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Effect of Pad Design and Bracket Manufacturing Method on Bracket Bond Strength

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Effect of Pad Design and Bracket Manufacturing Method on Bracket Bond Strength

Dustin Osborne, D.D.S.

Thesis submitted
to the School of Dentistry
at West Virginia University
in partial fulfillment of the requirements for the degree of

**Master of Science in
Orthodontics**

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Morgantown, West Virginia

2021

Keywords: SBS, MIM, ARI, milled, brazed, soldered, base

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ABSTRACT

Effect of Pad Design and Bracket Manufacturing Method on Bracket Bond Strength

Dustin Osborne, D.D.S.

Objective: The objective is to determine if there is a significant difference in shear bond strength and debonding characteristics between one-piece metal brackets made by metal injection molding (MIM) and multi-piece metal brackets made by machining then soldering/brazing with differing pad designs.

Methods: A total of thirteen metal orthodontic brackets manufactured by 8 different companies were divided into two groups: one-piece MIM and multi-piece brackets. Each group consisted of 10 brackets for a total of 130 brackets. Brackets were bonded to stainless steel tubes with a universal bonding technique. Samples were tested on the universal Instron testing machine to measure the shear bond strength. Force required to debond each bracket was recorded. Brackets were observed after debond and an ARI score assigned. Data were analyzed using a two sample t-test.

Results: The mean shear bond strength and ARI scores for the entire study sample were 3.7 ± 1.7 and 4.2 ± 0.7 , respectively. The results of two sample t test showed that there was no significant difference between the one-piece MIM brackets (3.5 ± 1.7) and the multi-piece brackets (4.0 ± 1.8) in mean shear bond strength ($t(128)=1.33$, $p=0.18$). But the mean of ARI scores of the multi-piece brackets (4.4 ± 0.7) was significantly higher than the one-piece MIM brackets (4.0 ± 0.7) ($t(128)=3.5$, $p=0.006$).

Conclusion: One-piece metal orthodontic brackets manufactured by MIM and multi-piece brackets manufactured by machining then soldering/brazing exhibit similar shear bond strengths. However, one-piece brackets showed a significantly lower ARI score than multi-piece brackets, indicating a higher percentage of adhesive left on the one-piece bracket surface after debond.

DEDICATION

To Mom, Thank you for being a constant source of love and support. I never could have made it anywhere in life without you. I appreciate all your hard work and never-give-up attitude. You've played an essential role in shaping me into the man I am today.

To Dad, Thank you for always pushing me to be my best and working hard to give the best childhood for Adam and I. You taught me that character counts and sometimes all you need to fix the problem is a bigger hammer. Thank you for the life you have given me.

To Adam, Thank you for being the best brother I could ask for and our parents second favorite son. You've inspired me to work hard and challenge myself in more ways than you know. You set a prime example for me and a tough act to follow as a younger brother. Without your lead, I would not be the person I am today.

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To Tom, Thank you for being a great friend who's always willing to listen and advise me when life throws its' curveballs. Your support has been incredible.

To Queso, Thank you for being a great friend and setting such a high academic bar for me. I probably would have given up and may not have pushed myself to the next level then the next level then the next level without you.

To Max, Thank you for being a great friend and always ready to have a good time. I appreciate your continued support and look forward to future adventures.

To Cheese, Thank you for being a friend, wildcard and a great source of entertainment. I'm happy to have you as a friend and can't wait to see what life has in store for you.

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Residents, Thank you for what you all have taught me. I've learned so much and been able to make many changes to who I am professionally and personally because of you all.

Dr. Ronnie Sparks, Thank you for teaching me everything you know and allowing me to bother you in your practice. Thank you for being a friend and mentor, always advising me on my toughest decisions. Your knowledge is inspiring and I hope for the worlds' sake you're able to teach more as time goes on. Future residents depend on your knowledge and guidance. You're an amazing example of what orthodontists should strive to be.

Dr. Larry Kalaskey, Thank you for being a great teacher, friend and mentor. I always appreciate your generosity and support. I appreciate you letting me come to shadow in your practice and showing me how to be successful. You've shown me it's possible to be a great orthodontist and still have an incredible life outside of work. Work hard, play hard.

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Chapter 1: Introduction

Background

Correction of malocclusions has been in practice for hundreds of years. Orthodontists move teeth to an ideal position within their respective bones for form and function, not just esthetics.

Malocclusions have been classified into three categories; class one, two and three. These classes are based solely on the relationship between the upper and lower permanent first molars. In a class one malocclusion, the mesiobuccal cusp tip of the upper first molar occludes directly with the buccal groove of the mandibular first molar; although the molar relationship is ideal, the malocclusion may be in the form of crowding, spacing, deep-bite, etc. In a class two malocclusion, the mesiobuccal cusp tip of the upper first molar falls anterior to the buccal groove of the mandibular first molar. Finally, in a class three malocclusion, the mesiobuccal cusp tip of the upper first molar occludes posterior to the buccal groove of the mandibular first molar. The causes of each type of malocclusion may be attributed to dental, skeletal or a combination of discrepancies. Not every malocclusion requires orthodontic intervention; that will be dependent of a barrage of other factors. The prevalence of class one malocclusions is predominant, followed by class two, then class three^{12,16,18-21}.

