2016

Analysis of Slot Height Accuracy and Precision of Stainless Steel Orthodontic Brackets Manufactured by Metal Injection Molding and Computer Numerical Control Milling Using Stereomicroscopy

Mark D. Angeloni
Medical University of South Carolina

Analysis of slot height accuracy and precision of stainless steel orthodontic brackets manufactured by metal injection molding and computer numerical control milling using stereomicroscopy

Mark D. Angeloni, D.M.D.

A thesis submitted to the faculty of the Medical University of South Carolina in partial fulfillment of the requirement for the degree of Master of Science in Dentistry in the College of Dental Medicine.

Department of Pediatric Dentistry and Orthodontics
Division of Orthodontics

2016

Approved by:

Dr. Luis Leite

Dr. Lawrence Littman

Dr. Jompobe Vuthiganon

Analysis of slot height accuracy and precision of stainless steel orthodontic brackets manufactured by metal injection molding and computer numerical control milling using stereomicroscopy

Mark D. Angeloni, D.M.D.

A thesis submitted to the faculty of the Medical University of South Carolina in partial fulfillment of the requirement for the degree of Master of Science in Dentistry in the College of Dental Medicine.

Department of Pediatric Dentistry and Orthodontics
Division of Orthodontics

2016

Approved by:

____
Dr. Luis Leite

____
Dr. Lawrence Littman

____
Dr. Jompobe Vuthiganon

TABLE OF CONTENTS

Acknowledgements

This research would not have been possible without the guidance and support of many, and I would like to take this opportunity to express my sincere gratitude. I am forever grateful for my committee members, Drs. Luis Leite, Lawrence Littman, and Jompobe Vuthiganon who were extremely helpful throughout this process. I am appreciative of Ms. Abigail Lauer, who worked extremely hard to complete the statistical analysis, more than once, in a timely manner. I would like to thank OPAL, and specifically William Vaughn, Jack Phillips, and David Maggerts. I am extremely thankful for Dr. Nancy Smythe and her assistance and guidance throughout the acquisition stage of this research project, without her none of this would have been possible.

MARK DANIEL ANGELONI. Analysis of slot height accuracy and precision of stainless steel orthodontic brackets manufactured by metal injection molding and computer numerical control milling using stereomicroscopy. (Under the direction of Dr. Luis Leite)

Objective: It is the objective of this study to determine the dimensional accuracy and precision that is achievable by two manufacturing methods of stainless steel orthodontic brackets, CNC milling and metal-injection molding. To determine this, we propose the following specific aims: 1) to determine the actual dimensions of the slots in both milled and MIMed orthodontic bracket and standard deviations. 2) Using mathematical models to determine if the dimensional difference, if one exists, between milled and MIMed brackets will result in a difference in third order tooth movement (torque) realization (effective torque vs nominal torque). The actual bracket slot dimensions from both manufacturing techniques will be used in the mathematical model, which determines effective torque produced by a rectangular archwire within a rectangular slot. And 3) to determine if there is a statistical difference in the precision of the two different manufacturing methods.

Materials and Methods: In this study ten brackets of two different types of 0.022 in (0.559 mm) slot maxillary right central incisor stainless steel conventional brackets were investigated: GAC OmniArch (GAC, Bohemia, NY, USA) and OPAL Avex (OPAL Orthodontics, South Jordan, UT, USA), both brackets with MBT prescription, which is 17° torque for the maxillary central incisors. The GAC stainless steel brackets are produced by the MIM process. The OPAL stainless steel brackets are produced by the CNC milling process. The mesial profiles of the brackets were imaged using ZEN imaging software through a Carl Zeiss Stemi508 microscope (Carl Zeiss MicroImaging GmbH, Jena, Germany), at 45x magnification. The brackets were carefully aligned so that the slots were

