The Feasibility Of Bonding Orthodontic Brackets To Laser Treated Enamel Surfaces.

BY

DR. ZVI KANTOROWITZ

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in the

Section of Orthodontics, Faculty of Dentistry

The University of Manitoba

Winnipeg, Manitoba, CANADA

National Library of Canada
Acquisitions and Bibliographic Services
395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale du Canada
Acquisitions et services bibliographiques
395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

Our file Notre référence

0-612-32148-7

Canada

The Feasibility Of Bonding Orthodontic Brackets To Laser Treated Enamel Surfaces.

BY

DR. ZVI KANTOROWITZ

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in the

Section of Orthodontics, Faculty of Dentistry

The University of Manitoba

Winnipeg, Manitoba, CANADA

TABLE OF CONTENTS

A. ACKNOWLEDGMENTS

I would like to thank Dr. Robert Baker for accepting the challenge of supervising and supporting this project during the past two years, for his insight and advice in the planning and executing of the experimental work, and during the writing of this thesis.

A special thanks for Dr. John Featherstone, who introduced me to dental research and taught me how quality research should be done, for his support throughout this project, by donating laboratory equipment, materials and personnel in the Department of Restorative Dentistry at UCSF, and especially by donating his knowledge and time.

To Larry Watanabe, who contributed his knowledge and time to develop the shear bond strength testing methodology for this project, to carry out the experiments and operate the scanning electron microscope, always with a smile and maintaining a high spirit.

Many thanks for Dr. Dan Fried and the laser lab technicians at UCSF for making the effort to accommodate the requirements of the research protocol, while under the time constraint of my visits to UCSF.

This work could never have been completed, if not for my wife, Orly, who accompanied me on the road less traveled over the past ten years, and I would have never got as far as I did , if not for my parents, who gave me a supportive home all my life, with constant encouragement to excel in whatever venue I chose.

The financial support of the following organizations is greatly appreciated:

- Alpha Omega Foundation of Canada - Research Award
- The Canadian Foundation for the Advancement of Orthodontics - Research Award
- The American Association of Orthodontists Foundation - Graduate Program Fund
- NIH/NIDR Grant DE09958 (Dr. John D. B. Featherstone)

Materials donations by the following companies are also greatly appreciated.

- GC America
- 3M Unitek
- GAC International

B. SUMMARY

The purpose of this project was to examine the possibility of treating enamel surfaces with laser irradiation, instead of acid etching, prior to the bonding of orthodontic brackets. The specific aim of this study was to compare shear bond strengths of orthodontic buttons bonded to enamel surfaces treated with a carbon dioxide (CO_2) laser vs. conventional methods, utilizing a composite resin and a resin-modified glass ionomer cement. The effects of the laser treatment on the enamel surfaces were also studied.

In order to resolve some of the problems associated with shear bond strength testing in orthodontics, a new method was developed by modifying the Single Plane Shear Test Assembly (SPSTA). Shear bond strengths of orthodontic brackets bonded with composite resins and with light-cured glass ionomer cements (GIC), to teeth treated by means of several different laser conditions were measured and compared to the shear bond strengths to etched and non-etched surfaces, and, for GIC only, to polyacrylic acid conditioned enamel, as well. Laser beam parameters varied among groups only in their pulse fluence (Energy/Surface area).

The effects of the various pre-bonding treatments on the enamel surface were studied in two ways. Firstly, surface effects were assessed qualitatively with a scanning electron microscope in C-Fast mode. Secondly, the depth to which each treatment had affected the surface was measured by a digital image analysis of thin cross-sections of treated teeth under a light microscope with magnifications of up to 1000x.

Shear bond strengths to laser treated enamel was higher than to non-treated enamel, and lower than to acid-etched enamel, for both materials, in all laser treated groups. However, composite resin reached a bond strength which may be considered acceptable (mean = 11.84 MPa), only in the group treated with the highest laser fluence (9.5 J/cm^2), which may have adverse effects in a vital tooth. GIC mean bond strengths following irradiation at three different fluences (3.5, 5.0 and 9.5 J/cm^2) were similar to that measured for the polyacrylic-conditioned enamel (Mean = 9.76 MPa). Bond failure was in the enamel/cement interface in all samples.

SEM examination of the laser treated surfaces revealed partial melting and fusion, which increasingly covered the surface, as the laser fluence increased. At the highest fluence tested, 9.5 J/cm^2, the entire treated area was undulated, with numerous sites of exfoliation and pitting, and covered with globular residues which appear like balls of melted enamel.

Cross-sectional imaging of laser treated teeth, showed an increase in the depth of surface effects, such as cratering, as the fluence increased. The highest fluence used (9.5 J/cm^2), resulted in craters and pits, as deep as 110 μm.

In conclusion, composite resins bonded well to laser irradiated enamel, only when relatively high fluences are used. These high fluences may have adverse effects on vital teeth. Resin-modified glass ionomer cements bonded well to laser irradiated enamel, even when low fluences were used. The CO_2 laser may enhance clinical performance of GIC instead of acid etching, potentially decreasing caries formation around brackets and without endangering tissue integrity. The shear bond strength testing resulted in a low variation of measurements and the method is proposed as a standardized test.

C. INTRODUCTION

Currently, orthodontic brackets are often bonded to the enamel surface with light cured composite resins. The clinical procedure includes the following steps[1]:

1. The buccal surfaces of the teeth are polished with pumice, then rinsed and dried.
2. The enamel is etched with 37% phosphoric acid for 15-60 seconds, then rinsed and dried.
3. While maintaining a dry field, resin primer is placed on the etched surfaces.
4. Composite paste is placed on the retentive face of the bracket, the bracket is pressed against the enamel in the desired position, and excess bonding material is removed.
5. The bonding material is then cured for 20 seconds on each, of the mesial and distal sides of the bracket with a 470 nm light source.

There are a few drawbacks to this procedure. It involves a series of technique-sensitive steps and requires a completely dry field of operation from start to finish. After debonding, remaining bonding material residues require mechanical removal which is time consuming and often times results in the enamel surface being scratched[2]. In addition, regardless of the bonding agent, orthodontic brackets also serve as a plaque trap, resulting in decalcification around bracket margins, also known as white spot lesions, which develop within a few weeks of bracket placement[3,4,5].

One possible solution to the demineralization problem might be the use of glass ionomer cements instead of composite resins. These cements leach fluoride over a long period of time into the adjacent enamel and have the capacity to capture fluoride from fluoridated dentifrices. The presence of fluoride has been shown to decrease enamel demineralization around orthodontic brackets and to increase surface remineralization[6,7]. Glass ionomers of the newer generations are hybrids that contain different resins and are light-curable[8]. Unlike composite resins, which bond mechanically into the etched enamel, the hybrid glass ionomers (GIC) create a physiochemical bond. This bond can be achieved without etching of the surface[9] and the bond strength is superior to the chemically-cured glass ionomers[10,11]. In addition, these materials require a wet environment to achieve an ionic bond, not a desiccated surface as required by composite resins. Another advantage of GIC is their ease of removal after debonding.

Unfortunately, glass ionomer cements have repeatedly demonstrated lower shear bond strength relative to composite resins in vitro[10,11]. In the few clinical studies which tested these cements, the failure rate was 3-12%, compared to less than 2% with composite resins[9,12,13]. These clinical trials were done on small sample groups with selected case difficulty and for a relatively short time span. These limitations may mean that in less controlled circumstances the failure rate may be even higher. Bond failure interrupts the process of orthodontic tooth movement and may undermine the patient's confidence in the orthodontist.

The purpose of this project was to try a novel approach to solve some of the problems described above. The overall idea is that CO_2-laser treatment of the enamel surface can allow for bonding of orthodontic brackets, with adequate bond strength, without the need for any other surface preparation. In order for laser irradiation to prepare enamel for resin bonding, it should be able to create a uniformly retentive surface without adversely affecting the pulp and surrounding tissues. To achieve this task, the laser energy has to be absorbed as much as possible in the outer layer of the enamel causing ablation of the surface.

Bonding orthodontic brackets to laser etched teeth was attempted by Roberts, who concluded "...laser bonding took considerably longer, was less reliable in terms of bond strength, and produced more discomfort than conventional acid etching"[14]. Another study which measured tensile bond strength of orthodontic brackets to acid *vs.* laser-etched enamel, had very poor results in the laser group and concluded that "...etching enamel with the Nd:YAG laser is an ineffective pretreatment for bonding brackets to enamel"[15]. However, both studies used a Nd:YAG laser which emits light at a wavelength of 1.06μm which is absorbed poorly by enamel (absorption coefficient, $\mu a < 1\ cm^{-1}$) [16]. The CO_2 laser, on the other hand, emits light at wavelengths between 9.3 to 10.6μm which absorbs thousands of times more efficiently than Nd:YAG laser in enamel ($\mu a = 800\text{-}6{,}000\ cm^{-1}$). Only two studies measured bond strength of composite resin to CO_2 laser etched enamel surfaces[17,18]. In both cases, 10.6μm wavelength was used, and only one of several laser conditions tested, allowed for reasonable bond strength. However, the energy densities (fluences) used to achieve proper bond strength were in both cases relatively high (24 and 35 J/cm^2). These high energies may result in an undesirable increase in pulp temperature, and physical and chemical phase changes, at the surface.

Recent studies have shown the possibility of achieving similar enamel surface ablation with lower fluences, which are safer to the pulp, by using other wavelengths, and adjusting different beam parameters[16,19,20]. For bonding with the glass ionomer cement, a primed noncontaminated surface is required, rather than physical adhesion sites. Such preparation requirement may be achieved with even lower laser fluences.

If successful, such treatment may eliminate the polishing and etching steps. It may also increase the bond strength of glass ionomers to a level, which is clinically acceptable, and thus eliminate the need for a completely dry field. In addition, CO_2 laser treatment of enamel has been shown to decrease subsequent demineralization and to increase remineralization by fluoride[21,22]. It is therefore possible that this pre-bonding laser treatment may, in addition, decrease the incidence of demineralization around orthodontic brackets, and increase the remineralization by fluoride from dentifrices and glass ionomer cements.

In order to test the hypothesis, that CO_2-laser treatment of the enamel surface can achieve clinically acceptable bonding of orthodontic brackets, a series of *in vitro* studies should be taken to identify optimal laser beam characteristics that allow for clinically acceptable bracket bond strength, while maintaining tooth vitality and integrity. These laser beam conditions should then be tested *in vivo*. This thesis represents the first step in that sequence.

The aim of this specific study was to compare shear bond strengths of orthodontic appliances bonded to enamel surfaces treated with CO_2 laser irradiation vs. conventional methods, utilizing a composite resin and a modified glass ionomer cement. The effects of the laser treatment on the enamel surface were also studied.

D. RATIONALE FOR THE METHOD OF SHEAR BOND STRENGTH TESTING

Although pure shear force does not occur in the oral cavity, and is not the cause for clinical failure, the shear bond strength is used as an indication of the suitability of the bond to withstand the intra-oral forces during orthodontic treatment. Unfortunately, the methods used for shear bond strength testing are not standardised. Tooth selection and preparation, type of attachment, unit of measurement, statistical analysis method and the method of debonding force application vary considerably among these studies[23]. Differences in the direction of force application to cause bond failure or in the bracket position relative to that force, result in different stress patterns in the bracket/cement/enamel complex[24] (Figure 1). These variations between the different methods result in a spectrum of experimental results, which are often conflicting and do not allow for comparison between studies[25,26].

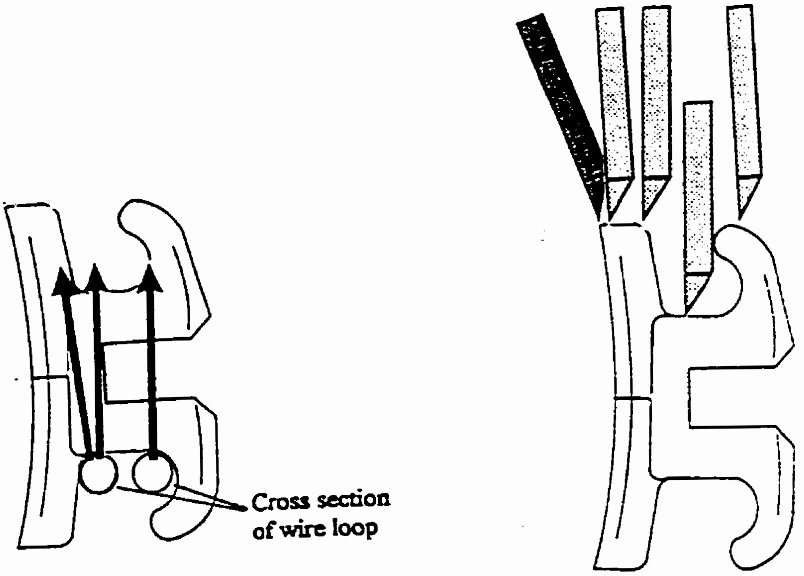


Figure 1: Variation in force direction and point of application in shear bond strength studies

In addition, some of the methods used for shear bond strength testing do not control for undesirable variation <u>within the experimental design</u>. Variation in the anatomy of teeth results in different degrees of adaptation of curved brackets to the tooth surface. Variation in enamel composition due to exposure to fluoridated water may effect chemical bond. Variation in the size of the bonded area is directly proportional to the force required for failure. Variation in the actual force effecting the bracket due to inconsistent placement of a shearing knife or a wire loop, also affects the failure measurement. These variations, and others, within the methods, result in a greater variation within groups in the same study, yielding a wide range of results and masking differences between groups (Table 4-Table 5, page 47).

In order to resolve some of the problems associated with shear bond strength testing in orthodontics, a new method was developed in cooperation with Larry Watanabe of The University of California at San Francisco (UCSF) Department of Restorative Dentistry. The method controls for many of the undesired variables associated with these types of experiments and hopefully, would be adopted by other research groups in the field, as a standard test. The method uses a modification of the Single Plane Shear Test Assembly (SPSTA)[27,28], which is currently under review by the International Standard Organization (ISO), as a standard method for shear bond strength tests in dentistry.

The design of the shear bond strength test is intended to limit the variables to those which are being studied, surface preparation and bonding agent. The following is a detailed description of the test components and the rationale behind each one of them.

a. Reproducible enamel surface.

When human teeth are used, natural variation in morphology results in enamel surfaces of different curvature. These two factors may influence the bond strength and introduce variability into the study. Bovine incisor teeth, which can be easily obtained in large quantities, have a large, and a relatively flat surface, covered by a thin cementum-like layer. Bovine teeth have been found to have similar results in adhesion tests with both, composite resins and glass ionomer cements, when compared with human teeth[29,30,31].

The crowns of freshly extracted bovine teeth are cleaned thoroughly with water and a toothbrush, and stored in double deionized water (DDW) with thymol, a medium that does not affect the chemical composition of the enamel[32]. Shear bond strength tests performed on teeth stored in DDW with thymol, between 24 hours and up to five years, yielded similar results, regardless of the storage time[33].