Many different appliances may be used in treating malocclusions. Orthodontists have traditionally used metal brackets bonded to the facial/buccal surface of a tooth for movement; at least since the introduction of composite bonding materials that allow for adequate bonding strength of metal to enamel. Brackets have evolved over time in shape, size, material, etc. to meet the needs of practicing orthodontists. Many factors must be considered when making improvements to bracket design; patient comfort, style, durability, user-friendliness and strength are of utmost importance. With the introduction of clear aligners, orthodontists now have more

choices than ever for modality of moving teeth. Clear aligners have come to prominence with the introduction of Invisalign™ in 1988²³. This, however, is just another tool for the orthodontists' tool belt when deciding what method is best for treating a particular patient. Ultimately, it comes down to provider preference. With so many options to choose from, it's important that no matter which modality is selected, both the patient and doctor have the most pleasant experience possible. A contributing factor to dissatisfaction in orthodontic treatment is frequency of unplanned emergency visits. In utilizing traditional metal brackets, emergency visits are commonly caused by brackets debonding from the tooth surface^{1,6-11}. This phenomenon can be caused by many factors such as amount of orthodontic force, intraoral age of bracket, patient habits, etc³. Less commonly, the bracket itself may break, causing more patient discomfort and necessitating a more complex replacement procedure²². These are costly for both patient and provider in time and expense. To minimize these emergencies, selecting a product that has the best chance of remaining in place and in one piece for the duration of treatment is beneficial to all. With this knowledge in mind, orthodontic companies have developed different manufacturing techniques that may promise greater bracket strength and decreased debonding frequency.

Modern orthodontic brackets began with the introduction of the edgewise bracket by Dr. Angle in 1928. Edgewise simply refers to the orientation of the wire when engaged in the bracket. This bracket was narrow in the mesiodistal direction with only a single set of tie wings. The tie wings are the portion of the bracket that allow for placement of an "o-tie" or ligature to force wire engagement within the bracket itself. An additional set of tie wings was later added to orthodontic brackets, developing the "twin" bracket, which is still the most common used orthodontic bracket style today, according to Iijima. This twin bracket design was introduced by

Swain and allowed for better tip, rotation and mesial-distal root movement control. The bracket had to become larger mesiodistally to accommodate the second set of tie wings. Early twin bracket design consisted of multiple pieces later joined to form a single unit. Figure 1 shows the standard design of a multi-piece orthodontic twin bracket. The tie wings contain the slot which receives the orthodontic wire and are located on the right and left sides of the profile in the figure. The brazing layer joins the profile to the base of the bracket. A second brazing layer may be needed to join the retentive mesh to the other side of the base.

Bracket bases can have mesh or non-mesh retentive features added. For mesh bases, different gauge wires are used for larger or finer retentions areas. Wire gauges range from 40-100, with 100 gauge being the finest mesh size to accommodate a 155-micron particle size filler according to Gange. Mesh may be attached to the bracket base by welding or brazing. Welding is less commonly used today due to compromised mesh integrity, wire fracture, and production of stress concentrated areas leading to adhesive fracture. In contrast, during brazing, mesh integrity is maintained. During brazing, the filler is melted at temp above 450 degrees and below melting point of metal to be joined. The brazing layer typically consists of silver, gold or non-precious alloys. Additional means of added retention can come from etching, silanation, surface activation or a combination. Etching creates surface roughness that increases area for bonding. Silanation uses a silane-coupler to increase surface wetness for increased bonding area. Surface activation is a process of electrochemical cleaning to remove debris before bonding.

Each component of the bracket may be made by different manufacturing techniques; machining, milling, casting or molding.

Figure 1: Twin Bracket Anatomy

The adherence joints create inherent points of weakness within the bracket and are more likely sites for bracket failure. The process of making multi-piece brackets is costly as each component is made separately and joined later. Components made by casting or milling are subject to 50-90% materials loss during the manufacturing process. To combat weak joints and introduce a less expensive manufacturing process, metal injection molding (MIM) has been recently implemented in fabricating orthodontic brackets. MIM is the process of liquifying metal alloy and injecting them into premade bracket molds (Figure 2).

Figure 2: MIM process

Brackets are made larger initially to compensate for porosity shrinkage that occurs in the steps of sintering and debinding after the molding is complete. Utilization of MIM in orthodontic bracket manufacturing has allow for a truly one-piece bracket with built-in retentive features and no weak spots from brazing or soldering. This process does come with its' downsides; for example, weak spots may no longer exist within the bracket, but the bracket as a whole may be weaker and therefore more likely to experience breakage at any given point. This weakness comes from remaining porosity after shrinkage to final size has occurred.

The objective of this study is to determine the relative durability, shear bond strength and characteristics of bond failure of one-piece MIM brackets compared to multi-piece brackets manufactured by casting, milling, MIM, or a combination with different bracket base designs.

Statement of the Problem

Do one-piece MIM metal brackets have the same in-vitro shear bond strength as multi-piece milled/machined metal brackets bonded to standardized stainless steel utilizing a common bonding technique?

Is there an effect of bracket pad design on shear bond strength of one-piece MIM metal brackets vs. multi-piece milled/machined metal brackets?

What are typical bracket debonding findings?

Significance of the problem

Traditional bracket manufacturing methods are costly and inefficient. As a potential alternative, brackets manufactured by MIM are more cost efficient. The MIM manufacturing technique holds the technological advantage and promises to be area of great research as new methods for fabrication develop. For now, differences in strength exist between multi-piece cast/milled brackets and one-piece MIM brackets due largely to porosities left after the MIM process.

Traditionally, two-piece brackets yield greater overall strength and perform better in lab tests.

This project will provide a true comparison between one-piece and multi-piece brackets. The aim will be to determine the manufacturing process that yields the greatest strength and will likely be the most reliable bracket to use in orthodontic procedures. The results of this study may be used to further develop and improve the MIM technique to eventually obtain similar strength to brackets made by casting or milling. More research will be required, as this will be an in vitro study. Similar future studies will need to be conducted in vivo to give more accurate results.

