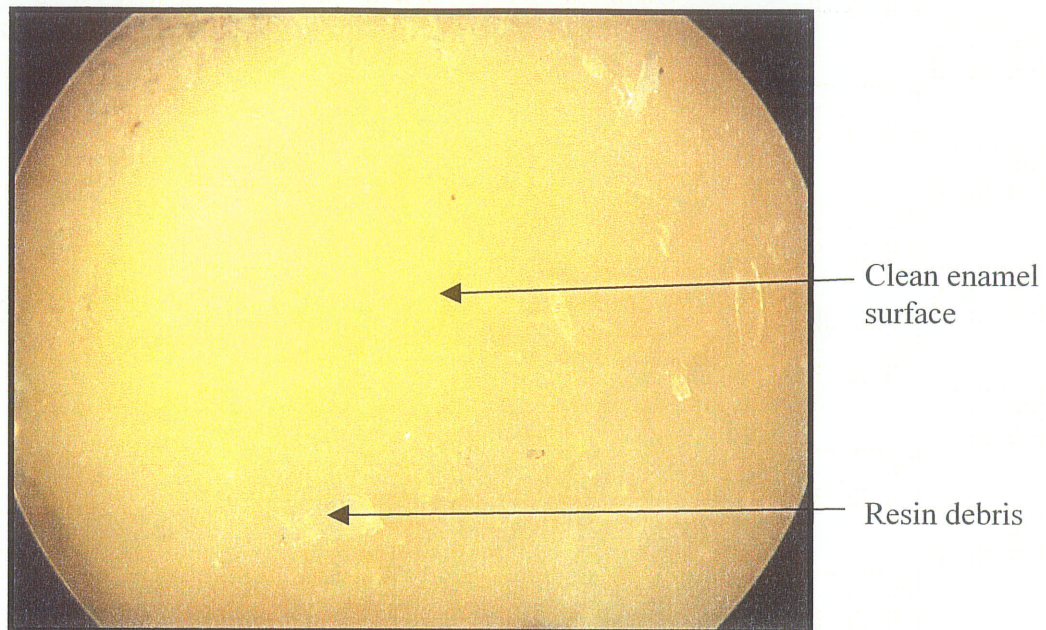
**Figure 4.12.** Typical debond at the bracket base-enamel interface with an ARI score of 2 (More than half of the adhesive left on the tooth) (A) Photomicrograph (B) SEM.





**Figure 4.13.** Typical debond at the bracket base-enamel interface with an ARI score of 1 (Less than half of the adhesive left on the tooth) (A) Photomicrograph (B) SEM.





**Figure 4.14.** Typical debond at the bracket base-enamel interface with an ARI score of 0 (No adhesive left on the tooth) (A) Photomicrograph (B) SEM. Note thin layer of bond resin remaining on enamel surface not visible on photomicrograph.

## **CHAPTER 5**

### **DISCUSSION**

|                                                                                                                                                                 | <b>Page</b> |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| <b>5.1</b> <i>In vivo</i> versus <i>in vitro</i> bond strength findings                                                                                         | 87          |
| <b>5.2</b> Clinically acceptable bond strength                                                                                                                  | 87          |
| <b>5.3</b> Shear-peel bond strengths of orthodontic brackets bonded<br>with composite resin to enamel substrate                                                 | 89          |
| <b>5.4</b> Shear-peel bond strengths of orthodontic brackets bonded<br>to composite resin substrate alone                                                       | 97          |
| <b>5.5</b> Comparison of shear-peel bond strengths of orthodontic<br>brackets bonded to composite resin substrate alone or with<br>adhesive to enamel substrate | 103         |
| <b>5.6</b> Evaluation of the null hypothesis                                                                                                                    | 105         |



## **5.1 *In vivo* versus *in vitro* bond strength findings**

Bond strength values obtained from *in vitro* studies should be evaluated with caution as they may not represent the clinical setting accurately. Zachrisson (2000) provided three reasons for this: 1) the continually increasing tensile or shear loads applied to bonded brackets in the laboratory are not representative of the force applications that occur clinically. Clinical force applications to brackets are not constant. They are usually of a short duration and force levels can range from very low to very high; 2) the type of debonding force applied by testing machines is not the same as the force applied in clinical debonding. In this study, the shear-peel load was applied as close as possible to the bracket base-adhesive interface. In the clinical setting, debonding forces are usually applied at the bracket tie-wings which are a significant distance from the bracket base-adhesive interface. This would result in a combination of shear-peel and torsional loading (Katona, 1997); and 3) the complex environment of the mouth with variations in temperature, stresses, saliva, humidity, acidity, and plaque is not reproducible in the laboratory. It is important for the clinician to recognize that *in vitro* testing can provide an idea of the potential clinical success of a bonding system by comparing and quantifying laboratory bond strengths. Therefore, clinical trials should also be conducted to confirm or refute *in vitro* findings.

## **5.2 Clinically acceptable bond strength**

All of the bracket groups achieved bond strengths greater than 2.86 MPa, which according to Keizer et al (1976) indicates clinically acceptable bond strengths. Reynolds

(1975) stated that the minimum tensile bond strength required by a bracket to resist the displacing forces placed upon it is in the range of 5 to 8 MPa. Keizer et al (1976) gave a shear bond strength range of 2.86-7.59 MPa.

Reynolds (1975) noted that the ability to withstand tensile or shearing forces depended on two main factors: 1) the strength of the bond between enamel, adhesive, and attachment and 2) the surface area of the attachment. For clinical success, bond strengths should be high enough to withstand occlusal and orthodontic forces. Bond strengths should also be high enough to resist accidental debonding during placement of the archwire and during the course of orthodontic treatment. Newman (1965) found that the larger the attachment, the greater the force it withstood. As previously stated, the current bracket base surface areas are smaller due to esthetic demand. Therefore, the interaction between enamel, adhesive, and bracket plays an important role in the overall bond strength and it is affected by a number of variables. These include variables such as type of adhesive used, substrate, and bracket base design. Since only one type of adhesive (Transbond XT) was used in the present study, the effect of this variable on overall bond strength was deemed to be controlled. The use of a constant force during bracket placement ensured that the adhesive thickness was similar for all types of brackets. Within each of the two substrate types (bonding to composite resin alone versus bonding with resin to enamel), the effect of the variability of adhesive thickness on overall bond strength can be individually determined. This investigation could thus be focused primarily on the importance of the effect of bracket base treatment on shear bond strength and secondarily on the effect of substrate on shear bond strength.

### **5.3 Shear-peel bond strengths of orthodontic brackets bonded with composite resin to enamel substrate**

Bonding with foil-mesh brackets has become popular among orthodontists because of their ease of use and their effective retention, particularly during the lengthy treatment times typical of conventional practice. A disadvantage of the foil-mesh bracket is their unesthetic metallic appearance. Decreasing the bracket size may enhance esthetics, but this smaller bracket may also result in a less bondable bracket base surface area available to withstand clinical debond forces (MacColl et al, 1998).

Each group in our study yielded mean shear-peel bond strength values of between 14.5 and 26.8 MPa, which are relatively higher than the results reported by Sharma-Sayal et al (2003) (2.2-9.7 MPa), Cucu et al (2002) (10-11.4 MPa), and MacColl et al (1998) (8.9-16.4 MPa). Our study supports the viewpoint of Zachrisson (1977) that improving and simplifying the clinical operating procedures rather than increasing the adhesive strength of the currently available adhesives or brackets is more important. Furthermore, increased bond strength to enamel could provoke more damage of the enamel. The work of Retief (1974) on bond failure at the enamel-adhesive interface indicated that fractures in the enamel could occur with bond strengths as low as 13.5 MPa. This is comparable with the mean tensile bond strength of 14.5 MPa for enamel previously reported by Bowen and Rodriguez (1962). Newman (1965) reported that orthodontic forces should not exceed 14.5 MPa, due to the deleterious effects on the enamel surface. Although enamel can often withstand much greater forces than 14.5 MPa during debonding, the clinician should avoid using any bracket-conditioner-adhesive combination that can result



in bond strengths significantly greater than 13.5 MPa (Retief, 1974). The current findings indicated that all brackets tested produced mean shear-peel bond strengths greater than 14.5 MPa, which would appear to be relatively unsafe to the enamel, however, no enamel fractures were discovered. It must be remembered that Retief's conclusions were made more than 30 years ago, and many changes in bonding technology and testing procedures since then, could invalidate Retief's findings 3 decades later (Wiltshire 2005, personal communication).

The results of this study showed that bracket bases such as Primekote, OptimeshXRT, and Ormesh whose bonding surface area ranged from 12.9 to 14.0 mm<sup>2</sup> exhibited no statistically significant difference in shear-peel bond strength. This finding is in partial agreement with that of Cucu et al (2002), who found no significant differences in shear bond strength with surface areas between 8.92 and 14.00 mm<sup>2</sup>. This study found that the Victory series brackets demonstrated significantly higher shear-peel bond strengths than all the other test groups, despite having a smaller bonding surface area of 9.81 mm<sup>2</sup>. The findings in this study are not directly comparable to that of MacColl et al (1998), who found no significant differences in shear bond strength between bracket bases whose bonding surface areas varied between 6.82 and 12.35 mm<sup>2</sup>. They did, however, find that a reduction of the bonding surface area to 2.83 mm<sup>2</sup> resulted in a statistical decrease in shear bond strength, and it can only be speculated that this decrease would also be of clinical significance. Our study did not address the critical surface area below which clinical performance would be unacceptable. Contrary to expectations, the bond strength appeared to be indirectly proportional to the surface area in our study. One possible

explanation for this trend involves recognizing that the same force was used to control adhesive thickness for all bracket groups. Therefore, brackets with smaller bonding surface areas would experience a higher force per unit area. This would create a slightly thinner adhesive layer which could result in fewer air bubbles or other defects, and thus a higher bond strength. This theory appears to explain the trend in the results.

The manufacturer has proposed that the titanium alloy in the Ti-Orthos2 bracket base should increase bond strength over stainless steel because it is a more resilient alloy, thereby giving rise to a “shock absorber effect” (Personal communication Michael Swartz of sds Ormco, 2004). The results of our study do not lend support to this theory since the Ti-Orthos2 group demonstrated a shear-peel bond strength lower than the corresponding Ormco stainless steel groups and had the overall lowest mean shear-peel bond strength of any of the bracket types. Stainless steel appears to be a superior alloy for adhesive retention compared to titanium, however, titanium may provide a sufficiently high bond strength for clinical use and yet may be the least likely to fracture enamel.

The open area of a bracket base is defined as the percentage of the bracket base area available for adhesive to penetrate and was identified by Matasa (1989) as a variable that affects mesh performance and bond strength. The open areas of the 3M Victory and TP Primekote brackets and those of the Ormco OptimeshXRT and Ormesh brackets are 31.5% and 30%, respectively. The greater area available for resin to penetrate into the mesh may account for the significantly higher mean shear-peel bond strengths of the Victory group, however, it does not explain the non-significant difference between the

Primekote, OptimeshXRT, and Ormesh groups. Despite the largest open area of 35%, the Ti-Orthos2 group demonstrated the lowest mean shear-peel bond strength. Therefore, factors other than open area are likely to explain the results obtained.

Matasa (1989) also identified mesh size as an important variable affecting mesh performance and bond strength. Mesh size is defined as the number of openings per linear inch. Theoretically, the smaller apertures found in the finer mesh sizes (100) weaken the bond between the adhesive and base because there are smaller spaces between wires for adhesive to penetrate (Reynolds and von Fraunhofer, 1976). The results of this study did not support this theory since bracket base groups of the coarser 80 mesh size demonstrated mean shear-peel bond strengths significantly higher (Victory), non-significantly higher (Primekote), and significantly lower (Ti-Orthos2) than groups with a finer mesh size of 100. The result in our study is in accordance with Cucu et al (2002) who also compared 80 and 100 mesh size brackets. Therefore, factors other than mesh size are likely to explain the results obtained.

Matasa (1989) also identified mesh wire diameter as an important variable affecting mesh performance and bond strength. In theory, a thin diameter will lead to mesh wire breakage, while a thick diameter will limit the penetration of adhesive. The results of our study did not support this theory since bracket base groups with thicker mesh wire diameters (Victory, Primekote) demonstrated higher mean shear-peel bond strengths. Also, no evidence of wire mesh failure was observed during the evaluation of the fracture



samples. Therefore, factors other than mesh wire diameter are likely to explain the results obtained.

The mean bond strengths recorded in our study was closely related to similar other studies and ranged from 14.5 to 26.8 MPa, compared to 16 to 25 MPa reported in other studies (Surmont et al., 1992; Powers et al., 1997; MacColl et al., 1998). Any differences may be attributed to variations in the types of samples tested (human or animal teeth), or types of teeth used (incisor, canine, premolar, or molar, young or old permanent teeth, deciduous teeth, or simply the natural variation between teeth of the same type or age) (Lopez, 1980). Another problem that has always existed when comparing *in vitro* bond strengths is the method of testing. There are differences in the method of evaluating bond strengths (tensile, shear, peel), the machines used in testing, and the type of mounting apparatus (Smith and Shivapuja, 1993). Table 5.1 illustrates the large variation in testing parameters in these studies, some of which are not even specified. There may even be some merit in increasing the crosshead speed for orthodontic applications.

| Study                     | Testing Parameter        |                |
|---------------------------|--------------------------|----------------|
|                           | Crosshead Speed (mm/min) | Load cell (kg) |
| Lopez, 1980               | Not specified            | Not specified  |
| Surmont et al., 1992      | 0.5                      | Not specified  |
| Smith and Shivapuja, 1993 | 0.5                      | Not specified  |
| MacColl et al., 1998      | 0.5                      | 50             |

**Table 5.1.** Testing parameters and values used in comparable bond strength studies.

Of interest are the large ranges of bond strength values and coefficients of variation such as are seen in Table 4.11. A general guideline is that the highest value is usually about

twice that of the lowest value (Personal communication Wiltshire, 2005). This was observed in each of the groups except for the Ormco OptimeshXRT and Ti-Orthos2 groups wherein the highest value was approximately three times that of the lowest value. These two groups also demonstrated the highest coefficients of variation. However, the OptimeshXRT and Victory groups showed the highest standard deviations. Since the samples were tested according to a systematic protocol and by one operator, methodological and operator factors cannot be used to explain the large variability. Maijer and Smith (1981) suggest that weld spurs and weld spots, as a consequence of joining attachment to base, can lead to variations in retentive strength. Although welding is still performed by the manufacturer to attach the mesh screen to the foil backing, brazing is the common method of joining the attachments to the base (Personal communication Michael Swartz of sds Ormco, 2004). Brazing does not cause the profound damage to the mesh such as weld spots and spurs that can be caused by spot welding (Personal communication Michael Swartz of sds Ormco, 2004). Also as stated previously, no evidence of these types of defects were observed during the evaluation of the fracture samples. Therefore, the presence of weld spots and spurs cannot be used to explain the large variability. Knox et al (2001) suggested that variations in bracket base design can improve adhesive penetration and curing light penetration. Although the protocol for adhesive application and light-curing was systematically controlled, it is possible that the OptimeshXRT, Ti-Orthos2, and Victory base configurations allow for varying degrees of air entrapment. This would increase the variability of adhesive penetration into the mesh, and thus, increase the variability of values about the mean.