photographed perpendicular to the slot. The images were calibrated and evaluated using the GNU Image Manipulation Program (GIMP) software. Using the software, points were selected and transferred for analysis into an Excel spreadsheet. In each photo 3 points were selected on the left (gingival) wall, the right (incisal) wall, and the floor. The points were all plotted on a 2-dimensional Cartesian (x,y) coordinate system, which was given by the GIMP software. Using Excel, a trend-line was generated for the walls and the floor, using linear regression. This analysis allowed for the determination of the bottom and top slot height as well as the angle between the slot walls. In addition to these measurements, the torque play for each bracket was determined for five different, commonly used rectangular wires. Nominal values for the archwires were used to determine torque play. The archwire dimensions used were: 0.016in × 0.022in, 0.017in × 0.025in, 0.018in × 0.025in, 0.019in × 0.025in, and 0.021in × 0.025in. The torque play is the more clinically applicable information. Furthermore, all of the brackets evaluated in the study were additionally imaged using scanning electron microscopy (SEM) allowing for more precise subjective evaluation of the bracket slots, in addition to the objective forms of evaluation previously mentioned. The SEM images revealed any surface inconsistencies within the bracket slots, that could affect bracket-wire interaction, and therefore tooth movement.

Results: The bottom slot dimension for the OPAL sample had a mean of 0.0216in, with a standard deviation of 0.0002in, and a maximum of 0.0219in. The entire sample being below the nominal slot height of 0.022 in. The GAC bracket slots on the other hand had a mean of 0.0230in, with a standard deviation of 0.0003in, and a maximum of 0.0234in. The entire sample of GAC brackets evaluated had a bottom slot height above 0.022in. On average, the AVEX OPAL bracket slot heights were 2% below the nominal value, whereas the GAC OmniArch brackets were 4.5% oversized. All of the brackets in each sample were divergent, meaning that the top height of the bracket slot was greater than the bottom height, and there was no difference between the two groups when considering divergence angle. There was a statistical difference found for the deviation angles for wires of commonly used nominal sizes. Furthermore, comparison of the two groups was performed to test the deviation from the mean for each individual sample. This essentially would test the precision of the manufacturing techniques. It was determined that there was a statistical difference in the precision of the bracket slot heights between the two groups. The SEM images offer more insight into the shape of the bracket slot and surface appearance of the brackets.

Conclusions: In conclusion, it was determined that there was a statistically significant difference between the two samples of brackets, GAC OmniArch and AVEX OPAL, in the outcome variables of bottom slot height, top slot height, and deviation angle for the five nominally sized archwires used in the mathematical model, which effects torque realization. In addition, it was determined that there is a statistically significant difference between the two samples, in terms of deviation from the mean, for those outcome variables. Therefore it can be concluded that there is a statistically significant difference between the two samples in terms of both accuracy and precision

Introduction

In order to understand the importance of the orthodontic bracket, it is of the utmost importance to understand the development of the orthodontic system that is currently used by the vast majority of orthodontists in the world today, namely the Straight Wire Appliance (SWA). The term straight-wire appliance was originally coined to describe a patented appliance developed by Dr. Larry Andrews. The SWA has the ability to exert control of each individual tooth in all three dimensions by the close fit of rectangular archwires in accurately made brackets. The brackets, themselves, incorporate angulation, or tip, and inclination, or torque, individualized for each tooth, as well as in-out position, so that wire bending is simplified (Andrews 1976). The three dimensional control of the tooth, with the specific in/out position of the tooth, the angulation, and the inclination is termed the bracket prescription, and this system is also referred to as a "preadjusted" appliance.

The concept for the SWA began with a paper written by Andrews entitled "The Six Keys of Normal Occlusion" (AJO 62, September 1972). From the study of 120 ideal untreated occlusions Andrews proposed the following tooth position and occlusal norms: 1) class I molar occlusion with the upper first molar tipped mesially with the distal cusp in contact with marginal ridge of second molar, 2) correct mesio-distal crown angulation (tip), since the tip of each tooth affects the space that it occupies, 3) correct bucco-palatal crown angulation (torque), 4) absence of rotations (except the upper first molar must be slightly disto-palatally rotated for a correct intra- and inter-arch fit), 5) no spaces and 6) flat occlusal plane or surve of Spee (COS), which has an effect on overbite (Andrews 1972).