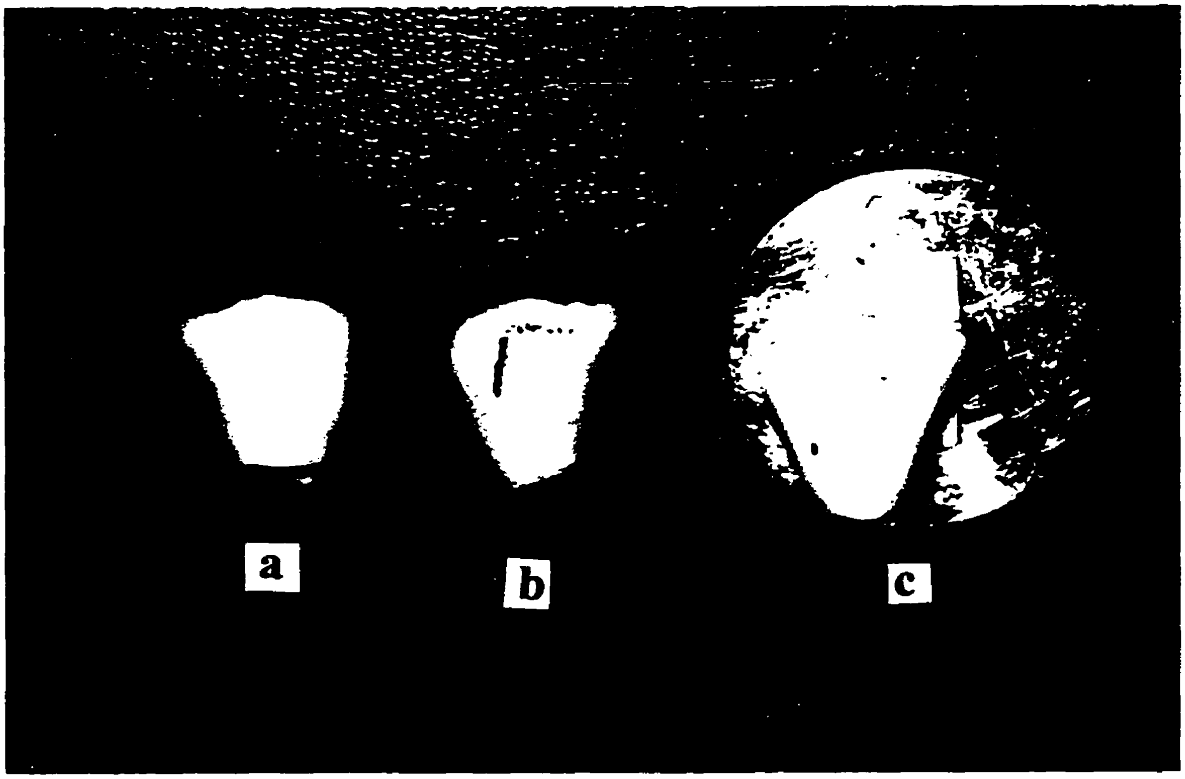


Figure 2: a. Crown of bovine incisor, b. After polishing, c. After laser irradiation

A simple serial polishing process yields a large, flat, clean and reproducible enamel surface (Figure 2). The serial polishing of the labial surfaces is executed on a manual strip grinder (Handimet I, Buehler Ltd., Evanston, Illinois). Polishing strips of 240, 320, 400 and 600 grit silicon carbide paper are used sequentially with each tooth and each spot on the 600 grit strip is only used once, to ensure consistent results. Since the polishing process leaves unidirectional grooves, which may influence the results of a shear bond strength test, it should be done in an occluso-gingival direction and the shear force is applied in the same direction.

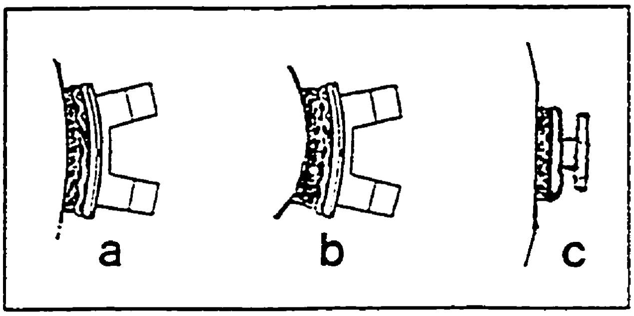
Figure 3: Handimet I strip grinder.

b. Reproducible appliance/tooth compatibility.

Another factor influencing bond strength is the adaptation of the bracket base to the tooth surface. Bracket bases have a curvature that is designed to fit the tooth curvature. As mentioned earlier, variation in tooth morphology means that each tooth can relate differently to the curved bracket base. This lack of precision can also cause variation in the bond strength. A consistent and reproducible adaptation between the bonded attachment and the enamel surface is achieved by using <u>a flat based orthodontic attachment and a flattened enamel surfaces</u>, achieved by the serial polishing process, described above (Figure 4).

In this method flat mesh-based rounded lingual buttons (GAC International, Central Islip, NY) are used. The benefit of a rounded attachment, rather than a rectangular bracket, is the elimination of corners, projections and planes which may be engaged in an uneven fashion by the force delivery system. For example, if the bracket base is not precisely parallel to the shearing knife edge, it would be hit at an angle, absorbing the full shearing force in one corner, resulting in a different stress distribution than that expected in a flush engagement. In the case of a rounded attachment, the shearing knife is always tangential to the attachment base, no matter where it is engaged, thus affecting it in the same manner (Figure 5).

Figure 4: Adaptation between curved bracket bases and teeth varies with anatomy (a, b), and is reproducible between flat base and polished enamel (c).



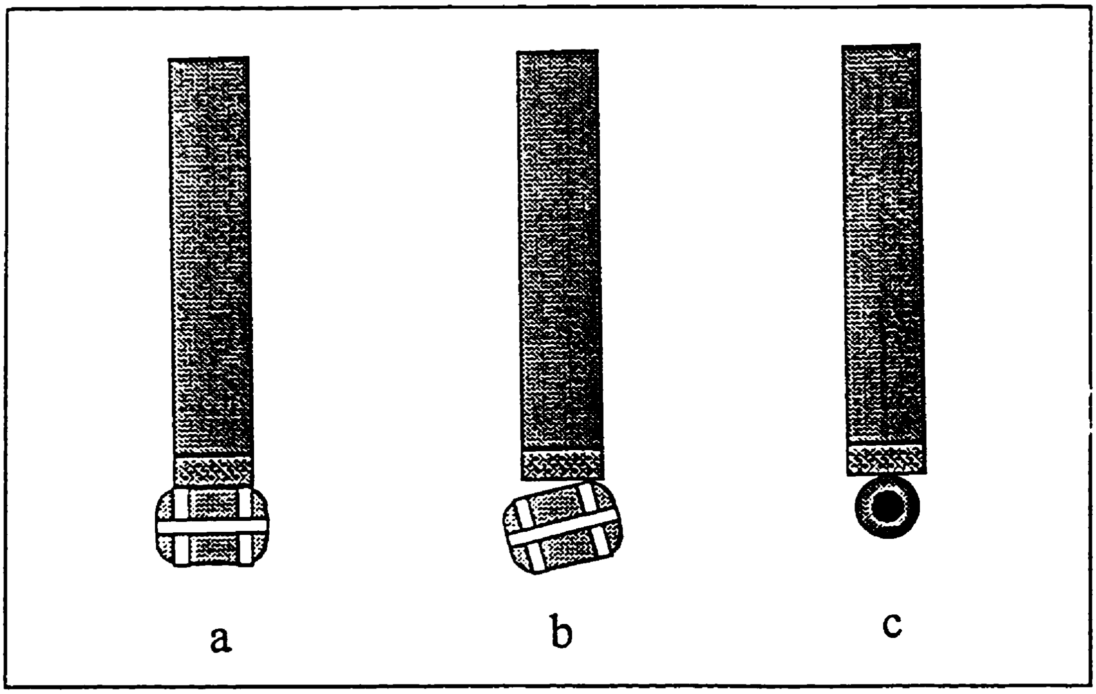


Figure 5: a. Horizontal alignment of shearing knife and bracket, b. Slight misalignment results in different stress distribution through the bracket base. c. Round attachment - force is always tangent to button - reproducible horizontal engagement.

c. Constant area of bonded surface.

The force required to shear a bracket off depends on the total bonded area. When a bonding agent is placed on a surface it spreads in all directions. The area it will occupy depends on the material, the surface composition and morphology, and the pressure on the bonding agent at the time of application. Many investigators have attempted to control this variable by applying constant pressure while bonding, and/or removing excess material around the bracket. The bonded area is often assumed to be the area covered by the bracket. However, due to uneven spread of the cement underneath the bracket, and due to variation in the cleaning instrument angle and shape, the actual area which is bonded is unknown, and therefore, may be different between specimens. In addition, the removal of excess bonding material may pull the material, weakening its bond strength or conversely, strengthen the material by a "high beaming" effect (Introducing a fold in the material increases its stress resistance, like high beams used for construction). The provision of a constant area of bonded surface in this method is achieved by the use of an adhesive mylar strip. Using a sharp office hole puncher, a 3.1mm diameter hole is made in the mylar strip. Using the adhesive side, the strip is then affixed to the prepared enamel surface, leaving a constant exposed area. The bonding agent spreads and covers the hole completely, resulting in a reproducible bonded area in all specimens. The orthodontic button diameter (3.2mm) is slightly larger than the bonded surface and covers the hole consistently.

d. True shear force.

As mentioned earlier, a myriad of methods, using shearing knives and wire loops, have been employed in an attempt to create a shearing force through the bracket/cement/enamel complex. These techniques, when applied to the bonded attachment, do not produce a true shearing force, but rather a shear-peel combination. The wire loop is placed under the bracket wings and then pulled by a testing machine (such as an Instron). Shearing knives are placed in different locations by different researchers. They may be placed at the edge of the bracket base, between the wings and the base, or against the tips of the wings (Figure 1). The various places that these elements engage the bracket and the angles in which the forces are directed create different combinations of tensile and compressive stresses in the bracket, the cement and the enamel[24].

In order to create a real shear force through the bracket/cement/enamel complex a modified single plane shear test assembly (SPSTA) is used. The SPSTA consists of two Delrin material plates (Figure 6). After the punctured mylar strip is placed on the polished enamel surface, it is affixed to the surface of plate I with the tooth suspended through a counter-sunk funnel-shaped hole in the plate (Figure 7a). Green die stone (Die-Keen green, Miles Inc., South Bend, IN) is poured into the hole to hold the tooth in this position. The polished enamel surface is now flush with the surface of the plate (Figure 7b)

The orthodontic button is now bonded to the tooth with the bonding agent to be tested (Figure 7d). Petroleum jelly is placed around the edges of the cement. Plate II is attached with two screws to plate I. A small counter-sunk hole in plate II is now right on top of the bonded button (Figure 7d). Composite resin (Z100, Unitek, Monrovia CA) is condensed into the small hole around the bonded button in increments, which are light cured for 40 seconds each. The SPSTA is now ready for testing.

The SPSTA is attached to a universal testing machine (Instron Model 1122, Canton, MA) with two alignment plates (Figure 7e), the two screws that hold the two plates together are removed, leaving only the bonding agent holding plate A and B together. The SPSTA allows the force of the machine to occur in one plane only, which is parallel to the enamel-bonding agent interface. The machine cross head speed should be set to 0.5mm/min., in order to avoid increased variation in measurements, which is associated with higher speeds. The force failure measurements (in Newtons) should be divided by the bonded area to yield the stress required for failure and represented in MegaPascals(MPa).

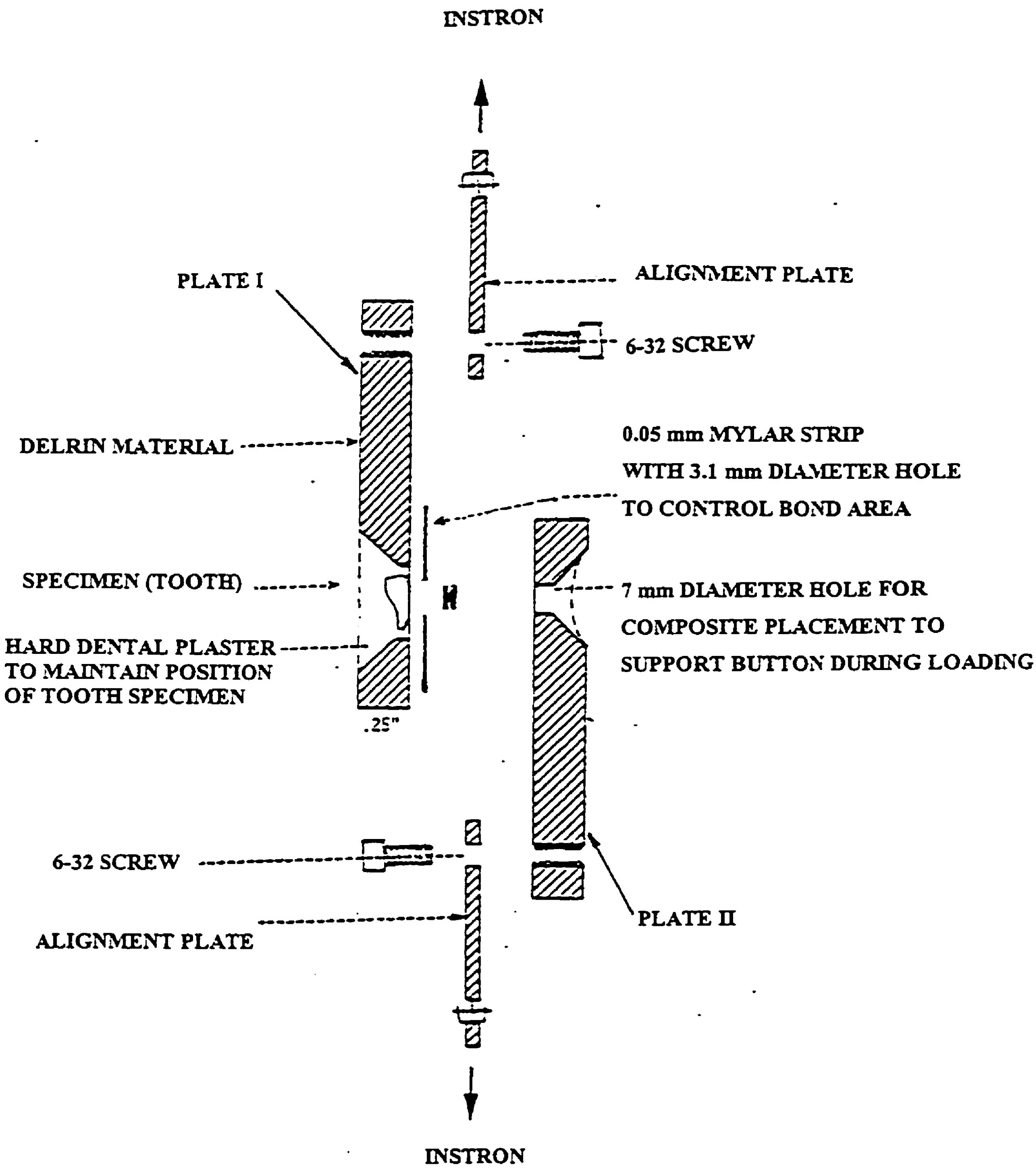


Figure 6: Exploded view of the modified Single Plane Shear Test Assembly (SPSTA)