Clinically, bond failures usually occur more often at the adhesive-enamel interface than the bracket base-adhesive interface. This failure usually indicates that *in vivo* moisture contamination, likely from saliva, has occurred. Moisture contamination is a major factor contributing to adhesion failure in clinical orthodontics (Reynolds and von Fraunhofer, 1976). Bond failure at the bracket base-adhesive interface results in adhesive remnants being firmly attached to the enamel. Removal of large amounts of adhesive can be time-consuming and may cause enamel surface damage (Zachrisson, 1994). Ideally in orthodontics, one would like an adequate bond, which fails at the adhesive-enamel interface as this would make debonding and polishing much easier. Most investigators reported that in many cases the site of bond failure was within the adhesive itself or at the bracket base-adhesive interface (Reynolds and von Fraunhofer, 1976; Gorelick 1977; Faust et al., 1978; Evans and Powers 1985; Wiltshire 1994). The debonding strength values may represent the true adhesive force of composite to enamel only if cohesive fractures can be avoided. In orthodontic bond strength testing, cohesive fractures in the composite resin (ARI score 1 and 2) reflect the internal strength of the composite rather than the actual adhesion of the test system (Zachrisson et al., 1996). Since a small proportion of bond failures in the five base test groups occurred adhesively (ARI score 0 and 3) and an even smaller proportion of failures occurred adhesively between bracket base and resin, it is difficult to attribute the statistically significant differences in mean shear-peel bond strength to differences in bracket base to adhesive bond strength and therefore to bracket base treatment. Additionally, it is possible that bond strength may be related to the quality of the etch of the enamel substrate. Although the etchant was controlled in our study, the etchability and quality of etch of the enamel, could not. This



could have accounted for the variability of the data (Wiltshire 2005, personal communication).

The high bond strength to resin substrate observed in the Victory and Primekote groups is reflected in the lower ARI scores. Since this translates to less resin retained on the enamel, it may suggest that Victory and Primekote bases have the potential for less resin clean-up clinically than the other base groups, which demonstrated higher ARI scores. Again, etchability and etch quality could play a role (Wiltshire 2005, personal communication).

The results of this study suggest that there may be a relationship between the variation in bond strength and the ARI. All bracket test groups demonstrated ARIs predominantly between 1 and 2. This represents varying degrees of the cohesive strength of the composite resin adhesive (Zachrisson et al., 1996). Therefore, the mean shear-peel bond strength of each group represents the average load required primarily to fracture the composite resin cohesively and, secondarily to fracture the base-resin and resin-enamel interfaces adhesively. Since the mean shear-peel bond strength represents the average of not one but several different loads, the large variation in ARI scores may explain the large variation in individual bond strengths values.

#### 5.4 Shear-peel bond strengths of orthodontic brackets bonded to composite resin substrate alone

Few *in vitro* studies have been conducted to date that isolate and examine the bracket base-adhesive interface (Dickinson and Powers, 1980; Buzzitta et al., 1982; Regan and van Noort, 1989; Willems et al., 1997; Knox et al., 2000). When bonding to composite resin substrate alone, each group in our study yielded mean shear-peel bond strength values of between 13.4 and 22.4 MPa compared with 2 to 23 MPa reported in other studies as shown in Table 5.2 (Dickinson and Powers, 1980; Buzzitta et al., 1982; Regan and van Noort, 1989; Willems et al., 1997; Knox et al., 2000).

| Study                      | Mode of Testing | Resin Used and Bond Strength (MPa)  | Orthodontic Resin?     |
|----------------------------|-----------------|-------------------------------------|------------------------|
| Dickinson and Powers, 1980 | Tension         | Unspecified resin (2.8 – 18.3)      | Unknown                |
| Buzzitta et al., 1982      | Tension         | Highly filled Solo Tech (13.3)      | Unknown                |
| Regan and van Noort, 1989  | Tension         | Advantage (6.3)<br>Phase II (10.7)  | Unknown                |
|                            | Shear           | Advantage (10.9)<br>Phase II (19.4) | Unknown                |
| Willems et al., 1997       | Shear           | Concise (4 – 13)                    | No                     |
| Knox et al., 2000          | Tension         | Concise (13-23)                     | No                     |
|                            |                 | right On (12-16)                    | Yes                    |
|                            |                 | Transbond XT (2-5)                  | Yes                    |
|                            |                 | Fuji Ortho LC (6-12)                | Yes, but it is a RMGIC |

**Table 5.2.** Mode of testing, type of resin used, and bond strength in comparable studies.

Our study is in agreement with those studies at the higher end of magnitude of bond strengths. For the studies in the lower range, any differences between these studies and

ours may be attributed to variations in the types of non-tooth substrates tested (bracket-resin-bracket, silane treated metal bars, or plastic cylinders), types of bracket bases tested (different base treatments, mechanical retentive elements, mesh sizes, mesh wire diameters), and types of adhesives used (composite resin, RMGIC, unspecified) (Table 5.2). Another problem that has always existed when comparing *in vitro* bond strengths is the method of testing. There are differences in the mode of evaluating bond strengths (tensile, shear), the machines used in testing, testing parameters (crosshead speed, load cell), and the type of mounting apparatus.

The results of our study showed that bracket bases such as Victory, OptimeshXRT, Ti-Orthos2, and Ormesh with surface areas of 9.81 and 14.0 mm<sup>2</sup> exhibited no statistically significant difference in mean shear-peel bond strength. This finding is in agreement with that of Willems et al (1997) who found no significant differences in shear bond strength with surface areas between 7.90 and 11.49 mm<sup>2</sup>. Our study found that Primekote brackets demonstrated significantly higher shear-peel bond strengths than all the test groups, despite having an intermediate surface area of 12.9 mm<sup>2</sup>. The findings in our study are not directly comparable to that of MacColl et al (1998) and Cucu et al (2002) because those studies examined bonding to enamel, and thus, did not isolate the base-adhesive interface. Contrary to expectations, the bond strength appears to be unrelated to the surface area in our study. One possible explanation for this trend involves recognizing that the same force was used to control adhesive thickness for all bracket groups. Therefore, brackets with smaller bonding surface areas would experience a higher force per unit area and this would create a slightly thinner adhesive layer which



could result in fewer air bubbles or other defects, and thus a higher bond strength. However, the results showed that the group with the smallest bonding surface area (Victory) did not yield the highest bond strength. Factors other than surface area are likely to explain the results obtained.

The open area of a bracket base is defined as the percentage of the bracket base area available for adhesive to penetrate and was identified by Matasa (1989) as a variable that affects mesh performance and bond strength. The open areas of the 3M Victory and TP Primekote brackets and those of theOrmco OptimeshXRT and Ormesh brackets are 31.5% and 30%, respectively. The greater area available for resin to penetrate into the mesh may account for the significantly higher mean shear-peel bond strengths of the Primekote group, however, it does not explain the non-significant difference between the Victory, OptimeshXRT, and Ormesh groups. Despite the largest open area of 35%, the Ti-Orthos2 group demonstrated the lowest mean shear-peel bond strength. Therefore, factors other than open areas that vary by only 5% are likely to explain the results obtained. Testing brackets whose meshes have larger open areas might explain the results, but these were not tested in our study.

Matasa (1989) also identified mesh size as an important variable affecting mesh performance and bond strength. Mesh size is defined as the number of openings per linear inch. Theoretically, the smaller apertures found in the finer mesh sizes (100) weaken the bond between the adhesive and base because there are smaller spaces between wires for adhesive to penetrate (Reynolds and von Fraunhofer, 1976). The

results of our study did not support this theory since bracket base groups with the coarser 80 mesh size demonstrated mean shear-peel bond strengths significantly higher (Primekote), non-significantly higher (Victory), and non-significantly lower (Ti-Orthos2) than groups with a finer mesh size of 100. Therefore, factors other than mesh size are likely to explain the results obtained.

Matasa (1989) also identified mesh wire diameter as an important variable affecting mesh performance and bond strength. In theory, a thin diameter will lead to mesh wire breakage, while a thick diameter will limit the penetration of adhesive. The results of our study did not support this theory since bracket base groups with thicker mesh wire diameters (Primekote, Victory) demonstrated higher mean shear-peel bond strengths. Also, no evidence of wire mesh failure was observed during the evaluation of the fracture surfaces. Therefore, factors other than mesh wire diameter are likely to explain the results obtained.

Of interest is the moderately large ranges of bond strength values and coefficients of variation as seen in Table 4.11. A general guideline is that the highest value is usually about twice that of the lowest value (Personal communication William Wiltshire, 2005). This was observed in each of the groups. The OptimeshXRT group exhibited the highest coefficient of variation, but the Primekote group showed the highest standard deviation. Since the samples were tested according to a systematic protocol and by one operator, methodological and operator factors cannot be used to explain the large variability. Maijer and Smith (1981) suggest that weld spurs and weld spots, as a consequence of

joining attachment to base, can lead to variations in retentive strength. Although welding is still performed by the manufacturer to attach the mesh screen to the foil backing, brazing is the common method of joining the attachments to the base (Personal communication Michael Swartz of sds Ormco, 2004). Brazing does not cause the profound damage to the mesh such as weld spots and spurs that can be caused by spot welding (Personal communication Michael Swartz of sds Ormco, 2004). Also as stated previously, no evidence of these types of defects were observed during the evaluation of the fracture samples. Therefore, the presence of weld spots and spurs cannot be used to explain the large variability. Knox et al (2001) suggested that variations in bracket base design can improve adhesive penetration and curing light penetration. Although the protocol for adhesive application and light-curing was systematically controlled, it is possible that the OptimeshXRT and Primekote base configurations allow for varying degrees of air entrapment. This would increase the variability of adhesive penetration into the mesh, and thus, increase the variability of values about the mean.

As discussed in section 5.3, cohesive fractures in composite resin (ARI score 1 and 2) reflects the internal strength of the composite rather than the actual adhesion of the test system (Zachrisson et al., 1996). Since a large proportion of bond failures in the five base test groups occurred adhesively (Fracture Interface Score 1) it is possible to attribute the statistically significant differences in mean shear-peel bond strength to differences in bracket base treatment, which is the purpose of this study. Although Primekote brackets are micro-etched, scanning electron micrograph (SEM) views (Figure 4.7) show that the potential increase in micromechanical roughness is obliterated by the Primekote coating.



On a speculative note, the significantly highest mean shear-peel bond strength suggests that the Primekote polymer coating provides a surface that may have a very low surface tension to allow for strong molecular adhesion. Sandblast micro-etching treatment appears to contribute to the high mean shear-peel bond strength observed in the Victory bracket base group. It is possible that the etching process provides the advantage of increased micromechanical bonding to resin, but not the strong molecular adhesion as seen in the Primekote group. Metal plasma spray treatment contributed to the low mean shear-peel bond strength exhibited by the OptimeshXRT group. The relatively higher mean shear-peel bond strength of the untreated Ormesh base suggests that metal plasma spray treatment confers no advantage in terms of increased micromechanical retention of resin and may contribute to less adhesive penetration or less light-cure penetration.

As stated previously on page 6, the manufacturer has proposed that the titanium alloy in the Ti-Orthos2 bracket base should increase bond strength over stainless steel because it is a more resilient alloy, thereby giving rise to a “shock absorber effect” (Personal communication Michael Swartz of sds Ormco, 2004). The results of our study do not lend support to this theory since the Ti-Orthos2 group demonstrated a shear-peel bond strength that was nonsignificantly lower than the corresponding Ormco stainless steel groups and had the overall lowest mean shear-peel bond strength of any of the bracket types. Therefore, stainless steel appears to be as good, if not superior, alloy for adhesive retention compared to titanium.

The results of our study suggest that there may be a relationship between the variation in bond strength and the Fracture Interface Score (FIS). All bracket test groups demonstrated Fracture Interface Scores predominantly between 1 and 2. This represents varying degrees of the cohesive strength of the composite resin adhesive combined with the adhesive strength of the base-adhesive interface (Zachrisson et al., 1996). Therefore, the mean shear-peel bond strength of each group represents the average load required primarily to fracture the base-adhesive interface and, secondarily to fracture the composite resin cohesively. Since the mean shear-peel bond strength represents the average of not one but several different loads, the large variation in Fracture Interface Scores may explain the large variation in individual bond strengths values. Furthermore, the large variation in values probably reflect, not so much individual factors (voids, base design, mesh size, etc) but a combination of these factors, enigmatically inter-related.

### **5.5 Comparison of shear-peel bond strengths of orthodontic brackets bonded to composite resin substrate alone or with composite resin to enamel substrate**

Current *in vitro* protocols of bond strength studies evaluate the cohesive strength of the composite resin, and the adhesive strength of the bracket-resin and resin-enamel interfaces, reporting only the weakest link in this system. The results of the enamel substrate component of this study were no exception to the above statement. As discussed in section 5.3, since only a small proportion of bond failures in the five test groups occurred adhesively (ARI score 0 and 3) and an even smaller proportion of failures occurred adhesively between bracket base and resin, it is difficult to attribute the statistically significant differences in mean shear-peel bond strength to differences in

bracket base treatment. As discussed in section 5.4, since a large proportion of bond failures in the five test groups occurred adhesively at the bracket base-adhesive interface (Fracture Interface Score 1) the statistically significant differences in mean shear-peel bond strength can be attributed to differences in bracket base treatment. Therefore, since the bond between the bracket base and the adhesive was of most interest in this study, the elimination of enamel as a component of the sample ensured that the fracture took place at that interface.

Of interest is the observation that the Victory and Primekote bracket groups changed bond strength rankings when the bonding substrate changed from enamel to composite resin. Many studies have evaluated the bond strength of brackets to enamel substrate, and only a few have evaluated the bond strength of brackets to composite resin substrate. However, no study has compared the effect of substrate on bond strength. The results of our study attempted to compare the effect of substrate, but found that this comparison could not be made. Since the mean bond strengths derived from each of the substrate tests represent different modes of fracture (ARI 0-3, FIS 1-3), comparison of the two substrates cannot be used to yield meaningful conclusions.

