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BOND STRENGTH OF THERMALLY DEBONDED, REBONDED CERAMIC BRACKETS

BY

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled:

"SHEAR/PEEL BOND STRENGTH OF REPOSITIONED CERAMIC BRACKETS"

submitted by Peter Gerard Gaffey in partial fulfillment of the requirements for the degree of Master of Science

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Supervisor

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Date: April 07/94

Many people have had a profound influence on my life. This work is dedicated to those people.

My wife Narelle, and children, John, Benjamin, Samuel, and Kate, who show tolerance and understanding allowing me freedom to focus on this task.

My Mum and Dad, who with a large number of offspring and little funds, provided us with quality education.

Dr. Donald Scott, friend and confrere who has enthusiastically supported my endeavour to understand the principles of orthodontics.

Len Muir, my sponsor, who "turned on the light" on August 8, 1979.

To all these people - Thank you.

God grant me the serenity
to accept the things I cannot change,
the courage to change the things I can,
and the wisdom to know the difference.

The Uplift

When the drays are bogged and sinking, then it's no use sitting thinking,
You must put the teams together and must double-bank the pull.
When the crop is light and weedy, or the fleece is burred and seedy,
Then the next year's crop and fleeces may repay you to the full.

So it's lift her, Johnny, lift her,
Put your back in it and shift her,
While the jabber, jabber, jabber of the politicians flows.
If your nag's too poor to travel
Then get down and scratch the gravel
For you'll get there if you walk it - if you don't, you'll feed the crows.

Shall we waste our time debating with a grand young country waiting
For the plough and for the harrow and lucerne and the maize?
For it's work alone will save us in the land and that fortune gave us
There's no crop but what we'll grow it; there's no stock but what we'll raise.

When the team is bogged and sinking
Then it's no use sitting thinking.
There's a roadway up the mountain that the old back leader knows:
So it's lift her, Johnny, lift her,
Put your back in it and shift her,
Take a lesson from the bullock - he goes slowly, but he goes!

Andrew Barton Paterson (1864-1941)

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ABSTRACT

Proper bracket position is critical to effective orthodontic mechanics. Inaccurate bracket position may necessitate bracket removal and rebonding. The study's purpose was to investigate; (1) amount of bonding resin remaining on single crystal bracket base following electrothermal debonding and (2) bond strength of thermally debonded, rebonded single crystal ceramic brackets under different treatment conditions. 112 single crystal ceramic brackets were bonded to bovine teeth, then thermally debonded. During this debonding process, 12 brackets fractured and were discarded. Remaining bracket bases (n=100) were inspected for resin, classified with an Adhesive Remnant Index (ARI) and randomly assigned to four treatment groups (n=25). The experimental groups and control group (new brackets) (n=25) were bonded to 125 fresh bovine teeth. Groups were (1) control (new brackets) (2) silane coupling agent (3) heat + silane coupling agent (4) hydrofluoric acid + silane coupling agent (5) heat + hydrofluoric acid + silane coupling agent. A shear/peel force was applied with an Instron™ machine. ARI index showed 79% of brackets had no resin on base. The shear/peel bond strength (MPa) was found to be significantly greater for the control group than for all other groups ($P < 0.01$). Results indicate that treatment of thermally debonded ceramic bracket base with silane and heat + silane results in a reduced but clinically acceptable bond strength. Treatment groups that used hydrofluoric acid, resulted in a bond strength that was not clinically acceptable.

CHAPTER ONE

1.1: Introduction

Since the advent of bonded brackets, operators have searched for a simple and effective method of relocating bonded brackets. According to Andrews, "the clinician must position brackets correctly on the teeth to assure a functional end result."[1] Inaccurately located brackets should be repositioned during treatment in order to take full advantage of the archwire slot values and sliding mechanics.[2]

Regan, LeMasney and van Noort investigated tensile bond strength of rebonded stainless steel brackets, with treatment of bases carried out at chairside.[3] A decrease in bond strength was noted with photo-etched and cast bases. This fall in bond strength was considered important clinically and the author felt these brackets should not be reused. Foil-mesh brackets have a suitable bond strength following treatment of the base with a green stone and rebonding.

In 1990 Lew and Djeng reported a chairside method of recycling ceramic brackets.[4] This method involves "the heating of the 'used' ceramic brackets to cherry red to burn off the residual composite resin from the bracket base. The bracket base is then rinsed with 100 percent alcohol and left to dry." The brackets are then resilinated and rebonded. Lew, Chew and Lee in 1991 reported on the shear bond strength of recycled ceramic brackets.[5] These brackets were debonded using a Transcend Debonding Instrument[a]. The brackets were treated as described above then rebonded. Shear bond strength of 'new' ceramic brackets was about 40 percent greater

[a] Unitek Corporation/3M 2724 S. Peck Road, Monrovia, CA 91016

than the recycled brackets. There was no record of the number of brackets fractured during debonding and the state of the bracket prior to rebonding.

A number of articles in orthodontic literature specified concern regarding damage to enamel during the debonding of ceramic brackets.[6-29] Sheridan introduced electrothermal debracketing (ETD™)[b] in 1986; a new concept in bracket removal.[24] ETD™ transfers heat through the bracket, allowing bond failure at the bracket-adhesive interface as the heat deforms the adhesive.[11] This debonding process leaves the base of a bracket relatively free from resin. [30]

The purpose of this study was to;

1. investigate use of ETD™ to incorporate ceramic bracket rebonding,
2. evaluate bond strengths of rebonded ceramic brackets.

1.2: Statement of Problem

During placement of orthodontic ceramic brackets, clinicians may inadvertently place a bracket in an incorrect position. With conventional treatment, the operator removes the bracket, cleans the tooth surface and places a new bracket. This process usually destroys the bracket and has the potential to damage tooth structure.

Using a new bracket each time increases the cost of providing treatment, particularly if brackets are purchased in 'one-patient' kits. This issue may be addressed if the bracket was debonded, base treated, and rebonded in the correct position.

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[b] "A" Company; A division of Johnson & Johnson INC. 11436 Sorrento Valley Rd, San Diego, California, 92121.

1.3: Research Questions.

The research questions to be investigated:

- Does the electrothermal debracketing instrument (ETD™) leave a debonded ceramic bracket in a reusable condition?
- Is bond strength of an electrothermally debonded ceramic bracket, treated with a silane coupling agent, adequate for clinical use?
- Is bond strength of an electrothermally debonded ceramic bracket, treated with heat and a silane coupling agent, adequate for clinical use?
- Is bond strength of an electrothermally debonded ceramic bracket, treated with hydrofluoric acid and a silane coupling agent, adequate for clinical use?
- Is bond strength of an electrothermally debonded ceramic bracket, treated with heat and hydrofluoric acid, and a silane coupling agent, adequate for clinical use?

1.4: Hypotheses

H1: The electrothermal debracketing instrument (ETD™) leaves a debonded ceramic bracket with no resin remaining on the base.

H2: There is no difference between shear/peel bond strength of a ceramic bracket and a rebonded ceramic bracket treated with one of the five treatment methods.

1.5 Review of Literature

1.5.1 Tooth Preparation For Direct Bonding

The initial step in bonding is thorough cleansing of the enamel surface to remove the pellicle. Often this is accomplished with a rubber cup and flour of pumice resulting in 5.0μm of enamel being lost.[31,32] When the prophylaxis is carried out with a bristle brush and pumice, 10.7μm of enamel is lost.[33]

An alternative method for cleansing the enamel surface is to use an air-powder polisher. This instrument was introduced in 1977 by Dentsply[c] and shown to be an effective method for plaque and stain removal in clinical situations.[36] The air-powder polisher has been shown to be as effective as a rubber cup and pumice. Air polishing has several advantages: it is more effective, time efficient, and it generates no heat.[35,36] Deposits are removed from the tooth surface by a stream of sodium bicarbonate particles sprayed with water and compressed air onto the tooth surface. The air polisher is effective in cleansing enamel prior to acid.[35] G-rbo *et al.* found no statistical difference between tensile strength of bonds on the teeth cleansed with the air-powder polisher and those cleaned with a rubber cup and pumice.[31]

1.5.2 Acid Etch Technique

Development of the acid etch technique has had a profound effect on many phases of clinical dentistry. Michael Buonocore pioneered the field in 1955 with publication of his paper entitled "A simple method of increasing adhesion of acrylic filling materials to enamel surfaces".[37] Recognizing that one major shortcoming of resin filling materials is their lack of adhesion to dentine and enamel, Buonocore embarked on development of the acid etch

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[c] Prophy-Jet, Densply/Cavitron. Long Island City, N.Y.

technique. He chose phosphoric acid (H_3PO_4) to etch enamel at a concentration of 85 percent applied to the cleansed enamel surface for 30 seconds. The increased bond strength of acrylic resin to etched enamel compared to unetched enamel was attributed by Buonocore to a large increase in surface area of enamel available for interaction with resin as a result of the etching process.

Silverstone suggested that etching of enamel with H_3PO_4 results in a superficial etched zone and subsurface qualitative porous zones.[38] Enamel from the superficial etched zone is permanently lost but the subsurface porous zones re-mineralize in the oral environment.[39,40] Dental resin flows into the porous zones, cures and establishes a mechanical bond to the etched enamel.[41] The depth of etch or amount of surface enamel lost during the etching procedure is dependent on the type of acid used, acid concentration, duration of etching, and chemical composition of enamel.[4]

The most widely used concentrations of H_3PO_4 in clinical practice exceed 30 percent. This is partly based on the findings of Chow and Brown[43] who demonstrated an application of H_3PO_4 solutions greater than 27 percent H_3PO_4 to enamel results in formation of monocalcium phosphate monohydrate. Where the acid concentration is lower than 27 percent, the main reaction product is dicalcium phosphate dihydrate. Monocalcium phosphate monohydrate is more soluble than dicalcium phosphate dihydrate and will more readily be washed from the enamel surface after etching.[43] Legler *et al.*. found the duration of etch rather than concentration of H_3PO_4 has no significant effect on shear bond strength.[44] They suggested acid concentration may be reduced clinically without producing an adverse effect on retention of bonded brackets.