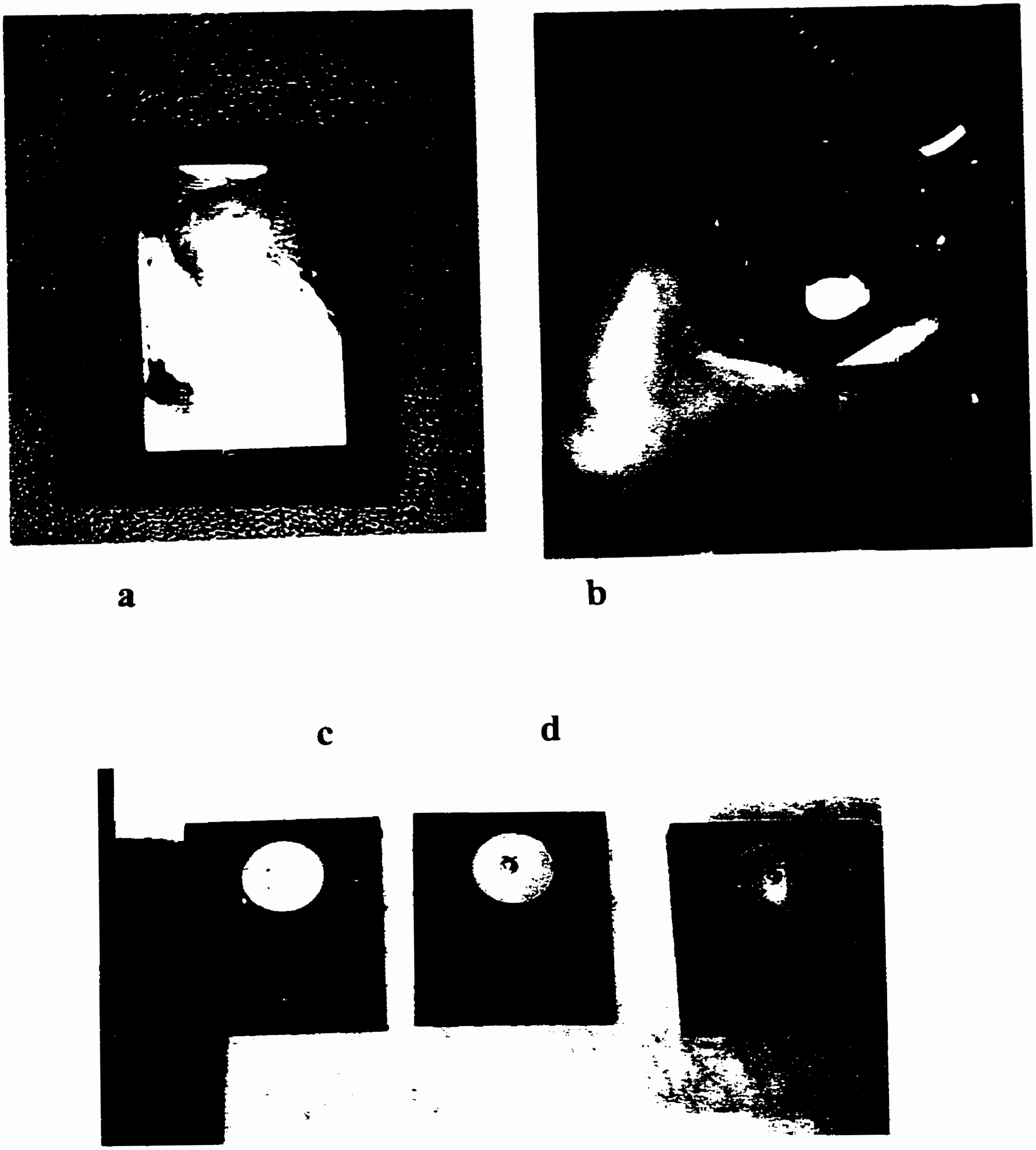


Figure 7: Steps in preparation of a specimen in the SPSTA: a. Tooth with mylar strip in plate I, b. Stone is poured to fix sample in plate I, c. Plate I with tooth set in stone, d. Button bonded to sample

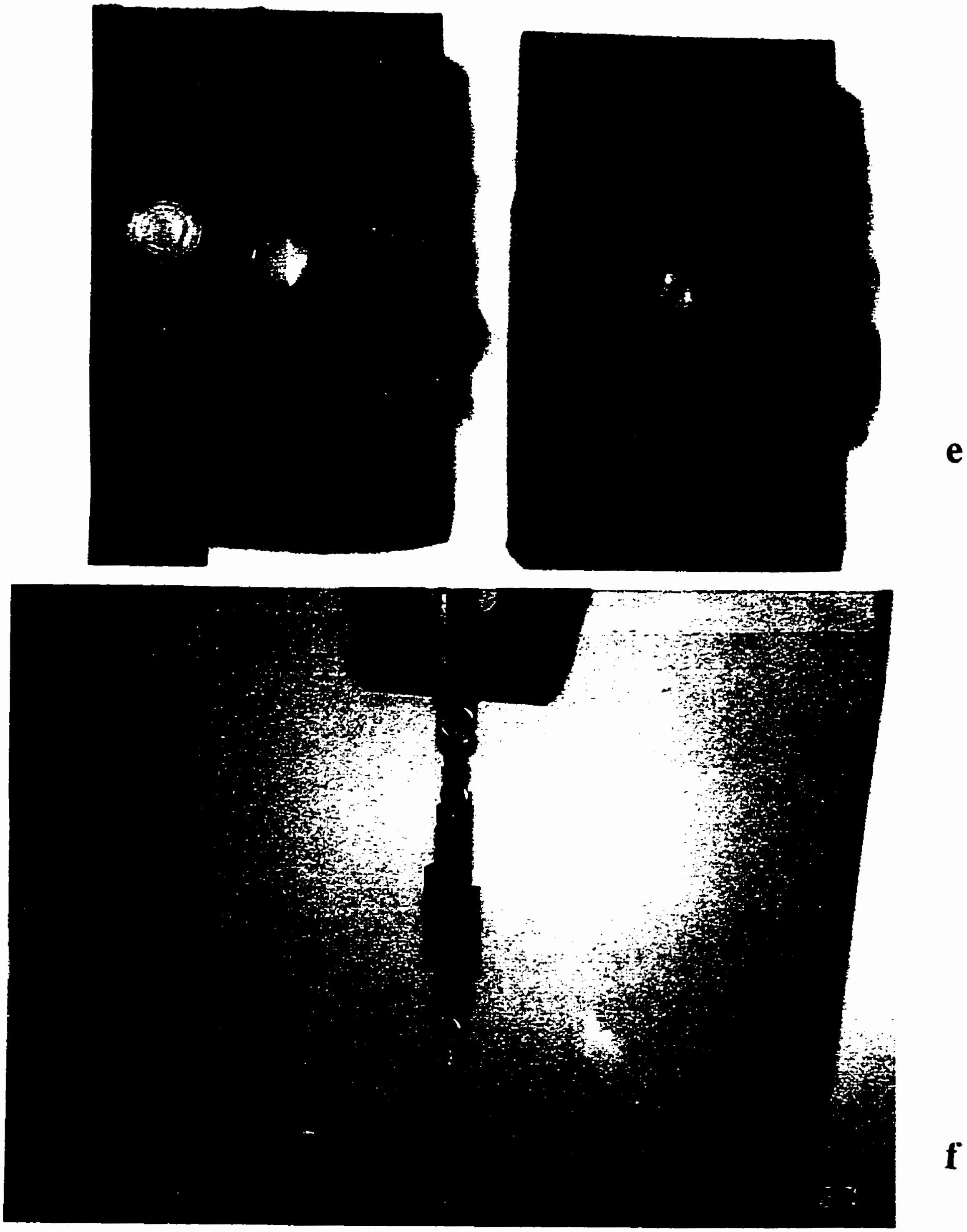


Figure 7 (continued): e. Plate II is attached to plate I with two screws, and resin is placed to set plate II and button together, f. SPSTA assembly attached to Instron, screws are now removed.

E. MATERIALS AND METHODS

The following experiments were performed:

1. Shear bond strength of orthodontic buttons bonded with a composite resin, to laser treated enamel, compared with non-treated and acid etched enamel controls.
2. Shear bond strength of orthodontic buttons, bonded with a resin-modified glass ionomer cement to laser treated enamel, compared with non-treated, acid etched and conditioner treated enamel controls.
3. Surface and cross-sectional evaluation of laser irradiation effects on tooth enamel.

1. EXPERIMENTAL DESIGN OUTLINE:

- a. Bovine incisor teeth were polished to produce a flat enamel surface.
- b. The surfaces were prepared for bonding either by laser irradiation or by a conventional method (acid etching, GC conditioner).
- c. Flat-based orthodontic button was bonded to each surface with either a light cured composite resin or a resin modified glass ionomer cement.
- d. Shear bond strength was measured utilizing a modified single plane shear test assembly in a universal testing instrument (Instron).
- e. Shear bond strengths of experimental groups were compared to control groups, statistically, and to clinically acceptable levels, as reported in the literature.
- f. Laser irradiation effects on the enamel were assessed using scanning electron microscopy of surfaces and light microscopy analysis of thin cross sections.

2. SURFACE PREPARATION FOR BONDING

Freshly extracted bovine incisors were collected at a Winnipeg slaughter house (Burns Meats Inc.). The roots were removed with a water-cooled high-speed handpiece with a carbide bur and the crowns were washed with water and stored in double deionized water with thymol. Shear bond strength testing took place within the next two weeks. The buccal surfaces underwent serial polishing to 600 grit on a manual strip grinder (Handimet I, Buehler Ltd., Evanston, Illinois), as described above (page 16). Seven pre-bonding treatments were tested on the polished enamel surfaces, including four different laser conditions and three controls.

a. Rationale for choice of laser treatment parameters

Laser treatment was done in the laser laboratory of Dr. John Featherstone in the Department of Restorative Dentistry at the University of California in San Francisco (UCSF). The lab is equipped with several laser devices, with several wavelengths and different power output combinations. This set-up allows for a choice of a variety of laser beam parameters, based on previous knowledge, rather than what is available. In addition, the lab is equipped with several detectors and a thermal camera which allow for measurements of the actual energy output and the beam's profile. These instruments were proven to be extremely important in previous studies, due to the fact that laser output is not always coincident with manufacturers specifications or the instrument's settings (Dan Fried, unpublished data).

The physical bond of composite resins requires an irregular surface, which can be produced by the process of laser ablation, achieved by using high fluences. However, high energy deposits may cause irreversible damage, if the pulp temperature rises significantly. Therefore, the laser beam parameters have to be such that they will cause ablation to the outer enamel layer, with minimal absorbed energy and minimal pulp temperature rise. Resin-modified glass ionomers, on the other hand, require access to the mineralized tissue to establish the chemical bond. Therefore, their bond strength may be increased by removing organic material and exposing the mineralized crystals, which may be achieved by using lower laser fluences.

Laser beam parameters include: wavelength, pulsed *vs.* continuous mode, pulse energy, pulse duration, number of pulses, repetition rate and energy density (fluence). In previous studies it was found that a small change in any of these parameters can produce a significantly different effect on dental enamel[21,34]. Based on these studies and additional unpublished data, a set of parameters that produced surface ablation, with minimal increase in pulp temperature was selected.

The CO_2 laser is capable of emitting light at four different wavelengths in the infra-red region, between 9.3 and 10.6 μm, all of which are highly absorbed by enamel, with current commercially available CO_2 lasers emitting light at 10.6 μm. A custom built, tunable CO_2 laser (Pulse System Inc., Los Alamos, NM), located in this laboratory, offers all of the above wavelengths, with pulse duration variable from 50 to 500 μs and pulse energy from 0 to 240 mJ. SEM images from previous studies (unpublished data), showing enamel surfaces treated by various combinations of beam parameters produced by the same laser were reviewed. A set of parameters that produced a rough surface using a low fluence and a low number of pulses was identified. These parameters were, a wavelength of 10.3 μm, pulse fluence 10 J/cm^2, pulse duration 100 μs, 10 pulses and repetition rate 10Hz.

As mentioned earlier, the undesirable increase in pulp temperature is directly correlated with the absorbed energy, which is dependent on the energy per pulse and the number of pulses used[20]. It was noted that while 10 laser pulses at these specific parameters achieved ablative effects, 25 pulses caused further melting and fusion, yielding a smoother and less retentive surface. Hence, using 10 pulses is a better choice from both, ablative and pulp safety perspectives.

Since GIC may not require surface ablation, and in order to decrease the potential for pulp damage, two fluences below the ablation threshold and two above it were applied in this study, while maintaining all other parameters constant. The ablation threshold for this wavelength is with fluence of approximately 5.5 J/cm^2, per pulse, and therefore the fluences used were: 3.5, 5.0, 7.5 and 9.5 J/cm^2.

Since the orthodontic button used has a diameter of 3.2 mm, and allowing some margins for ease of placement, a 4x4 mm square area was laser treated on each of the polished enamel surfaces. To ensure uniform and consistent laser irradiation of all samples, each tooth was moved relative to the laser beam by a computer controlled XY stage. Although the spot size was 0.99 mm, due to non-homogenous energy distribution throughout the beam, laser irradiation was applied every 0.5 mm. This pattern results in overlapping and homogenous coverage of the entire surface. In each position, ten pulses of laser irradiation, each of 100 µs duration, were applied, over a period of one second.

b. Control surfaces

1) Non-treated enamel surfaces - These polished surfaces were bonded without any additional treatment of the enamel.
2) Acid etched enamel surfaces- These surfaces were etched with 37% phosphoric acid (3M Unitek, Monrovia , CA) for 30 seconds and then rinsed with water for 30 seconds.
3) Conditioner treated enamel surfaces - These surfaces were treated with 10% polyacrylic acid (GC Conditioner) for 20 seconds and then rinsed with water for 30 seconds. This surface treatment was used as a control only for glass ionomer cement.