When the enamel is replaced with a highly standardized bonding surface, namely the composite resin substrate alone, the range of values is similar but the strength is less in magnitude. One would expect that when using enamel, whose characteristics vary between individual teeth (Willems et al., 1997), rather than the composite specimens, that have very uniform characteristics, a very large variability in the result would be

introduced. This expectation was confirmed. Since the enamel variable does not exist in the resin bonded group, a lower degree of variation was expected and observed.

## **5.6 Evaluation of the null hypothesis**

From the results of this study, the first null hypothesis which states that there will be no statistically significant difference in the shear-peel bond strength of the different bracket base treatment groups when bonded to composite resin adhesive alone is rejected. There is a statistically significant difference ( $p < 0.05$ ) between the shear-peel bond strengths of the different bracket base treatment groups.

The second null hypothesis which states that there will be no statistical difference in the shear-peel bond strength of the different bracket base treatment groups when bonded to composite resin adhesive and human enamel is rejected. There is a statistically significant difference ( $p < 0.05$ ) between the shear-peel bond strengths of the different bracket base treatment groups.

The third null hypothesis which states that there will be no statistical difference in the shear-peel bond strength when bonding brackets to composite resin alone or composite resin and enamel together is rejected. There is a statistically significant difference ( $p < 0.05$ ) between the shear-peel bond strengths of each bonding substrate.



# **CHAPTER 6**

## **CONCLUSIONS AND RECOMMENDATIONS**

|                            | <b>Page</b> |
|----------------------------|-------------|
| <b>6.1 Conclusions</b>     | <b>107</b>  |
| <b>6.2 Recommendations</b> | <b>108</b>  |

## 6.1 Conclusions

From this study, the following conclusions can be made:

1. Enamel is not an effective substrate to compare the *in vitro* shear-peel bond strengths of different orthodontic bracket bases as this does not allow examination of the base-adhesive interface.
2. When bonding to composite resin alone, all groups demonstrated bond failures predominantly at the base-adhesive interface with Primekote bracket bases demonstrating the lowest number of totally adhesive fractures with resin substrate.
3. Differences in the bond strengths of the bracket bases examined may be attributed to differences in bracket base bonding surface treatment and not to factors such as surface area, open area, mesh size, mesh wire diameter, weld spots and weld spurs.
- 4.Ormco OptimeshXRT metal plasma spray treatment does not improve bond strength or confer any retentive advantage over the corresponding untreated mesh (Ormesh).
5. Sandblasted micro-etching treatment of Victory bases confers no retentive advantage over untreated mesh.
6. Primekote polymer coating treatment exhibits a retentive advantage over other forms of treated and untreated bases.

7. Successful bonding *in vitro* can be achieved with the stainless steel orthodontic bracket bases examined, with shear-peel bond strengths equal to or greater than that achieved with titanium bracket bases *in vitro*.
8. The *in vitro* data from this study may not accurately reflect the clinical situation and should be interpreted with caution.

## 6.2 Recommendations

From the results of our *in vitro* study and an investigation of the literature, the following recommendations are made:

1. Primekote polymer-coated bases should be used over the other treated and untreated bases examined when a greater bond strength between bracket and resin adhesive is desired.
2. Primekote and Victory bracket bases should be used when less resin cleanup from enamel is desired clinically.
3. When indicated clinically, Ti-Orthos2 bracket bases should be used to retain resin adhesive with equal effectiveness as the stainless steel brackets examined.
4. Future studies that compare treatments of orthodontic bracket bases should employ bonding to composite resin substrate only as this effectively isolates the bracket base-resin interface as the site of failure.
5. Future studies that employ composite resin substrate only should recognize that cohesive fractures do occur, but should not include samples of totally

cohesive fractures within resin in the calculation of mean shear-peel bond strength of base to resin adhesive, when comparing treatments of orthodontic bracket bases. If the initial site of fracture can be positively identified as occurring at the bracket base-adhesive interface, the data from this partially cohesive failure can be included in the analysis.

6. Future studies that compare treatments of orthodontic bracket bases should isolate the precise reason for differences in bond strength.
7. Future studies that compare treatments of orthodontic bracket bases should quantify the degree of porosity to determine whether any correlation exists between porosity and bond strength.
8. In the quest to improve orthodontic bonding, manufacturers should continue their efforts to reduce the time required, steps involved and technique sensitivity while minimizing the effect on enamel.
9. Future *in vitro* studies should be directed at improving standardization of materials and methods, which would improve the comparability of results between studies.



## APPENDIX

|       |                     |                            |                           |
|-------|---------------------|----------------------------|---------------------------|
| 1 MPa | 1 N/mm <sup>2</sup> | 145.04 lbf/in <sup>2</sup> | 10.20 kgf/cm <sup>2</sup> |
|-------|---------------------|----------------------------|---------------------------|

Conversion table for bond strengths (Craig, 1997)

## REFERENCES

Anusavice KJ. Phillip's Science of Dental Materials. St. Louis: Saunders; 2003. 11<sup>th</sup> ed.

Artun J, Bergland S. Clinical trials with crystal growth conditioning as an alternative to acid-etch enamel pretreatment. *Am J Orthod* 1984;85:333-40.

Bishara SE, Fehr DE, Jakobsen JR. A comparative study of the debonding strengths of different ceramic brackets, enamel conditioners, and adhesives. *Am J Orthod Dentofacial Orthop* 1993;104:170-9.

Bishara SE, Gordan VV, VonWald L, Olson ME. Effect of an acidic primer on shear bond strength of orthodontic brackets. *Am J Orthod Dentofacial Orthop* 1998;114:243-7.

Bowen RL, Rodriguez MS. Tensile strength and modulus of elasticity of tooth structure and several restorative materials. *JADA* 1962;64:378-87.

Buonocore MG, Gwinnett AJ. Penetration of resin dental materials into enamel surfaces with references to bonding. *Arch Oral Biol* 1968;13:61-70.

Buzzitta VA, Hallgren SE, Powers JM. Bond strength of orthodontic direct-bonding cement-bracket systems as studied in vitro. *Am J Orthod* 1982;81:87-92.

Carter NE, McCabe JF. Laboratory studies of a dual-cured glass ionomer cement as an orthodontic bonding agent (Abstr). *Am J Orthod Dentofacial Orthop* 1995;74:852.

Chamda RA, Stein E. Time-related bond strengths of light-cured and chemically cured bonding systems: an in vitro study. *Am J Orthod Dentofacial Orthop* 1996;110:378-82.

Compton AM, Meyers CE Jr, Hondrum SO, Lorton L. Comparison of the shear bond strength of a light-cured glass ionomer and a chemically cured glass ionomer for use as an orthodontic bonding agent. *Am J Orthod Dentofacial Orthop* 1992;101:138-44.

Cook PA. Methods of attachment for palatal arches: an evaluation. *Br J Orthod* 1987;14:285-91.

Cook PA, Youngson CC. An in vitro study of the bond strength of a glass ionomer cement in the direct bonding of orthodontic brackets. *Br J Orthod* 1988;15:247-53.

Craig RG, Ward ML. *Restorative Dental Materials*. St. Louis: Mosby, Inc; 1997. 10<sup>th</sup> ed.

Cucu M, Driessen CH, Ferreira PD. The influence of orthodontic bracket base diameter and mesh size on bond strength. *SADJ* 2002;57:16-20.

Dasch W, Turner DS, Powers JM. Bond strength of a light-cured glass ionomer orthodontic adhesive (Abstr.). *J Dent Res* 1993;72:224.

David S. Fluoride uptake from a glass ionomer cement used as an orthodontic bracket adhesive. *Br J Orthod* 1994;21:117.

Davis EL, Joynt RB, Weiczowski G, MacDonald A. Evaluation of glass ionomer cements as luting agents for orthodontic brackets (Abstr.). *J Dent Res* 1988;67:360.

Delport A, Grobler SR. A laboratory evaluation of the tensile bond strength of some orthodontic bonding resins to enamel. *Am J Orthod Dentofacial Orthop* 1988;93:133-7.

De Saeytjdt C, Carels CE, Lesaffre E. An evaluation of a light-curing composite for bracket placement. *Eur J Orthod* 1994;16:541-5.

Dickinson PT, Powers JM. Evaluation of fourteen direct-bonding orthodontic bases. *Am J Orthod* 1980;78:630-9.

Diedrich P, Dickmeiss B. Physical comparison and scanning electron microscopy study of the adhesion of various metal brackets. *Fortschr Kieferorthop* 1983;44:298-310.

Driessen C, Coetzee WJC, van Biljon BD, Sonnekus H. Results of the Bencor Multi-T System for testing shear and tensile bond strength. *J Dent Res* 1989;68:726 (Abstr).



Droese V, Diedrich P. The tensile bonding strength of metal plasma-coated bracket bases. *Fortschr Kieferorthop* 1992;53:142-52.

Espinosa HD. In vitro study of resin-supported internally etched enamel. *J Prosthet Dent* 1978;40:526-30.

Evans R, Oliver R. Orthodontic bonding using glass ionomer cement: an in vitro study. *Eur J Orthod* 1991;13:493-500.

Evans LB, Powers JM. Factors affecting in vitro bond strength of no-mix orthodontic cements. *Am J Orthod* 1985;87:508-12.

Ewoldsen N, Beatty MW, Erickson L, Feely D. Effects of enamel conditioning on bond strength with a restorative light-cured glass ionomer. *J Clin Orthod* 1995;29:621-4.

Fajen VB, Duncanson MG Jr, Nanda RS, Currier GF, Angolkar PV. An in vitro evaluation of bond strength of three glass ionomer cements. *Am J Orthod Dentofacial Orthop* 1990;97:316-22.

Faust JB, Grego GN, Fan PL, Powers JM. Penetration coefficient, tensile strength, and bond strength of thirteen direct bonding orthodontic cements. *Am J Orthod* 1978;73:512-25.

Ferguson JW, Read MJ, Watts DC. Bond strengths of an integral bracket-base combination: an in vitro study. *Eur J Orthod*. 1984;6:267-76.

Fischer-Brandies H, Tragner-Born J. Glass ionomer cements used as bonding materials in orthodontics. *Orthod Fr* 1989;60:827-34.

Fischer-Brandies H, Zimehl R, Theusner J, Bauer J. Thermic influence in glass ionomer cement used as bracket adhesive (Abstr.). *Eur J Orthod* 1993;15:444.

Fields HW Jr. Bonded resins in orthodontics. *Pediatr Dent* 1982;4:51-60.

Fox NA, McCabe JF, Gordon PH. Bond strengths of orthodontic bonding materials: an in-vitro study. *Br J Orthod* 1991;18:125-30.

Gorelick L. Bonding metal brackets with a self-polymerizing sealant-composite: a 12-month assessment. *Am J Orthod* 1977;71:542-53.

Gwinnett AJ. State of the art and science of bonding in orthodontic treatment. Council on Dental Materials, Instruments and Equipment. *J Am Dent Assoc* 1982;105:844-50.

Hallgren A, Oliveby A, Twetman S. L(+)-lactic acid production in plaque from orthodontic appliances retained with glass ionomer cement. *Br J Orthod* 1994;21:23-6.

Hanson GH, Gibbon WM, Shimizu H. Bonding bases coated with porous metal powder: a comparison with foil mesh. *Am J Orthod* 1983;83:1-4.

Harris AM, Joseph VP, Rossouw E. Comparison of shear bond strengths of orthodontic resins to ceramic and metal brackets. *J Clin Orthod* 1990;24:725-8.

Hotz P, McLean JW, Sced I, Wilson AD. The bonding of glass ionomer cements to metal and tooth substrates. *Br Dent J* 1977;142:41-7.

International Organization for Standardization. ISO/TR 11405 Dental Materials – guidance on testing of adhesion to tooth structure. Geneva, Switzerland: WHO, 1994.

Jaochakarasiri P, Techasombooranakit K, Nathason D, Giannelly A, Giordano R. Shear bond strength of glass ionomer bonded orthodontic brackets (Abstr.) *J Dent Res* 1995;74:461.

Jassem HA, Retief DH, Jamison HC. Tensile and shear strengths of bonded and rebonded orthodontic attachments. *Am J Orthod* 1981;79:661-8.

Joseph UP, Harris AMP, Grobler SR. Bond strength of orthodontic brackets using a new glass ionomer (Abstr.). *J Dent Res* 1994;73:197.

Katona TR. A comparison of the stresses developed in tension, shear peel, and torsion strength testing of direct bonded orthodontic brackets. *Am J Orthod Dentofacial Orthop* 1997;112:244-51.

Keizer S, ten Cate JM, Arends J. Direct bonding of orthodontic brackets. *Am J Orthod* 1976;69:318-27.

Klockowski R, Davis EL, Joynt RB, Wieczkowski G Jr, MacDonald A. Bond strength and durability of glass ionomer cements used as bonding agents in the placement of orthodontic brackets. *Am J Orthod Dentofacial Orthop* 1989;96:60-4.

Knoll M, Gwinnett AJ, Wolff MS. Shear strength of brackets bonded to anterior and posterior teeth. *Am J Orthod* 1986;89:476-9.

Knox J, Hubsch P, Jones ML. The influence of bracket base design on the strength of the bracket-cement interface. *J Orthod* 2000;27:249-54.

Knox J, Kralj B, Hubsch P, Middleton J, Jones ML. An evaluation of the quality of orthodontic attachment offered by single- and double-mesh bracket bases using the finite element method of stress analysis. *Angle Orthod* 2001;71:149-55.

Lopez JJ. Retentive shear strengths of various bonding attachment bases. *Am J Orthod* 1980;77:669-78.



Low T, von Fraunhofer JA. The direct use of composite materials in adhesive dentistry. Br Dent J 1976;141:207-13.

MacColl GA, Rossouw PE, Titley KC, Yamin C. The relationship between bond strength and orthodontic bracket base surface area with conventional and microetched foil-mesh bases. Am J Orthod Dentofacial Orthop 1998;113:276-81.

Mackay F. The effect of adhesive type and thickness on bond strength of orthodontic brackets. Br J Orthod 1992;19:35-9.

Maijer R, Smith DC. Variables influencing the bond strength of metal orthodontic bracket bases. Am J Orthod Dentofacial Orthop 1981;79:20-34.

Manufacturer manual. 116094. Ortholux XT light curing unit. 3M/Unitek, Monrovia, CA, 2000.

Matasa CG. Adhesion and its ten commandments. Am J Orthod Dentofacial Orthop 1989;95:355-6.

Material Safety Data Sheet a. 712-031. Transbond XT Light Cure Adhesive Paste. 3M Unitek, Monrovia, Calif, 2000.

Material Safety Data Sheet b. 712-032. Transbond XT Light Cure Adhesive Primer. 3M Unitek, Monrovia, Calif, 2001.

McCabe JF. Resin-modified glass ionomers. *Biomaterials* 1998;19:521-527.