The SWA was developed to facilitate attainment of these norms using archwires without the need for in/out, angulation, and inclination bends therefore finishing cases with “straight” archwires. In many cases, even with the SWA, wire bends in all three dimensions are needed to attain the ideal location of a teeth. In addition, increased torque within the wire, and other auxiliaries may be required, even assuming ideal bracket location; reasons for this will be explained.

The important features of the straight-wire appliance are built in the bracket design, which contains the so-called “prescription”. As previously stated, this determines the three dimensional control of each individual teeth. Expressing the prescription of the bracket and desired control of the tooth requires ideal bracket positioning. Generally brackets are placed on the facial axis (FA) point of the tooth, which is the center of the tooth based on the mesiodistal width, the long axis, and the occluso-(or incis-) gingival height of the tooth. This is the point at which the long axis of the tooth (looking down on the occlusal table or incisal edge of the tooth to the root), and the horizontal axis of the crown intersect. Accurate bracket placement is vital since it affects in/out values, angulation, inclination, vertical alignment, and rotations (Andrews 1976).

Specific features of the bracket design include: 1) in-out adjustment incorporated into bracket bases, 2) tip, or angulation, incorporated into the bracket slot so that the slot is placed on an angle to allow the crown to tip mesially; this is individualized for each tooth, and 3) torque, or inclination, incorporated into the walls of the bracket slot to ensure when the tooth is angulated in a bucco-lingual plane, and is individualized to each tooth and finally, 4) bracket bases are contoured to permit ease of placement on the FA point and to give a good fit against the tooth surface (Andrews 1976). Again, it is the interface between the orthodontic bracket, specifically the bracket slot, and the archwire that will determine the position of the teeth.

It is evident from this information that aside from accurate bracket placement, the manufacturing and standardization of orthodontic brackets is of the utmost importance to realize the desired tooth position. In using edgewise mechanics, and specifically, the SWA, the placing of archwires in a preadjusted bracket is designed to produce three-dimensional tooth-moving forces. These forces are created as a result of the intimate fit of wire into the bracket slot, therefore any ‘‘play’’ or ‘‘slop’’ between these components will result in incomplete transmission of the bracket prescription to the tooth. For example, when retracting a maxillary incisor to reduce an overjet, slop between the bracket and wire results in palatal tipping of the crown, with the root of the tooth concurrently moving labially (Cash, Good et al. 2004).

It is apparent that the movement that is most affected by play in the bracket slot/archwire interface is the inclination, or torque. Proper buccolingual inclination of both posterior and anterior teeth is considered essential to providing stability and proper occlusal relationship in orthodontic treatment. Torque of the maxillary incisors is particularly critical in establishing an esthetic smile line, proper anterior guidance, and Class I canine and molar relationship, because undertorqued anterior teeth can preclude the distal movement of the anterior maxillary dentition while maintaining proper inclination.

Furthermore, undertorqued incisors decrease the available dental arch perimeter, because it has been shown that for every 2.5° of anterior inclination, about 1 mm of arch length is generated. In addition, undertorqued posterior segments have a constricting effect on the maxillary arch because they do not allow appropriate cusp-to-fossa relationships between the maxillary and mandibular teeth (Gioka and Eliades 2004).

In general, maxillary central incisor torque in preadjusted appliances ranges from 7° in the Andrews prescription to 22° in the bioprogressive prescription. The lack of standardization in torque values can be partially explained on the basis of individual preferences in tooth position or differences pertinent to treatment philosophy. Also, as Gioka *et al* state, “this variation might imply the illogical nature of directly transferring the incisor inclination observed in esthetically pleasing and functionally sound dentitions to the bracket slot” (Gioka and Eliades 2004).