3. BONDING AGENTS

a. Light-cured composite resin

Light-cured composite resin used in this study was Transbond XT light cured orthodontic bonding agent (3M Monrovia, CA.). Enamel surfaces to receive attachments bonded with this material were prepared with either laser irradiation, acid etching or no treatment, following the polishing process. Immediately after surface preparation, they were rinsed with water for 30 seconds and then dried with oil-free air. Primer was placed on the specified area and light-cured for 5 seconds, followed by application of the bonding material to the meshed back of the button and placement of the button on the tooth. The resin was then light-cured for 40 seconds. The light-curing device (Demetron #401, Demetron Research Corp., Danbury, CT) was held by a fixed attachment, and all samples were positioned for curing at a constant position, as close as possible to the light source, as in the clinical situation.

b. Light-cured glass ionomer cement

Light-cured glass ionomer cement used in this study was Fuji ORTHO LC light cured orthodontic bonding agent (GC Corp., Kyoto, Japan). Enamel surfaces to receive attachments bonded with this material were prepared with either laser irradiation, acid etching, GC conditioner or no treatment, following the polishing process. Immediately after surface preparation, the teeth were rinsed with water for 30 seconds and then kept moist with wet laboratory tissue throughout the bonding process, and until the shear test was performed. Powder and liquid were mixed according to the manufacturer instructions, the mixed cement applied to the meshed back of the button, and the button placed on the tooth. The cement was light-cured for 40 seconds, in the same manner described for the composite resin above.

4. EXPERIMENTAL GROUPS:

In total, there were 13 experimental groups (Table 1), with ten teeth in each group, to undergo shear bond strength test. For each of the seven surface preparations, two additional teeth were examined under SEM and two others were used for cross-sectional analysis.

5. SHEAR BOND STRENGTH

Shear bond strength was measured by mounting the teeth into the SPSTA, as described in page 21, and testing the bonded attachments to failure in a universal testing machine (Instron Model 1122, Canton, MA), with a cross head speed of 0.5 mm/min. Shear bond strength was calculated as the force required for bond failure (Newtons) divided by the bonded area (mm), and represented in Megapascals (MPa).

Surface Preparation	Transbond XT	Fuji Ortho LC
Non-treated enamel control	✓	✓
GC Conditioner control (10% polyacrylic acid)		✓
Acid etch control	✓	✓
Laser at 3.5 J/cm^2	✓	✓
Laser at 5 J/cm^2	✓	✓
Laser at 7.5 J/cm^2	✓	✓
Laser at 9.5 J/cm^2	✓	✓

Table 1: Experimental groups

6. SITE OF FAILURE.

All samples were examined by the same operator (ZK) under a stereoscopic light microscope, at a magnification of 30x, using a gross visual assessment method to determine the sight of bond failure, and for presence of residual bonding agent.

7. STATISTICAL ANALYSIS

Statistical analysis of shear bond strength measurements was done using Analysis of Variance (ANOVA) with the more conservative, post-ANOVA, Tukey test applied[35]. However, since ANOVA assumes a similar variance in all groups tested, and since in this study, the two acid etched control groups had a larger variance than all other groups, they were not included in the ANOVA. For these two groups the Mann-Whitney-Wilcoxon Rank test (MWW) was applied[36].

8. LASER EFFECTS ON THE ENAMEL SURFACE

a. Surface evaluation under scanning electron microscope (SEM).

For each of the seven surface treatments (4 laser conditions, etching, conditioner and no treatment), two teeth were treated but not bonded. The surfaces of these teeth were viewed under SEM (Topcon SX-40A wet-SEM, Topcon Instruments, Pleasanton, CA) in c-fast mode at 50x, 250x and 1000x magnifications, for a qualitative evaluation of the laser's effects on the enamel.

b. Digital image analysis of thin cross-sections of treated teeth.

In a separate experiment, two additional teeth were treated with each of the surface preparations tested. The only difference was that the highest laser fluence used was actually 9.25 J/cm^2 rather than 9.5 J/cm^2. Two cross-sections, approximately 100μm thick, were taken through the treated area in an occluso-gingival direction, by a microtome (Series 1000 Deluxe Hard Tissue Microtome, Scifab, LaFayette, CO.). Each sample was viewed under the light microscope with magnification of 50x, 100x and 500x. The profile of the treated area was observed and digitized by a capturing device (CCD). Image analysis software (Bioquant 3.12), allowing for ultimate magnification of 1000x, was used to measure the depth of surface affected by the various treatments. The measurements were done to the most extreme points (i.e. bottoms of pits or craters), relative to the plane of the polished surface.

F. RESULTS

1. SHEAR BOND STRENGTH

Mean shear bond strength of composite resin and glass ionomer cement (GIC) bonded to the 4 laser treated groups and the control groups, in Megapascals (MPa) are displayed in Figure 14 and Table 2. Whenever the difference between two means is greater than 2.49, these two groups are statistically different ($P<0.05$, ANOVA - Tukey). MWW Rank Test showed Composite resin to acid etch> GIC to acid etch > Composite resin to 9.5 J/cm^2 ($P<0.05$). The range of measurements and coefficient of variation for each group are also displayed in Table 2. The coefficient of variation is calculated as the standard deviation divided by the mean, and represents the deviation as percentage of the mean, regardless of its magnitude.

For the composite resin, all laser treated groups had mean shear bond strengths higher than the non-treated control group, but only the 7.5 and 9.5 J/cm^2 groups, statistically higher ($p<0.05$), and all were lower than acid-etched control (20.84 MPa). Mean shear bond strength had risen as the laser fluence increased, reaching a mean of 11.84 MPa in the 9.5 J/cm^2 group.

For the glass ionomer cement, the 3.5, 5.0 and 9.5 J/cm^2 laser treated groups had mean shear bond strengths (7.96, 7.52 and 8.42 MPa, respectively) which were statistically higher than the non-treated control group (4,84 MPa), and similar to the conditioner treated group (9.76 MPa, $p<0.05$). All were lower than acid-etched control (13.18 MPa).

GROUP	MEAN (MPa)	S.D. ± (MPa)	RANGE (MPa)	VARIATION COEFFICIENT
<u>TRANSBOND XT</u>				
Non-treated control	1.10	0.77	0.00 - 2.74	
acid etch control	20.84	4.92	10.97 - 29.26	24%
Laser 3.5 J/cm^2	3.40	1.19	1.95 - 5.73	35%
Laser 5.0 J/cm^2	2.91	1.82	0.73 - 5.00	63%
Laser 7.5 J/cm^2	5.64	1.18	3.90 - 7.56	21%
Laser 9.5 J/cm^2	11.84	1.65	9.26 - 14.14	14%
<u>Fuji ORTHO LC</u>				
Non-treated control	4.84	1.88	0.61 - 7.31	39%
Conditioner control	9.76	1.89	7.31 - 12.68	19%
acid etch control	13.18	2.82	10.00 - 17.07	21%
Laser 3.5 J/cm^2	7.96	2.17	4.39 - 11.46	27%
Laser 5.0 J/cm^2	7.52	1.81	5.49 - 10.61	24%
Laser 7.5 J/cm^2	6.00	1.58	3.17 - 8.29	26%
Laser 9.5 J/cm^2	8.42	1.66	6.22 - 11.09	20%

Table 2: Means, standard deviations and range of shear bond strength measurements (MPa)

2. SITE OF FAILURE

Stereomicroscopic examination of all specimens after debonding, showed most enamel surfaces to have no cement residues (Figure 8). In a few samples (8 of 130), randomly found among all groups, small specks of cement residues were found on the enamel, close to the edges of the mylar strip. These specks, covering less than 1% of the surface, are considered artifacts related to the methodology. Due to the finding of no adhesive residues, no further quantification method, such as ARI scoring, was applied.

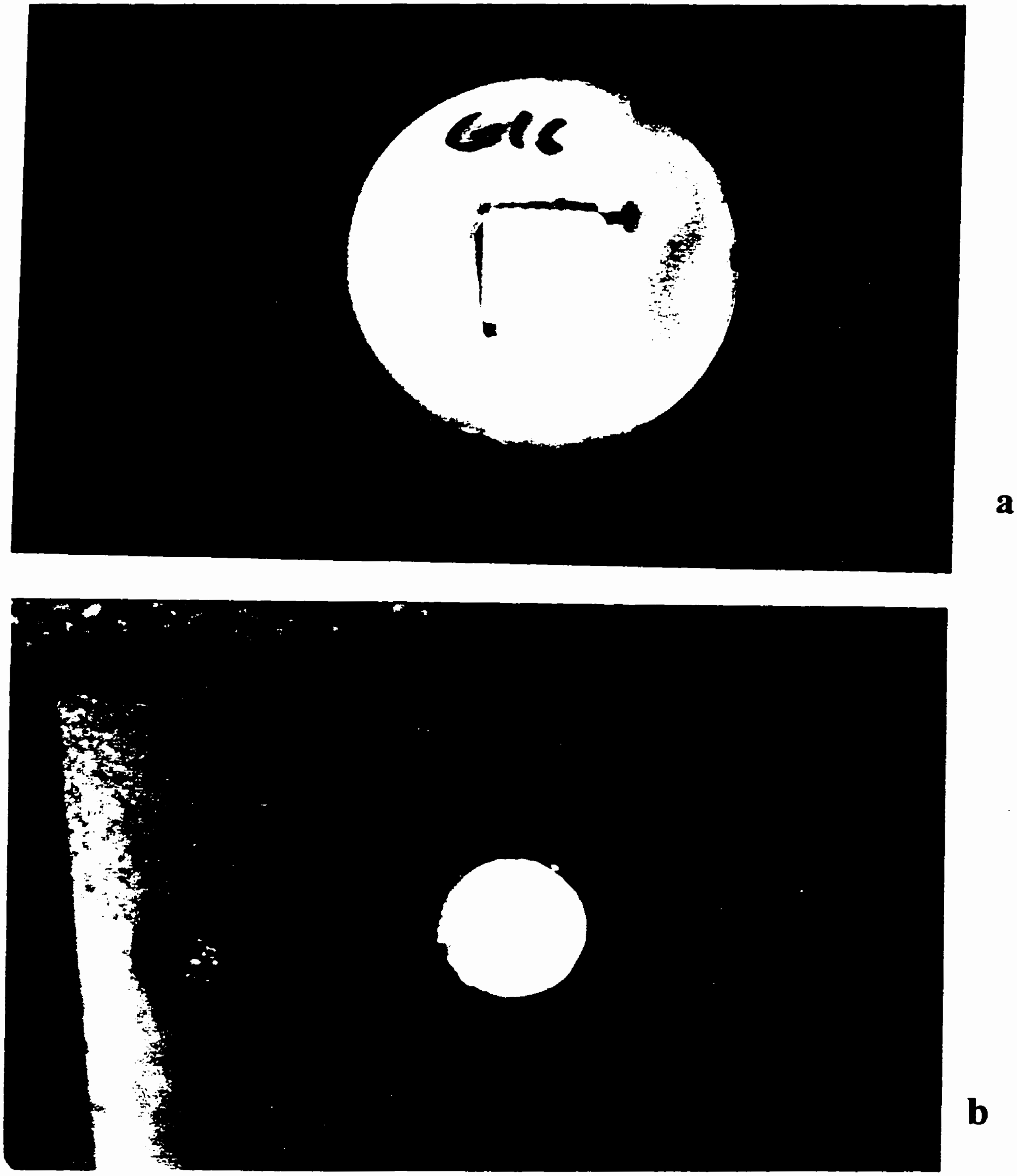


Figure 8: Typical samples after debonding. (a,b) Bonded with Glass ionomer cement

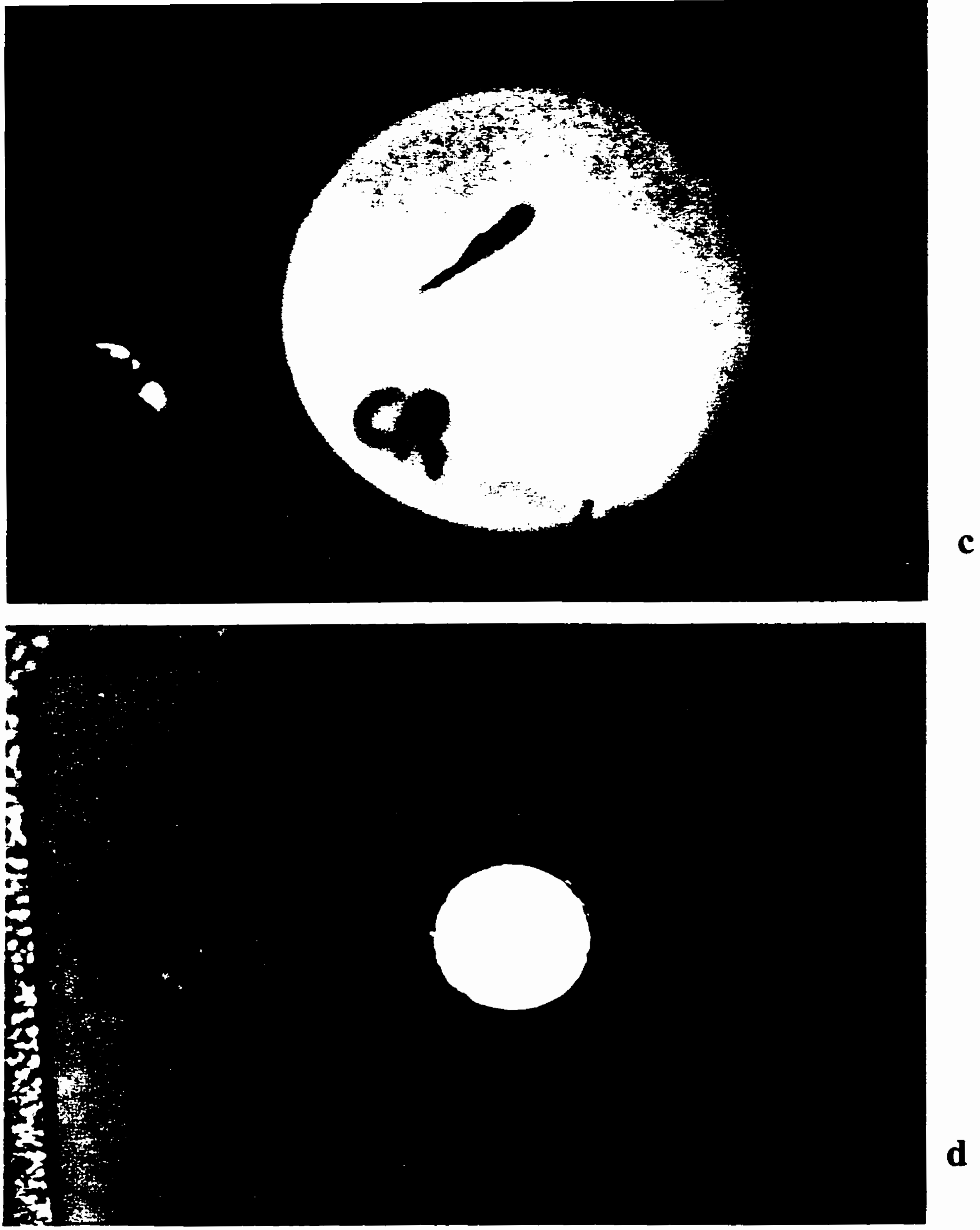


Figure 8 (continued): (c,d) Bonded with composite resin. Both teeth (a,c) have no adhesive remnants and show the pattern of laser etching. Both buttons (b,d) completely retained the adhesives

3. SCANNING ELECTRON MICROSCOPY APPEARANCE OF ENAMEL SURFACE

Surface changes due to laser irradiation were more pronounced as the fluence increased (Figure 9). In the 3.5 J/cm^2 group, a very mild crescent shaped effect is seen, while in the 5 J/cm^2 group, the crescent shaped effects are more pronounced, and are organized according to the scanning pattern of the laser beam. Higher magnification shows these effects to consist of melting and fusion of the surface (Figure 10). In the 7.5 and 9.5 J/cm^2 groups, the lower magnification shows the effects to cover the whole surface. In the 9.5 J/cm^2 group, in addition to the melting and fusion, the surface is undulated, with numerous sites of exfoliation and pitting, and is also covered with globular residues, which appear like balls of melted enamel (Figure 11). Exfoliation does not appear on the surfaces of teeth exposed to the lower laser fluences, and there are fewer pits as the fluence decreases.