McCabe JF, Carrick TE. Output from visible-light activation units and depth of cure of light-activated composites. *J Dent Res* 1989;68:1534-9.

McCourt JW, Cooley RL, Barnwell S. Bond strength of light-cure fluoride-releasing base-liners as orthodontic bracket adhesives. *Am J Orthod Dentofacial Orthop* 1991;100:47-52.

Miller J, Fryar B, Moore B, Garner L. Glass ionomer cement as an orthodontic bonding agent (Abstr.). *J Dent Res* 1989;68:386.

Miller JR, Mancl L, Arbuckle G, Baldwin J, Phillips RW. A three-year clinical trial using a glass ionomer cement for the bonding of orthodontic brackets. *Angle Orthod* 1996;66:309-12.

Millett D, McCabe JF, Gordon PH. The role of sandblasting on the retention of metallic brackets applied with glass ionomer cement. *Br J Orthod* 1993;20:117-22.

Mizrahi E, Smith DC. Direct attachment of orthodontic brackets to dental enamel. A preliminary clinical report. Br Dent J 1971;130:392-6.

Newman GV. Epoxy adhesives for orthodontic attachments: Progress report. Am J Orthod 1965;51:901-5.

Newman SM, Murray GA, Yates JL. Visible lights and visible light-activated composite resins. J Prosthet Dent 1983;50:31-5.

Newman GV, Newman RA, Sun BI, Ha JL, Ozsoylu SA. Adhesion promoters, their effect on the bond strength of metal brackets. Am J Orthod Dentofacial Orthop 1995;108:237-41.

Norevall LI, Sjogren G, Persson M. Tensile and shear strength of orthodontic bracket bonding with glass ionomer cement and acrylic resin. An in vitro comparison. Swed Dent J 1990;14:275-84.

O'Brien KD, Watts DC, Read MJ. Residual debris and bond strength--is there a relationship? Am J Orthod Dentofacial Orthop 1988;94:222-30.

Odegaard J, Segner D. Shear bond strength of metal brackets compared with a new ceramic bracket. Am J Orthod Dentofacial Orthop 1988;94:201-6.

Oen JO, Gjerdet NR, Wisth PJ. Glass ionomer cements used as bonding materials for metal orthodontic brackets. An in vitro study. *Eur J Orthod* 1991;13:187-91.

Ostertag AJ, Dhuru VB, Ferguson DJ, Meyer RA Jr. Shear, torsional, and tensile bond strengths of ceramic brackets using three adhesive filler concentrations. *Am J Orthod Dentofacial Orthop* 1991;100:251-8.

Powers JM, Kim HB, Turner DS. Orthodontic adhesives and bond strength testing. *Semin Orthod* 1997;3:147-56.

Proffit WR. *Contemporary Orthodontics*. St. Louis: Mosby, Inc; 2000. 3<sup>rd</sup> ed.

Regan D, van Noort R. Bond strengths of two integral bracket-base combinations: an in vitro comparison with foil-mesh. *Eur J Orthod* 1989;11:144-53.

Retief DH. Failure at the dental adhesive-etched enamel interface. *J Oral Rehab* 1974;1:265-84.

Reynolds IR. A review of direct orthodontic bonding. *Br J orthod* 1975;2:171-8.

Reynolds IR, von Fraunhofer JA. Direct bonding in orthodontics: A comparison of attachments. *Br J Orthod* 1977;4:65-9.



Reynolds IR, von Fraunhofer JA. Direct bonding of orthodontic attachments to teeth: The relation of adhesive bond strength to gauze mesh size. *Br J Orthod* 1976;3:91-5.

Rezich PM, Panneton MJ, Barkmeier WW. In vitro evaluation of fluoride and non-fluoride releasing orthodontic adhesives on bracket bond strength. *J Esthet Dent* 1989;1:101-4.

Rezk-Lega F, Ogaard B. Tensile bond force of glass ionomer cements in direct bonding of orthodontic brackets: an in vitro comparative study. *Am J Orthod Dentofacial Orthop* 1991;100:357-61.

Rock WP, Abdullah MS. Shear bond strengths produced by composite and compomer light cured orthodontic adhesives. *J Dent* 1997;25:243-9.

Rosenstein P, Binder RE. Bonding and rebonding peel testing of orthodontic brackets. *Clin Prev Dent* 1980;2:15-7.

Sargison AE, McCabe JF, Gordon PH. An ex vivo study of self-, light-, and dual-cured composites for orthodontic bonding. *Br J Orthod* 1995;22:319-23.

Scott GG, Garcia-Godoy F, Summitt JB. Shear bond strength of brackets bonded with glass ionomers (Abstr). *J Dent Res* 1995;74:187.

sdsOrmco, personal communication, Michael Swartz, 2004.

Sharma-Sayal SK, Rossouw PE, Kulkarni GV, Titley KC. The influence of orthodontic bracket base design on shear bond strength. *Am J Orthod Dentofacial Orthop* 2003;124:74-82.

Shin KS, Lee KS. The effects of surface treatments on shear bond strengths of light-cured and chemically cured glass ionomer cements to enamel (Abstr). *J Dent Res* 1995;74:187.

Silverman E, Cohen M, Demke RS, Silverman M. A new light-cured glass ionomer cement that bonds brackets to teeth without etching in the presence of saliva. *Am J Orthod Dentofacial Orthop* 1995;108:231-6.

Siomka LV, Powers JM. In vitro bond strength of treated direct-bonding metal bases. *Am J Orthod* 1985;88:133-6.

Smith DC, Maijer R. Improvements in bracket base design. *Am J Orthod Dentofacial Orthop* 1983;83:277-81.

Smith NR, Reynolds IR. A comparison of three bracket bases: an in vitro study. *Br J Orthod* 1991;18:29-35.

Smith RT, Shivapuja PK. The evaluation of dual cement resins in orthodontic bonding. Am J Orthod Dentofacial Orthop 1993;103:448-51.

Surmont P, Dermaut L, Martens L, Moors M. Comparison in shear bond strength of orthodontic brackets between five bonding systems related to different etching times: an in vitro study. Am J Orthod Dentofacial Orthop 1992;101:414-9.

Thanos CE, Munholland T, Caputo AA. Adhesion of mesh-base direct-bonding brackets. Am J Orthod 1979;75:421-30.

3M/Unitek, personal communication, Enrique Nikutowski, 2004.

TP Orthodontics, Inc., personal communication, Bill Beasley, 2005.

TP Orthodontics, Inc, personal communication, Deva Devanathan, 2004.

Wang WN, Tarng TH. Evaluation of the sealant in orthodontic bonding. Am J Orthod Dentofacial Orthop 1991;100:209-11.

White LW. Glass ionomer cement. J Clin Orthod 1986;20:387-91.

Willems G, Carels CE, Verbeke G. In vitro peel/shear bond strength of orthodontic adhesives. J Dent 1997;25:263-70.

Willems G, Carels CE, Verbeke G. In vitro peel/shear bond strength evaluation of orthodontic bracket base design. J Dent 1997;25:271-8.

Wilson AD, Kent BE. A new translucent cement for dentistry. Br Dent J 1972;132:133-35.

Wiltshire WA. Shear bond strengths of a glass ionomer for direct bonding in orthodontics. Am J Orthod Dentofacial Orthop 1994;106:127-30.

Wiltshire WA, personal communication, 2005.

Wright WL, Powers JM. In vitro tensile bond strength of reconditioned brackets. Am J Orthod 1985;87:247-52.

Zachrisson BU. Orthodontic bonding to artificial tooth surfaces: Clinical versus laboratory findings. Am J Orthod Dentofacial Orthop 2000;117:592-94.

Zachrisson BU. A post treatment evaluation of direct bonding in orthodontics. Am J Orthod 1977;71:173-89.

Zachrisson YO, Zachrisson BU, Buyukyilmaz T. Surface preparation for orthodontic bonding to porcelain. Am J Orthod Dentofacial Orthop 1996;109:420-30.



## Effect of orthodontic bracket bases on the shear-peel bond strength

**Manish K. Aggarwal, BSc (Hons), DDS,<sup>a</sup> William A. Wiltshire, BChD, BChD (Hons), MDent, MChD, DSc,<sup>b</sup> Peter T. Williams, BSc, DDS, MSc,<sup>c</sup> Robert J. Schroth, DMD, MSc<sup>d</sup>**

Winnipeg, Manitoba, Canada

<sup>a</sup> Orthodontic Resident, University of Manitoba, Winnipeg, Manitoba, Canada

<sup>b</sup> Professor and Head of Orthodontics, Department of Preventive Dental Science, University of Manitoba, Winnipeg, Manitoba, Canada

<sup>c</sup> Senior Scholar, Department of Preventive Dental Science, University of Manitoba, Winnipeg, Manitoba, Canada

<sup>d</sup> Assistant Professor, Department of Preventive Dental Science, University of Manitoba, Winnipeg, Manitoba, Canada

Address for correspondence: Dr. W.A. Wiltshire, Head of Orthodontics, Faculty of Dentistry, University of Manitoba, 780 Bannatyne Ave, Winnipeg, Manitoba, Canada, R3E 0W2

Keywords: Orthodontics, shear-peel bond strength, bracket base

## Effect of orthodontic bracket bases on the shear-peel bond strength

### ABSTRACT

*Background* Increasing patient demand for more esthetic orthodontic appliances has motivated manufacturers to reduce the size of bracket bases. To compensate for this decrease in bondable surface area, each manufacturer has treated the base mesh by various methods with the claim of superior bond strength. Thus, one of the aims of this investigation was to compare the effect of bracket base treatments on shear-peel bond strength. Although most studies use enamel as a testing substrate, a few studies use composite resin alone as a testing substrate to isolate the base-resin interface. Thus, one of the aims of this investigation was to compare the effect of bonding substrate on shear-peel bond strength. *Methods* For the enamel substrate group, 30 specimens each of 5 bracket types were bonded to human third molars with light-cured composite resin adhesive (Transbond XT, 3M Unitek). For the resin substrate group, 30 specimens each of 5 bracket types were bonded to Transbond XT composite resin. Brackets were shear-peel tested 24 hours later using a Zwick Universal Testing machine with a crosshead speed of 0.5 mm/min, employing a load cell of 10 kN. For the enamel substrate group, the Adhesive Remnant Index was used to quantify the amount of resin remaining on the enamel surface after debonding. For the resin substrate group, the Fracture Interface Score was used to describe the mode of fracture at the base-resin interface. Representative specimens were inspected under the scanning electron microscope. *Results* One-way analysis of variance and Tukey's multiple comparison tests were conducted at a probability value of .05 or less. For the enamel substrate group, the mean shear-peel bond strengths were as follows: Victory (microetched) ( $26.80 \pm 5.73$  MPa), Primekote (polymer coated) ( $19.41 \pm 3.21$  MPa), Ormesh (untreated control) ( $18.25 \pm 3.47$  MPa), OptimeshXRT (plasma spray coating) ( $17.79 \pm 5.24$  MPa), and Ti-Orthos2 (untreated titanium) ( $14.50 \pm 3.71$  MPa). For the resin substrate group, the mean shear-peel bond strengths were as follows: Primekote ( $22.35 \pm 3.07$  MPa), Victory ( $16.29 \pm 2.47$  MPa), Ormesh ( $14.88 \pm 2.50$  MPa), OptimeshXRT ( $13.38 \pm 2.47$  MPa), and Ti-Orthos2 ( $13.37 \pm 2.09$  MPa). *Conclusions* Statistically significant differences ( $p < 0.05$ ) were found between brackets of different base treatments when bonded to enamel substrate. However, the large proportion of cohesive fractures within the resin adhesive suggests that enamel should not be used as a substrate when testing for differences in base treatment. Statistically significant differences ( $p < 0.05$ ) were also found between brackets of different base treatments when bonded to resin substrate alone. The large proportion of adhesive fractures at the bracket base-resin substrate interface suggests that resin substrate should be used when testing for differences in base treatment. All bracket bases were deemed to have sufficient bond strengths to enamel, without enamel fracture.

Brackets have been reduced in size to respond to patient demands for improved appearance. This has resulted in a reduction in the bracket base area available for bonding to enamel. To improve bond strengths, enhancements in bracket base design have become an area of investigation. While chemical bonding can be obtained between some adhesives and both enamel and stainless steel brackets, the bond strength is often too low to give a clinically satisfactory result. Therefore, mechanical retentive features in the bracket base are relied upon solely for improved bond strength<sup>1-2</sup>. Brackets originally had perforated metal bases, but these have been replaced by stainless steel foil-mesh bases<sup>3-6</sup>. Mesh features that may influence the bond strength include rough and smooth wires, mesh size<sup>1,5,9-10</sup>, wire diameter, and weld spots<sup>7-8</sup>. Some examples of base modifications to improve bond strength include integral brackets<sup>2, 11-12</sup>, sintered bases<sup>13-14</sup>, and photo-etched bases<sup>6</sup>.

Bond failures can occur: (1) adhesively at the enamel-resin interface, (2) cohesively within adhesive, or (3) adhesively at the base-resin interface. The most common site of failure *in vitro* between foil-mesh brackets and resin adhesives is at the base-resin interface<sup>1-2,4,6,14-24</sup>. Recent developments in the bracket base are dependent upon improving (1) the mechanical interlock of the resin adhesive to the wire mesh and (2) the chemical forces of adhesion at the base-resin adhesive interface<sup>4,7,15,25-27</sup>.

Bracket pretreatments such as microetching and chemical coatings are available to enhance the bond between resin adhesives and metal brackets<sup>28</sup>. Microetching is performed by the manufacturer to increase surface roughness, thereby increasing surface energy and bonding surface area<sup>29</sup>. MacColl et al found that microetching of foil-mesh bases significantly increased bond strengths as compared to an untreated foil-mesh

base<sup>30</sup>. Siomka and Powers<sup>28</sup> found that microetching increased the bond strength of an integral grooved base by 56% whereas the bond strength of a foil-mesh base was unaffected.

Polymer coating is applied by the manufacturer to overcome the inability of orthodontic adhesives to bond chemically to stainless steel bracket bases. TP bases (TP Orthodontics, Inc., LaPorte, IN) coated with Primekote (TP Orthodontics, Inc., LaPorte, IN) claim not only mechanical retention of adhesive to the mesh, but also a chemical bond to both the metal mesh and the orthodontic resin adhesive. Metal plasma-coating is another bond enhancing technique. Stainless steel alloy is thermally sprayed onto the mesh base by the manufacturer to augment mesh surface roughness and surface area available for micromechanical bonding, and therefore enhance bond strengths. Willems et al<sup>22</sup> found thatOrmco's Optimesh (Ormco, Orange, CA) plasma-coated mesh base demonstrated a 40% increase in tensile and shear bond strength over Ormco's Ormesh uncoated mesh base. Droese and Diedrich<sup>31</sup> found that mesh bases coated with metal plasma showed 2 to 4 times higher mean tensile bond strengths in relation to uncoated mesh bases, depending on adhesive used. They attributed this enhancement of adhesion to the increase in the active retentive surface created by the metal plasma.