Etching time has reduced from four minutes in 1973 to fifteen seconds in current times.[15] Not all investigators have found a fifteen second etch adequate. Viljoen *et al.*. found a failure rate of 4.6 percent for a fifteen second etch, where a 30 second etch under the same conditions resulted in a 3.4 percent bond failure rate.[45] Viljoen's findings are questioned when studies of Nordenvall, Barkmeier, Britton and Wang are considered.[13,46-48] These four *In vitro* studies, carried out independently and over a ten year period, show a fifteen-second etch using 37 percent phosphoric acid was sufficient to achieve good retention. *In vivo* studies carried out by Carstensen and Labart arrived at similar conclusions.[49,50] The physical form of an acid (whether liquid or gel) has no effect on quality, or duration of etch required to produce a clinically acceptable bond.[53]

Enamel is lost during the etching process. This loss is between 3.9 and 9.9 microns for a 90 second, 30 percent etch.[52,33] Enamel removed during etching is rich in fluoride. Fluoride is not evenly distributed in enamel as its concentration follows a negative exponential distribution with the greatest concentration in surface enamel.[54] Etching may make enamel more susceptible to decalcification during orthodontic treatment. Clinicians have reported enamel decalcification underneath and adjacent to bonded attachments during orthodontic treatment occurs frequently.[55,56]

An alternative to acid etching was investigated by Von Fraunhöfer, Allen and Orbell who studied the effect of laser etching of enamel for direct bonding of orthodontic appliances.[57] Four power settings on the laser etching unit were used: 80mJ, 1W, 2W, and 3W. Their findings show an acceptable shear bond strength could be achieved at laser power settings of 1 to 3W but not at the lowest setting (80mJ). Mean shear bond strengths obtained with laser treatment of the enamel at 80mJ, 1W, and 2W were lower than that achieved with acid etching. This study concluded that laser etching may save clinical time, but the savings are not great and may not justify the capital expenditure involved.

1.5.3 Adhesives

1.5.3.1 Adhesion and Surface Contact.

Adhesion is defined as molecular attraction exerted between surfaces of bodies in contact or attraction between molecules at an interface. The molecular attractive forces involved in adhesion may be divided into physical and chemical forces. The former include Van der Waal's forces and those resulting from hydrogen bonds. Chemical forces that arise form covalent and electrovalent bonds.[37,59]

Since forces responsible for adhesion act over short distances, (in the order of Angström units), little or no adhesion can be achieved between two surfaces which are not flat at an atomic level. Surfaces which are flat at an atomic level will adhere spontaneously to each other if brought into contact. An example of adhesive forces uniting atomically smooth surfaces is seen in the bond between mica sheets. Strength of this adhesion is about 14,000 *psi*, as strong as the mica itself. In practice it is not possible to obtain such smooth surfaces, and the extremely small separation necessary for adhesion is achieved by introducing a liquid between the solid surfaces. The intermediate fluid flows into irregularities between surfaces to be bonded and produces the necessary molecular closeness required for adhesion.[59]

1.5.3.2 Wetting and Contact Angles

To obtain molecular closeness, the liquid adhesive must wet the surfaces of the materials to be bonded. Wetting is a manifestation of the attractive forces between the molecules of the adhesive and the adherend. When these attractive forces are strong, wetting occurs. The degree of wetting depends on the contact angle at which the boundary of the liquid adhesive meets the surface of the adherend (Fig I).

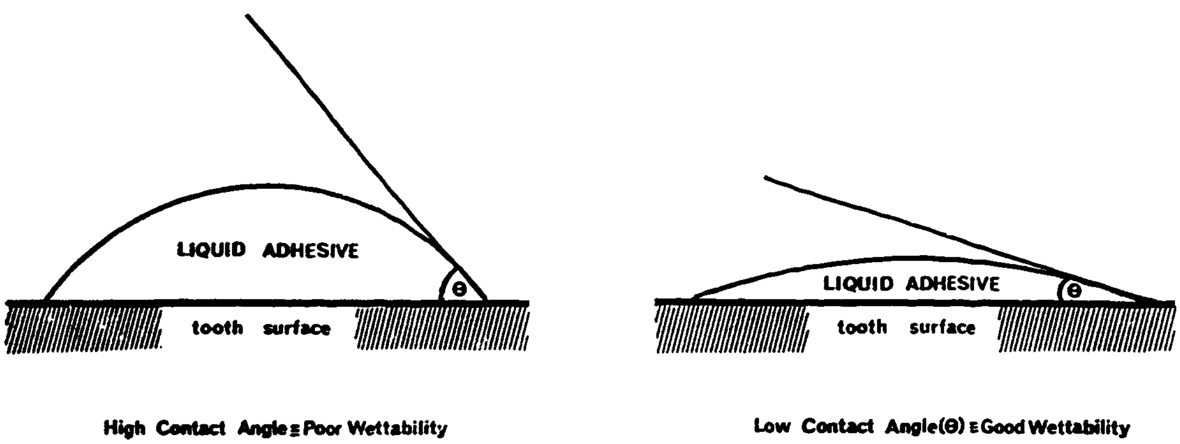

Figure I

Wetting decreases as the contact angle increases. The viscosity and surface tension of the liquid adhesive and the nature of the solid surface also influence the wetting. Newman and Farcq found that water on the tooth surface gave a contact angle greater than 50° but when the tooth surface was treated with 85 percent H_3PO_4 a zero contact angle was produced.[60] This observation demonstrates the function of etching as being two-fold in that it provides mechanical retention and increases wettability of a resin.

For practical purposes, it is necessary not only to obtain molecular closeness but also to maintain it. For this reason, it is desirable that the liquid adhesive should solidify. This can be done either by using an adhesive with a volatile component which sets when this component evaporates or by using an adhesive that can polymerize and cross-link through the use of a catalyst.

1.5.3.3 Chronological Development of Dental Adhesives:

- Buonocore in 1955 used 85 percent phosphoric to etch enamel and achieve a bond between enamel and resin.[37]
- Sadler in 1958 attempted to cement orthodontic attachments directly to enamel, without etching; results were unsuccessful.[61]
- Bowen in 1962 patented a resin (Bis GMA) often referred to as "Bowens Resin".[62] It combines the setting versatility of acrylic resin with the strength and stability of epoxy resin.
- Newman applied Buonocore's findings to the direct bonding of orthodontic attachments to tooth surface (*in vivo*).[63] This was the first use of the acid etch technique for this purpose. He used an epoxy resin (diglycidyl ether of Bisphenol A with a polyamide curing agent) after etching with 40 percent phosphoric acid for 60 seconds. Cure time for this epoxy resin was 15 minutes. Work was carried out with modified acrylic resins reducing cure time to approximately 5 minutes.[28]
- Mitchell had failures with an epoxy resin but described a successful, although limited, clinical trial using black copper and gold direct attachments.[64]
- Retief, Dreyer and Gavron used an epoxy resin system designed to withstand maximum orthodontic forces (headgear to molar tubes and edgewise torque with rectangular wire). However the 30 minute curing time and high bond failure rate (25 percent) was considered impractical.[59]
- Photochemical polymerization was introduced by Buonocore in 1970.[65] The technique offered considerable advantages over chemically initiated polymerization since it provided the ideal combination of an indefinite working time followed by rapid setting. The first photochemical resin was sensitive to long wavelength ultra-violet radiation.

- Zinc polyacrylate (zinc polycarboxylate) was documented as a cement for directly bonding orthodontic attachments to enamel.[66] Adhesion is chemical in nature: ionic bonds are formed with the calcium of enamel hydroxyapatite. These cements have a low tensile strength, compared with filled diacrylates.
- In 1971 cyanoacrylates were tested *In vitro* but were unsatisfactory.[67]
- Wilson and Kent invented glass polyalkenoate (ionomer) cements; a hybrid of silicate and polycarboxylate cements.[68] This cement leaches fluoride over prolonged periods with a physiochemical bond to base metals and dental enamels.[68-73]
- Zinc polyacrylate (carboxylate) cement was introduced in 1972 and direct bonding of attachments with this cement were described by Mizrahi and Smith.[66,74]
- Visible light source is used to induce resin polymerization. Visible light source gained in popularity over the ultraviolet light source because the latter produces a greater depth of polymerization and it avoids eye damage.[75] Polymerization of light-activated resins under metal brackets by trans-illumination were shown to be successful because the tooth conducts visible light.[76]
- A survey conducted in the United States of America during 1979 found that 93 percent of orthodontists used chemically cured resin bonding for bracket placement.[77] A major drawback of this system is the inability of the practitioner to manipulate the setting time of the composite resin. This must be done rapidly when the chemically cured resins are used because polymerization starts immediately on mixing. If left around the bracket, excess composite resin will lead to plaque accumulation and resultant enamel

decalcification.[78,79] However, the clinician must wait until final setting of the composite resin to remove any excess from around the bracket.[80]

- By 1984 composite resins (acrylic resins containing a high percentage of an inert filler material) largely replaced the ultra-violet cured resins. Compared with unfilled resins, the filler resins have greatly improved thermal expansion qualities. A small quantity of a composite resin can be mixed so that it sets rapidly and develops full strength in only a few minutes.[81]

- In 1985 the literature reported on the development of resins requiring no mixing.[34-82] With these "no-mix" materials, the composite resin can be placed on the tooth surface in unpolymerized form, while the polymerization catalyst is placed on the back of the brackets.

- 1988: Lutz and Phillips suggested the best way to describe the filler type is to classify materials into: traditional, hybrid, heterogeneous microfilled, or homogeneous microfilled.[84] They reported that manufacturers commonly use submicron particles to control viscosity of adhesives. Li *et al.*. reported filler volume has a greater effect on physical and mechanical properties than filler size.[85]

- Selection for orthodontic purposes depends on viscosity, which must be sufficiently low to wet the microscopically rough tooth surface and the attachment used, yet adequate enough to prevent the bracket from floating (creeping) once placed in the correct position on the tooth. The organic filler content varies between different brands of adhesives. Eustaquio, Garner and Moore compared tensile strengths of brackets bonded to porcelain with orthodontic adhesive and porcelain repair systems.[86] Concise/Scotchprime™ proved to have strengths that should be acceptable clinically. Ultra-bond™ produced a bond significantly less in strength when compared with the other four systems.