Acid etched enamel (Figure 11) has a typical appearance of organized invaginations of approximately 4 μm (Prism diameter). In comparison, the pits and invaginations present in the 9.5 J/cm^2 treated enamel, are fewer and larger, ranging in size from 5 to 40 μm in diameter. Polyacrylic acid conditioned enamel does not show physical changes, at this magnification, retaining the appearance of the polishing grooves.

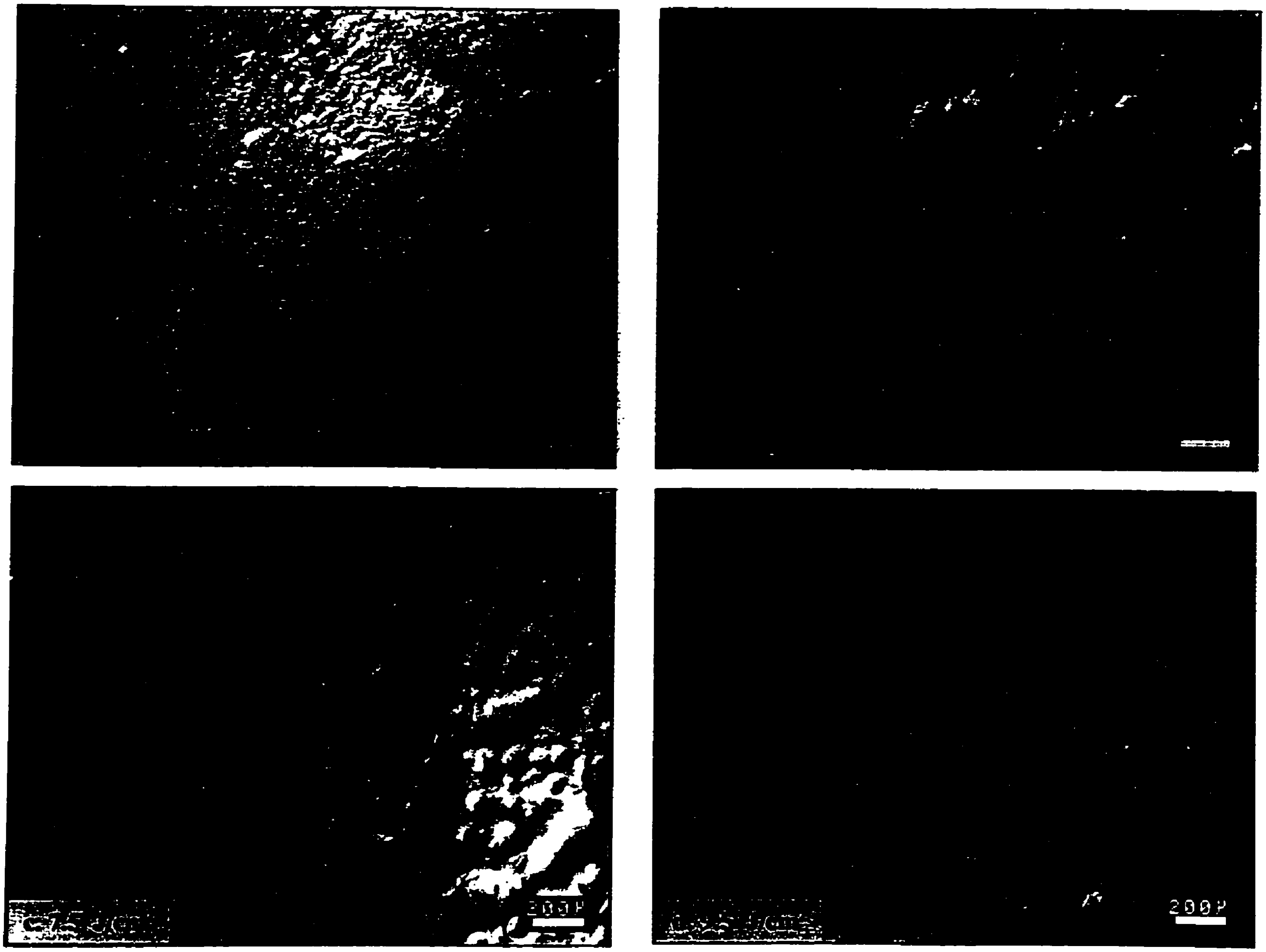


Figure 9: SEM of laser treated enamel (50x) a. 3.5 J/cm², b. 5 J/cm², c. 7.5 J/cm², d. 9.5 J/cm². Surface changes due to laser irradiation were more pronounced as the fluence increased.

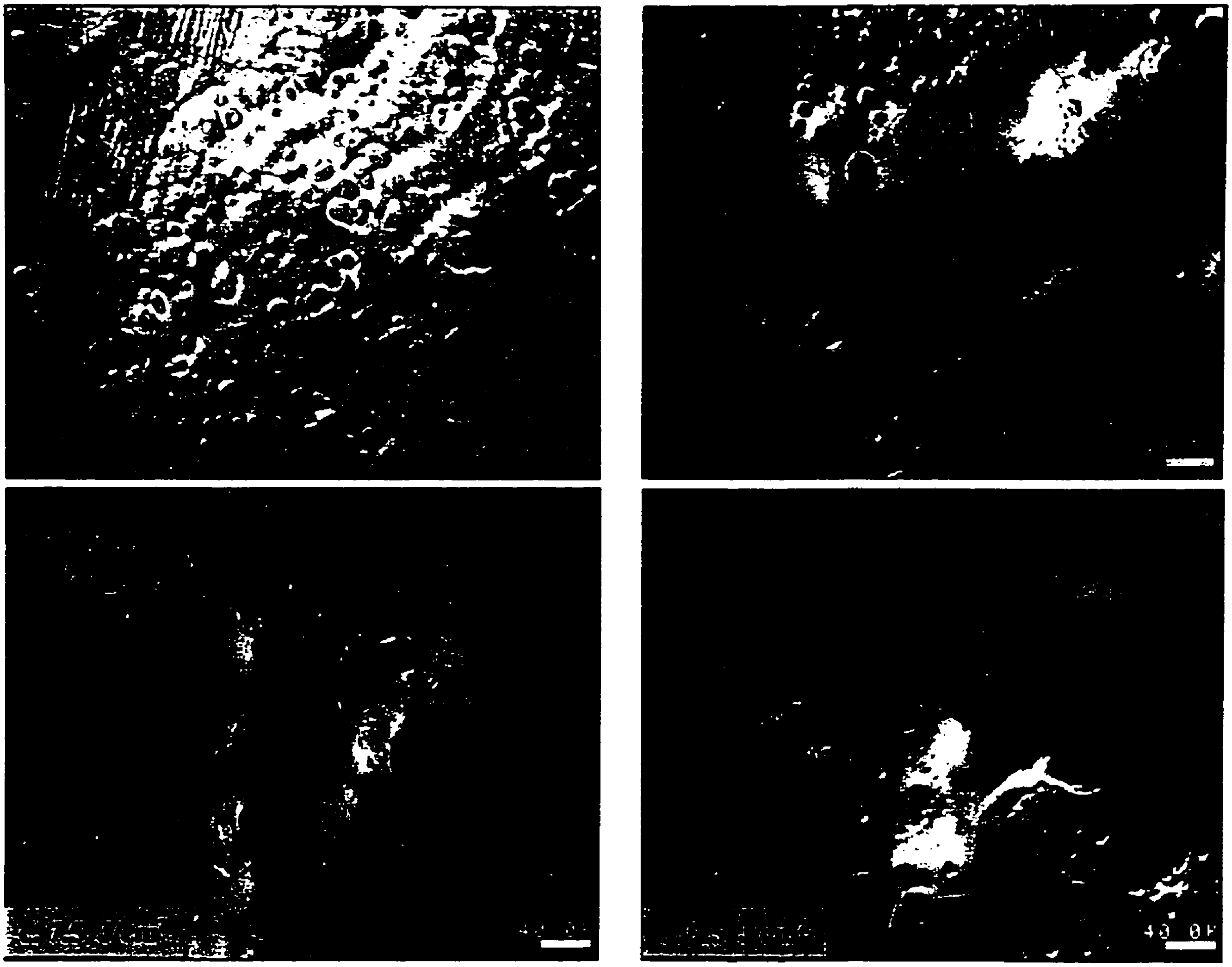


Figure 10: SEM of laser treated enamel (250x) a. 3.5 J/cm^2, b. 5 J/cm^2, c. 7.5 J/cm^2, d. 9.5 J/cm^2. In addition to the melting and fusion seen in all groups, the surface in the 9.5 J/cm^2 group, is undulated, with numerous sites of exfoliation and pitting, and is covered with globular residues, which appear like balls of melted enamel.

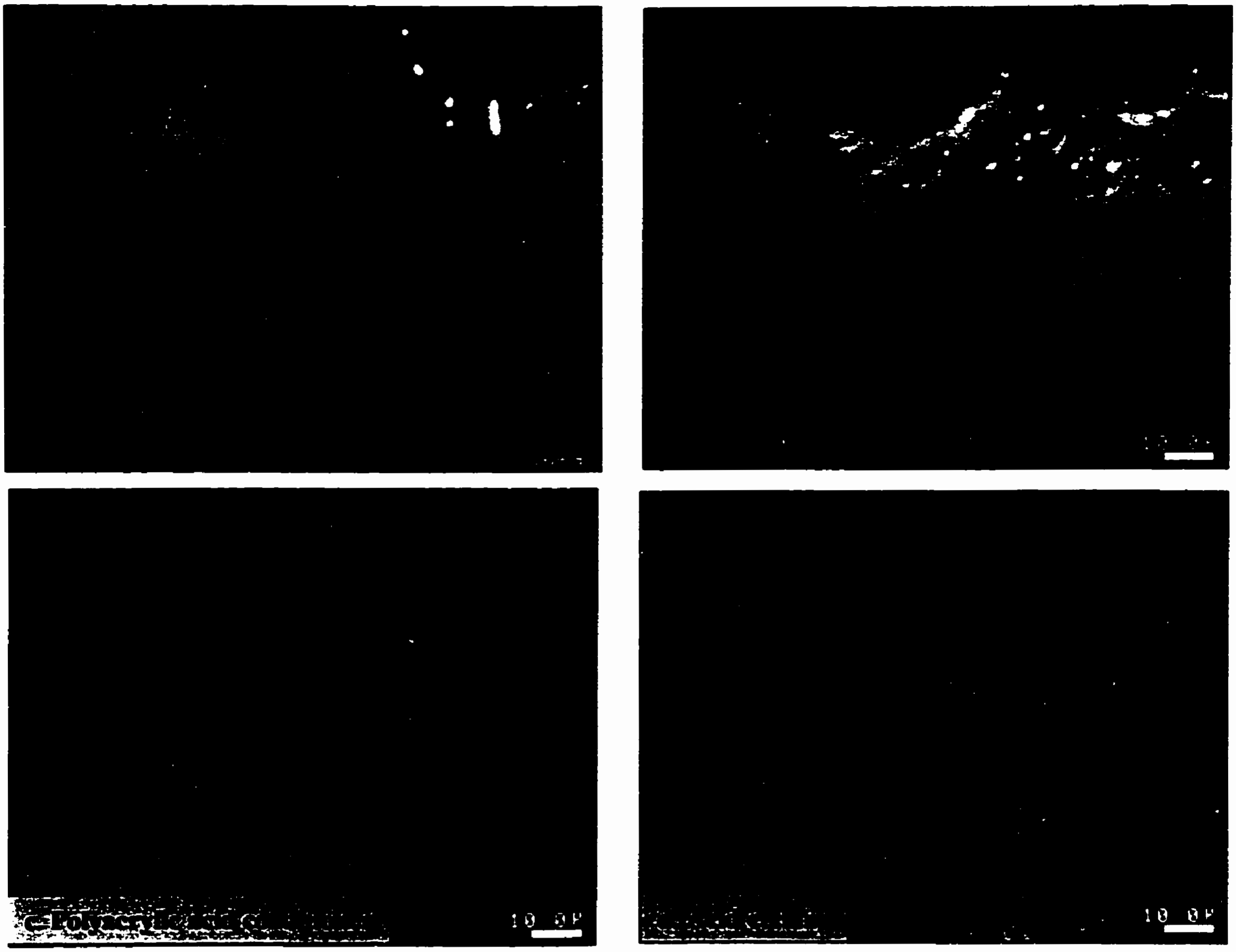


Figure 11: SEM (1000x) of laser treated enamel and controls a. 7.5 J/cm^2, b. 9.5 J/cm^2, c. polyacrylic acid conditioned enamel surface shows no morphological changes except for polishing grooves, d. Acid-etched enamel shows efficient retentive effects as compared to the laser retentive effects.

4. DIGITAL IMAGE ANALYSIS OF THIN CROSS SECTIONS OF TREATED TEETH

Cross sections of laser treated teeth exhibit serial craters which follow the pattern of laser irradiation (Figure 12).The depth of these craters varied between teeth in the same group, and even within the same sample. Due to these variations and to the limited number of samples, the results are presented as a range of crater depths found (Table 3), demonstrating an increase in craters depth as the laser fluence increased, up to 110 µm. Cross sections of control groups samples showed no craters or other effects at these magnifications.