Full torque expression should potentially be achieved by using an archwire of the appropriate size to fill the bracket slot. To be able to insert a full size rectangular archwire it necessitates a certain amount of ‘play’. Essentially, this means that the vertical dimension or height of the bracket slot must be greater than the height of the archwire, and the larger the discrepancy between the bracket slot and the archwire dimension, the greater the reduction in the amount of torque expressed relative to the nominal amount of torque in the bracket. (Joch, Pichelmayer et al. 2010).

In order to fully understand the interaction between the bracket slot and the archwire and the realization of torque, there are a few terms that must be explained. As previously stated, the term ‘torque’ in orthodontics primarily refers to buccolingual root inclination. At the bracket-archwire level incorporated torque, nominal torque, and effective torque have different definitions. To begin, incorporated torque (t) is defined as ‘an angle between the slot center plane and orthogonal plane to the base of the bracket. This can be seen in Figure 1.

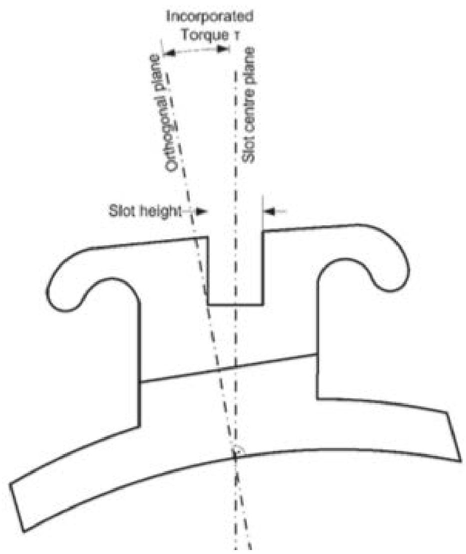

Figure 1. The incorporated torque is defined as the angle between the slot center plane and the orthogonal plane to the base of the bracket (Joch, Pichelmayer et al. 2010).

This is the amount of torque, in degrees, that will be presented specific to the bracket prescription. Next is nominal torque (t_{nom}). The nominal, or given dimensions of the archwires and brackets, as stated by the manufacturer, are used to define the nominal torque. Torque play (α) can be seen as the discrepancy between the size of the archwire and the size of the bracket slot. The interaction between the wire and the bracket slot can be seen in Figure 2.

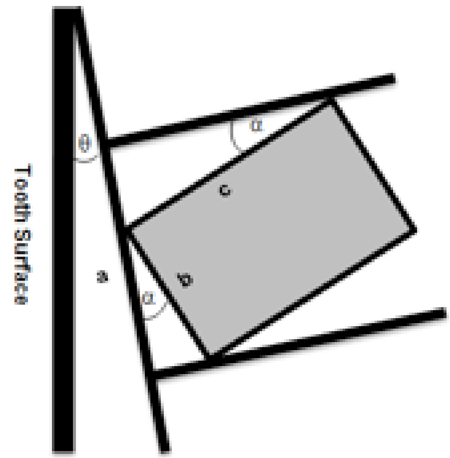

Figure 2: Diagram of the archwire / bracket slot relationship: prescription torque (θ), theoretical torque loss (α) due to different archwire dimensions (b): wire width and (c): wire depth, and bracket slot (a) (Nguyen, Bell et al. 2013).

Determining α allows the calculation of the torque play from the archwire and slot height dimensions using the following formula (1):

$$\alpha = \sin^{-1}\left[\frac{\mathrm{ac} \pm \mathrm{b}\sqrt{b^2 + c^2 - a^2}}{(b^2 + c^2)}\right]$$

Formula 1: Using the Figure 2, the above equation can be derived, yielding α. (Nguyen, Bell et al. 2013)

And finally, to determine effective torque (t_{eff}), the exact dimensions of the slot and archwire are required; as these are affected by production inaccuracies, precise measurements are necessary. Essentially, effective torque is defined as ‘the angle between the intersection of the measured archwire height and the orthogonal plane to the base of the bracket’. In addition, incorporated wire torque, torque added to the wire, has an effect on overall torque. Effective torque is calculated by the difference between incorporated torque (t), incorporated bracket torque plus incorporated wire torque (Meling, Odegaard et al. 1997), and torque play (α), using the formula (3): (Joch, Pichelmayer et al. 2010).