Another aim of this study will be to act as a pilot research project for an in vivo experiment, narrowing the field to comparisons of the best tested brackets in vitro.

Null Hypotheses

1. There is no significant intergroup difference in shear bond strength between one-piece brackets manufactured by the MIM process and multi-piece brackets with components manufactured by either MIM, milling or casting process
2. There is no significant intragroup difference in shear bond strength between different multi-piece brackets with components manufactured by MIM, milling, or casting.
3. There is no significant intragroup difference in shear bond strength between different one-piece brackets made by MIM.
4. There is no significant intergroup difference in shear bond strength between one-piece or two-piece brackets manufactured by MIM, casting, or milling and bracket pad design/retentive features (ex. Micro-etching, photo-etching, addition of mesh, etc.)
5. There is no significant intragroup difference in shear bond strength between one-piece brackets made by MIM and bracket pad design/retentive features.
6. There is no significant intragroup difference in shear bond strength between multi-piece brackets made with components manufactured by MIM, milling, or casting and bracket pad design/retentive features.
7. There is no significant difference in ARI score between one-piece MIM metal brackets and multi-piece brackets with components manufactured by MIM, milling, or casting.

Alternative Hypotheses

1. There is a significant intergroup difference in shear bond strength between one-piece brackets manufactured by the MIM process and multi-piece brackets with components manufactured by either MIM, milling or casting process

2. There is a significant intragroup difference in shear bond strength between different multi-piece brackets with components manufactured by MIM, milling, or casting.
3. There is a significant intragroup difference in shear bond strength between different one-piece brackets made by MIM.
4. There is a significant intergroup difference in shear bond strength between one-piece or two-piece brackets manufactured by MIM, casting, or milling and bracket pad design/retentive features (ex. Micro-etching, photo-etching, addition of mesh, etc.)
5. There is a significant intragroup difference in shear bond strength between one-piece brackets made by MIM and bracket pad design/retentive features.
6. There is a significant intragroup difference in shear bond strength between multi-piece brackets made with components manufactured by MIM, milling, or casting and bracket pad design/retentive features.
7. There is no significant difference in ARI score between one-piece MIM metal brackets and multi-piece brackets with components manufactured by MIM, milling, or casting.

Assumptions

1. Operator has been calibrated to place brackets in the exact same position with the exact same amount of pressure.
2. Bonding technique is executed in the same manner for all brackets.
3. Same amount of bonding material is applied to each bracket in the same manner in sufficient amount to retain bracket to stainless steel mounting tube.
4. No contamination of brackets or bonding medium due to the in vitro nature of this study.

5. Bracket base dimensions are assumed to be correctly reported by manufacturing company.

Limitations

1. Operator error will exist in placing brackets in the exact same position with the same amount of pressure.
2. Operator error in exactness of bonding technique between all brackets; slight variations will exist.
3. Operator error in apply the same amount of bonding material in the same manner to each bracket; slight variations will exist.
4. Contamination may exist due to in vitro nature of study completed in non-sterile environment.
5. Instron machine will simulate peel and shear force instead of pure shear force.
6. Operator error in verifying bracket measurements .
7. Discrepancies in ARI readings.

Delimitations

1. Single operator to reduce operator error between multiple operators calibrated differently.
2. Use of custom jig in bracket placement.
3. Use of adjustable base jig to ensure parallelism of applied force by Instron.
4. Two ARI readings taken at two week intervals to assess intraobserver accuracy.

Chapter 2: Review of the Literature

The orthodontic bracket acts as the bridge of energy transfer from the archwire to the teeth. The original edgewise bracket was introduced by Dr. Angle in 1928. This bracket design is narrow and has only one set of tie-wings; one incisal wing and one gingival wing. The narrowness of each bracket allows for the use of lighter forces due to a long interbracket distance. Bracket styles have evolved and new, more widely used designs have been introduced. The twin bracket design, developed by Swain, has two sets of tie-wings, which allow for better tip, rotation and mesial-distal root movement control. The twin style bracket is the most widely used orthodontic bracket style today⁵. Bracket bonding techniques have evolved as well, creating a stronger adherence of the bracket to the tooth surface. Acid etching was introduced by Buonocore in the 1950s and direct bracket-enamel bonding was introduced by Newman in 1960s. Standard bracket design consists of a stainless steel bracket comprised of a base, slot and wings. In an effort to maximize the bracket-enamel bond and bracket strength, variations in bracket base design and bracket manufacturing techniques have been explored. Some differences in bracket base design to increase bond strength include adding a layer of mesh, milling undercuts, sandblasting, and chemically etching. Bracket wings and bases are traditionally made with stainless steel; types 303, 304, 316 and 17-4PH being most widely used². A combination of desirable mechanical properties, corrosion resistance, and biocompatibility determine which stainless steel will be used. Some stainless steels, type 2205, do not contain nickel, which may be selected for use in patients with a metal allergy⁵. The wings and bases of brackets are made separately by casting and milling procedures. They are then soldered together. These processes may present many disadvantages. Both methods are inefficient and produce excessive waste; casting waste comes from sprue and runner material, while milling waste comes from material removed during the

machining process. Soldering of the two components is achieved with an alloy filler material. Differences in chemical composition of the stainless steel components will determine the solderability of the parts, however most stainless steels are compatible with soldering alloys containing silver, gold, copper or nickel. Silver and gold based solders were used originally, but each have shown corrosive properties and questionable mechanical characteristics. No brazing alloys available can fulfill the corrosion resistance, compatibility and strength requirements of a good solder²⁴. A more recent development in bracket manufacturing is by metal injection molding (MIM). This process requires metallic powders mixed with an organic binder to form a homogeneous mixture that can be injected into a mold and form the final desired shape. This method is less expensive than milling and casting due to a reduction of waste materials and eliminates the possibility of corrosion or bond failure at the wing-based interface. This method, however, is not without compromise. The MIM process is imprecise as the initial size of the injected shape is subsequently reduced by 20% in all dimensions as a result of the firing process. This process may also leave porosities in the final product that reduce the overall strength of the bracket. Studies using the Vickers hardness scale have shown MIM brackets ranging from 154-287 hardness as compared to a 400 hardness for conventional stainless steel brackets. This difference could influence mechanical properties and wear resistance for MIM brackets^{2,4,25}.