Laser treatment	Craters depth (µm)
3.5 J/cm^2	20 - 35
5.0 J/cm^2	30 - 45
7.5 J/cm^2	60 - 80
9.25 J/cm^2	60 - 110

Table 3: Range of craters depth (µm)

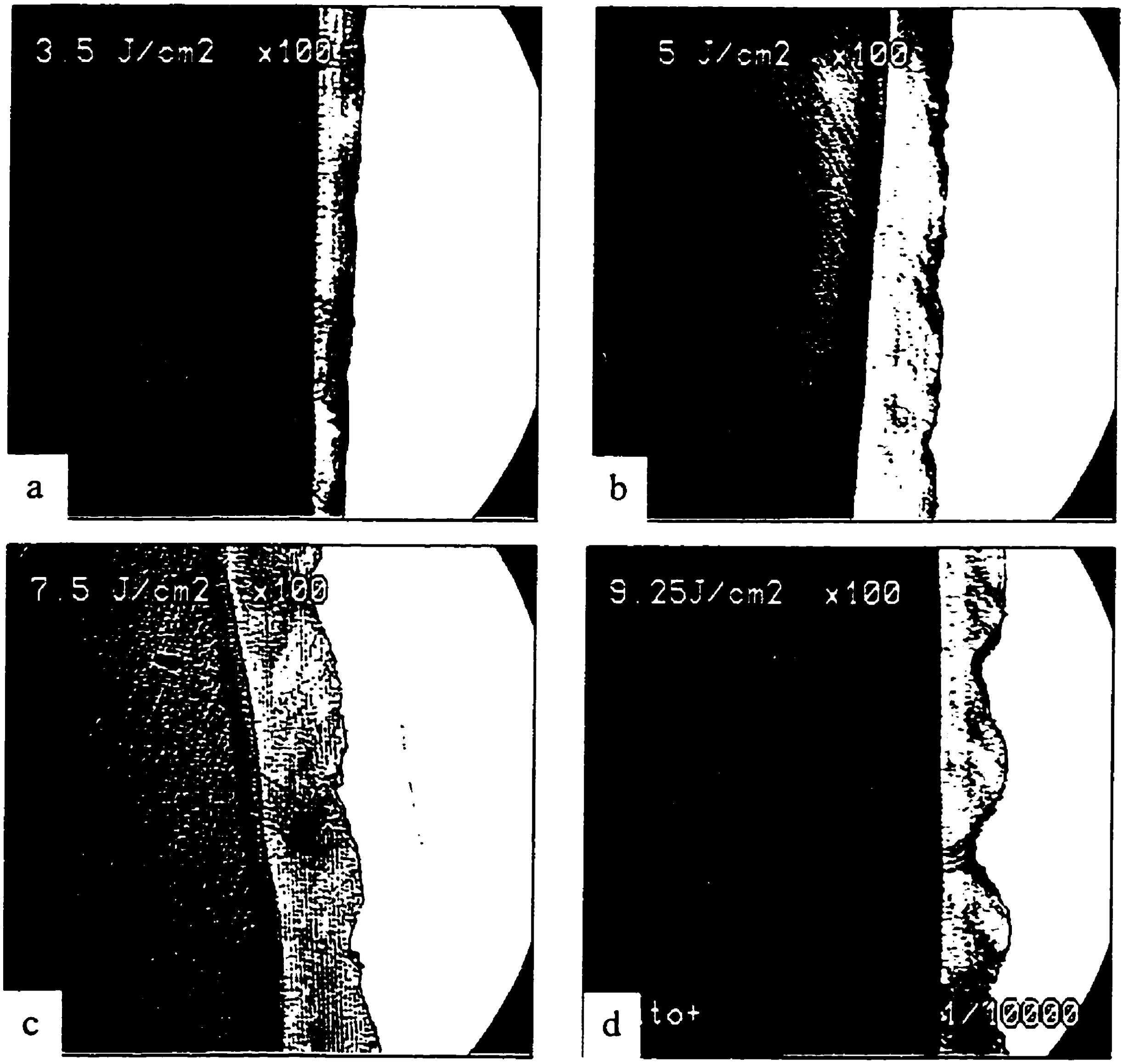


Figure 12: Digital image of cross-sections of laser treated teeth (100x) a. 3.5 J/cm^2, b. 5 J/cm^2, c. 7.5 J/cm^2, d. 9.5 J/cm^2. The depth of pits and craters, resulting from laser irradiation, increased as the laser fluence rose.

G. DISCUSSION

1. EVALUATION OF THE SHEAR BOND STRENGTH TESTING METHOD

Evaluation of a study methodology is usually done by comparing validity and reliability of the obtained results with those obtained by the existing "Gold Standard". Unfortunately, such a "Gold Standard" does not exist for shear bond strength testing, which is one of the reasons the current technique was developed. A comparison of the means and ranges of measurements obtained for the control groups in this study to those published for the same materials is presented in Table 4 and Table 5. Due to the variation in shear bond strength testing methods, there is a wide range of published results, and none can serve as a gold standard, for the sake of comparison.

Table 4 summarizes the results of a few recent studies that used Transbond XT and its chemically-cured relative, Concise (also by 3M Unitek). In those studies that tested the two materials, in identical conditions, similar results were obtained for both, allowing for the inclusion of Concise in this comparative table. The studies are listed in an ascending order according to their calculated coefficient of variation. The current study had a relatively low coefficient of variation, which may indicate that indeed, the testing method used was able to reduce some of the variables associated with shear bond strength studies.

AUTHOR	ADHESIVE	MEAN (MPa)	S.D. ± (MPa)	RANGE (MPa)	VARIATION COEFFICIENT
Viazis et al 1990[37]	Transbond XT	20.70	4.03	14.20 - 26.70	19%
	Concise	22.16	3.19	17.60 - 27.20	14%
Sinha et al 1995[38]	Concise	23.29	3.94	N/A	17%
Current study	**Transbond XT**	**20.84**	**4.92**	**10.97 - 29.26**	**24%**
Damon et al 1997[39]	Transbond XT	12.30	3.10	7.33 - 18.28	25%
Chamda et al 1996[40]	Transbond XT	7.08	1.76	4.17 - 9.81	25%
	Concise	5.76	2.01	2.70 - 8.09	35%
Norris et al 1991[41]	Transbond XT	18.60	6.30	N/A	34%
	Concise	19.70	3.40		17%
Ashcraft et al 1997[42]	Concise	17.4	5.20	10.00 - 26.00	30%
Ewoldsen et al 1995[43]	Concise	10.39	4.00	N/A	38%
Bishara et al 1997[25]	Transbond XT	7.20	3.1	2.30 - 11.60	43%
Martin et al 1994[26]	Transbond XT	19.60	9.6	2.50 - 31.70	49%
Lindauer et al 1997[44]	Transbond XT	9.10	4.6	N/A	51%
	Concise	9.60	4.6		48%

Table 4:Shear bond strength measurments from recent literature for Transbond XT and Concise composite resins

AUTHOR	SURFACE TREATMENT	MEAN (MPa)	S.D. ± (MPa)	RANGE (MPa)	VARIATION COEFFICIENT
Current study	**Non-treated**	**4.84**	**1.88**	**0.61 - 7.31**	**39%**
	Conditioned	**9.76**	**1.89**	**7.31 - 12.68**	**19%**
	Acid-etched	**13.18**	**2.82**	**10.00 - 17.07**	**21%**
Marulli et al 1997[45]	Non-treated	5.94	0.95	N/A	16%
	Acid-etched	7.84	1.01		13%
Beress et al 1997[46]	Non-treated	5.27	2.15	N/A	41%
	Acid-etched	17.69	4.60		26%
Ewoldsen et al 1995[43]	Non-treated	6.97	3.00	N/A	43%
	Conditioned	7.95	3.10		39%
	Acid-etched	6.51	2.10		32%
Kelly et al 1997[47]	Non-treated	11.90	3.80	N/A	32%
Wongsrimongkol et al 1997[48]	Acid-etched	13.48	2.14	N/A	16%

Table 5: Shear bond strength of Fuji Ortho LC and Fuji II LC to non-etched, 10% Polyacrylic acid conditioned, and acid-etched enamel in recent publications

Table 5 summarizes the results of a few recent studies that used Fuji Ortho LC and its restorative relative, Fuji II LC. The results obtained for non-treated enamel in this study are in agreement with most studies. The current study found a significant increase in bond strength when acid-etching and polyacrylic acid conditioning of the enamel were performed which is in agreement with Beress et al[46]. However, both Marulli et al[45] and Ewoldsen et al[43], found these surface treatment to enhance the bond strength marginally, and not statistically significantly.

Adhesive Remnant Index (ARI) is often used in conjunction with shear bond strength studies in an attempt to explain the results [39,53]. However, several studies suggest that cement residues are correlated with the type and direction of debonding force rather than with the adhesive bond strength [49,50,51], a result which is in agreement with the finite element model analysis described by Katona[24]. In most studies testing composite resins, adhesive residues remain on the enamel, because the shearing force deforms the bracket and failure occurs in the bracket/cement interface[52]. Therefore, these shear tests actually measure the force required to deform the bracket, which is less than the force required to shear the cement from the enamel. If the aim of a study is to compare the bond strength between different adhesives and the enamel, or between different surface preparations and the same adhesive, then it should measure the force required for failure in the enamel-cement interface.

Light microscope examination of the fractured specimens determines the site of bond failure. Since the cohesive shear strength of current bonding materials is far greater than their shear bond strength, then if a true shearing force is applied, it is anticipated that the failure will be either in the bracket/cement interface or the enamel/cement interface. In the present study, the stereomicroscopic examination of all specimens after debonding, showed most enamel surfaces to have no cement residues, indicating that the bond failure occurred in that interface (Figure 8). This result supports the contention that the shear test assembly used in this study delivers a true shear force through the enamel-cement interface. It may also explain why the shear bond strength measured for Transbond XT is high, in relation to other studies (Table 4).

The prepared enamel surfaces, which were polished down to 600 grit level, exhibited longitudinal grooves in the direction they were polished (Figure 11). Although these grooves were taken into consideration during the shear bond strength testing, by applying the force in the same direction as the grooves, it may be advisable to modify the tooth preparation process by polishing the surfaces to 2400 grit level. This modification achieves a smoother surface, as demonstrated by Komori et al[53], and would remove any variation which may be caused by these grooves.

It should be emphasized that the more the method controls for variations, the further it is from the clinical situation. In the clinical reality, the enamel surfaces and the forces affecting the brackets, are diversified, and therefore, a clinical conclusion can only be extracted from a clinical trial. However, a well controlled in vitro study, yields a reliable scientific information, which future clinical trials can be based upon.

2. CLINICALLY ACCEPTABLE LEVELS OF BOND STRENGTH

Bond failure in orthodontics occurs as a result of many factors, including occlusal and functional forces. Although true shear force is not a common clinical situation, the shear bond strength is traditionally used as an indicator for the survivability of the bond throughout the course of orthodontic treatment. As the shear bond strength increases, so does the survivability of the brackets, however, the risk of enamel fracture at debonding increases, as does the amount of adhesive remaining on the enamel surface. Thus, stronger is not necessarily better[56]. Since composite resins bond failure results clinically in adhesive remaining on the enamel, apparently due to failure at the bracket/resin interface, it is logical that lower bond strength to enamel can, not only survive treatment, but also reduce the risk of enamel fracture and discomfort during debonding and simplify cleanup[54,55,56].

Shear bond strength values that should be clinically sufficient were suggested by Reynolds[57] to be in the range of 60-80 kg/cm^2 (approximately 6-8 MPa) and by Komori[53] to be about 8.5 MPa. These values are positioned on the continuum of shear bond strength values in an area that theoretically, should provide an acceptable level of clinical retention of brackets, yet decrease the adverse effects during debonding. However, due to the variation in shear bond strength testing and the wide range of results, often reported for the same material, and the inherent limitation of such study to measure a clinical situation, using a certain shear bond strength value as clinically acceptable, would be illogical.

Because Fuji Ortho LC is a relatively new material, and due to the length of orthodontic treatment, there is very little evidence as to its clinical performance. The only clinical report about brackets bonded to non-etched enamel with Fuji Ortho LC, has claimed a survival rate of 96.8% [13]. However, the data presented in this study indicate an actual failure rate of 4.6% over a treatment period, which is not stated, but could not be longer than a year. A second study, by Fricker[12], recorded bracket failure over a 12 months period, in ten patients, where half of the brackets were bonded with a composite resin to acid etched enamel and the other half with Fuji II LC to polyacrylic acid conditioned enamel. Fricker had two failures with Fuji II LC (3.3%) and one with the resin (1.6%), which are very encouraging results, but should be viewed cautiously due to the limited number of patients and the short treatment period. Studies using other brands of light-cured glass ionomer cements cannot be compared to these two studies or to the in vitro results, due to the difference in composition and behaviour of these materials[58].

In view of these reports, it seems that Fuji Ortho LC, when bonded to non-etched enamel, may be "almost" strong enough to be deemed "clinically acceptable". In this study, using the modified SPSTA, the mean shear bond strength of Fuji Ortho LC to non-treated enamel was 4.84 MPa, ranging from 0.61 - 7.31 MPa. Therefore, it could be estimated that for a bond to be clinically acceptable, it should have a mean, and especially range of measurements, in this specific method, which are somewhat higher than those mentioned above. Clinical performance of Fuji Ortho LC, when acid etching or polyacrylic acid conditioning are used, is therefore anticipated to be better than to non-treated enamel.

3. LASER EFFECTS ON THE ENAMEL SURFACE

Laser irradiation effects on the enamel surface were demonstrated by SEM images and thin cross-sections of treated teeth. Changes to surface morphology included melting, fusion, ablation and pitting, and were more pronounced as the laser fluence increased. There is a dramatic change in surface appearance from the 3.5 and 5 J/cm^2 groups to the groups irradiated with the higher fluences (7 and 9.5 J/cm^2). This dramatic change coincides with the ablation threshold for these laser conditions, which is approximately 5.5 J/cm^2. The occasional melting observed in the 3.5 and 5 J/cm^2 groups is due to the heterogeneity of the laser beam, which results in "hot spots". The pattern of these "hot spots" is demonstrated by the thermal image (Figure 13), and is coincident with the pattern of surface effects in these groups (Figure 9).