- Mid to late 1980's saw the use of light cured resins resurface in orthodontics. Incorporation of air in mixing the composite resin could lead to a weakening of the bond strength of the resins and to increase surface porosity.[80] Light-cured composite resins exhibit markedly less porosity than chemically cured resins.[80] Lovis *et al.*. conducted a comparative study of bond strength between light and chemically cured resins used in orthodontics.[87] They found the failure rate of chemically-cured material was 16 percent and light-cured material was 23 percent. O'Brien *et al.*. carried out a similar study in 1989 and found no significant differences detected between failure rates for both types of adhesive.[88]

- During 1989 Cooley and Barkmeier discussed fluoride release from orthodontic resins. These resins initially released fluoride in very small amounts, with no measurable fluoride release detected after three days. Sonis and Snell investigated FluorEver OBA[d] [89] They reported a decrease in amount of decalcification around orthodontic brackets bonded with this resin. They also reported that the fluoride-releasing resin provided bracket retention rates similar to those of conventional orthodontic bonding systems.[90]

- Glass ionomer cements have been mainly used for cementation of bands.[91,92] However a 12-month clinical study by Fricker[93] in 1992 showed that direct bonding of orthodontic brackets with glass ionomer cement was clinically acceptable. These results agree with an *in vivo* study conducted by Voss and Molkner.[94,95] Studies by Klockowski *et al.*. show glass ionomer

[d] Macro-Chem Corporation, Billerica, Mass

cement has a lower bond strength than conventional resin cements[73] but are in a "clinically usable" range.[96]

1.5.3.4 Effect of Thermal Debonding on Resins

The temperature required at the enamel/resin interface to thermally debonded brackets was investigated by Ruggeberg and Lockwood.[22] They found a direct relationship between filler content and debonding temperature. If incidence of failure at the tooth/resin interface is to be lower to preclude chances of enamel fracture in this area, then a lower filler bonding resin would be more desirable. Resins with lower filler content have lower debonding temperatures.

In 1992 Rueggeberg and Lockwood studied thermal debracketing of single crystal sapphire brackets.[23] They found the mean debonding temperatures for twenty-three different commercially available orthodontic resins ranged form 45°C to 168°C. There is a relation between amount of filler used in a resin and the temperature at which it debonds. The higher the filler content, the higher the debonding temperature. These results are important clinically to minimize the risk of thermal damage to teeth while debonding sapphire brackets. Achieve Light™ (orthodontic bonding resin used in this study) has a mean debonding temperature of 90°C ± 22°C.[23]

1.5.4 Ceramic Brackets

Ceramics are a broad class of materials that includes precious stones, glasses, clays, mixtures of ceramic compounds, and metallic oxides. In essence, a ceramic is neither metallic nor polymeric. Ceramics are renowned for their hardness, resistance to high temperatures, and to chemical degradation. The atomic structure that imparts these advantages also accounts for the most glaring fault; their brittleness.

Metals can be deformed considerably without fracturing, even in the presence of significant impurities and at sharp intersections. This ductility is a function of their non-oxidized atomic structure. When metals are stressed, a shifting at grain boundaries causes a redistribution and relief of stresses.[97]

In contrast, ceramics used in orthodontic brackets have highly localized, directional atomic bonds. This oxidized atomic lattice does not permit shifting of bonds and redistribution of stresses. When stresses reach critical levels, the inter-atomic bonds break and failure occurs. This is called "brittle failure".[98]

Ceramic compounds, unlike metals, are also susceptible to crack propagation caused by minute imperfections or material impurities. High-strength ceramics can fail easily when cracks or imperfections allow stress to be concentrated in a specific area..[97]

Although sharp intersections can be tolerated by stainless steel alloys, geometry of ceramic brackets is critical in preventing stress build-up and brittle failure. Finite element analysis, an engineering application of computer models to analyze stress levels and distribution, has been used to design ceramic brackets. Rounded intersections minimize likelihood of brittle failure occurring at force levels substantially below a material's maximum strength.[97] A shallow scratch on the surface or a microscopic crack will drastically reduce the load required for fracture of ceramic brackets, whereas the same scratch or crack on a metal surface will have little effect on fracture under load.[35,135]

Stresses introduced during ligation and archwire activation, forces of mastication and occlusion, and forces applied during bracket removal with pliers or debracketing instruments are all capable of creating cracks in ceramic brackets that may lead to failure.

Ceramic brackets were first made available in the late 1980's, largely to overcome aesthetic and treatment limitations of the plastic brackets.[99] These brackets were known to be durable and to resist stains. They are custom molded for individual teeth and dimensionally stable. Ceramics show little elastic or plastic deformation, and notch sensitivity is high.[99] Single crystals of man-made sapphire are produced by making a molten mass of aluminum oxide at temperatures in excess of 2100°C. This mass is slowly cooled to allow a carefully controlled crystallization. The resultant crystal is purer than its natural counterpart.[97] Originally, "A" Company purchased the raw materials that had been grown by the Edge defined Film Growth process (EFG). Deficiencies were found in the crystals and weaknesses were seen in areas of high tensile force such as tie wings. A new method (Czocharlski method) has been utilized to grow crystals. Crystals grown by the Czocharlski process have less defects hence brackets are less prone to breakage.[100]

The raw material is known as "boule" and is machined from a slab to a rod. The orthodontic manufacturers purchase these large single crystals and machine them into shapes and dimensions of various brackets, using ultrasonic cutting techniques, diamond cutting, or a combination of the two.[100] After milling, the sapphire crystals are heat-treated to remove surface imperfections and relieve stresses induced by milling operations. [97]

The primary advantage to single-crystal manufacturing is elimination of possible stress-inducing impurities or imperfections. The disadvantage is the difficulty and added expense of milling the third-hardest known material. Single-crystal brackets have noticeably more optical clarity than polycrystalline brackets.

1.5.5 Bonding of Ceramic Brackets

There are two different mechanisms for bonding ceramic brackets; (1) a mechanical retention via indentations and/or undercuts in the bracket base (2) a chemical bonding using an adhesive intermediate.[97] Laboratory testing of mechanical retention indicates that adhesive-to-bracket bond strengths are less than those of equivalent-size foil/mesh metal brackets.[97]

Chemical bonding is used for "A"-Company's Starfire™ ceramic brackets. A silica layer is added to the aluminum oxide base, then this silica layer is treated with a silane coupling agent. The silane coupling agent used is unhydrolized and supplied by Union Carbide™.[100] The silane coupling agent bonds with the silica and any acrylic bonding material. The same chemical bonding mechanism is used for porcelain crowns and restorations. It produces exceptional bond strengths that can possibly exceed the brittle fracture resistance of thinner areas of a ceramic bracket. Stresses of debonding can be shifted from the bracket-adhesive interface to the adhesive-enamel interface.

Bonded stainless steel brackets have a relatively flexible metal base to absorb impact loads. A rigid, brittle ceramic bracket bonded to rigid brittle enamel has little ability to absorb stresses. If the bracket-to-adhesive bond is too strong, then failure can only occur within the ceramic, within the adhesive, or within the enamel. A sudden impact loading is more likely to cause failure in the more brittle ceramic and enamel than the polymeric bonding material.[7]

1.5.6 Debonding Ceramic Brackets.

Introduction of ceramic brackets created a new clinical challenge for the orthodontist. First, adhesion between the resin and the ceramic bracket bases has increased to a point where the most common site of bond failure during debonding has shifted from bracket base-adhesive interface (seen in debonding of metal brackets) to enamel-adhesive interface, a less desirable site. This shift has led to an increase in incidence of bond failures within the enamel surface. Birnie believes that brittleness of ceramic brackets has caused development of enamel cracks, and occasionally the loss of sections of enamel when brackets have failed during treatment or during debonding.[10]

Although tensile strength of the new ceramics is greater than stainless steel, less energy is required to cause fracture of ceramic brackets compared with conventional stainless steel brackets. This phenomenon is related to "fracture toughness," or ability of a material to resist fracture.[35] During loading, stainless steel will elongate approximately 20 percent of its original length before failing, while sapphire will elongate less than 1 percent before failing. Thus, ceramics are more likely to fracture than metals under the same conditions during debonding.

Introduction of ceramic brackets, with their particular physical properties, has created a need for a safer and more reliable method of debracketing these attachments. Bishara and Truelove raised questions concerning the potential for enamel fractures and cracks following conventional debonding.[11] Application of a force that peels the bracket base away from the tooth and causes bond failure at the adhesive-bracket interface in the most consistently atraumatic debonding technique.[101-104] Because of the nature of ceramic brackets, debonding methods that employ such a force often result in fracture of bracket or enamel. As a result, manufacturers have developed various debonding techniques specifically for ceramic brackets. These range from an electrothermal debracketing tool to air heating appliances designed to reduce the force necessary for debonding by raising the temperature at the bracket/adhesive interface.[9,23,24,27,105-107]

An innovative approach to bracket removal was introduced with the development of electrothermal debracketing (ETD™). ETD™ is the technique of removing bonded brackets from enamel surfaces with a cordless battery device that generates heat. The heat is transferred to the bracket by a blade placed in the bracket slot. The bracket is firmly held by a thumb-activated lock-on arm of the ETD™ unit. Heat is generated in the bracket at a rapid rate until the temperature in the bracket approaches 600°F.[108] At this temperature, stresses are concentrated at the bracket/resin interface and debonding occurs. The bracket can be gently torqued then lifted from the enamel surface without distortion of the bracket or excessive force on the underlying enamel. This debonding process occurs in approximately 3 to 4 seconds. An obvious advantage associated with use of ETD™ is a reduction in probability of enamel damage during debonding since a significant number of bond failures occurs at the bracket-adhesive interface.[12]

A limited number of investigations are available on the effect of electrothermal debonding on the living pulp.[8,19] Most studies on the effect of temperature on the pulp center around the thermal effect of frictional heat produced during dental procedures or setting of restorative filling materials.[109,110] Postle *et al.*, exposed dog teeth for 20 seconds to 102°, 201°, and 482°C. One month later irregular dentine was formed, but pulps of the teeth exposed to 102°, 201°C did not show signs of pathosis.[111] Abscesses or necrosis were seen in teeth exposed to 482°C. Brännström demonstrated pulpal pathosis in human teeth after application of a temperature of 100°C to exposed dentine for 45 seconds.[112] The most reliable guidelines relating to the amount of thermal activity pulpal tissue can tolerate was established by Zach and Cohen[113]. These studies were carried out on primate teeth. For a period of 5 to 20 seconds, a constant heat of 275°C was applied to the buccal surface of the teeth. Pulps were examined histologically after 2-91 days. The thermal injury appeared reversible as long as the pulpal temperature increase did not exceed 5.5°C. At 11.1°C, abscess formation occurs in 60 percent of the teeth and at 16.6°C, pulpal necrosis was found in all teeth.