Chapter 3: Materials and Methods

IRB Approval

Approval for exempt research was obtained from the Institutional Review Board of West Virginia University (# 1910741211) prior to the start of this study.

Acknowledgement of Not Human Subjects Research

10/11/2019

To: Chris Martin

From: WVU Office of Research Integrity & Compliance

Protocol Type: NHSR / Flex

Approval Date: 10/11/2019

Submission Type: Initial

Expiration Date: 10/10/2024

Funding: N/A

WVU Protocol #: 1910741211

Protocol Title: Effect of Bracket Pad Design and Bracket Manufacturing on Bond Strength

The West Virginia University Institutional Review Board has determined that your protocol submission of protocol 1910741211 does not meet the definition of human subjects research, as provided in 45 CFR 46. This determination was based on the following:

- Research means a systematic investigation designed to develop or contribute to generalizable knowledge. Most case reports and most oral histories are not generalizable and, therefore, not research. Many classroom projects, if not intended to be published, are also not considered research. Many quality improvement or program evaluation studies are not research.

The following documents were reviewed and acknowledged for use as part of this submission. Only the documents listed below may be used in the research. Please access and print the files in the Notes & Attachments section of your approved protocol.

WVU IRB acknowledgement of protocol 1910741211 will expire on 10/10/2024.

Protocol #: 1910741211

Phone: 304-293-7073

FWA: 00005078

Fax: 304-293-3098

IORG: 0000194

Email: IRB@mail.wvu.edu

If the study is to continue beyond the expiration date, a new application must be submitted to the WVU IRB. It is your responsibility to submit your protocol for review.

The Office of Research Integrity and Compliance will be glad to provide assistance to you throughout the research process. Please feel free to contact us by phone, at 304.293.7073 or by email at IRB@mail.wvu.edu.

Sincerely,

A handwritten signature in black ink that reads "Joseph Malcolm BS, CCRP". The signature is written in a cursive, flowing style.

Joseph Malcolm
Program Coordinator

Materials Collection

Several top orthodontic companies were contacted to determine the method in which their brackets are manufactured. Companies that manufacture brackets using both MIM and milling/machining techniques were asked to supply 10 upper lateral incisor brackets made by each process. Companies that manufacture brackets using only one of the two manufacturing methods were asked to supply 10 upper lateral incisor brackets made by that process.

Upper lateral brackets were selected due to a reasonable consistency in two dimensional size (inciso-gingival height and mesio-distal width) and bracket pad contour.

Brackets and Companies Included

1. 3M (Unitek)

Figure 3: Miniature Twin (MIM, 17-4SS, micro-etched base)

Figure 4: Victory Series LP (micro etch, 80 gauge mesh base)

2. American Orthodontics

Figure 5: Master Series (maximum retention pads, 80 gauge mesh over etched foil base, photo-chemically etched pads)

3. Forestadent

Figure 6: Mini-Mono (sandblasted mesh base)

Figure 7: Mini Sprint II (MIM, medical nickel-free stainless steel)

4. Rocky Mountain Orthodontics

Figure 8: Integra (MIM, 316L stainless steel)

5. Dynaflex

Figure 9: MTX (MIM, pylon base)

Figure 10: Atlas Mini (17-4SS, brazed 80 gauge foil mesh pad)

6. Dentaaurum

Figure 11: Discovery-Smart (MIM)

Figure 12: Equilibrium II

7. GC

LEGEND medium

The LEGEND™ collection is a traditional twin, metal bracket system available in a medium and mini size. LEGEND medium is manufactured by a Metal Injection Molding (MIM) and Computer Numerical Controlled (CNC) precision milling process for a consistent and precise bracket that features a 100% accurate slot and anatomically correct bonding pads for maximum bond retention.

Figure 13: Legend medium bracket

8.Ormco

Figure 14: Mini Diamond Twin

Figure 15: Mini-Twin

Groups	Bracket name	Manufacturing method	Company	Pieces	Retention
1	Miniature Twin	MIM	3M	One-piece	Micro-etch, built-in
2	Victory series	Machined (Milled)	3M	Multiple pieces	Micro-etch, added 80 gauge mesh
3	Master series	Machined (Milled)	American Ortho	Multiple pieces	Photo-etch base, added 80 gauge mesh
4	Mini-Mono	Milled	Forestadent	Multiple pieces	Sandblasted base, added mesh
5	MiniSprint II	MIM	Forestadent	One-piece	Hook base, built-in
6	Integra	MIM	Rocky Mountain	One-piece	Built-in
7	MTX	MIM	Dynaflex	One-piece	Pylon base, built-in
8	Atlas Mini	Machined (Milled)	Dynaflex	Multiple pieces	Added 80 gauge mesh
9	Discovery Smart	MIM	Dentaurum	One-piece	Laser structured built-in
10	Equilibrium 2	Milled	Dentaurum	One-piece	Laser structured built-in
11	Legend Medium	MIM	GC	One-piece	Micro etch, 80 gauge mesh built-in
12	Mini Diamond Twin	MIM	Ormco	Multiple pieces	80 gauge mesh added
13	Mini-Twin	MIM	Ormco	Multiple pieces	80 gauge mesh added