Although the comparison of manufactured base treatments requires only the testing of shear-peel bond strength (SPBS) between base and resin adhesive, bonding to enamel also requires evaluation in order to allow comparison with other studies to gain clinical significance. The purposes of the present study were to: (1) compare the effectiveness of several orthodontic bracket base treatments on the SPBS of orthodontic bracket bases bonded to composite resin substrate and to human enamel substrate, (2)



compare the influence of substrate (i.e. resin or enamel) on the SPBS of orthodontic bracket bases.

## **MATERIALS AND METHODS**

### **Preparation of composite resin substrate samples**

One hundred and fifty brass mounting cylinders (diameter 20 mm, height 13 mm) each with a well in the center of one face (diameter 5 mm, depth 5 mm) were fabricated (Fig 1). Transbond XT composite resin was injected into the well, manually packed with a resin plugger, trimmed flush with the top of the well with a cement spatula, and light-cured for 20 seconds with an Ortholux XT light curing unit (3M Unitek, Monrovia, CA).

### **Preparation of enamel substrate samples**

One hundred and fifty extracted human third molar teeth were selected based on the following criteria: intact buccal enamel, no visible cracks, caries or fluorosis, and an enamel topography that was suitable for intimate bonding with the curved base of the orthodontic brackets as determined by inspection with a binocular microscope at 20X magnification (Nikon SM2-10, Tokyo, Japan). The roots were removed and the crowns were individually fixed in stainless steel mounting rings with cold cure acrylic (Self-curing orthodontic resin, Dentsply Limited, England) so that the facial surface was exposed (Fig 2).

### **Bonding procedure**

The resin and enamel substrate samples were each randomly divided into five bracket base test groups of thirty samples each as follows: 3M Victory Series (3M Unitek, Monrovia, CA) stainless steel bases: basic wire mesh design roughened mechanically by

sandblasting with 50  $\mu\text{m}$  particle size grit, TP Orthodontics Primekote stainless steel bases: basic wire mesh design sandblasted with 150-200  $\mu\text{m}$  aluminum grit and treated chemically with a polymer coating,Ormco Mini 2000 Ormesh (Ormco, Orange, CA) stainless steel bases: untreated control with basic wire mesh design, Ormco Optimesh XRT stainless steel bases: same as the Ormesh brackets except that they are treated chemically with a thermal spray coating, Ormco Ti-Orthos 2 titanium bases: an untreated basic wire mesh design. Mesh-base specifications for the brackets used in this study are displayed in Table I. Lower first premolar brackets were used for all samples because they have a curved base which adequately adapts to the rounded topography of the human third molar enamel samples. All of the enamel facial surfaces were cleaned and polished with residue free, non-fluoridated pumice and water slurry for 10 seconds with a slow speed hand piece and rubber prophylactic cup<sup>32</sup>. The samples were thoroughly rinsed with tap water and dried with oil free compressed air for 30 seconds. For the resin substrate samples, Transbond XT adhesive paste was placed on each bracket base and the base was placed on the resin substrate without primer. Transbond XT adhesive paste is a light-cured, hybrid orthodontic resin. For the enamel substrate samples, the enamel surface was etched for 30 seconds with 37% phosphoric acid gel, rinsed for 20 seconds with a water spray, and dried with an oil free air source for 20 seconds until the enamel surface appeared chalky white in colour. Transbond XT primer was applied to the enamel surface in a thin layer. The adhesive paste was placed on each bracket base and the base was placed on the enamel surface. A force of 500 gm was applied to each bracket to assure complete seating of the bracket base against the substrate. Excess bonding material was removed with an explorer to provide a clean junction between the

bracket base and substrate for the shearing blade. Each bonded bracket was light cured for 20s (10s mesial and 10s distal).

### **Shear-peel bond strength testing**

Immediately after bonding, the samples were stored in distilled deionized water for 24 hours at 37 °C and 100% relative humidity in an incubator<sup>33-34</sup>. The samples were then mounted into the shear-peel testing device (Bencor<sup>TM</sup> Multi-T, Danville Engineering, San Ramon, CA, USA) and tested in a Zwick Universal Testing Machine (#1445, Zwick GmbH & Co., Ulm, Germany). The debond load was applied occlusogingivally, with a crosshead speed of 0.5 mm/minute using a 10 kN load cell. The load was applied to the bracket-substrate interface (Figs 3-4). A computer connected to the Zwick testing machine recorded the SPBS in megaPascals (MPa). Debonding procedures were carried out by one operator (MKA) to ensure consistency.

### **Evaluation of fracture sites**

The Adhesive Remnant Index (ARI)<sup>35</sup> was used to evaluate the amount of adhesive remaining on the enamel surface after debonding. For the bracket-enamel substrate test, the ARI was evaluated at 20X magnification as follows: 0 = no adhesive left on the tooth, 1 = less than half of the adhesive left on the tooth, 2 = more than half of the adhesive left on the tooth, 3 = all adhesive left on the tooth, with distinct impression of the bracket mesh. For the bracket-resin substrate test, since an index does not currently exist to evaluate the type of fracture at the bracket base-resin adhesive interface, the "Fracture Interface Score" (FIS) index was created. The categories of the FIS are: 1 = total adhesive fracture between base and resin substrate, 2 = partial adhesive-cohesive fracture, 3 = total cohesive fracture within composite resin substrate. Three months later 10% of

the sample was randomly selected and the FIS and ARI reevaluated by the same operator to assess intra-evaluator discrepancies.

### **Statistical analysis**

Descriptive statistics including the mean, standard deviation, minimum and maximum values, and coefficient of variation for each of the groups were calculated. A one-way analysis of variance and Tukey's post-hoc test were used to determine significant differences between mean SPBS. A chi-square test was used to determine significant differences between the ARI and FIS scores among the test groups. Significance for all statistical tests was predetermined at  $P \leq 0.05$ .

## **RESULTS**

### **Shear-peel bond strengths**

The comparative data for the mean SPBS of the groups tested is listed in Table II. The analysis of variance indicated that there were significant differences in mean SPBS among the test groups ( $p < 0.05$ ).

### **Comparison of brackets bonded to composite resin substrate**

The mean SPBS of the Primekote group was significantly higher than all the groups tested ( $p < 0.05$ ). The mean SPBS of the Victory group was higher than the Ormesh control group, but not significantly ( $p > 0.05$ ). However, it was significantly higher than both the OptimeshXRT group and the Ti-Orthos2 group ( $p < 0.05$ ). There was no statistically significant difference in the mean SPBS of the threeOrmco bracket groups ( $p > 0.05$ ). The standard deviations for all the tested groups were low, with coefficients of variation ranging from 13.7 to 18.5%. The OptimeshXRT group had the highest



coefficient of variation (18.5%) out of all the groups with mean SPBS ranging from 9.33 to 19.33 MPa.

#### **Comparison of brackets bonded to enamel substrate**

The mean SPBS of the Victory group was significantly higher than all the groups tested ( $p < 0.05$ ). The mean SPBS of the Primekote group was not significantly higher than the Ormesh control group or the OptimeshXRT group ( $p > 0.05$ ). The mean SPBS of the Ti-Orthos2 group was significantly lower than all the groups tested ( $p < 0.05$ ). The standard deviations for all the groups were low, with coefficients of variation ranging from 16.5 to 29.5%. The OptimeshXRT group had the highest coefficient of variation (29.5%) out of all the groups with mean SPBS ranging from 10.10 to 30.92 MPa.

#### **Comparison of bracket-composite resin substrate and bracket-enamel substrate groups**

The mean SPBS of the Ormesh control ( $p < 0.05$ ), OptimeshXRT ( $p < 0.001$ ), and Victory ( $p < 0.001$ ) brackets bonded to resin substrate were significantly lower than when bonded to enamel substrate. For the Ti-Orthos2 group, there was no significant difference in mean SPBS between resin and enamel substrates ( $p > 0.05$ ). The Primekote bracket-adhesive group was the only group where the mean SPBS was significantly greater than when bonded to enamel substrate ( $p < 0.05$ ).

#### **Fracture Interface Scores (FIS) and Adhesive remnant index (ARI) scores**

The FIS for the bracket-composite resin substrate and the ARI scores for the bracket-enamel substrate groups are listed in Tables III-IV. There was greater than 90% intraoperator agreement. The chi-square test indicated that there were significant differences in the FIS and ARI scores among the test groups in both the bracket-

composite resin substrate and bracket-enamel substrate groups, respectively ( $p < 0.001$  and  $p < 0.0001$ , respectively).

#### **Comparison of brackets bonded to composite resin substrate (Table III)**

Out of 150 brackets bonded to composite resin substrate, 123 (82%) failed adhesively whereas 27 (18%) failed either cohesively or through a mixed cohesive/adhesive failure. More partial adhesive-cohesive fractures occurred with Primekote brackets than with Ti-Orthos2 brackets, which tended to have more total adhesive fractures.

#### **Comparison of brackets bonded to enamel substrate (Table IV)**

3M Victory series and TP Primekote brackets both demonstrated bond failures largely between the bracket and adhesive with less than half of the adhesive remaining on the enamel surface. Ormesh, OptimeshXRT, and Ti-Orthos2 brackets demonstrated bond failures largely between the bracket and adhesive with more than half of the adhesive remaining on the enamel surface. These results suggest that less adhesive remains on the tooth surface when Victory and Primekote brackets are used. No enamel fractures occurred.

## **DISCUSSION**

All of the bracket groups achieved means SPBS greater than 2.86 MPa which is considered the minimum bond strength required by a bracket to resist the displacing forces placed upon it<sup>15,36</sup>. Since our study used only one type of adhesive, the effect of this variable on SPBS was controlled. Constant force during bracket placement ensured that the adhesive thickness was similar for all types of brackets. Therefore, this study could focus on the effect of bracket base treatment on mean SPBS.

Each enamel substrate test group yielded mean SPBS of between 14.5 and 26.8 MPa compared to similar orders of magnitude of 16 to 25 MPa reported in other recent studies<sup>27,30,37</sup>. Some studies have raised concern regarding bond strengths greater than 14.5 MPa<sup>38-40</sup>. In our study, however, no enamel fractures were noted, even with SPBS as high as 26.8 MPa.

Few *in vitro* studies have been conducted to date that isolate and examine the bracket base-adhesive interface<sup>7,12,22,41-42</sup>. When bonding to resin substrate, each group in our study yielded mean SPBS of between 13.4 and 22.4 MPa compared with 2 to 23 MPa reported in other studies<sup>7,12,22,41-42</sup>. Our study is in agreement with those studies at the higher end of magnitude of bond strengths. Any differences between studies in the lower range than ours may be attributed to variations in the types of non-tooth substrates tested (bracket-resin-bracket, silane treated metal bars, plastic cylinders), types of bracket bases tested (different base treatments, mechanical retentive elements, mesh sizes, mesh wire diameters), and types of adhesives used. There are also differences in the mode of evaluating bond strengths (tensile, shear)<sup>43</sup>, the machines used in testing, testing parameters (crosshead speed, load cell), and the type of mounting apparatus.

Although the enamel substrate test bracket bases ranged in surface area from 12.9 to 14.0 mm<sup>2</sup> no significant difference in mean SPBS were exhibited. This finding is in partial agreement with that of Cucu et al<sup>10</sup>. In our study Victory bases demonstrated significantly higher SPBS than all the other test groups, despite having a smaller surface area of 9.8 mm<sup>2</sup>. In the resin substrate test bracket bases ranging in surface area from 9.8 and 14.0 mm<sup>2</sup> also exhibited no significant difference in mean SPBS. This finding is in agreement with that of Willems et al<sup>22</sup>. Primekote brackets demonstrated significantly

higher mean SPBS than all the other test groups, despite having an intermediate surface area of 12.9 mm<sup>2</sup>. Contrary to expectations, the bond strength appeared to be unrelated to the surface area. One possible explanation for this trend involves recognizing that the same force was used to control adhesive thickness for all bracket groups. Therefore, brackets with smaller bonding surface areas would experience a higher force per unit area. This would create a slightly thinner adhesive layer which could result in fewer air bubbles or other defects, and thus a higher bond strength. However, the results showed that the group with the smallest bonding surface area (Victory) did not yield the highest bond strength. Factors other than surface area are likely to explain the results obtained.

The open area is the percentage of the bracket base area (Table I) available for adhesive to penetrate. Matasa identified it as a variable that affects mesh performance and bond strength<sup>44</sup>. For the enamel substrate test, the greater open area available for resin to penetrate into the mesh may account for the higher mean SPBS of the Victory group. However, it does not explain the nonsignificant difference between the Primekote, OptimeshXRT, and Ormesh groups. For the resin substrate test, the greater open area may account for the higher mean SPBS of the Primekote group. However, it does not explain the non-significant difference between the Victory, OptimeshXRT, and Ormesh groups. Despite the largest open area, Ti-Orthos2 bases yielded the lowest mean SPBS. Open areas between 30% and 35% do not explain our results.

Matasa also identified mesh size as a variable affecting mesh performance and bond strength<sup>44</sup>. Mesh size is the number of openings per linear inch. Theoretically, finer mesh sizes (100) weaken the base-adhesive bond because there are smaller spaces between wires for adhesive to penetrate<sup>1</sup>. Our results did not support this theory. Rather,



our results agree with Cucu et al who compared 80 and 100 mesh sizes<sup>10</sup>. Mesh size does not explain our results.

Matasa also identified mesh wire diameter as a variable affecting mesh performance and bond strength<sup>44</sup>. In theory, a thin diameter will lead to mesh wire breakage. Evaluation of the fracture samples showed no evidence of mesh wire breakage. A thick diameter will limit adhesive penetration. Our results did not support this theory. With both substrates, bases with thicker mesh wire diameters (Table I) showed higher mean SPBS. Mesh wire diameter does not explain our results.