Sheridan, Brawley and Hastings investigated the *in vitro* rise in temperature at the pulpal wall when ETD™ was used.[24] All ETD™ procedures in the sample elicited pulpal wall temperatures significantly below the primate baseline. *In vivo* studies by Sheridan *et al.*. in 1986 showed no evidence of necrosis or inflammation in teeth 2 weeks after electrothermal debonding metal brackets was performed. [106]

Brouns debonded ceramic brackets with the De-bond 200® device and found an average temperature increase between 1.8° and 2.0°C.[8] Brouns proposed a smaller bracket base design would lead to a higher amount of transferred heat per mm^2 resulting in a faster weakening of the bonding material and therefore less transfer of heat to the tooth.[8]

Rueggenberg and Lockwood[22] in their study on thermal debracketing noted room-temperature debonding demonstrated failure sites at the bracket/resin interface with the exception of cohesive enamel fractures. At elevated temperatures, the site of failure was shifted toward the tooth/resin interface. They found no evidence of overt enamel fracture when debonding was done at elevated temperatures. There is an inverse exponential relationship between temperature at debonding and load needed to cause bracket failure. A small amount of applied heat during bracket debonding creates a significant decrease in the force needed to cause removal.

1.5.7 Enamel Morphology Following Thermal Debonding.

Any adhesive remaining on enamel following bracket removal can be assessed according to the Adhesive Remnant Index (ARI).[104,27] The ARI system is used to evaluate amount of adhesive remaining on the tooth after debonding. This index system was developed by Årtun and Bergland in 1984.[81] The following is the criteria for the index :

Score 0 = No adhesive left

Score 1 = Less than half of the adhesive left

Score 2 = More than half of the adhesive left

Score 3 = All base covered by adhesive

Bishara debonded Starfire™ brackets with an electrothermal debracketing instrument, the bulk of adhesive remained on the tooth.[12] Bond failure occurred at the bracket-adhesive interface.

Adhesive can be removed by a number of methods. Three methods reported by Bishara in 1993; a technique involving a high-speed bur, a low-speed bur, and ultrasonic KJS tips.[12] The mean amount of enamel loss for the high-speed, low-speed, and ultrasonic techniques were 68.8 μm, 62.63 μm, and 49.97 μm, respectively. Although mean enamel loss observed in this study with the high-speed bur was greater, there was no statistically significant difference between the various techniques. These results are comparable to those reported by Fitzpatrick and Way.[52] Pus and Way also evaluated enamel loss with similar adhesive removal techniques and observed lesser amounts of enamel loss depending on the technique used for enamel clean-up.[33]

Bishara, using a scanning electron microscopic analysis, found a significantly rougher surface with the high-speed technique than with either the low-speed or ultra-sonic technique.[12] This roughness (at a microscopic level) blends into the surrounding tooth structure with time as a result of the normal mechanical influences of tooth brushing and mastication.

1.5.8 Silane Coupling Agents

Bond strengths obtained with ceramic brackets are, in part, a result of the introduction of a chemically mediated adhesion between the ceramic base and adhesive resin. Because of the inert composition of the aluminum oxide ceramic brackets, chemical cohesion between the ceramic base and adhesive resin is weak. A silane coupling agent is used as a chemical mediator between the adhesive resin and bracket base.

Silane coupling agent was first used in dentistry to coat the glass filler particles of composite resins to facilitate binding between the resin and glass filler.[114] Silane coupling agents have been used to bond porcelain teeth to acrylic denture bases, orthodontic attachments to porcelain crowns, and composite resins to the surface of porcelain crowns to allow their repair without complete replacement of the restoration.[115-118]

The silane molecule is a bifunctional molecule; one end is a reactive silanol group that can bind tenaciously to silica, while the other end of the molecule reacts with other acrylic resins and polymerizes, producing a cohesive bond with the resin material.[119] Although titanates and zirconates can be used for coupling agents, the ones most commonly used are organosilanes (3-methoxy-propyl-trimethoxy-silane).[120] In its hydrolyzed state, the silane contains silanol groups that can bond with silanols on the silica surface by formation of a siloxane bond (Si-O-Si). Methacrylate groups of the organosilane compound form covalent bonds with the resin when polymerized, thus completing the coupling process.[98,121] The link between silica and silane is achieved through hydrolysis and absorption of a silane on a ceramic surface and the covalent bonding between silane and resin matrix.[120] Because of the inert nature of the aluminum oxide crystals (from which the ceramic bracket is fabricated) the silanol group of the silane molecule will not react and bind to the bracket base unless a layer of silica is present. The base of each bracket is coated with silica glass to promote bonding between the silanol functional group of the silane molecule

Silane may improve bond strength via two mechanisms. Firstly, it provides a chemical link between composite resin and silica. Secondly, it promotes wetting of the silica surface and thus enhances the flow of the resin cement into the intricate pattern of micro-undercuts of the silica surface. Johnson reported bond strength of acrylic resin to porcelain with silane as a coupling agent is adequate to withstand orthodontic forces.[119]

Not all investigations of silane have found a positive correlation between acceptable bond strength and silane. Harris, Joseph and Rossouw found silane weakened the shear/peel bond strength of Transcend 2000 brackets to a clinically unacceptable level.[76] These investigators used freshly mixed silane and applied it to debonded bracket bases, following manufacturer's instructions. They stated that some "unknown characteristic" of the bracket base may have played a role in this unacceptable bond strength. Newman *et al.*, questioned the clinical effectiveness of silane to increase bond strength between brackets and a restorative material.[116]

Guess *et al.*. advocated use of silane coupling agents for adequate bond strength where brackets do not have mechanical retention built into the base.[122] However Carter reported a high bond strength that was clinically unacceptable when silane was used in conjunction with mechanical retention.[14]

1.5.9 Hydrofluoric Acid

Hydrofluoric acid has been used to improve bond strength of porcelain with composite resin.[123] Improvement in bond strength after hydrofluoric acid etching of the porcelain surface may be explained by the micro-mechanical interlocking between resin cement and etched porcelain. According to Strangel, Nathanson and Hsu, hydrofluoric acid dissolves glassy components of porcelain and created micro-pores and porosities.[124] This increased the surface area of porcelain and creates micro-undercuts which encourage composite resin to bond to porcelain surface.

Etched porcelain allows a silane coupling agents to chemically link resin to porcelain. Culler, Kruecher and Joos attributed this linkage to adsorption of a silane on a ceramic surface and covalent bonding between silane and the resin matrix.[120] Other studies have found silane coupling agents effective in improving composite resin-porcelain bond.[125,126]

1.5.10 Bovine Teeth

Choice of teeth used in bond strength studies varies with some investigators using animal teeth, while others prefer premolars extracted for orthodontic purposes.[127-129,158] The storage conditions of specimens prior to bond testing also have been different; saline solution, water, distilled water, and ten percent formalin are commonly used methods.[21,58,128,130,131]

To find a substitute for human teeth in adhesion tests, Nakamichi, Iwaku and Fusayama investigated bovine teeth.[132] Adhesion to enamel and the superficial layer of dentine showed no significant difference between human and bovine teeth although mean values were always slightly lower with bovine teeth.

Histochemical and comparative anatomical studies have revealed that all mammalian teeth are essentially similar.[133] Yu and Chang reported that critical surface tension was lower with bovine teeth than human teeth, resulting in slightly lower adhesive strength to both enamel and dentine with bovine teeth. Bovine enamel has large crystal grains and more lattice defects than human enamel, since bovine teeth develop more rapidly before and after eruption.[134]

1.5.11 Bond Strength

Bond strength may be measured in terms of three basic parameters; tensile, shear and torsional. The forces acting in the mouth are usually a combination of a number of these forces in unequal proportions. Variations in independent variables seen in the literature make comparisons of results difficult, even though individual results may be valid.

Due to cost of ceramic brackets and the number of independent variables examined, only one force parameter was observed; Shear/Peel. Shear force occurs when a stress is applied by two forces acting in opposite directions but not in the same line. These stresses tend to slide one part of a material past another along planes parallel to the applied forces. Shear/peel force is applied to a bracket at a distance from the bracket/resin interface. Bond strength can be measured with an Instron Testing Machine. A strain gauge records the force exerted on the brackets and should be calibrated by a proving ring before and after an experiment.

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CHAPTER TWO

Introduction 2.1

A simple method to relocate brackets has eluded operators since the advent of bonding attachments. According to Andrew's[1] "the clinician must position the brackets correctly on the teeth to assure a functional end result." Inaccurately located brackets should be repositioned during treatment to take full advantage of the archwire slot values and sliding mechanics.[2]

In 1990 Lew and Djeng reported on a chairside method of recycling ceramic brackets.[4] Lew, Chew and Lee in 1991 reported on the shear bond strength of recycled ceramic brackets.[5] These brackets were debonded using a Transcend Debonding Instrument[e]. The brackets were heated to remove residual bonding resin, silanated, then rebonded. Shear bond strength of 'new' ceramic brackets were about 40 percent greater than recycled brackets. There was no mention of the number of brackets fractured during debonding.