Table 1: Bracket Summary

Bonding Technique

In vivo bonding of orthodontic brackets normally consists of several steps that were replicated in this study to most accurately represent typical clinical technique. Teeth are first isolated to maintain a dry working field necessary for ideal bonding after the etching is complete. The facial surfaces of teeth are etched with 37% phosphoric acid, rinsed and dried. Many orthodontists will

then apply a bond material, such as Assure Plus®, to the etched surface of enamel; this step was included in this study. The bond is lightly air dried and cured. Then the bracket is then pasted with composite, placed on the tooth, sighted, excess composite removed, and cured. In many studies, extracted teeth are used to bond brackets to test shear bond strength and assign an ARI score. However, using extracted teeth adds another degree of variation as all teeth are not created equally and usually healthy teeth are not extracted. For this study, we standardized the material to which the brackets would be bonded. Stainless steel tubes were used in place of extracted teeth. The tubes were prepared by Vince Kish and each was cut to a similar length; however, length was not relevant for the purpose of this study. Each tube had the same circumference and area of curvature. This was necessary to standardize the bonding surface for each bracket. Stainless steel tubes were sand-blasted in preparation for bonding. One uniform coat of Assure Plus® was applied to the tube surface, lightly dried and light cured for ten seconds. According to the manufacturer, Assure Plus® can be used under any chemical, light or dual cure adhesive, regardless of manufacturer. This bond can be used on wet or dry normal or atypical enamel, dentin, cementum, composite, gold, amalgam, stainless steel, zirconia, acrylic and porcelain. Assure Plus® consists of BisGMA, Ethanol, 2-Hydroxyethyl Methacrylate, and 10-Methacryloyloxydecyl Dihydrogen Phosphate. Tubes were loaded into the mounting jig and tightened in place with an adjustable screw. GoTo® bonding adhesive was then applied to the back of each bracket using a buttering technique to ensure adequate coverage and engagement of retentive components on bracket pad. Brackets were then placed on tube with equal pressure to allow composite expression on three sides of each bracket. The fourth side was placed in parallel to mounting jig top surface, where no composite expression was possible. This ensured dimension accuracy and perpendicular placement of brackets to debonding force of the Instron

machine. Excess flash was removed. Brackets were light cured for ten seconds at each bracket edge. A total of 130 brackets were bonded to 39 tubes in groups of three based on bracket. Two tubes in each group of three had four brackets mounted 90° apart from one another around the circumference of the tube. One tube in each group of three had two brackets mounted 180° apart from one another around the circumference of the tube.

Figure 16: Brackets mounted to stainless steel tubes with mounting jig

Figure 17: Brackets mounted to stainless steel tube

Figure 18: Stainless steel mounting tube in mounting jig with brackets previously bonded.

Instron Machine

All brackets were placed in a calibrated Instron machine and subjected to a force adequate for bracket debonding. Tubes with bonded brackets were placed in custom mounting jig and secured in place with a vice. Debonding apparatus consisted of 0.016" stainless steel wire bent into loop shape and able to engage bracket under lower tie wings. The apparatus was designed to apply a debonding force occlusogingivally. The debonding apparatus was lowered to allow placement of the metal loop around the tie wings of each bracket. A nitrile glove fingertip was placed around bracket, tube and debonding apparatus to minimize bracket projectile motion on debonding. The Instron test was started and completed after the bracket was completely debonded from the tube surface. The vice was loosened, and tube rotated 90 or 180° to align next bracket for testing. Vice was retightened and experiment repeated. Force of debond was given in Newtons and recorded by operator during experimental procedure. In a study by Lindemuth and Hagge to determine Instron crosshead speed necessary for bond failures, they found that crosshead speeds in testing range from .05mm/min – 50mm/min. The viscoelasticity of adhesives is affected by the

rate of stress application. Slower speeds allow for increased recovery, thus increased SBSs; while faster speeds can induce brittle behavior, thus also increasing SBSs. The SBS and mode of failure was not statistically significant at various crosshead speeds. In a study comparing stainless steel orthodontic brackets with different adhesives, Sharma et al. found that SBS is the main factor needed in consideration of the success of bonding evolution. Brackets must be able to withstand intraoral forces during ortho treatment. Reynolds showed that 5.9-7.8 MPa resistances are sufficient¹⁷.

Figure 19: Stainless steel mounting tube with brackets bonded placed in Instron machine with debonding apparatus above.

After Debonding

Once each bracket was debonded from respective tube, brackets were separated into individually labeled storage containers until ready for review. Brackets were observed by naked eye and with optical microscope at 10x power to determine Adhesive Remnant Index (ARI) score. A modified ARI score was used to score each bracket. This modified scale consisted of scores ranging from 0-5. A score of 0 indicates no adhesive left on the tube. A score of 1 indicates 1-25% of adhesive left on the tube. A score of 2 indicates 26-50% of adhesive left on tube. A score of 3 indicates 51-75% of adhesive left on tube. A score of 4 indicates 76-99% of adhesive left on tooth. Finally, a score of 5 indicates all adhesive left on the tube. All ARI scores were recorded at the time of observation. A second observation took place two weeks later to increase intraobserver accuracy. ARI scores were recorded and data sets were sent to statistician for evaluation.