$$(3)\quad t_{eff} = t - \alpha$$

As Badawai *et al*. stated, torque expression can be achieved by filling the bracket slot and gradually increasing the archwire dimensions during treatment. However, the dimensions of the final working archwire never reach the full dimensions of the bracket slot; therefore, a percentage of the torque built into the bracket is lost because of the play between the archwire and the bracket slot. And furthermore, it has been shown that there is a considerable discrepancy between the theoretical and the measured bracket/archwire play. This play often extends to 100% of the prescribed torque, which essentially, is equivalent to using round wires (Badawi, Toogood et al. 2008). The "play" or deviation angle is the amount of rotation in degrees that a rectangular or square wire initially, in the passive state, must be twisted in order to engage the bracket walls or tube and generate biomechanical torque (Sebanc, Brantley et al. 1984).

Currently, there are two main manufacturing processes that are used to produce stainless steel orthodontic brackets, which are metal-injection molding (MIM), and computer-numerical control (CNC) milling. In a study of metallurgical characterization of orthodontic brackets produced by the MIM process by Zinelis, et al. comprehensively outline the MIM process. In general, in the MIM process, metal powders with particle sizes of a few microns are mixed with organic binders (typically, wax, thermoplastic resins, and other materials), lubricants, and dispersants, until a homogeneous mixture is obtained. Injection of this so-called "feedstock" is done using an injection molding machine, which is similar to those used in the plastics industry. The injected parts, called ‘‘green parts,’’ are formed into the desired geometry but at 17–22% oversize to compensate shrinkage after sintering (Zinelis, Annousaki et al. 2005). Sintering is the process of compacting and forming a coherent mass of material by heat and/or pressure without melting(2011).

As explained by Zinelis et al. the next procedure is the ‘‘debinding,’’ which is used to remove at least 90% of the organic binder from green parts by heat, solvent, or both. The green parts have now been transformed into ‘‘brown parts,’’ preserving the same size with a quite porous structure. The final stage of the MIM process is sintering, which is performed in a high-temperature furnace under vacuum or a controlled atmosphere. In this stage the residual binder is removed, and at the end of the process the parts have shrunk by 17–22%, reaching the precise desired dimensions because shrinkage is similar along the three axes. Nevertheless, in certain cases, secondary operations such as thermal or surface treatments are required. MIM products have tight tolerances of up to ±0.3% of the desired dimensions and density values more than 97% of the theoretical density of the material (Zinelis, Annousaki et al. 2005). The sequence of MIM production method is schematically presented in Figure 3.