A number of articles in orthodontic literature specified concern regarding damage to enamel during debonding of ceramic brackets.[6-22] Sheridan introduced electrothermal debracketing (ETD™)[f] in 1986; a new concept in bracket removal.[23] The ETD™ has a debonding tip especially tooled to fit "A" Company brackets. This debonding unit transfers heat through the bracket, allowing bond failure at the bracket-adhesive interface as the heat deforms the adhesive.[11] The debonding process leaves the base of

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[e] Unitek Corporation/3M 2724 S. Peck Road, Monrovia, CA 91016

[f] "A" Company; A division of Johnson & Johnson INC. 11436 Sorrento Valley Rd, San Diego, California, 92121.

a bracket relatively free from resin.[24] Studies have not demonstrated any pathologic pulpal reaction to ETD™ process.[25,18]

The purpose of this study is to;

(1) investigate the potential value of the ETD™ to provide debonded ceramic brackets in a physical state capable of being rebonded, and

(2) evaluate shear/peel bond strength of repositioned brackets with a variety of treatments to their bases.

2.2 Materials and Method

Starfire[f] single crystalline aluminaoxide brackets were used in this study. These brackets were upper central incisor brackets with the standard edgewise 0.022 X 0.028-inch slot.

Bovine teeth were chosen as a substitute for human teeth due to their greater availability and larger size.[26,27] Histochemical and comparative anatomical studies revealed all mammalian teeth are essentially similar.[28] Nakamichi, Iwaku and Fusayama[27] reported no significant differences in adhesion to enamel between human and bovine teeth, although values were slightly lower with bovine teeth. Therefore, bond strengths of brackets in this study are comparable to bond strengths found using human teeth.

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[f] "A" Company; A division of Johnson & Johnson INC. 11436 Sorrento Valley Rd. San Diego, California, 92121.
[g] Kerr Manufacturing Co., Romulus, Mich.
[h] 3M Dental Produ. St. Paul, MN 55144-1000

2.2.1 Tooth Preparation

Two hundred and thirty seven uppercentral bovine incisor teeth were stored in water following extraction at a local slaughterhouse. A flat enamel surface was obtained by wet sanding the labial surface with progressively finer silicon-carbide abrasive paper (final grit 400).[29,30]

Teeth were prepared for bonding by mounting in PVC rings. The PVC rings were then filled with acrylic resin [Fastcure][g]. The surface of these complexes received one more polish with 600 grit silicon carbide paper removing any acrylic flash material. Following this preparation, the teeth were cleansed of fine debris in an ultrasonic cleaning unit. Prepared teeth were stored in distilled water at room temperature until bonding.

2.2.2 Bonding Protocol

All teeth were subjected to a 30 second etch with 37 percent orthophosphoric acid, washed for 20 seconds then dried with warm air. Bonding material was applied in accordance with the manufacturer's instructions. Reliance™ light cured adhesive[f] with an average filler particle size of 0.04mm and filler weight of 52% was used. To control the adhesive thickness and maintain uniform bracket placement a bonding jig with a 2000gm load was used[29] (see Fig. I). Excess composite was removed carefully from the bracket-tooth interface, and the adhesive light cured.

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[f] "A" Company; A division of Johnson & Johnson INC. 11436 Sorrento Valley Rd, San Diego, California, 92121.

2.3 Adhesive Remnant Study

One hundred and twelve bovine teeth were bonded with ceramic brackets then thermally debonded using the ETD™. The ETD™ unit was used in accordance to manufacturers instructions. During this procedure twelve brackets were broken and discarded. Brackets bases were visually inspected for resin under a stereoscopic microscope at magnification X20. The Adhesive Remnant Index (ARI)[31] system was used to evaluate the quantity of adhesive remaining on the bracket following debonding.

ARI classification is listed below:

Score 0 = No adhesive on bracket base

Score 1 = Adhesive covering less than half of bracket base

Score 2 = Adhesive covering more than half of bracket base

Score 3 = Adhesive covering all bracket base

2.4 Bond Strength Study (BSS)

2.4.1 Bracket Base Treatment.

Three treatments procedures were used on debonded bracket bases.

- Silane coupling agent; Scotchprime™ Ceramic Primer No 2721[i] applied as per manufacture's directions.
- Heat; Protocol as described by Lew and Djeng.[4] Brackets were heated until they were cherry red to burn off the residual composite resin. Bracket bases were then rinsed with 100 percent alcohol and left to dry.
- Hydrofluoric Acid; Brackets were treated with hydrofluoric acid (PorceLock™ Porcelain Etching Solution No. 2061[j]) for five minutes then rinsed under cold water to remove all traces of acid.

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[i] 3M Dental Products St. Paul, MN 55144-1000

[j] Den-Mat Corp., 2727 Skyway Dr. Santa Maria, CA 93455

2.4.2 Experimental Groups

There were five experimental groups:

I. Control; Brackets not previously bonded (n=25)

II. Silane coupling agent; (n=25)

III. Heat and Silane coupling agent; (n=25)

IV. Hydrofluoric Acid + Silane coupling agent; (n=25)

V. Heat + Hydrofluoric Acid + Silane coupling agent; (n=25)

The remaining one hundred and twenty five prepared teeth were randomly assigned to five groups. The five groups of brackets were bonded to these teeth as per bonding protocol. Following bonding, teeth were independently coded to facilitate blinding, then stored in water at room temperature for three days.

2.5. Bond Strength Measurement.

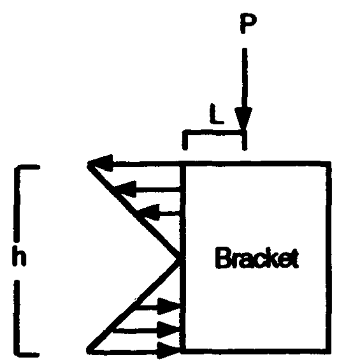
Shear/peel bond strength was tested with an Instron Universal Testing Machine (Instron Corp., Canton, Mass.). Testing was carried out in random order with each bonded unit placed in a holding jig to allow a force to be applied 1mm from the resin/base interface. Cross-head speed of 0.02 inch per minute was used. Load at failure was recorded in Newtons and the bond failure was calculated as stress per unit area (MPa). The mean and standard deviation were calculated for each group. One-way analysis of variance was followed by a Scheffè procedure for multiple comparisons to determine any significant differences between bracket treatments.

Shear/peel force can be analyzed into its components by the following formulas:

$$Shear\ force = \frac{P}{h\,d}$$

$$\text{Peel force} = \frac{6PL}{h^2 d}$$

where, P = debonding force, d = width of bracket, h = height of bracket, L = distance from bracket/resin interface to point of force application.



Free body diagram of a bracket being tested with the Instron Testing Machine (viewed from the mesial aspect).

Where h= 3.22mm, L= 1.00mm, d= 3.86mm

Shear to peel ratio for this experiment is **0.53**

This ratio was calculated with two assumptions:

1. The shear force is uniformly distributed.
2. The stresses for peel are linearly distributed from top to bottom of the bracket.

2.6 Results

During debonding some brackets fractured. One hundred and twelve brackets were debonded, twelve fractured during this process. Fractures occurred at the tie wings on all brackets.

Results of the ARI study (listed in Table I) show seventy nine percent of bracket bases had a score of 0, sixteen percent scored as 1, while five percent scored as 2.

Descriptive statistics of the shear/peel bond strengths for each base treatment are shown below in Table II and Boxplots of bond strengths are shown in Figure III.

A boxplot was chosen as it displays a summary of statistics, instead of plotting actual values. It plots the median, the 25th percentile, the 75th percentile, and values that are far removed from the rest. The lower boundary of the box is the 25th percentile and the upper boundary is the 75th percentile. The horizontal line inside the box represents the median. Fifty percent of the results have values within the box. The length of the box corresponds to the interquartile range, which is the difference between the 75th and 25th percentiles.

The boxplot includes two categories of values with outlying values. Cases with values that are more than 3 box-lengths from the upper or lower edge of the box are called extreme values. Cases with values that are between 1.5 and 3 box-lengths from the upper or lower edge of the box are called outliers. The largest and smallest observed values that are not outliers are also shown. Lines are drawn from the ends of the box to these values. (These lines are sometimes called whiskers and the plot is called a box-and-whiskers plot.)

One way analysis of variance followed by a Scheffé test of multiple comparisons show a significant difference ($p<0.01$) between all pairs of groups except for hydrofluoric acid and silane versus the combination of heat, hydrofluoric acid and silane.

2.7 Discussion

The first portion of this study investigated the bonding surface of brackets following thermal debonding. Resin left on the base of the debonded bracket was removed prior to rebonding. Seventy nine percent of debonded brackets were resin free, while sixteen percent of brackets had less than half the bracket base covered by resin and five percent of brackets had more than half the bracket base covered with resin. This means four out of five thermally debonded brackets will only require treatment with silane coupling agent prior to rebonding. These results agree with Bishara's and Trulove's study[11].

The aim of the second part of the study was to evaluate a method of repositioning bonded ceramic brackets. Ceramic brackets are more expensive than metal brackets. Using a new bracket each time a bracket is repositioned increases the cost of providing treatment, particularly if brackets are purchased in 'one-patient' kits.

Studies published by Lew, Chew and Lee,[5] discussed a comparison of shear bond strength between new and recycled ceramic brackets. They debonded polycrystalline brackets using the Unitek debonding tool. This debonding process places a torquing force on the ceramic bracket and could potentially damage the underlying tooth structure. Although the authors did not detail bracket damage during debonding, the physical effect of this debonding technique could leave the bracket with surface imperfections. Swartz discussed the ability of high-strength ceramics to fail easily from surface cracks or imperfections. These surface anomalies allow concentration of stresses to propagate into bracket fracture.[32]

During debonding, twelve percent of brackets fractured and were discarded. Fractures occurred predominantly at the tie wing. Possible reasons for these fractures are; (1) insufficient heat delivered to bracket at time of debonding, (2) application of force too early in the debonding procedure, (3) surface crack or check on bracket resulting in crack propagation and fracture of the bracket.[35] However, debonding was accomplished during the same procedure by reversing torque direction thus applying force to the unbroken tie wings. Bracket removal is important as the ETD™ reaches 600°F prior to debonding resulting in a high bracket temperature. If the fractured bracket is not removed, risk of pulp damage is increased. This site of fracture agrees with the findings of the Bishara and Trulove's study (1990) where they conventionally debonded 'Starfire' brackets. However, when Bishara and Trulove[11] used ETD™ to debond 20 ceramic brackets they reported no bracket fractures.