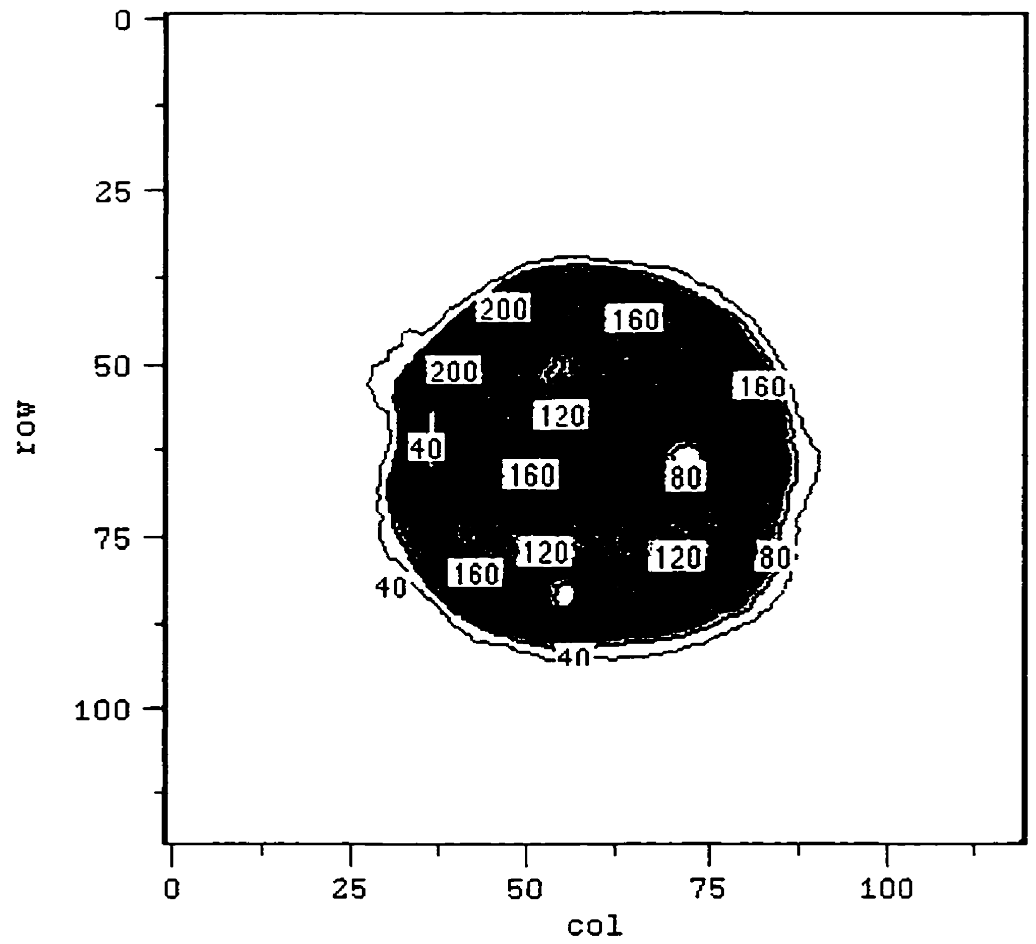


Figure 13: Thermal image of laser beam, presented as a cross-sectional energy contour map, demonstrating uneven energy distribution. Note two crescent shaped "hot" areas in the periphery, exhibiting a 40-100% increased intensity.

The same trend follows in the cross-sectional images, where an increase in crater depth correlated with the increased energy deposition. However, these craters are not the result of the average fluence, calculated for these laser pulses. Rather, they are the outcome of the "hot spots", which are the products of the uneven energy distribution throughout the laser beam, which is commonly found in lasers, and particularly CO_2 lasers. This deleterious effect should be considered when the desired fluence is calculated. Although acid-etched enamel did not show any damage or loss using this method of imaging, it is estimated that enamel loss due to acid-etching and the debonding process is between 5 -60 μm[59,60].

4. BOND STRENGTH TO LASER IRRADIATED ENAMEL

The composite resin (Transbond XT) and the resin-modified glass ionomer cement (Fuji Ortho LC) interaction with the laser irradiated enamel surfaces follow different trends, as demonstrated by Figure 14. As expected, composite resin bond strength to non-treated controls was very weak, measuring only 1.1 MPa. Bond strength was higher in all laser treated groups, increasing in magnitude as the laser beam fluence increased. The bond strength in the groups treated with low level energy, 3.5 and 5 J/cm^2, was still fairly low and was not statistically different from the non-treated enamel. The groups treated with energy levels above the ablation threshold, 7.5 and 9.5 J/cm^2, had significantly higher bond strength, with the 9.5 J/cm^2 group measuring between 9.26 to 14.1 MPa, with a mean of 11.84 MPa. These values may suggest that this laser treatment can provide a clinically acceptable bond between enamel and composite resin.

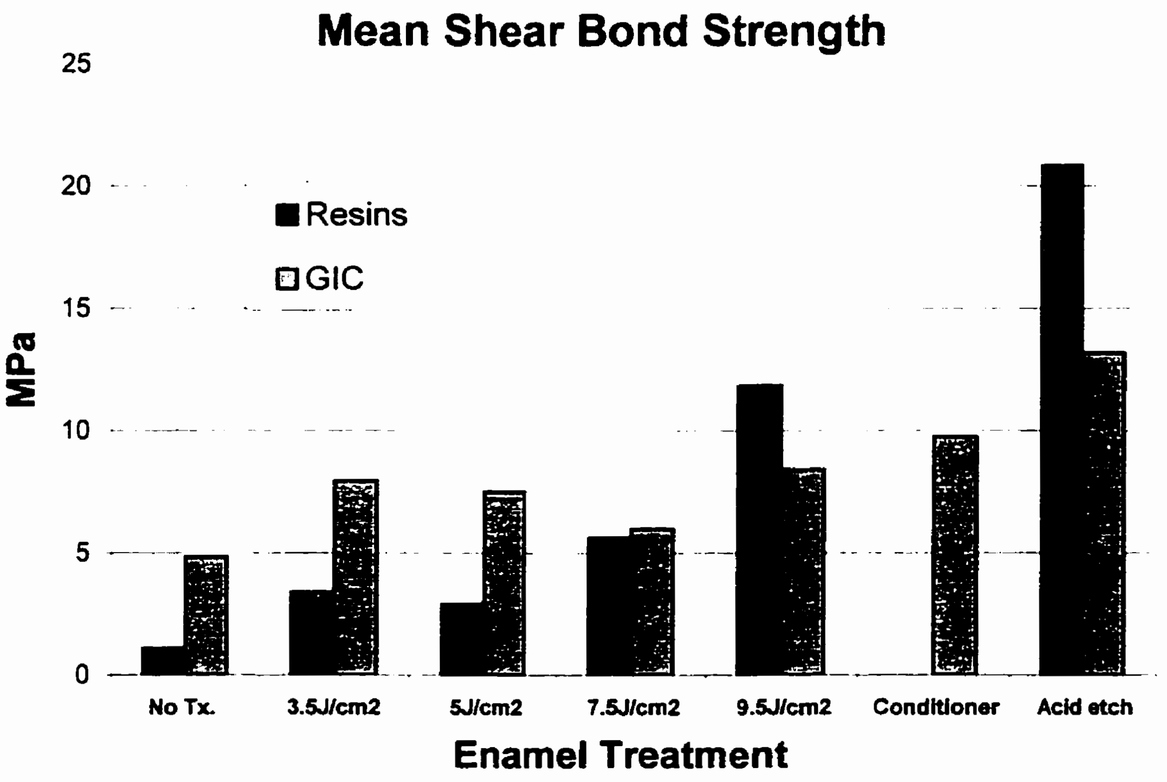


Figure 14: Mean shear bond strength

The trend exhibited by the composite resin groups can be explained by their bonding characteristics and the SEM observations of the laser effects on the enamel surface. Composite resins adhere to enamel by a micro-mechanical bond, created by their ability to flow and occupy indentation and invaginations prior to their setting. Their bond strength to enamel increases with the increase in the area of the retentive surface[61]. The SEM images demonstrated that the increase in laser beam energy resulted in an increase in the surface roughness, and its retentiveness, hence the increased bond strength

The same rationale can also explain why the bond strength to the acid etched group is higher. Surface ablation induced by the highest fluence yielded a disorganised cluster of changes which included pits and invaginations, ranging in size from 5 to 40 μm. In comparison, acid-etching effects each enamel prism separately, resulting in a highly organised arrangement of 4 μm wide retentive cups. The increased number of retentions and more homogenous effect achieved by the acid etch, result in an increase in the total retentive area engaged by the bonding agent, which can explain its higher bond strength.

The interaction between the resin-modified glass ionomer cement (Fuji Ortho LC) and the laser treated enamel surfaces was very different than that seen with the composite resin. The groups irradiated with fluences of 3.5, 5.0 and 9.5 J/cm^2, had significantly higher mean bond strengths than the non-etched control. The means of these three groups (7.96, 7.52 and 8.42 MPa, respectively) were almost identical and not statistically different from each other and similar to the group treated with 10% polyacrylic acid conditioner (9.76 MPa). Based on the above discussion regarding clinically acceptable bond strength, and the limited clinical evidence existing, it can be estimated that these laser beam parameters can provide a clinically acceptable bond between enamel and Fuji Ortho LC resin-modified glass ionomer resin.

The trend exhibited by the four experimental groups can be explained by the bonding mechanism of resin-modified glass ionomer cements, which combines physical and chemical bonds. It is probable, that the lower laser energy treatment removed organic material from the surface and from the outer layer of the enamel, and/or caused a change in its molecular structure, priming it for the chemical bond, and/or lowered the surface energy, similar to the effect obtained by the polyacrylic acid conditioner. The higher energy densities may have offset this effect by damaging the surface morphology and integrity, and probably changing its molecular structure, as well. This will explain the lower bond strength measured for the group treated with fluence of 7.5 J/cm^2. The higher bond strength measured in the 9.5 J/cm^2 group is probably due to the resin component bonding physically, similar to that seen in the composite resin group.

Relatively high bond strengths between composite resin and enamel surfaces were achieved in this study, using laser irradiation energy levels far lower than previously reported[17,18]. However, this result was only achieved with the highest fluence used, and further studies need to be done to examine the effects on adjacent tissues, especially the tooth pulp. Pulp temperature rise is correlated with the cumulative energy deposited into the tooth, which depends on the pulse energy and the number of pulses. If the energy per pulse can not be reduced, without loosing the etching effect, a lower number of pulses can be assessed as well, to minimize the risk to the pulp. However, according to studies by Fried et al[20], the energy conditions used in the present study are unlikely to cause undesirable temperature rise in the pulp. The above used parameters should also be tested to confirm their ability to inhibit caries progression in enamel. If indeed these parameters are safe and effective in vivo, laser irradiation may be considered to replace pumicing and etching before bracket bonding, while decreasing the incidence of enamel decalcification around orthodontic brackets during treatment.

Similar safety and clinical survivability studies should be performed with Fuji Ortho LC, using the lower laser fluence. If successful, the combination of laser irradiation and this cement may offer more benefits to the orthodontist and the patient. A 2-3 seconds laser treatment of each tooth would eliminate the need for pumicing and etching. The wet environment required for proper bonding by Fuji Ortho LC, eliminating the need for maintaining a dry field, would allow convenient placement of the brackets immediately after laser irradiation. These benefits and the clean tooth surface at the time of debonding, all translate to a reduction in the risk of enamel damage and a reduction in chair time, benefiting both, the patient and the orthodontist. In addition the patient would have a better protection against decalcification during orthodontic treatment, due to the caries inhibitory effect of the laser treatment[21], the higher incorporation of fluoride to laser irradiated enamel[22] and the release of fluoride from the glass ionomer.

It is important to stress that current commercially available laser devices produce a different wavelength, have different energy characteristics, and are not capable of producing the specific irradiation parameters used in this study. Any attempt to use them clinically may result in permanent damage to vital tissues.

H. CONCLUSIONS

1. The shear bond strength testing method described in this dissertation, resulted in complete shearing of the adhesive from the enamel surface, thus measuring true shear bond strength.

2. Shear bond strength measurements were consistent with published results and had better than average coefficients of variation.

3. This reproducible and highly controlled method is proposed for consideration as a standard shear bond strength testing method in orthodontics.

4. Composite resin (Transbond XT), achieved an acceptable bond strength to enamel irradiated with 10.3 μm wavelength CO_2 laser, at 9.5 J/cm^2 per pulse.

5. Resin-modified glass ionomer (Fuji Ortho LC), achieved an acceptable bond strength to enamel irradiated with 10.3 μm wavelength CO_2 laser, at three different fluences, 3.5, 5.0 and 9.5 J/cm^2 per pulse.

6. Laser irradiation effects on the enamel surface, including melting, fusion and pitting, were enhanced as the fluence increased. Only mild effects were seen in several "hot spots" when the fluence was below the ablation threshold for 10.3 μm wavelength laser light (approximately 5.5 J/cm^2). These effects dramatically changed to a fully covered stormy appearing surface, when fluences above this threshold were used.

7. Occasional "hot spots", resulting from uneven energy distribution in the laser beam, may create localized surface effects, such as cratering, which may have deleterious effects.

I. APPENDIX

1. LIST OF FIGURES

2. LIST OF TABLES

3. EQUIPMENT SPECIFICATIONS

1. Laser - Tunable CO_2 Laser (Custom nade), Pulse System Inc., Los Alamos, NM.
2. Scanning electron microscope - ISI TOPCON SX40A wet-SEM, Topcon Instruments, Pleasanton, CA.
3. Universal testing machine - Instron Model 1122, Instron Ltd., Canton, MA.
4. Curing light - Demetron Model #VCL 401, Demetron Research Corp., Danbury, CT.
5. Strip Grinder - Handimet I, Buhler Ltd., Evanston, ILL.
6. Microtome - Series 1000 Deluxe Hard Tissue Microtome, Scifab, LaFayette, CO.

4. MATERIALS SPECIFICATIONS

1. Composite resin - Transbond XT, Lot No. 060796, 3M Unitek, Monrovia, CA.
2. Resin primer - Transbond XT Light Cure Adhesive Primer, Lot No. 022396, 3M Unitek, Monrovia, CA.
3. Resin modified glass ionomer cement - Fuji Ortho LC, Lot No. 120161, GC America, Chicago, ILL.
4. Orthodontic button - Flat base bondable lingual buttons, #30-000-00 GAC International, Central Islip, NY.
5. 37% Phosphoric etching acid - Transbond XT EtchGel, Lot No. 053096, 3M Unitek, Monrovia, CA.
6. 10% Polyacrylic acid conditioner - GC Dentin Conditioner, Lot No. 220741, GC America, Chicago, ILL.
7. Die stone for SPSTA - Die-Keen Green, Miles Inc., South Bend, IN.
8. Composite resin for SPSTA - Z100, 3M Unitek, Monrovia, CA.

J. REFERENCES

1. ZACHRISSON BU. **Bonding in orthodontics.** In: Grabber TM and Vanarsdll RL Jr. Editors, ORTHODONTICS - CURRENT PRINCIPLES AND TECHNIQUES, 2nd ed. Mosby, St. Louis, 1994:542-555

2. ZACHRISSON BU, SKOGAN O, HOYMYHR S. **Enamel cracks in debonded, debanded and orthodontically untreated teeth.** AM J ORTHOD DENTOFAC ORTHOP 1980;77:307-19.

3. GORELICK L, GEIGER AM, GWINNETT AJ. **Incidence of white spot formation after bonding and banding.** AM J ORTHOD DENTOFAC ORTHOP 1982; 81:93-8.

4. ØGAARD B, RØLLA G, ARENDS J. **Orthodontic appliances and enamel demineralization: part I, lesion development.** AM J ORTHOD DENTOFAC ORTHOP 1988;94:68-73.

5. MIZRAHI E. **Surface distribution of enamel opacities following orthodontic treatment.** AM J ORTHOD DENTOFAC ORTHOP 1983;84:323-31.

6. VALK JWP, DAVIDSON CL. **The relevance of controlled fluoride release with bonded orthodontic appliances.** J DENT 1987; 15:257-60.

7. O'REILLY MM, FEATHERSTONE JDB. **Demineralization and remineralization around orthodontic appliances: an in vivo study.** AM J ORTHOD DENTOFAC ORTHOP 1987;92:33-40.