Scores	Adhesive Remnant Index
0	No adhesive remained on enamel
1	Less than 50% of the adhesive remained on enamel
2	More than 50% of the adhesive remained on enamel
3	All adhesive remained on enamel

Table 2: Original ARI

Score	Definition
0	No adhesive left on the tooth
1	1%–25% of adhesive left on the tooth
2	26%–50% of adhesive left on the tooth
3	51%–75% of adhesive left on the tooth
4	76%–99% of adhesive left on the tooth
5	All adhesive left on the tooth with distinct impression of bracket mesh

Table 3: Modified ARI

Statistical Analysis

SAS (version 9.4, 2013, SAS Institute Inc. Cary, NC) was used to conduct the statistical analysis for the current study. Two sample t test was incorporated to compare the difference in mean shear bonding strength and ARI scores between the two bracket designs, MIM brackets and Milled/cast brackets. Intra-class correlation coefficients (ICC) were calculated to evaluate the reliability of the measurements. We considered statistical significance for all tests with a two-sided p-value of less than 0.05.

Chapter 4: Results

A total of 130 brackets, 80 one-piece MIM and 50 multi-piece brackets, from top bracket manufacturing companies, were included in the current study. The shear bond strength of the brackets was calculated by dividing the debonding force by the pad area. The units of force in newtons (N) were thus converted to megapascals (MPa). The mean shear bonding strength and ARI scores for the study sample were 3.7 ± 1.7 and 4.2 ± 0.7 respectively. The results of two sample t test showed that there was no significant difference between the one-piece MIM brackets (3.5 ± 1.7) and the multi-piece brackets (4.0 ± 1.8) in mean shear bonding strength ($t(128)=1.33$, $p=0.18$). The mean of ARI scores for the multi-piece brackets (4.4 ± 0.7) is significantly higher than the mean of ARI scores for the MIM brackets (4.0 ± 0.7) ($t(128)=3.5$, $p=0.006$). For error measurements, all brackets' ARI scores were measured by the same researcher a second time with a two-week interval in between. The intra-class correlation coefficient [ICC=0.95, 95% CL (0.94-0.97)] indicates a high level of agreement between the two sets of ARI measurements.

Results Tables and Figures

ari score				
ARI	Frequency	Percent	Cumulative Frequency	Cumulative Percent
2	2	1.54	2	1.54
3	19	14.62	21	16.15
4	64	49.23	85	65.38
5	45	34.62	130	100.00

Table 4: Distribution of ARI scores assigned to debonded brackets.

The UNIVARIATE Procedure Variable: ARI (ari score)

group=Milled

Moments			
N	50	Sum Weights	50
Mean	4.44	Sum Observations	222
Std Deviation	0.70450446	Variance	0.49632653
Skewness	-1.2379222	Kurtosis	1.6496126
Uncorrected SS	1010	Corrected SS	24.32
Coeff Variation	15.8672175	Std Error Mean	0.09963198

Basic Statistical Measures			
Location		Variability	
Mean	4.440000	Std Deviation	0.70450
Median	5.000000	Variance	0.49633
Mode	5.000000	Range	3.00000
		Interquartile Range	1.00000

Extreme Observations			
Lowest		Highest	
Value	Obs	Value	Obs
2	7	5	35
3	46	5	36
3	9	5	37
3	8	5	39
4	50	5	40

Table 5 a,b,c: Moments (a), basic measurements (b) and extreme observations (c) for ARI scores of multi-piece brackets

The UNIVARIATE Procedure
Variable: sbs (shear bonding strength=debonding force/pad area)

group=Milled

Moments			
N	50	Sum Weights	50
Mean	3.9642	Sum Observations	198.21
Std Deviation	1.82669333	Variance	3.33680853
Skewness	0.65925974	Kurtosis	0.57650459
Uncorrected SS	949.2477	Corrected SS	163.503618
Coeff Variation	46.079747	Std Error Mean	0.25833345

Basic Statistical Measures			
Location		Variability	
Mean	3.964200	Std Deviation	1.82669
Median	3.860000	Variance	3.33681
Mode	1.690000	Range	8.93000
		Interquartile Range	2.26000

Extreme Observations			
Lowest		Highest	
Value	Obs	Value	Obs
0.57	24	6.25	17
1.54	40	7.19	12
1.67	34	7.54	7
1.69	31	7.56	20
1.69	30	9.50	46

Table 6 a,b,c: Moments (a), basic measurements (b) and extreme observations (c) for shear bond strength of multi-piece brackets.

The UNIVARIATE Procedure
Variable: ARI (ari score)

group=MIM

Moments			
N	80	Sum Weights	80
Mean	4	Sum Observations	320
Std Deviation	0.69355076	Variance	0.48101266
Skewness	-0.2334989	Kurtosis	-0.1660403
Uncorrected SS	1318	Corrected SS	38
Coeff Variation	17.338769	Std Error Mean	0.07754133

Basic Statistical Measures			
Location		Variability	
Mean	4.000000	Std Deviation	0.69355
Median	4.000000	Variance	0.48101
Mode	4.000000	Range	3.00000
		Interquartile Range	0

Extreme Observations			
Lowest		Highest	
Value	Obs	Value	Obs
2	110	5	112
3	129	5	113
3	115	5	114
3	109	5	125
3	100	5	128

Table 7 a,b,c: Moments (a), basic measurements (b) and extreme observations (c) for ARI scores of one-piece. Brackets

The UNIVARIATE Procedure
Variable: sbs (shear bonding strength=debonding force/pad area)

group=MIM

Moments			
N	80	Sum Weights	80
Mean	3.5495	Sum Observations	283.96
Std Deviation	1.65585108	Variance	2.74184278
Skewness	1.02147716	Kurtosis	1.10570366
Uncorrected SS	1224.5216	Corrected SS	216.60558
Coeff Variation	46.6502627	Std Error Mean	0.18512978

Basic Statistical Measures			
Location		Variability	
Mean	3.549500	Std Deviation	1.65585
Median	3.275000	Variance	2.74184
Mode	1.960000	Range	7.74000
		Interquartile Range	1.95500

Extreme Observations			
Lowest		Highest	
Value	Obs	Value	Obs
1.13	58	6.82	110
1.16	67	6.84	96
1.18	53	7.71	87
1.23	122	8.07	99
1.31	69	8.87	93

Table 8 a,b,c: Moments (a), basic measurements (b) and extreme observations (c) for shear bond strength of multi-piece brackets.