The aim of bond-strength studies is to determine whether the strength of the system can withstand forces applied during treatment and function. Reynolds[33] suggested that a range of 60 to 80kg/cm^2 would meet most orthodontic needs. This range calculates into 5.89 to 7.85 MPa. Ceramic brackets have a history of damage to enamel during debonding due to excessive bond strength.[6-22] Retief found that damage to enamel could occur at bond strengths as low as 13.53 MPa.[34]

Treatment of debonded brackets with a silane coupling agent yielded the highest bond strength of all treatment groups. This bracket treatment was the quickest and simplest of all bracket treatments. Bond strength of this group is 12.7 ± 3.3MPa and is a reduction of 25% relative to the non treatment group. Due to randomization of brackets in this study, 21% of brackets in this group could have some resin on their base. If all brackets in this group were resin free on rebonding, an increase in bond strength could be anticipated. The bond strength is below the level resulting in enamel damage cited by Retief[34], but above the minimum clinically required.

If resin remains on the bracket base following electrothermal debonding, it can be removed by heat[4]. Bond strength of the heat and silane group was 8.8 ± 3.5 MPa, which is clinically acceptable.[33] A reduction in bond strength from both silane and control groups is noted. This reduction could be attributed to contamination of the base during the heating process. This is evidenced when viewing an electron micrograph of a bracket which has been heated but not cleaned with alcohol (Fig. IV). This micrograph shows residue remaining prior to washing when heat is used to remove resin. Bond strength of this group was lower than found by Lew.[4] The reduction could be due to: differences in ceramic materials, methods of retention, bonding resin and teeth.

Use of hydrofluoric acid as a base preparation resulted in radical reduction in bond strengths. This occurs because the silica layer on the base is extremely thin and is removed by the hydrofluoric acid. This is evident when the electron micrographs of the bases of the bracket treated with hydrofluoric acid is viewed in contrast to an untreated base (Fig. V and VI). Silane forms a weak bond with aluminumoxide which resulted in the low bond strength of these groups. The bond strength for the group treated with hydrofluoric acid and silane was 1.5 ± 2.0 MPa and for heat, hydrofluoric acid and silane group it was 0.7±1.0 MPa. Both these bond strengths are not clinically acceptable.

Silane coupling agent was used in this study because it chemically mediates adhesion between the ceramic base and adhesive resin. Because of the inert composition of the aluminum oxide ceramic brackets, chemical cohesion between the ceramic base and adhesive resin is impossible. Therefore, a silane coupling agent was used as a chemical mediator between the adhesive resin and bracket base.

The bond strengths observed in this study may be higher than those witnessed clinically. This is bec[illegible] [illegible]ro studies of bonding are ideal with moisture contamination, bon[illegible] temperature and other oral variables being eliminated [illegible] Clinical studies that investigated long term bond strength of [illegible]tioned ce[illegible]mic brackets would be advantageous to the orthodontic practitioner. These studies could have new values for bond strength as bond strength varies when brackets are bonded to aged composite.[29]

2.8 Conclusions

This study was carried out to determine the amount of resin remaining on bracket base following electrothermal debonding and the bond strength of thermally debonded, [illegible]bonded ceramic brackets under different treatment conditions.

From the study the following observations were made;

1 After electrothermal debonding, 79% of brackets were resin free, 16% had less than half their base covered by resin while 5% had more than half of their base covered by resin.

clinically since the brackets should still have an adequate bond strength to withstand normal orthodontic and occlusal forces.

3 Rebonding thermally debonded ceramic brackets treated with heat and a silane coupling agent resulted in a significant decrease in shear/peel bond strength. This reduction was not considered sufficient to be important clinically since the brackets should still have an adequate bond strength to withstand normal orthodontic and occlusal forces.

4. Rebonding thermally debonded ceramic brackets treated with hydrofluoric acid resulted in a significant decrease in shear/peel bond strength. This reduction was considered to be important clinically since the brackets did not have an adequate bond strength to withstand normal orthodontic and occlusal forces.

Acknowledgment.

This study was supported by the McIntyre Research Fund. All bonding materials were graciously donated by the respective manufactures. A special note of thanks goes to "A" Company for their generous donation of brackets, the Electrothermal Debonding Unit and technical advice.