8. SIDHU SK, WATSON TF. **Resin-modified glass-ionomer materials. Part 2: clinical aspects.** DENT UPDATE 1996;1:12-16.

9. COOK PA. **Direct bonding with glass ionomer cement.** J CLIN ORTHOD 1990;24:509-11

10. FAJEN VB, DUNCANSON MG, NANDA RS, CURRIER GF, ANGOLKAR PV. **An in vitro evaluation of bond strength of three glass ionomer cements.** AM J ORTHOD DENTOFAC ORTHOP 1990;97:316-22.

11. COMPTON AM, MEYERS CE, 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 DENTOFAC ORTHOP 1992; 101:138-44.

12. FRICKER JP. **A 12-month clinical evaluation of a light activated glass potyalkenoate (ionomer) cement for the direct bonding of orthodontic brackets.** AM J ORTHOD DENTOFAC ORTHOP 1994;105:502-5.

13. 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 DENTOFAC ORTHOP 1995;108:231-6

14. ROBERTS-HARRY DP. **Laser etching of teeth for orthodontic bracket placement: a preliminary clinical study.** Lasers Surg Med 1992;12:467-470

15. CORPAS-PASTOR L, MORENO JV, GARRIDO JDL, MURIEL VP, MOORE K, ELIAS A. **Comparing the tensile strength of brackets adhered to laser-etched enamel vs. acid-etched enamel.** J AM DENT ASSOC 1997;128:732-737

16. FEATHERSTONE JDB, BARRETT-VESPONE NA, FRIED D, KANTOROWITZ Z, LOFTHOUSE J, SEKA W. **Rational choice of laser conditions for inhibition of caries progression.** LASERS IN DENTISTRY, SPIE, Bellingham, WA 1995;2394:57-67

17. WALSH LJ, ABOOD D, BROCKHURST PJ. **Bonding of resin composite to carbon dioxide laser-modified human enamel.** DENT MATER 1994;10:162-6.

18. LIBERMAN R, SEGAL TH, NORDENBERG D, SEREBRO LI. **Adhesion of composite materials to enamel: comparison between the use of acid and lasing as pretreatment.** LASERS SURG MED 1984;4:323-7.

19. MCCORMACK SM, FRIED D, FEATHERSTONE JDB, GLENA RE, SEKA W. **Scanning electron microscope observations of CO2 laser effects on dental enamel.** J DENT RES 1995;74:1702-8.

20. FRIED D, SEKA W, GLENA RE, FEATHERSTONE JDB. **Thermal response of hard dental tissues to 9- through 11-μm CO_2-laser irradiation.** OPT ENG 1996;35:1976-84

21. FEATHERSTONE JDB, BARRETT-VESPONE NA, FRIED D, KANTOROWITZ Z, LOFTHOUSE J, SEKA W. **CO_2 laser inhibition of artificial caries-like lesion progression in dental enamel.** J DENT RES (In press 1998).

22. KANTOROWITZ Z, FEATHERSTONE JDB, FRIED D. **Augmentation of CO2 laser inhibition of in vitro caries by fluoride.** J DENT RES 1996;75 (Spec Iss):25, Abst. 63

23. FOX NA, MCCABE JF, BUCKLEY JG. **A critique of bond strength testing in orthodontics.** BR J ORTHOD 1994;21:33-43

24. KATONA TR. **The effects of load location and misalignment on shear/peel testing of direct bonded orthodontic brackets - a finite element model.** AM J ORTHOD DENTOFAC ORTHOP 1994;106:395-402

25. BISHARA SE, OLSEN M, VON WALD L. **Comparison of shear bond strength of precoated and uncoated brackets.** AM J ORTHOD DENTOFAC ORTHOP 1997;112:617-621

26. MARTIN S, GARCIA-GODOY F. **Shear bond strength of orthodontic brackets cemented with a zinc oxide-polyvinyl cement.** AM J ORTHOD DENTOFAC ORTHOP 1994;106:615-20

27. WATANABE LG, LACY AM, DAVIS DR. **Shear bond strength: Single plane versus conventional lap shear.** J DENT RES 1987;67 (Spec Iss):383, Abst. 2159

28. WATANABE LG, MARSHALL WG, MARSHALL SJ. **Dentin shear strength: effects of tubule orientation and intra-tooth location.** DENT MATER 1996;12:109-115

29. NAKAMICHI I, IWAKU M, FUSAYAMA T. **Bovine teeth as possible substitutes in the adhesion test.** J DENT RES 1983;62:1076-1081

30. SILVA CM, CORDAZZI JL, PEREIRA JC, FRANCISCHONE CE. **Shear bond strength of an adhesive system in human, bovine and swinish teeth.** J DENT RES 1996;75(Spec Iss):393, Abst. 3005

31. SMITH HZ, CASKO JS, LEINFELDER KF, UTLEY JD. **Comparison of orthodontic bracket bond strengths: Human vs. bovine enamel.** J DENT RES 1976;55:B153, Abst. 367

32. RUEGGEBERG FA. **Substrate for adhesion testing to tooth structure - Review of the literature.** DENT MATER 1991;7:2-10

33. WILLIAMS VD, SVARE CW. **The effect of five-year storage prior to bonding on enamel/composite bond strength.** J DENT RES 1985;64:151-154

34. KANTOROWITZ Z, FEATHERSTONE JDB, FRIED D. **Caries prevention by CO2 laser treatment: Dependency on the number of pulses used.** J AM DENT ASSOC (In press 1998)

35. HASSARD TH. **Understanding biostatistics.** Mosby, Philadelphia, PA. 1991; Ch. 5:75-97

36. ANDERSON DR, SWEENEY DJ, WILLIAMS TA. **Introduction to statistics.** 2nd ed. West Publication Co., St. Paul, MN. 1991; Ch. 17:636-44

37. VIAZIS AD, CAVANAUGH G, BEVIS RR. **Bond strength of ceramic brackets under shear stress: An in vitro report.** AM J ORTHOD DENTOFAC ORTHOP 1990;98:214-21

38. SINHA KP, NANDA RS, DUNCANSON MG, HOSIER MJ. **Bond strength and remnant adhesive resin on debonding for orthodontic bonding techniques.** AM J ORTHOD DENTOFAC ORTHOP 1995;108:302-7

39. DAMON PL, BISHARA SE, OLSEN ME, JAKOBSEN JR. **Bond strength following application of chlorhexidine on etched enamel.** ANGLE ORTHOD 1997;67:169-72

40. CHAMDA AC, STEIN E. **Time related bond strength of light-cured and chemically cured bonding systems: An in vitro study.** AM J ORTHOD DENTOFAC ORTHOP 1996;110:378-82

41. NORRIS RA, MCCOURT JW, NORLING BK. **Bond strength of thermocycled mesh backed vs. silica coated brackets.** J DENT RES 1991;70(Spec. Iss.);297, Abst. 251

42. ASHCRAFT DB, STALEY RN, JACKOBSON JR. **Fluoride release and shear bond strength of three light-cured glass ionomer cements.** AM J ORTHOD DENTOFAC ORTHOP 1997;111:260-5

43. 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

44. LINDAUER SJ, BROWNING H, SHROFF B, MARSHALL F, ANDERSON RHB, MOON PC. **Effect of pumice prophylaxis on the bond strength of orthodontic brackets.** AM J ORTHOD DENTOFAC ORTHOP 1997;111:599-605

45. MARULLI R, COHEN SM, VAIDYANATHAN TK. **A comparison of ionomer and composite cements for orthodontic bonding.** J DENT RES 1997;76(Spec Iss):190, Abst. 1409

46. BERESS A, TJAN AHL, SCHLENKER WL, WONGSRIMONGKOL T. **Effects of surface treatment on brackets bond strength using glass-polyalkenoate.** J DENT RES 1997;76(Spec Iss):191, Abst. 1417

47. KELLY JM JR., TURNER DS. **Enhanced orthodontic adhesives and their effect on enamel following debonding.** J DENT RES 1997;76(Spec Iss):379, Abst. 2928

48. WONGSRIMONGKOL T, TJAN AHL, SCHLENKER WL, BERESS A. **Surface contamination on bond strength of brackets luted with glass-polyalkenoate.** J DENT RES 1997;76(Spec Iss):190, Abst. 1416

49. KINCH AP, TAYLOR H, WARLTIER R, OLIVER RG, NEWCOMBE RG. **A clinical study of amount of adhesive remaining on enamel after debonding, comparing etch time of 15 and 60 seconds.** AM J ORTHOD DENTOFAC ORTHOP 1989;95:415-21

50. BENNETT CG, SHEN C, WALDRON JM. **The effect of debonding on the enamel surface.** J CLIN ORTHOD 1984;18:330-4

51. OLIVER RG. **The effect of different methods of bracket removal on the amount of residual adhesive.** AM J ORTHOD DENTOFAC ORTHOP 1988;93:196-200

52. JOSEPH VP, ROSSOUW E. **The shear bond strength of stainless steel and ceramic brackets used with chemically and light-activated composite resins.** AM J ORTHOD DENTOFAC ORTHOP 1990;97:121-5

53. KOMORI A, ISHIKAWA H. **Evaluation of a resin-reinforced glass ionomer cement for use as an orthodontic bonding agent.** ANGLE ORTHOD 1997;67:189-96

54. JOSEPH VP, ROSSOUW E. **The shear bond strength of stainless steel orthodontic brackets bonded to teeth with orthodontic composite resins and various fissure sealants.** AM J ORTHOD DENTOFAC ORTHOP 1990;98:66-71

55. MASKERONI AJ, MEYERS CE, LORTON L. **Ceramic bracket bonding: A comparison of bond strength with polyacrylic acid and phosphoric acid enamel conditioning.** AM J ORTHOD DENTOFAC ORTHOP 1990;97:168-75

56. KUSY RP. **When is stronger better?** (Commentary) AM J ORTHOD DENTOFAC ORTHOP 1994;106(2):17A

57. REYNOLDS RI. **A review of direct orthodontic bonding.** BR J ORTHOD 1975;2: 171-8

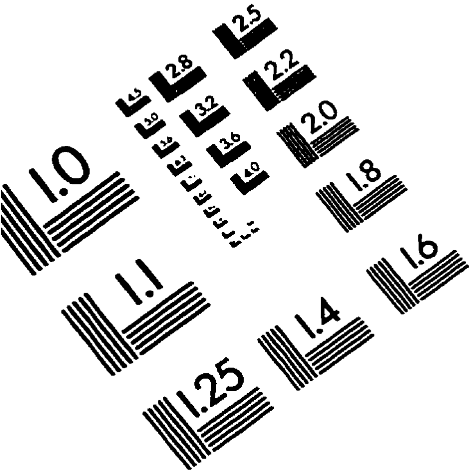
58. WRIGHT AB, LEE RT, LYNCH E, YOUNG KA. **Clinical and microbiologic evaluation of a resin modified glass ionomer cement for orthodontic bonding.** AM J ORTHOD DENTOFAC ORTHOP 1996;110:469-75

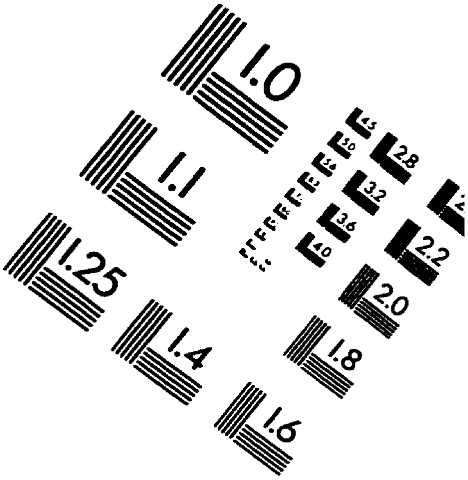
59. BROWN CRL, WAY DC. **Enamel loss during orthodontic bonding and subsequent loss during removal of filled and unfilled adhesives.** AM J ORTHOD DENTOFAC ORTHOP 1978;74:663-71

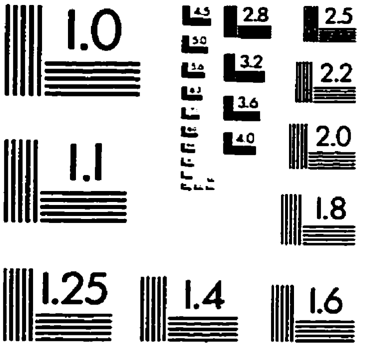
60. DIEDRICH P. **Enamel alterations from bracket bonding and debonding: A study with the scanning electron microscope.** AM J ORTHOD DENTOFAC ORTHOP 1981;79:500-22

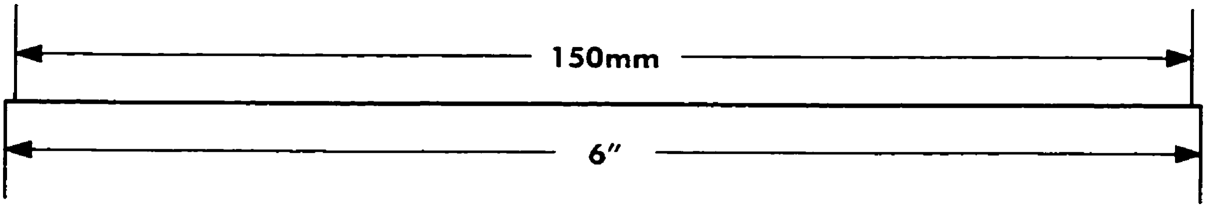
61. O'BRIEN WJ. **Dental Materials: Properties and Selection.** Quintessence Publishing Co., Inc. Chicago 1989; Ch. 4:74-80; Ch.7:139-42

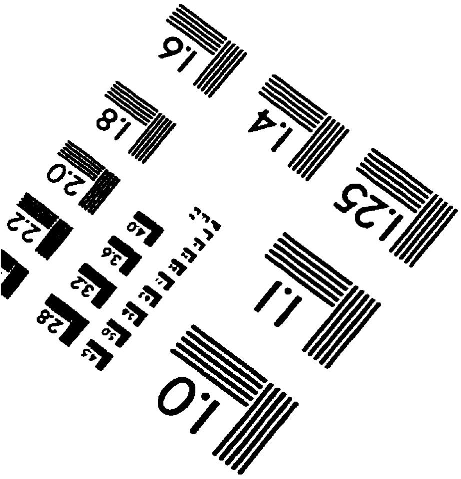
IMAGE EVALUATION
TEST TARGET (QA-3)

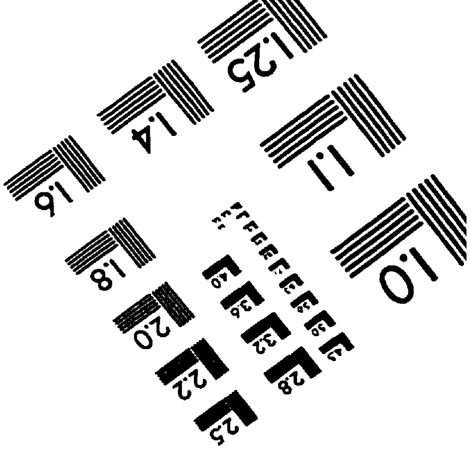












APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989