The TTEST Procedure

Variable: sbs (shear bonding strength=debonding force/pad area)

group	N	Mean	Std Dev	Std Err	Minimum	Maximum
Milled	50	3.9642	1.8267	0.2583	0.5700	9.5000
MIM	80	3.5495	1.6559	0.1851	1.1300	8.8700
Diff (1-2)		0.4147	1.7233	0.3107		

group	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
Milled		3.9642	3.4451	4.4833	1.8267	1.5259	2.2763
MIM		3.5495	3.1810	3.9180	1.6559	1.4331	1.9613
Diff (1-2)	Pooled	0.4147	-0.2000	1.0294	1.7233	1.5355	1.9637
Diff (1-2)	Satterthwaite	0.4147	-0.2161	1.0455			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	128	1.33	0.1843
Satterthwaite	Unequal	96.471	1.30	0.1951

Equality of Variances				
Method	Num DF	Den DF	F Value	Pr > F
Folded F	49	79	1.22	0.4319

Table 9 a,b,c,d: T-test values for measurements (a), differences (b), variances (c) and equality of variances (d) of shear bond strength for one-piece and multi-piece brackets.

The TTEST Procedure

Variable: sbs (shear bonding strength=debonding force/pad area)

Figure 20: T-test distribution of shear bond strength of one-piece and multi-piece brackets.

The TTEST Procedure

Variable: ARI (ari score)

Variable: ARI (ari score)

group	N	Mean	Std Dev	Std Err	Minimum	Maximum
Milled	50	4.4400	0.7045	0.0996	2.0000	5.0000
MIM	80	4.0000	0.6936	0.0775	2.0000	5.0000
Diff (1-2)		0.4400	0.6978	0.1258		

group	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
Milled		4.4400	4.2398	4.6402	0.7045	0.5885	0.8779
MIM		4.0000	3.8457	4.1543	0.6936	0.6002	0.8215
Diff (1-2)	Pooled	0.4400	0.1911	0.6889	0.6978	0.6218	0.7951
Diff (1-2)	Satterthwaite	0.4400	0.1896	0.6904			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	128	3.50	0.0006
Satterthwaite	Unequal	102.92	3.49	0.0007

Equality of Variances				
Method	Num DF	Den DF	F Value	Pr > F
Folded F	49	79	1.03	0.8873

Table 10 a,b,c,d: T-test values for measurements (a), differences (b), variances (c) and equality of variances (d) of ARI scores for one-piece and multi-piece brackets.

The TTEST Procedure
Variable: ARI (ari score)

Figure 21: T-test distribution of ARI scores of one-piece and multi-piece brackets.

Figure 22: Wilcoxon distribution of shear bond strength of one-piece and multi-piece brackets.

Figure 23: Wilcoxon distribution of ARI scores of one-piece and multi-piece brackets.

Null Hypotheses Testing

1. **Accepted.** There is no significant intergroup difference in shear bond strength between one-piece brackets manufactured by the MIM process and multi-piece brackets with components manufactured by either MIM, milling or casting process
2. **Accepted.** There is no significant intragroup difference in shear bond strength between different multi-piece brackets with components manufactured by MIM, milling, or casting.

3. **Accepted.** There is no significant intragroup difference in shear bond strength between different one-piece brackets made by MIM.
4. **Accepted.** There is no significant intergroup difference in shear bond strength between one-piece or two-piece brackets manufactured by MIM, casting, or milling and bracket pad design/retentive features (ex. Micro-etching, photo-etching, addition of mesh, etc.)
5. **Accepted.** There is no significant intragroup difference in shear bond strength between one-piece brackets made by MIM and bracket pad design/retentive features.
6. **Accepted.** There is no significant intragroup difference in shear bond strength between multi-piece brackets made with components manufactured by MIM, milling, or casting and bracket pad design/retentive features.
7. **Rejected.** There is no significant difference in ARI score between one-piece MIM metal brackets and multi-piece brackets with components manufactured by MIM, milling, or casting.

Chapter 5: Discussion

Clinical Implications:

Emergency appointments in an orthodontic practice increase time and expense to both patient and provider. In many cases, these “emergencies” are 100% preventable. Bracket failures are among the most common types of unscheduled visit¹. They can be a source of frustration for both parties and may lead to a less pleasant overall treatment experience. If these failures become a common occurrence, treatment outcomes have an increased likelihood of suffering. Selecting a bracket that decreases the chance of bond failure would benefit both patient and provider. When brackets debond from the tooth surface, the failure can occur at one of three locations; the tooth-

composite interface, the bracket-composite interface or within the composite itself. If the failure occurs at the tooth-composite interface, many times this is due to contamination of the prepared tooth surface at the time of bracket placement. If the surface of the tooth is contaminated after the etching procedure, surface area for composite acceptance by enamel can decrease significantly. If the failure occurs within the composite itself, this may be due to a failure within the bonding system; more likely a manufacturing error than operator error as long as bonding instructions were followed as given. If the bond failure occurs at the bracket-composite interface, this is where selecting the right bracket with the right pad design becomes crucial. Bond failures here typically result from one of two scenarios; either the composite was inadequately applied or the bracket pad design is not sufficient to retain composite when subjected to force. In the case of application, the operator may not apply enough composite material to fill the entire surface area of the pad. To avoid this, the operator should ensure composite expression from all four sides of the bracket on placement. Additionally, the operator should make sure the depth of composite placement within the bracket pad is adequate to cover all available surface area. This may be accomplished by applying the composite in a buttering fashion, back-and-forth across the pad of the bracket. If composite application and amount are not the issue, then bracket selection can play a critical role. Choosing a bracket with the ideal amount of surface area to accept the most composite and minimize the likelihood of breakage is imperative to successful outcomes in practice. That being said, many other variables in practice need to be considered and ultimately a provider should choose what bracket works best within their practice. Other factors to be considered before buying a particular bracket would be bonding system used, staff preference, ease of use, patient comfort and esthetics to name a few. Brackets with larger bases and thus greater pad surface area will tend to show better results in debond studies¹²⁻¹⁴. This is obviously

due to the increased surface area for composite acceptance. However, as the size of the bracket increases, patient comfort decreases. Larger brackets may be more difficult to handle and harder to place for some providers. Other providers will have greater difficulty in handling and placement of smaller brackets. Again, providers should select what works best for them in their respective practice as well as what will lead them to the best treatment outcomes. Not all brackets are created equally, as such, neither are orthodontists. The results of this study indicate that there is no difference in one-piece MIM brackets and multi-piece brackets in shear bond strength. However, ARI scores were significantly different. Multi-piece brackets had significantly higher ARI scores, meaning more composite was left on the stainless steel tube when compared with the amount left on the tube by one-piece MIM brackets. Thus, within the brackets studied, one-piece MIM brackets on average retained composite better than multi-piece brackets. The majority of multi-piece brackets had an added layer of 80 gauge mesh brazed onto the base, while one-piece MIM brackets had built-in retentive features such as pylons. Operator error could have contributed to this finding; further research is needed.

Recommendations:

Further in-vitro studies are needed to verify the accuracy of this study's results. The variety of brackets on the market is vast and with so many choices, any provider can easily become overwhelmed when deciding which product is right for them. Testing brackets from different companies than the ones used in this study would be beneficial for a source of more data on the topic. Testing brackets made the same company but manufactured by different methods may also prove useful in eliminating variation in between different companies. MIM processes may have slight variations between different companies that could lead to differences in clinical results. Machining brackets could also be done by several different methods by various companies and

even within a single company. Testing multi-piece brackets that are manufactured the same way would eliminate an additional variable from this study. For example, selecting multi-piece brackets that are soldered together instead of brazed could give additional data worth investigating. Testing brackets for different teeth could provide interesting results as well. In this study, we observed upper lateral incisor brackets only. In future studies, testing central incisor, canine, premolar or molar brackets could lead to different conclusions. This may be due to the different forces experienced by each bracket depending on the location within the mouth. Incisor brackets will experience a shear force, while canine brackets will feel a ripping/tearing force. Molar and premolar brackets will experience a grinding force and may be more likely to fail due to the increased usage of posterior teeth during the chewing cycle. This study used a single operator to bond all brackets in order to decrease inconsistencies between multiple operators. In order to better calibrate a future operator, multiple operators should be used to initially to bond sample brackets and test each to ensure consistent debonding forces. This will allow the study operator to know the range of force (newtons) within which each bracket should fail. The bonding technique recommended by the bond manufacturer was followed for the specific surface being bonded, in this case stainless steel, in this study and would be recommended for future studies. Different bonding systems may be utilized as long as all brackets within the study are subjected to the same system and techniques.

Chapter 6: Summary and Conclusion

The purpose of the study was to determine if there is a significant difference in durability, shear bond strength and debonding characteristics between one-piece metal brackets made by metal injection molding and multi-piece metal brackets made by machining then soldering/brazing

with differing pad designs. Upon contacting top orthodontic bracket manufacturers, 130 different multi- and one-piece metal orthodontic brackets manufactured by MIM and machining were obtained. Brackets were bonded to stainless steel tubes with a universal bonding technique. Each bracket was subjected to a force sufficient for total debonding by an Instron machine. Force required to debond each bracket and ARI scores were recorded. The mean shear bonding strength and ARI scores for the study sample were 3.7 ± 1.7 and 4.2 ± 0.7 respectively. The results of two sample t test showed that there was no significant difference between the one-piece MIM brackets (3.5 ± 1.7) and the multi-piece brackets (4.0 ± 1.8) in mean shear bonding strength ($t(128)=1.33$, $p=0.18$). The mean of ARI scores for the multi-piece brackets (4.4 ± 0.7) is significantly higher than the mean of ARI scores for the one-piece MIM brackets (4.0 ± 0.7) ($t(128)=3.5$, $p=0.006$). Metal orthodontic brackets manufactured by MIM and those manufactured by machining then soldering/brazing exhibit similar shear bond strengths. However, one-piece MIM brackets showed a significantly lower ARI score than multi-piece machined brackets, indicating a higher percentage of adhesive resin left on the one-piece MIM bracket surface after debond when compared to the percentage of resin left on the multi-piece brackets at debond. This may be due to differences in pad retentive design, but further research is needed. No brackets were broken during this study; all failures occurred at the pad-adhesive-metal interface.

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