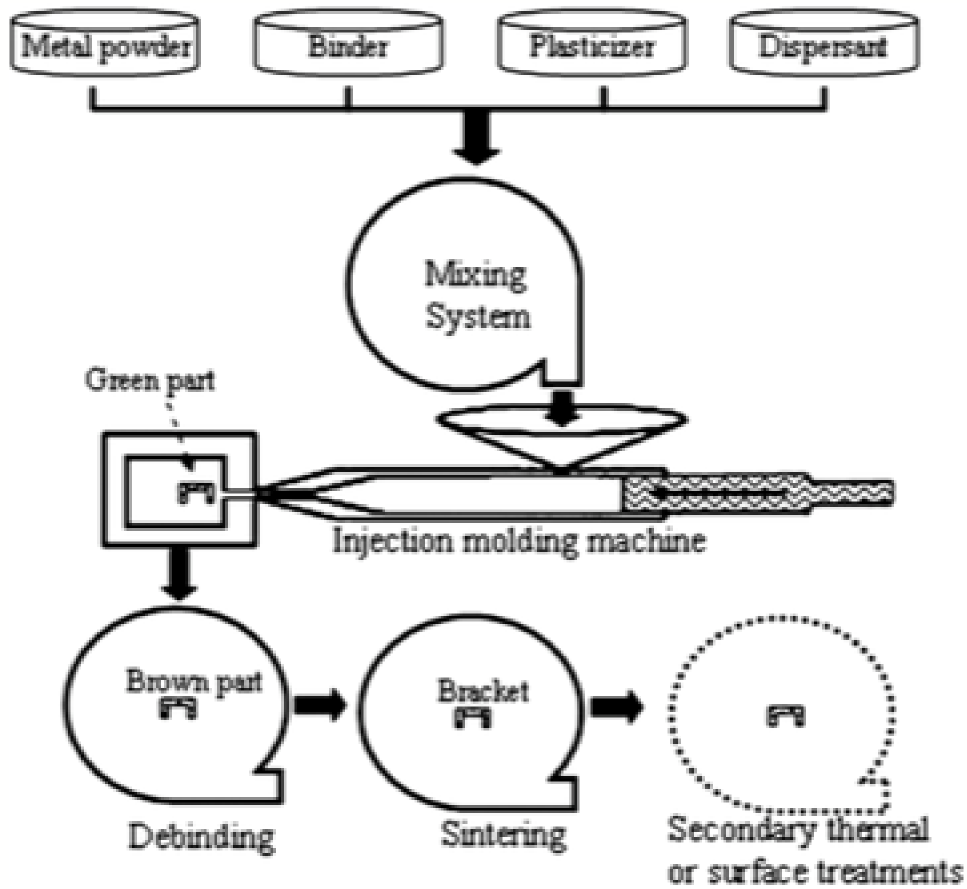

Figure 3. Schematic representation of the MIM process (Zinelis, Annousaki et al. 2005).

Among the currently available manufacturing processes, MIM is the least expensive mainly due to material savings during the production cycle because runners and sprues can be easily recycled and reused. Casting is the most expensive because it is estimated that 90% of the metal used is wasted in sprues and runners and 50% to 75% of the material used becomes scrap during machining. MIM is considered the most competitive technology for the production of large quantities of complex and intricate parts, whereas milling is economically beneficial only for geometrically simple parts. In addition, MIM allows the use of any alloy for the production of orthodontic brackets, which is not always the case with the other processes (Zinelis, Annousaki et al. 2005).

Apart from the economic advantages, the production method may have serious implications in the clinical performance of orthodontic brackets. The use of new alloys for the production of MIM brackets with different mechanical properties may affect their mechanical performance under clinical conditions. As single-piece appliances, MIM brackets are expected to be free of the corrosion consequences associated with the galvanic couple of brazing alloys with stainless steel (Zinelis, Annousaki et al. 2005). This is an issue when the bracket and the base are made separately and then fixed together.

In their study evaluating four different types of brackets produced using the MIM process, Zinelis et al determined that all of the brackets tested showed porosity, which may be a function of the shrinkage of the green parts during sintering. Although theoretically the MIM parts have a density of more than 97% of the nominal value, a large numbers of factors (alloy, powder type, debinding method, sintering heat rate, sintering hold time etc.) may influence porosity development during the manufacturing process (Zinelis, Annousaki et al. 2005). The drawbacks of this manufacturing method and possible effects on consistency of dimensions of orthodontic brackets produced therein are evident, with the major issue being the shrinking that the appliance undergoes during the process. A small percentage difference in shrinkage can have a large effect due to the small scale in which bracket slot dimensions exist.

The CNC milling process begins with design of the orthodontic bracket via computer design software. This process is familiarly known as CAD. Next, the CAD file of the bracket design is evaluated by a computer-aided manufacturing software. This software is used to virtually manufacture the bracket, and determine the best and most efficient process to produce the bracket. This process ensures that there will be no issues when the process moves to the manufacturing line. In addition, prototypes are made using the milling machine prior to the production line. The process for the stainless steel orthodontic brackets begins with a blank of 17-4 stainless steel. This blank is mounted precisely, and different shaped carbide drill bits are used to cut from the blank to produce the orthodontic bracket. Generally, the shape and lifespan of the drill bits are proprietary information, not released by manufacturers (Margetts 2016).