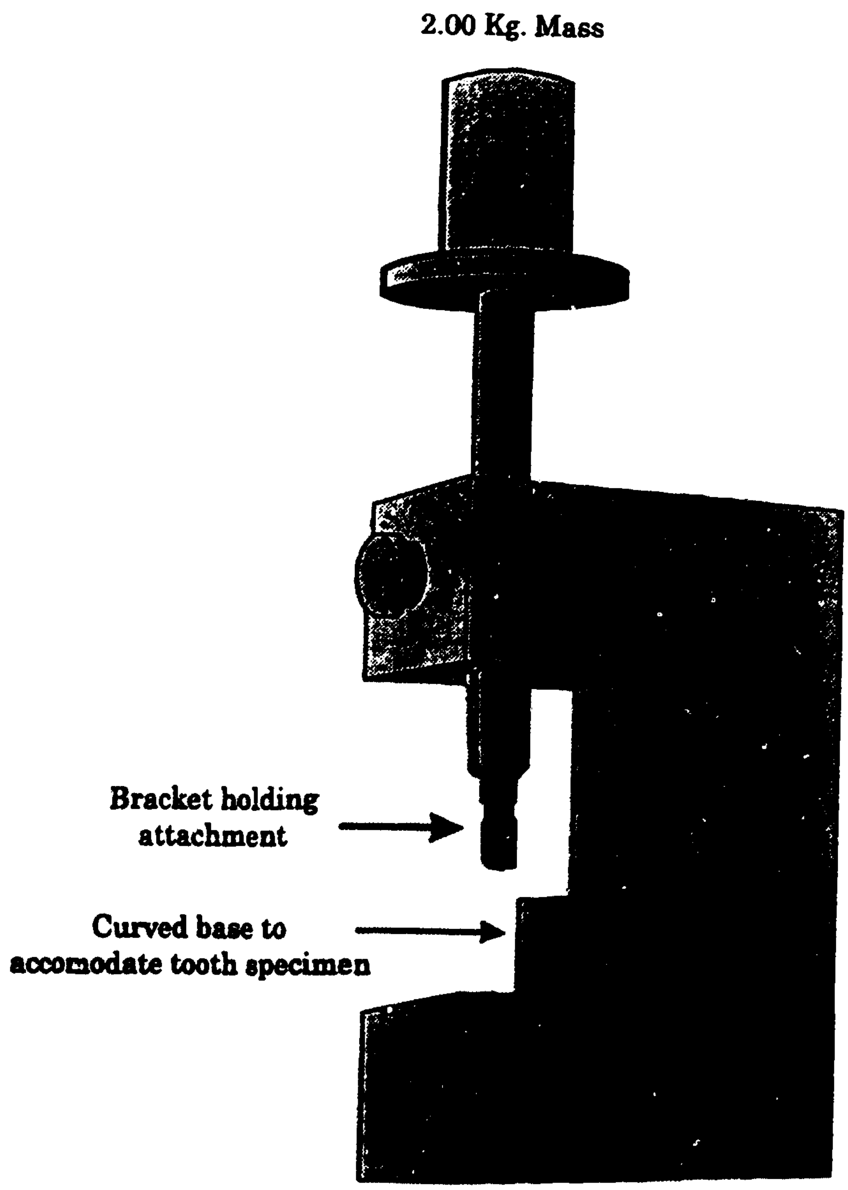


Figure 1. Bonding Jig

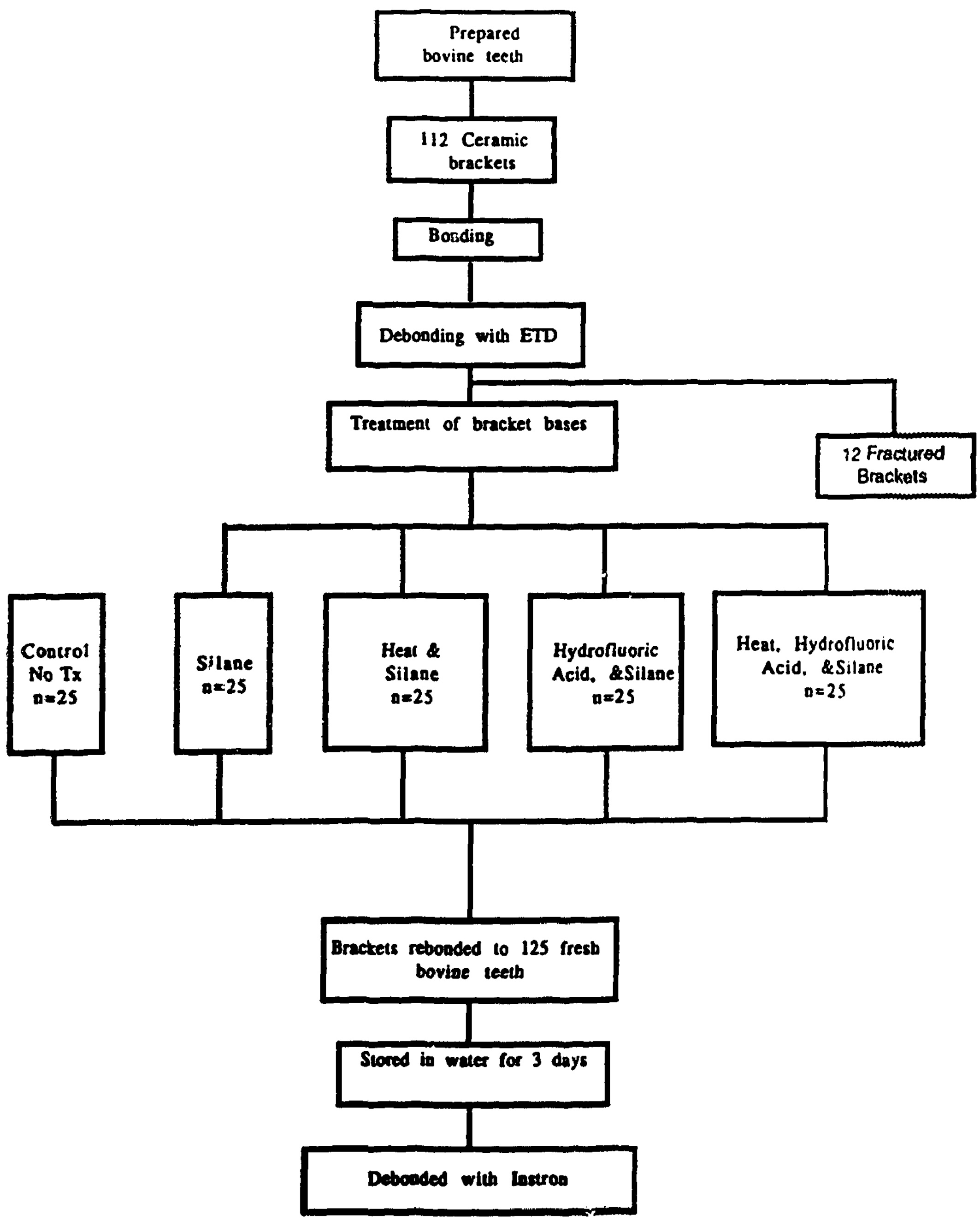


Figure II. Flow diagram of study

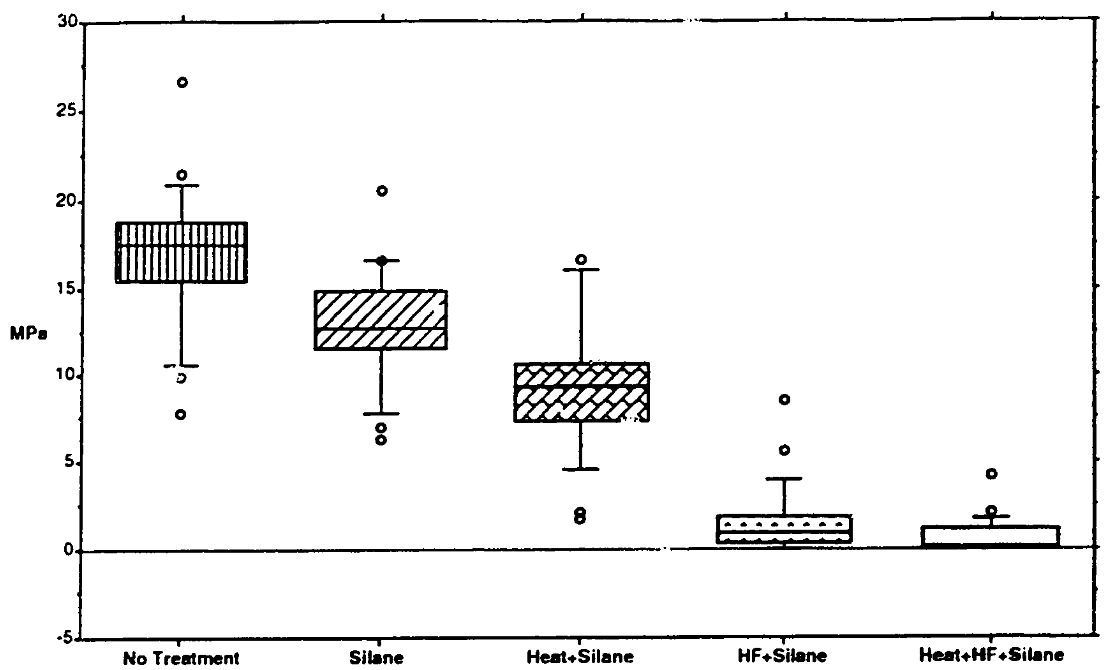


Figure III. Boxplots of Shear/Peel Bond Strengths (MPa)

ARI SCORE	Percent
0	79
1	16
2	5
3	0

Table I. Adhesive Remnant Index (ARI) Results

	Mean	Std. Dev	Minimum	Maximum	Coef. Var.
No Tx	16.9	4.00	7.9	26.6	23.4%
Silane	12.7	3.3	6.4	20.6	25.7%
Heat+ Silane	9.1	3.7	1.8	16.6	40.9%
HF+Silane	1.6	2.0	0	8.5	129.1%
Heat+HF+ Silane	0.7	1.0	0	4.2	142.9%

Table II

Descriptive Statistics of Shear/Peel Bond Strengths (MPa)

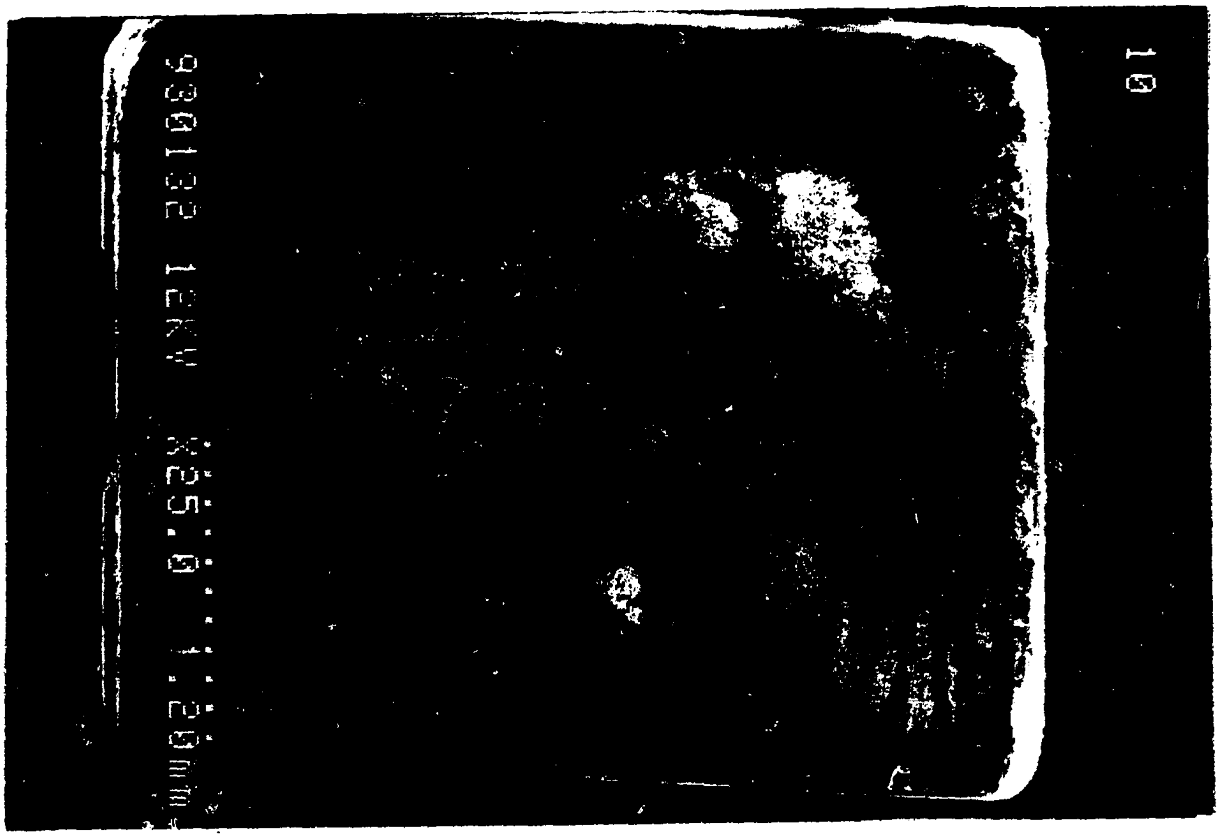


Figure IV.
Scanning Electron Micrograph of a bracket, heated to remove resin but not cleaned with alcohol.