Current *in vitro* protocols of bond strength studies evaluate the cohesive strength of the composite resin, and the adhesive strength of the bracket-resin and resin-enamel interfaces, reporting only the weakest link in this system<sup>45</sup>. The enamel substrate test results of this study were no exception to the above statement. Since only 30 of 150 failures occurred adhesively (ARI 0 and 3) and an even smaller number (13 of 150) occurred adhesively between base and resin (ARI 3) (Table IV), it is difficult to attribute the differences in mean SPBS to differences in bracket base treatment. In contrast, a large proportion of the resin substrate samples failed adhesively at the base-adhesive interface (FIS 1) (Table III). The differences in mean SPBS can be attributed to differences in bracket base treatment. Therefore, since the bond between base and adhesive was of most interest in our study, the elimination of enamel as a component of the sample ensured that the fracture took place at that interface. The characteristics of enamel vary between individual teeth, thus a large variability in the results was introduced<sup>22</sup>. Resin specimens have relatively uniform characteristics. Since the enamel variable does not exist in the resin substrate group, a lower degree of variation was

expected and observed. Additionally, although the etchant was controlled in our study, the etchability and quality of etch of the enamel could not, resulting in increased variability in the enamel substrate group.

Although Primekote brackets are micro-etched, scanning electron micrograph views (Fig 7) show that the potential increase in micromechanical roughness is obliterated by the Primekote coating. On a speculative note, the significantly highest mean SPBS of these brackets suggests that Primekote polymer coating treatment may provide a very low surface tension for strong molecular adhesion. Micro-etching treatment appears to contribute to the high mean SPBS observed in the Victory group. The micro-etching process may provide the advantage of increased micromechanical attachment to resin (Fig 8), but not the strong molecular adhesion as is speculated to occur in the Primekote group. The relatively higher mean SPBS of the untreated Ormesh base (Fig 9) suggests that metal plasma spray treatment of the OptimeshXRT base (Fig 10) confers no improvement in micromechanical retention of resin. The manufacturer has proposed that titanium alloy should increase bond strength over stainless steel because it is a more resilient alloy, thereby giving rise to a “shock absorber effect”. Our results do not support this theory since the Ti-Orthos2 group (Fig 11) showed a lower mean SPBS than the correspondingOrmco stainless steel groups and had the lowest mean SPBS of any of the bracket types.

## CONCLUSIONS

Judging from our study protocol, the following conclusions are made:

1. Enamel is not an effective substrate to compare the shear-peel bond strengths of bracket bases as this does not allow isolated examination of the base-adhesive

interface. Future studies that compare treatments of bracket bases should employ bonding to resin substrate only. Such studies should recognize that cohesive fractures do occur, but should not include samples of totally cohesive fractures within resin in the bond strength calculation. If the initial site of fracture can be positively identified as occurring at the bracket base-adhesive interface, the data from this partially cohesive failure can be included in the analysis.

2. When bonding to composite resin alone, all groups demonstrated bond failures predominantly at the bracket base-adhesive interface. Primekote bracket bases demonstrated the lowest number of totally adhesive fractures when bonded to resin substrate suggesting less resin cleanup from enamel clinically.
3. Differences in the bond strengths of the bracket bases examined may be attributed to differences in bracket base bonding surface treatment and not to factors such as surface area, open area, mesh size, and mesh wire diameter.
4. Ormco OptimeshXRT metal plasma spray treatment does not improve bond strength or confer any retentive advantage over Ormesh untreated mesh.
5. Sandblasted micro-etching treatment of Victory bases confers no retentive advantage over untreated mesh (Ormesh).
6. Primekote polymer coating treatment exhibits a retentive advantage over the other forms of treated and untreated bases examined.
7. Acceptable bond strengths *in vitro* can be achieved with both types of stainless steel and titanium orthodontic bracket bases used in our study.

## REFERENCES

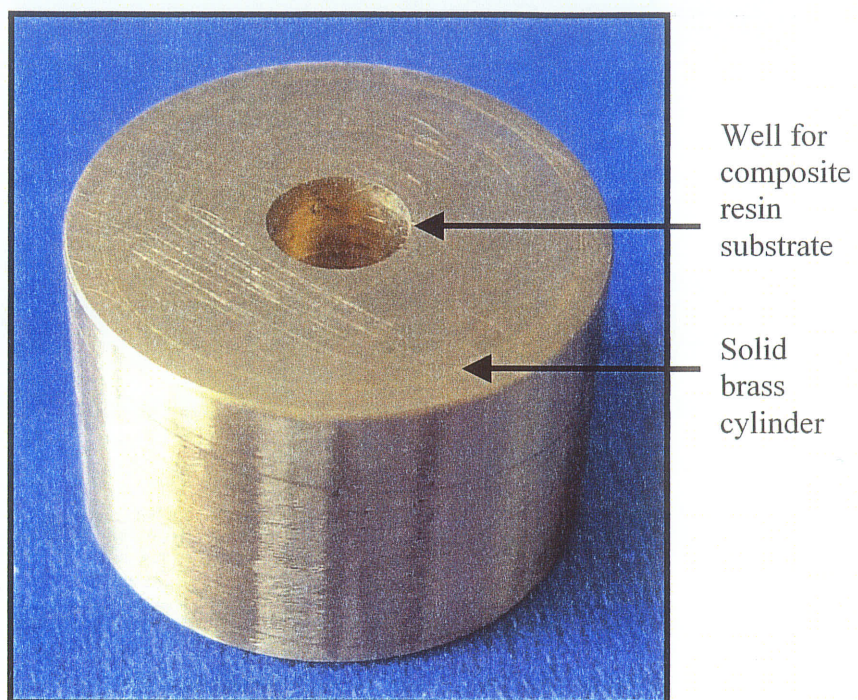
1. Reynolds IR, von Fraunhofer JA. Direct bonding of orthodontic attachments to teeth: The relation of adhesive bond strength to gauze mesh size. Br J Orthod 1976;3:91-5.

2. Ferguson JW, Read MJ, Watts DC. Bond strengths of an integral bracket-base combination: an in vitro study. *Eur J Orthod*. 1984;6:267-76.
3. Reynolds IR, von Fraunhofer JA. Direct bonding in orthodontics: A comparison of attachments. *Br J Orthod* 1977;4:65-9.
4. Faust JB, Grego GN, Fan PL, Powers JM. Penetration coefficient, tensile strength, and bond strength of thirteen direct bonding orthodontic cements. *Am J Orthod* 1978;73:512-25.
5. Thanos CE, Munholland T, Caputo AA. Adhesion of mesh-base direct-bonding brackets. *Am J Orthod* 1979;75:421-30.
6. Lopez JL. Retentive shear strengths of various bonding attachment bases. *Am J Orthod* 1980;77:669-78.
7. Dickinson PT, Powers JM. Evaluation of fourteen direct-bonding orthodontic bases. *Am J Orthod* 1980;78:630-9.
8. Maijer R, Smith DC. Variables influencing the bond strength of metal orthodontic bracket bases. *Am J Orthod Dentofacial Orthop* 1981;79:20-34.
9. Low T, von Fraunhofer JA. The direct use of composite materials in adhesive dentistry. *Br Dent J* 1976;141:207-13.
10. Cucu M, Driessen CH, Ferreira PD. The influence of orthodontic bracket base diameter and mesh size on bond strength. *SADJ* 2002;57:16-20.
11. Diedrich P, Dickmeiss B. Physical comparison and scanning electron microscopy study of the adhesion of various metal brackets. *Fortschr Kieferorthop* 1983;44:298-310.
12. Regan D, van Noort R. Bond strengths of two integral bracket-base combinations: an in vitro comparison with foil-mesh. *Eur J Orthod* 1989;11:144-53.
13. Hanson GH, Gibbon WM, Shimizu H. Bonding bases coated with porous metal powder: a comparison with foil mesh. *Am J Orthod* 1983;83:1-4.
14. Smith DC, Maijer R. Improvements in bracket base design. *Am J Orthod Dentofacial Orthop* 1983;83:277-81.
15. Keizer S, ten Cate JM, Arends J. Direct bonding of orthodontic brackets. *Am J Orthod* 1976;69:318-27.

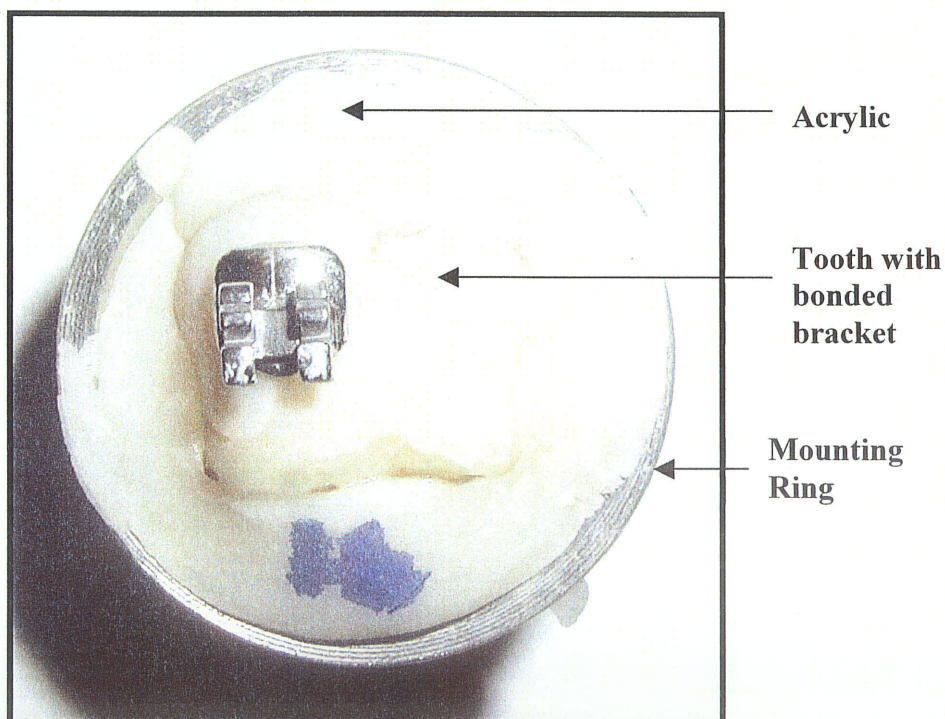
16. Gorelick L. Bonding metal brackets with a self-polymerizing sealant-composite: a 12-month assessment. *Am J Orthod* 1977;71:542-53.
17. Rosenstein P, Binder RE. Bonding and rebonding peel testing of orthodontic brackets. *Clin Prev Dent* 1980;2:15-7.
18. Jassem HA, Retief DH, Jamison HC. Tensile and shear strengths of bonded and rebonded orthodontic attachments. *Am J Orthod* 1981;79:661-8.
19. Fields HW Jr. Bonded resins in orthodontics. *Pediatr Dent* 1982;4:51-60.
20. Odegaard J, Segner D. Shear bond strength of metal brackets compared with a new ceramic bracket. *Am J Orthod Dentofacial Orthop* 1988;94:201-6.
21. Harris AM, Joseph VP, Rossouw E. Comparison of shear bond strengths of orthodontic resins to ceramic and metal brackets. *J Clin Orthod* 1990;24:725-8.
22. Willems G, Carels CE, Verbeke G. In vitro peel/shear bond strength evaluation of orthodontic bracket base design. *J Dent* 1997;25:271-8.
23. O'Brien KD, Watts DC, Read MJ. Residual debris and bond strength--is there a relationship? *Am J Orthod Dentofacial Orthop* 1988;94:222-30.
24. Millett D, McCabe JF, Gordon PH. The role of sandblasting on the retention of metallic brackets applied with glass ionomer cement. *Br J Orthod* 1993;20:117-22.
25. Wright WL, Powers JM. In vitro tensile bond strength of reconditioned brackets. *Am J Orthod* 1985;87:247-52.
26. Knoll M, Gwinnett AJ, Wolff MS. Shear strength of brackets bonded to anterior and posterior teeth. *Am J Orthod* 1986;89:476-9.
27. Surmont P, Dernaut L, Martens L, Moors M. Comparison in shear bond strength of orthodontic brackets between five bonding systems related to different etching times: an in vitro study. *Am J Orthod Dentofacial Orthop* 1992;101:414-9.
28. Siomka LV, Powers JM. In vitro bond strength of treated direct-bonding metal bases. *Am J Orthod* 1985;88:133-6.
29. Newman GV, Newman RA, Sun BI, Ha JL, Ozsoylu SA. Adhesion promoters, their effect on the bond strength of metal brackets. *Am J Orthod Dentofacial Orthop* 1995;108:237-41.
30. MacColl GA, Rossouw PE, Titley KC, Yamin C. The relationship between bond strength and orthodontic bracket base surface area with conventional and microetched foil-mesh bases. *Am J Orthod Dentofacial Orthop* 1998;113:276-81.



31. Droese V, Diedrich P. The tensile bonding strength of metal plasma-coated bracket bases. *Fortschr Kieferorthop* 1992;53:142-52.
32. Bishara SE, Gordan VV, VonWald L, Olson ME. Effect of an acidic primer on shear bond strength of orthodontic brackets. *Am J Orthod Dentofacial Orthop* 1998;114:243-7.
33. International Organization for Standardization. ISO/TR 11405 Dental Materials – guidance on testing of adhesion to tooth structure. Geneva, Switzerland: WHO, 1994.
34. Wiltshire WA. Shear bond strengths of a glass ionomer for direct bonding in orthodontics. *Am J Orthod Dentofacial Orthop* 1994;106:127-30.
35. Artun J, Bergland S. Clinical trials with crystal growth conditioning as an alternative to acid-etch enamel pretreatment. *Am J Orthod* 1984;85:333-40.
36. Reynolds IR. A review of direct orthodontic bonding. *Br J orthod* 1975;2:171-8.
37. Powers JM, Kim HB, Turner DS. Orthodontic adhesives and bond strength testing. *Semin Orthod* 1997;3:147-56.
38. Bowen RL, Rodriguez MS. Tensile strength and modulus of elasticity of tooth structure and several restorative materials. *JADA* 1962;64:378-87.
39. Newman GV. Epoxy adhesives for orthodontic attachments: Progress report. *Am J Orthod* 1965;51:901-5.
40. Retief DH. Failure at the dental adhesive-etched enamel interface. *J Oral Rehab* 1974;1:265-84.
41. Knox J, Hubsch P, Jones ML. The influence of bracket base design on the strength of the bracket-cement interface. *J Orthod* 2000;27:249-54.
42. Buzzitta VA, Hallgren SE, Powers JM. Bond strength of orthodontic direct-bonding cement-bracket systems as studied in vitro. *Am J Orthod* 1982;81:87-92.
43. Katona TR. A comparison of the stresses developed in tension, shear peel, and torsion strength testing of direct bonded orthodontic brackets. *Am J Orthod Dentofacial Orthop* 1997;112:244-51.
44. Matasa CG. Adhesion and its ten commandments. *Am J Orthod Dentofacial Orthop* 1989;95:355-6.
45. Zachrisson YO, Zachrisson BU, Buyukyilmaz T. Surface preparation for orthodontic bonding to porcelain. *Am J Orthod Dentofacial Orthop* 1996;109:420-30.



**Fig 1.** Custom fabricated cylinder with well for composite resin substrate.



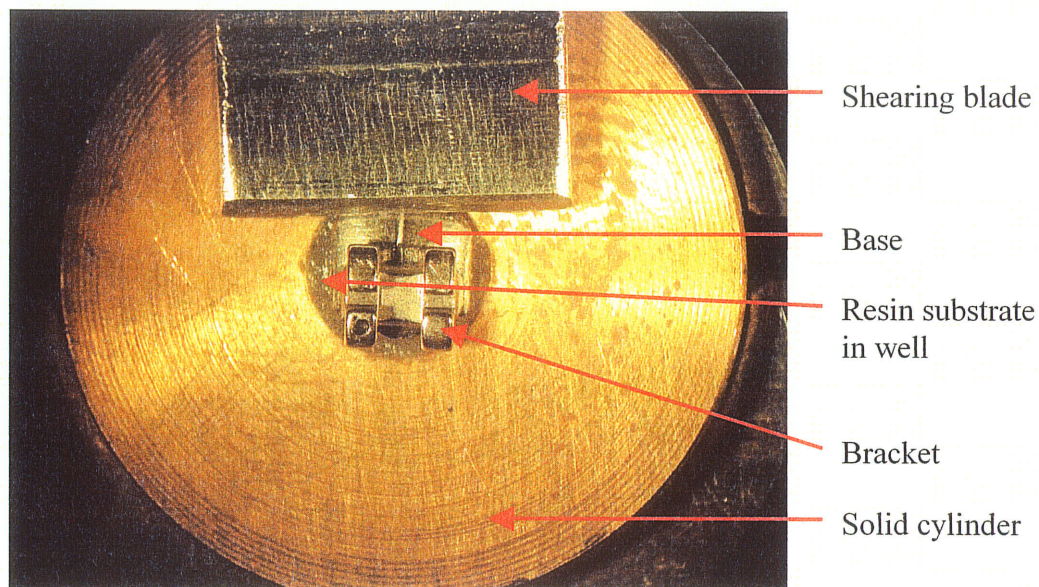
**Fig 2.** Tooth crown enamel sample with orthodontic bracket bonded to exposed facial surface, mounted in stainless steel ring filled with cold cure acrylic.



| Bracket                   | Mesh size | Mesh wire diameter (inches, mm) | Open area (%)* | Bracket base surface area (mm <sup>2</sup> ) |
|---------------------------|-----------|---------------------------------|----------------|----------------------------------------------|
| 3M Victory Series         | 80        | .0055, 0.140                    | 31.5           | 9.81                                         |
| TP Orthodontics Primekote | 80        | .0055, 0.140                    | 31.5           | 12.9                                         |
| Ormco Optimesh XRT        | 100       | .0050, 0.127                    | 30             | 14                                           |
| Ormco Ti-Orthos 2         | 80        | .0040, 0.102                    | 35             | 14                                           |
| Ormco Mini 2000 Ormesh    | 100       | .0050, 0.127                    | 30             | 14                                           |

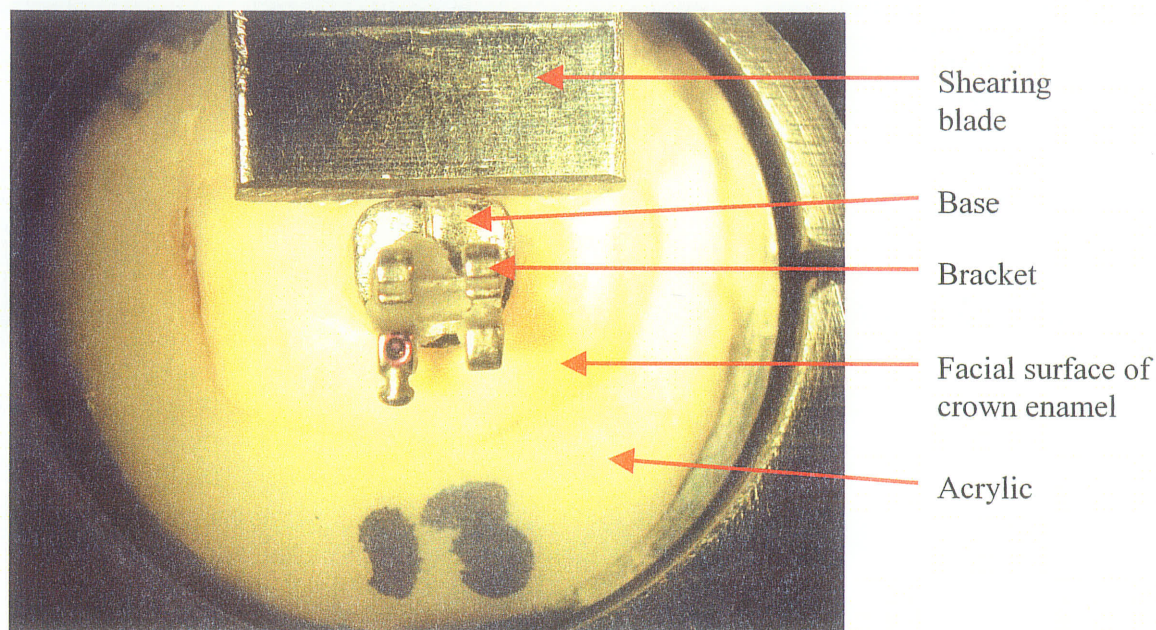
\* Determined by the manufacturer

**Table I.** Mesh-base specifications of the five brackets compared in this study.



**Fig 3.** Bracket bonded to resin substrate in the well of the brass ring is shown mounted in the Bencor Multi-T testing apparatus (Danville Engineering, San Ramon, CA, USA). Knife-edged shearing blade positioned parallel to the bracket base-resin substrate interface.





**Fig 4.** Bracket bonded to the tooth, embedded in the stainless steel ring is shown mounted in the Bencor Multi-T testing apparatus (Danville Engineering, San Ramon, CA, USA). Knife-edged shearing blade positioned parallel to the enamel-bracket base interface.

| Test Groups<br>N=30 each                       | Mean<br>SPBS<br>(MPa) | Std.<br>Dev<br>(MPa) | Coefficient of<br>Variation<br>(%) | Maximum<br>(MPa) | Minimum<br>(MPa) |
|------------------------------------------------|-----------------------|----------------------|------------------------------------|------------------|------------------|
| <b>Bonded to composite<br/>resin substrate</b> |                       |                      |                                    |                  |                  |
| Ormesh                                         | 14.88                 | 2.50                 | 16.80                              | 19.49            | 10.32            |
| OptimeshXRT                                    | 13.38                 | 2.47                 | 18.50                              | 19.33            | 9.33             |
| Ti-Orthos 2                                    | 13.37                 | 2.09                 | 15.60                              | 17.75            | 9.79             |
| Victory                                        | 16.29                 | 2.47                 | 15.20                              | 20.83            | 11.67            |
| Primekote                                      | 22.35                 | 3.07                 | 13.70                              | 28.60            | 14.56            |
| <b>Bonded to enamel<br/>substrate</b>          |                       |                      |                                    |                  |                  |
| Ormesh                                         | 18.25                 | 3.47                 | 19.00                              | 23.19            | 11.64            |
| OptimeshXRT                                    | 17.79                 | 5.24                 | 29.50                              | 30.92            | 10.10            |
| Ti-Orthos 2                                    | 14.50                 | 3.71                 | 25.60                              | 25.77            | 8.67             |
| Victory                                        | 26.80                 | 5.73                 | 21.40                              | 40.11            | 17.44            |
| Primekote                                      | 19.41                 | 3.21                 | 16.50                              | 27.65            | 12.76            |

**Table II.** Descriptive statistics of the shear-peel bond strengths (SPBS) in megapascals (MPa) for all groups tested. Groups with a dot joined by a vertical line showed no statistical differences in their mean bond strengths at a 95% confidence level (ANOVA with Tukey's post hoc test).

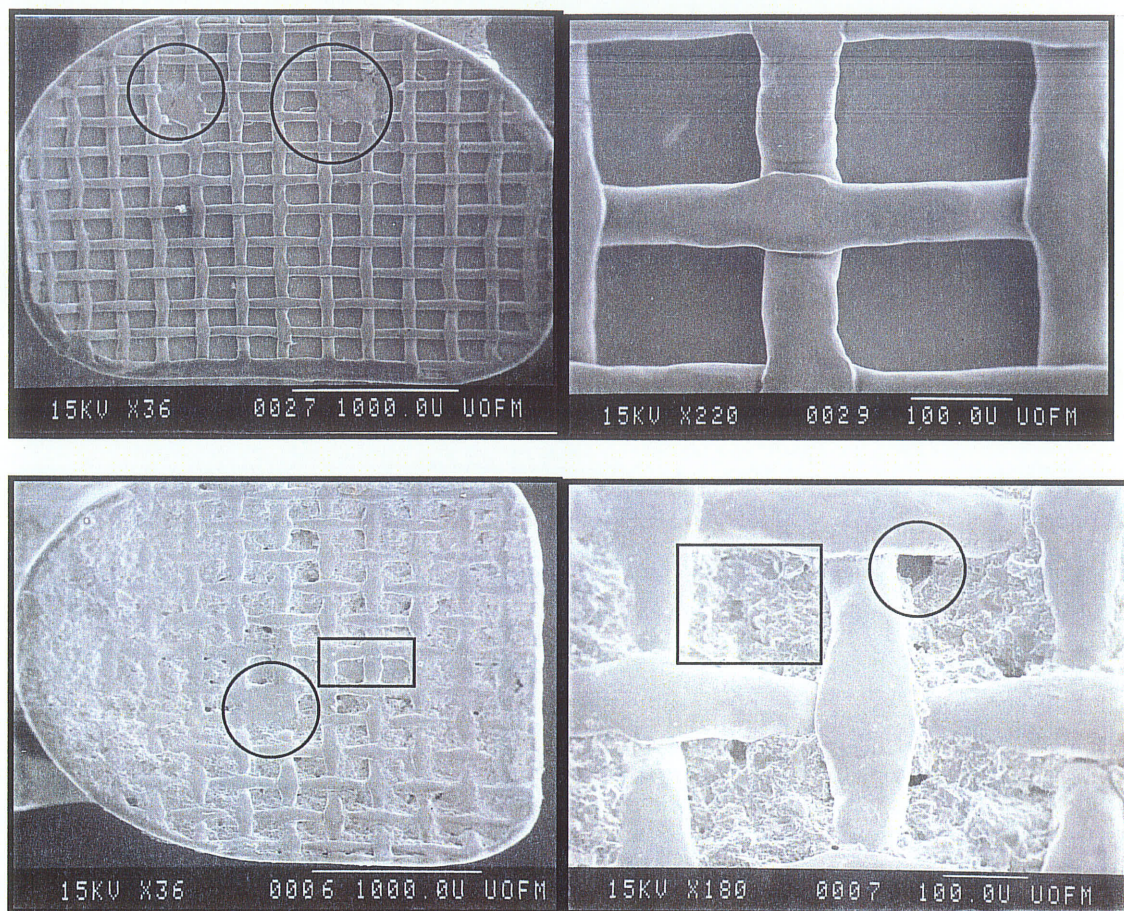
| Test Groups (N=30)                                | Fracture Interface Score (FIS) |                                        |                             |
|---------------------------------------------------|--------------------------------|----------------------------------------|-----------------------------|
|                                                   | 1 = Total adhesive fracture    | 2 = Partial adhesive-cohesive fracture | 3 = Total cohesive fracture |
| Ormco Mini 2000 Ormesh untreated mesh control (%) | 27 (90.0)                      | 0 (0.0)                                | 3 (10.0)                    |
| Ormco OptimeshXRT (%)                             | 26 (86.7)                      | 0 (0.0)                                | 4 (13.3)                    |
| Ormco Ti-Orthos2 (%)                              | 28 (93.3)                      | 0 (0.0)                                | 2 (6.7)                     |
| 3M Victory series (%)                             | 24 (80.0)                      | 0 (0.0)                                | 6 (20.0)                    |
| TP Primekote (%)                                  | 18 (60.0)                      | 5 (16.7)                               | 7 (23.3)                    |

**Table III.** Fracture Interface Scores (FIS) – bracket-composite resin substrate. FIS 1 = Total adhesive fracture between bracket base and composite resin substrate, FIS 2 = Partial adhesive-cohesive fracture, FIS 3 = Total cohesive fracture within composite resin substrate.

| Test Groups (N=30)                                | Adhesive Remnant Index (ARI) |              |              |             |
|---------------------------------------------------|------------------------------|--------------|--------------|-------------|
|                                                   | 3                            | 2            | 1            | 0           |
| Ormco Mini 2000 Ormesh untreated mesh control (%) | 6<br>(20.0)                  | 14<br>(46.7) | 10<br>(33.3) | 0<br>(0.0)  |
| Ormco OptimeshXRT (%)                             | 4<br>(13.3)                  | 13<br>(43.3) | 10<br>(33.3) | 3<br>(10.0) |
| Ormco Ti-Orthos2 (%)                              | 2<br>(6.7)                   | 15<br>(50.0) | 13<br>(43.3) | 0<br>(0.0)  |
| 3M Victory series (%)                             | 1<br>(3.3)                   | 5<br>(16.7)  | 17<br>(56.7) | 7<br>(23.3) |
| TP Primekote (%)                                  | 0<br>(0.0)                   | 7<br>(23.3)  | 16<br>(53.3) | 7<br>(23.3) |