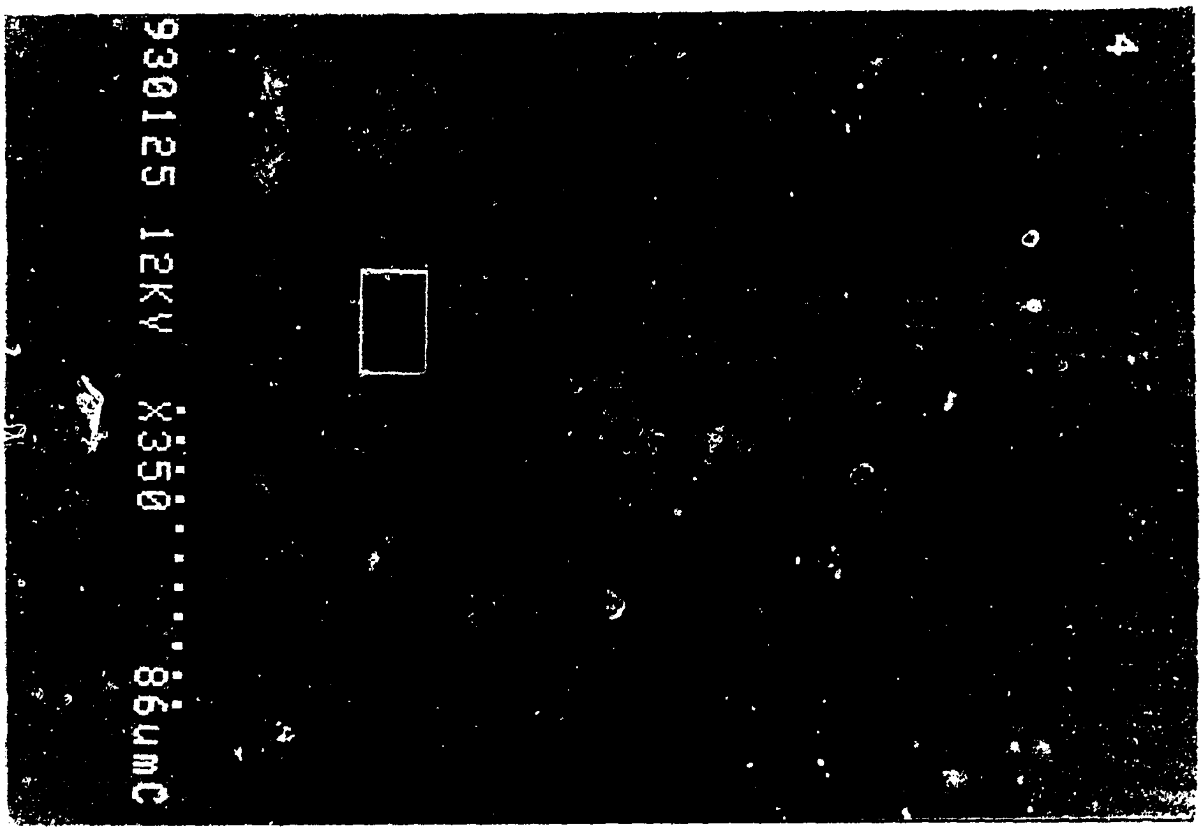


Figure V. Scanning Electron Micrograph of a bracket treated with hydrofluoric acid.

Figure VI.
Scanning Electron Micrograph of an untreated bracket.

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CHAPTER THREE

This study was carried out to ascertain whether electrothermal debonding left brackets in a physical rebondable state and to examine bond strength of rebonded ceramic brackets with a variety of treatment conditions.

3.1 Amount of Residual Adhesive

For a bracket to be rebonded, it is preferable that its base be free of resin. Resin remaining on the base should be removed prior to rebonding. After debonding, bracket bases were visually inspected for resin and classified according to an Adhesive Remnant Index. Seventy nine percent of the debonded brackets were resin free, sixteen percent had less than half the base covered by resin, while five percent had more than half base covered by resin. This means four out of five thermally debonded brackets will only require treatment with a silane coupling agent prior to rebonding. These results agree with Bishara's and Trulove's study[1].

3.2 Fracture of Brackets During Debonding

During debonding all brackets were loaded with a couple. Ten point seven one percent fractured during this process and were discarded. Fractures occurred predominantly at the tie wing. This site of fracture agrees with the findings of the Bishara and Trulove's study (1990) when they conventionally debonded Starfire™ brackets.[1] However, when Bishara and Trulove used ETD™ to debond 20 ceramic brackets they reported no bracket fractures. All fractured ceramic brackets were debonded during the same procedure by reversing the direction of the couple and thus applying force to the unbroken tie wings. Bracket removal is important as the ETD™ reaches 600°F prior to debonding[37] resulting in a high bracket temperature. If the fractured bracket is not removed, the risk of pulp damage is raised.[24]

Possible explanation for these fractures are;

(1) Insufficient heat delivered to the bracket from the ETD™ unit at time of debonding. The physical process of thermal debonding is not fully understood. The process is thought to be due to either; a large coefficient of thermal expansion leading to breaking of the bond between bracket and resin, or softening of the resin to break this bond. What is important is that sufficient heat is delivered to effect debonding.[24]

(2) Application of force too early in the debonding procedure. This would have the same effect insufficient heat delivered to the bracket at the time of debonding. The debonding process was executed after the ETD™ tip was inserted in the bracket for a period of not less than three seconds. This procedure was standardized for all debondings.

(3) Surface crack or check on bracket resulting in crack propagation and fracture of the bracket[2,3] Eliades *et al.*. discussed how stresses applied at surface flaws of single-crystal alumina brackets can result in cohesive fracture of the bracket.[3]

3.3 Bond Strength Study

Repositioning bonded ceramic brackets requires a technique that is simple, quick and does not damage the underlying tooth structure. Sheridan reported the technique of electrothermal debonding in 1986.[4] Heat is transferred through the bracket, resulting in bond failure at the bracket-adhesive interface.[1] This debonding process does not damage the enamel and leaves the bracket base relatively free from resin.[5]

Repositioning of a bracket allows the operator to take full advantage of the archwire slot values and sliding mechanics.[6] When rebonding a ceramic bracket during treatment, the operator may damage the bracket and a new bracket is then required. Studies published by Lew[7] discussed a comparison of shear bond strength between new and recycled ceramic brackets. These brackets were removed using the Unitek™ debonding wrench (3M). The physical effect of this debonding technique could leave the bracket with surface imperfections. Swartz discussed the ability of high-strength ceramics to fail easily from surface cracks or imperfections. These surface anomalies allow concentration of stresses to propagate into bracket fracture.[8]

Ceramic brackets are more expensive than metal brackets. Using a new bracket each time increases the cost of providing treatment, particularly if brackets are purchased in 'one-patient' kits.

3.3.1 *Units*

The bond strength of a bracket is a measure of force necessary to break the bracket from the tooth surface and is directly proportional to the area of the bracket base. Therefore, bond strength must be accurately depicted by measuring it as a force per unit of area, for example MPa.

Bond strength may be measured in terms of three basic parameters; tensile, shear and torsional. The forces acting in the mouth are usually a combination of a number of these forces in unequal proportions. Variations in independent variables seen in the literature make comparisons of results difficult, even though individual results may be valid.

Difficulty exists when an investigator examines a shear force as this requires accurate placement of the force at the bracket/resin interface.

This study applied the force at a distance from the bracket resin interface, the force is of a shear/peel nature.

Shear to peel ratio for this experiment was calculated as 1:1.87. This ratio was calculated with two assumptions:

1. The shear force is uniformly distributed.
2. The stresses for peel are linearly distributed from top to bottom of the bracket.

3.3.2 *Bovine Teeth*

Bovine teeth were chosen as a substitute for human teeth due to their greater availability and larger size.[9,10] Histochemical and comparative anatomical studies revealed all mammalian teeth are essentially similar.[11] Nakamichi, Iwaku and Fusayama[10] reported no statistically significant differences in adhesion to enamel between human and bovine teeth, although the values were slightly lower with bovine teeth. Therefore, bond strengths of brackets in this study are comparable to bond strengths found using human teeth.

3.3.3 *Bond Strength; What is Clinically Acceptable?*

The aim of all bond-strength studies is to determine whether the strength of a system can withstand forces applied during treatment and function. Reynolds[12] suggested range of 60 to $80 kg/cm^2$ (5.89 to 7.85 MPa) would meet most orthodontic needs. Ceramic brackets have a history of damage to enamel following debonding due to excessive bond strength.[6-22] Retief found damage to enamel could occur at bond strengths of 13.53 MPa.[33]

By using a flat bonding surface on enamel, a standardized bonding technique, and one investigator, inconsistencies were minimized. Variations in bond strength within groups have been attributed to several factors such as subtle inconsistencies in the treatment of the base, presence of slight contamination on the base of the bracket, porosity within the bonding adhesive, and differences in the enamel prism micromorphology. These variations have been reported by other researchers [7,34,35]

3.3.4 Treatment of Bases

3.3.4.1 *Silane Coupling Agent*

Treatment of debonded brackets with a silane coupling agent yielded the highest bond strength of all treatment groups. This bracket treatment was the quickest and simplest of all bracket treatments. Mean bond strength of this group is 12.7 ± 3.3 MPa is a reduction of twenty-five percent on the control group. Due to randomization of brackets in this study, 21 percent of brackets in this group could have some resin on their base. If all brackets in this group were resin free on rebonding, an increase in bond strength could be anticipated. The bond strength is below the level resulting in enamel damage cited by Retief[33]

3.3.4.2 *Heat and Silane Coupling Agent*

Resin can be left on the bracket base following electrothermal debonding, it is removed by heat.[36] Mean bond strength of the heat and silane coupling agent group was 8.8 ± 3.5 MPa, which is clinically acceptable.[12] A reduction in bond strength from both silane and control groups is noted. This reduction could be attributed to contamination of the base during the heating process. This is evidenced when viewing an electron micrograph of a bracket which has been heated but not cleaned with alcohol (Fig. IV). Bond strength of this group was lower than found by

Lew.[36] The reduction could be due to: differences in ceramics materials, methods of retention, bonding resin and teeth.

3.3.4.3 *Hydrofluoric Acid + Silane Coupling Agent, and Hydrofluoric Acid, + Heat + Silane Coupling Agent*

Hydrofluoric acid was used as a bracket base treatment to obtain micro-undercuts and thereby increase the retention of the rebonded bracket. This treatment resulted in clinically unacceptable bond strengths. This occurred because the silica layer on the base of the bracket is removed. The function of the silica enables silination of the bracket. The manufacturer ("A" Company) applies the silica layer by immersing the bracket in a bath of unhydrolized silane coupling agent, then heating the brackets to 600°C. This process leaves a silica residue on the bracket which is sintered to the aluminaoxide.[37] The silica layer is extremely thin and was removed by the hydrofluoric acid (Fig V and VI). Silane forms a weak bond with aluminaoxide which resulted in low bond strength of these groups.

Brackets treated with hydrofluoric acid and a silane coupling agent had a bond strength of 1.6 ± 2.0 MPa. Brackets treated with heat, hydrofluoric acid and a silane coupling agent had a bond strength of 0.7±1.0 MPa. Both of these bond strengths are not clinically acceptable.

3.4 Recommendation

Bond strengths observed in this study may be higher than those witnessed clinically. This is because *In vitro* studies of bonding are ideal with moisture contamination, bonding pressure, temperature and other oral variables being eliminated or controlled.[18]. Clinical studies that investigated the long term bond strength of repositioned ceramic brackets would be beneficial to the orthodontic practitioner. These studies would have new values for bond strength as bond strength varies when brackets are bond to aged composite.[38]

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