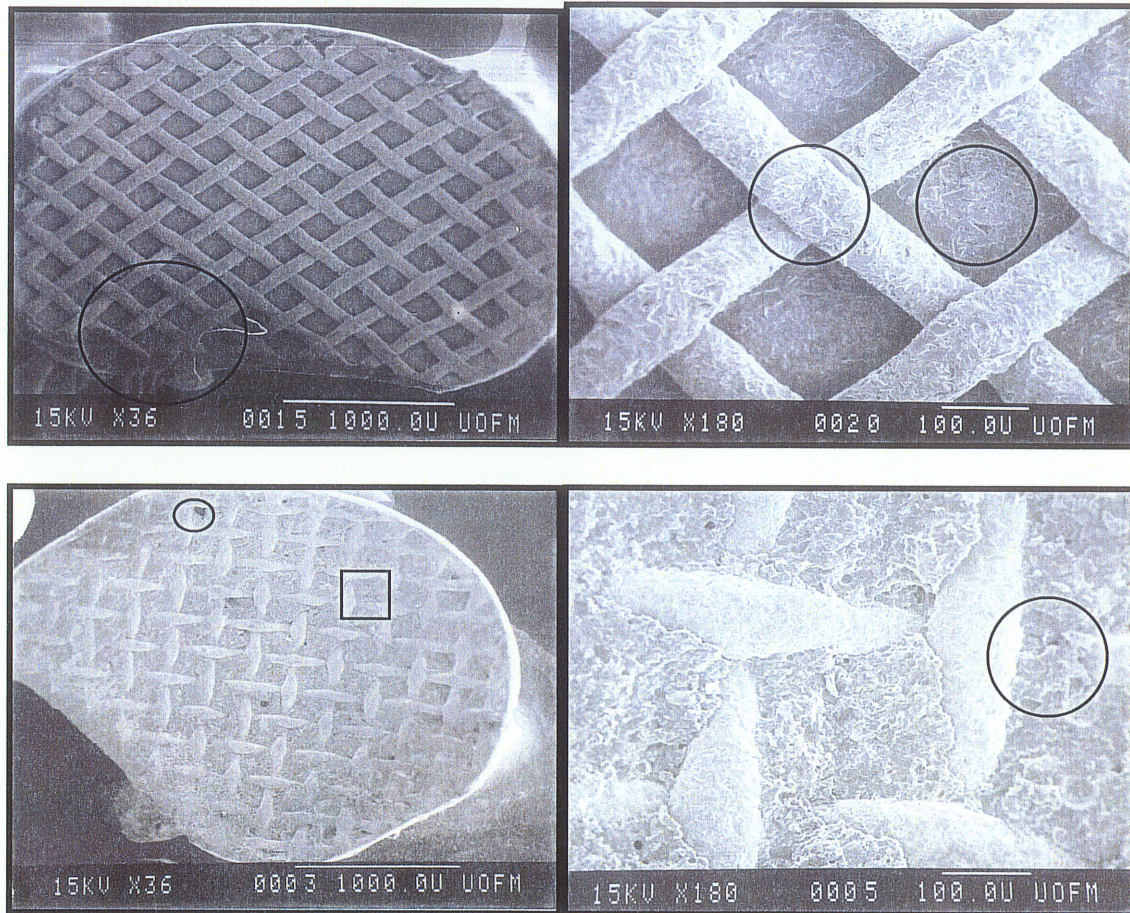
**Table IV.** Adhesive Remnant Index (ARI) scores – bracket-enamel substrate. ARI 0 = No adhesive left on the tooth, ARI 1 = Less than half of the adhesive left on the tooth, ARI 2 = More than half of the adhesive left on the tooth, ARI 3 = All adhesive left on the tooth, with distinct impression of the bracket mesh.





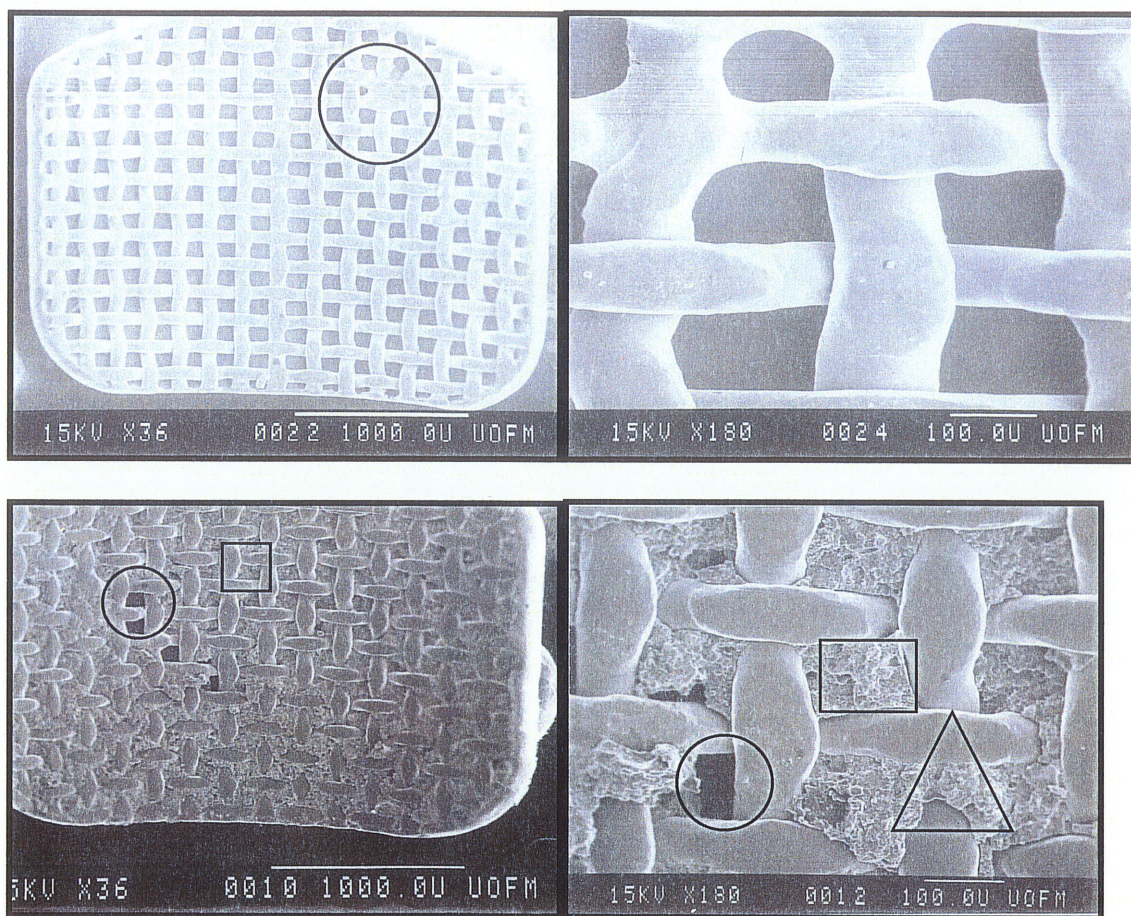
**Fig 5.** SEM of TP Primekote bracket base. **A.** before bonding; original magnification 36X. Note mesh defects (circles). **B.** before bonding; original magnification 180X. Note lack of micromechanical roughness. **C.** after debonding; original magnification 36X. Note resin overlapping mesh wires (circle) and resin pull-out (rectangle). **D.** after debonding; original magnification 180X. Note resin porosity (circle) and resin embedded between mesh wires (rectangle).





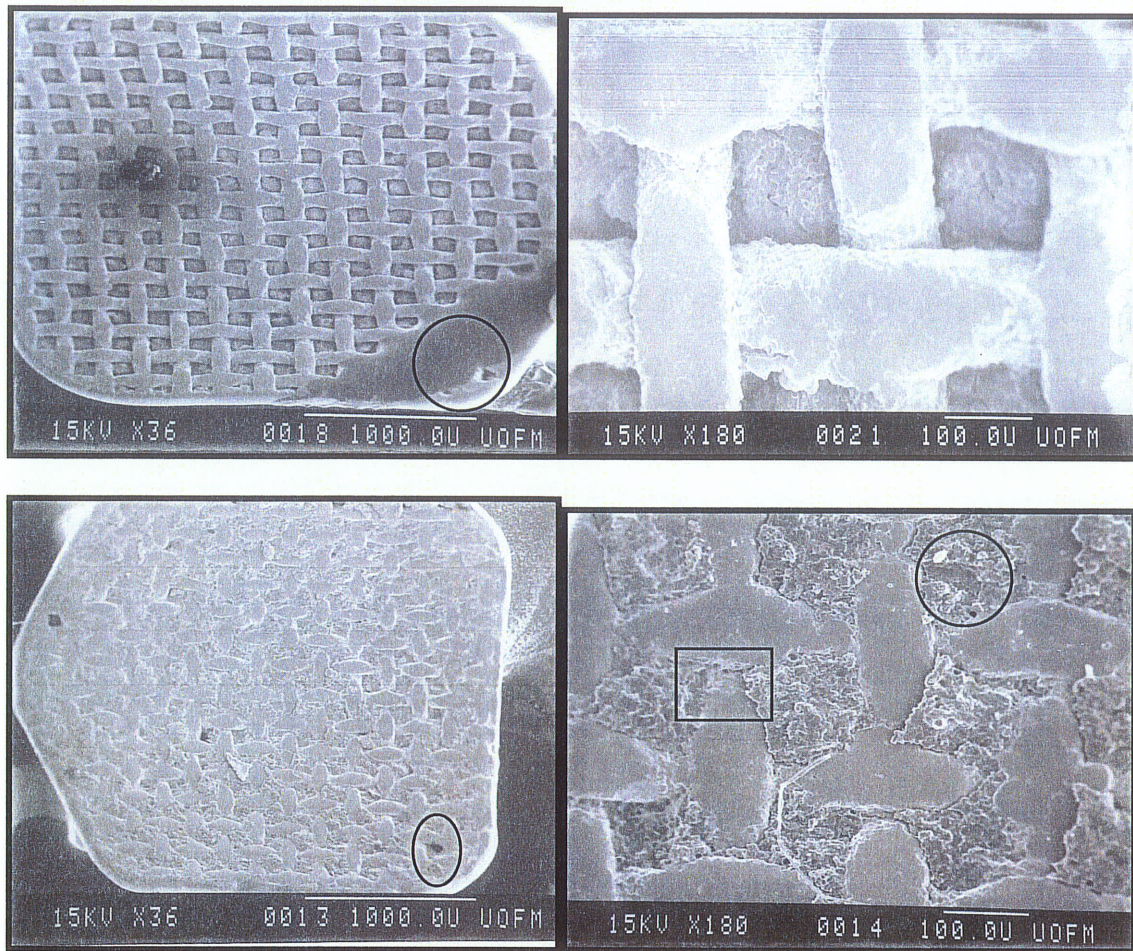
**Fig 6.** SEM of 3M Victory series bracket base. **A.** before bonding; original magnification 36X. Note area of mesh obliterated by silver DAG (circle). **B.** before bonding; original magnification 180X. Note microetched foil and mesh wire surface (circles). **C.** after debonding; original magnification 36X. Note regions of porosity (circle) and resin embedded between mesh wires (rectangle). **D.** after debonding; original magnification 180X. Note resin overlapping mesh wires (circle).





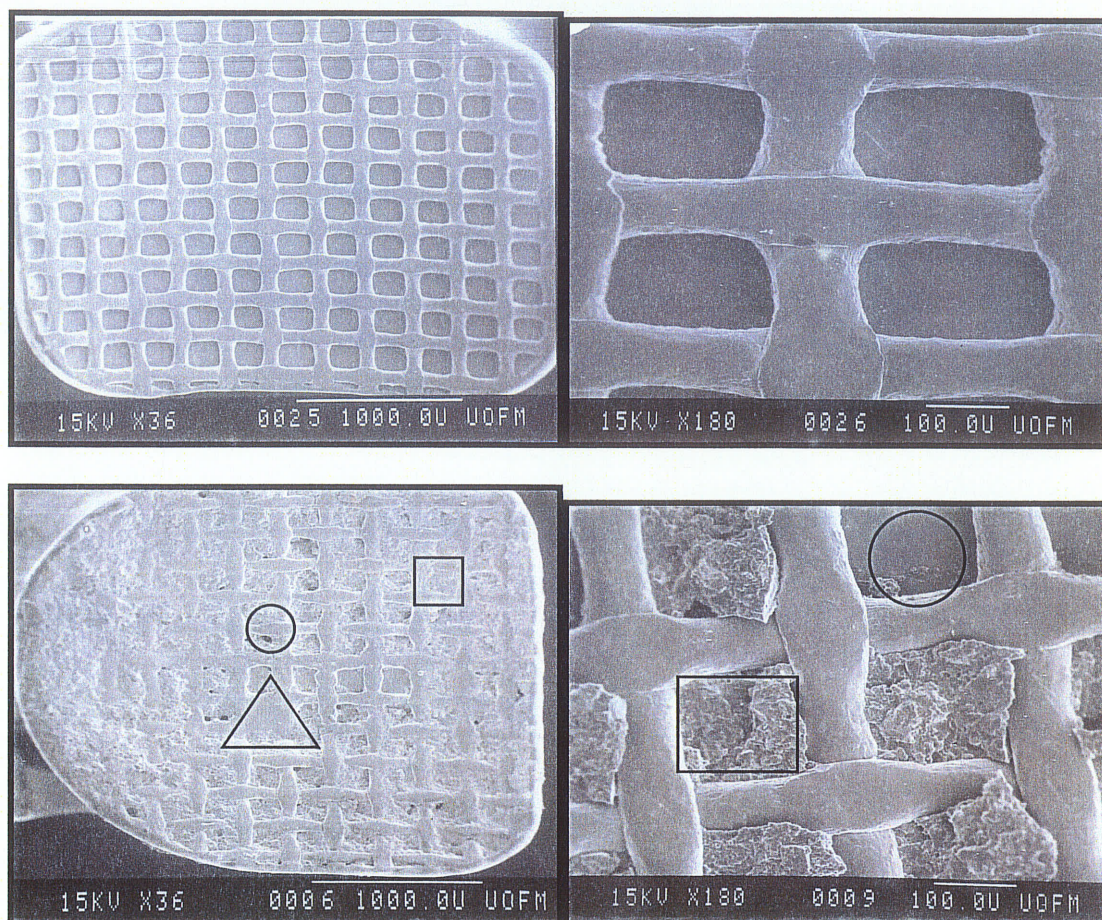
**Fig 7.** SEM of Ormco Ormesh untreated control bracket base. **A.** before bonding; original magnification 36X. Note mesh defect (circle). **B.** before bonding; original magnification 180X. Note lack of micromechanical roughness. **C.** after debonding; original magnification 36X. Note regions of resin pull-out (circle) and resin embedded between mesh wires (rectangle). **D.** after debonding; original magnification 180X. Note regions of resin pull-out (circle), resin embedded between mesh wires (rectangle), and resin overlapping mesh wires (triangle).





**Fig 8.** SEM of Ormco OptimeshXRT bracket base. **A.** before bonding; original magnification 36X. Note contaminant and area of mesh obliterated by silver DAG (circle). **B.** before bonding; original magnification 180X. Note increase in surface area of mesh wire due to metal plasma spray coating. **C.** after debonding; original magnification 36X. Note resin porosity (circle) **D.** after debonding; original magnification 180X. Note regions of resin embedded between mesh wires (circle) and resin overlapping mesh wires (rectangle).





**Fig 9.** SEM of Ormco Ti-Orthos2 bracket base. **A.** before bonding; original magnification 36X. Note lack of micromechanical roughness. **B.** before bonding; original magnification 180X. Note lack of micromechanical roughness. **C.** after debonding; original magnification 36X. Note regions of porosity (circle), resin embedded between mesh wires (rectangle), and resin overlapping mesh wires (triangle). **D.** after debonding; original magnification 180X. Note regions of resin pull-out (circle) and resin embedded between mesh wires (rectangle).