It is an objective of this study to determine the dimensional accuracy and precision that is achievable by these two manufacturing methods, CNC milling and metal-injection molding. Based on this information, we hypothesize that milled bracket slots are more accurate and precise than metal-injection molded bracket slots. In addition, we hypothesize that this difference is statistically significant when the bracket slots are compared with realization of effective torque. The null hypotheses being that there is not a statistically significant difference in bracket slot dimension between milled orthodontic brackets and those produced by the MIM process, the effective torque realized is not statistically significant when comparing the two techniques of bracket manufacturing, and that there is no difference in precision of the two manufacturing methods. To test these hypotheses, we propose the following specific aims: 1) to determine the actual dimensions and standard deviations of the slots manufactured by the two methods. This will be completed using a Carl Zeiss STEMI508 stereomicroscope at 45x magnification images, in order to accurately measure beyond micrometers. Ten brackets from each manufacturer GAC OmniArch (GAC, Bohemia, NY, USA), which are produced by the MIM process and OPAL Avex (OPAL Orthodontics, South Jordan, UT, USA), which are produced by the CNC milling process, both brackets with same prescription, which has a 17° torque for the maxillary central incisors will be examined, and compared to determine which is most accurate and precise to the specified dimensions of the slot. 2) Using mathematical models to determine if the dimensional difference, if one exists, between milled and MIMed brackets will result in a difference in third order tooth movement (torque) realization (effective torque vs nominal torque). The actual bracket slot dimensions from both manufacturing techniques will be used in the mathematical model, which determines effective torque produced by a rectangular archwire within a rectangular slot. This mathematical model was previously determined and has been used in numerous studies. The effective torque in all cases will be determined and compared with the nominal torque, with the use of an ideal archwire dimension (dimensional variability of archwires will not be measured or included). These will be compared in order to determine if a statistically significant difference is realized. And 3) to determine if there is a statistical difference in the precision of the two different manufacturing methods.

Review of Literature

During the late 1990s, accurate measurements of bracket slots height did not receive adequate attention, even though close slot tolerances are essential for accurate torque control and the fact that many of these factors were previously studied for years. Meling and Odegaard et al. performed numerous studies in order to better understand the state of bracket slot tolerances, and determine implications, as well as to give recommendations. Odegaard et al. described an instrument to measure the torsional twist with a high degree of accuracy, wherein the rotational deflection could be recorded to the nearest 1/50°. In this context, play is defined as the angular rotation of the wire from its passive position (wire cross-section parallel to slot walls) to the position where two diagonal corners make contact to the opposing slot wall. In their study, using the equation developed, which takes into account, wire size, wire bevel, and angle of twist, it is possible to estimate bracket slot height. It is also possible to determine effective torque, using the relationship among effective and nominal torques as well as torsional play, which is nominal torque minus torsional play is equal to effective torque. The formula assumes the edge bevel to be a perfectly circular section (90° of an arch), which is known not to be the case. In addition, the method does not directly address the effect of a slot taper. The calculated slot height obtained by this method is an estimate of the effective slot height, which is a combination of bracket slot height and slot taper, and is indirectly taken into account. Within the equation that is used to determine slot height it is known that 0.1° of change in torsional play corresponds to 0.9 μm change in slot height. Since the method error was less than 0.1° it follows that the bracket slot height could be calculated with a high degree of accuracy (Meling T, Odegaard J et al. 1998).

In their study, they showed that Ormco medium standard edgewise 0.018-inch brackets had a bracket slot height of 0.475 mm (0.0187 inches) at a distance of 0.03 mm from the slot base. Furthermore, a slight taper, or divergence of 1.85° was observed. The estimated bracket slot in this investigation was 0.476 ± 0.0032 mm (0.0187 ±0.00013 inches). There is some intrasample variation in bracket slot height, the range being 0.470 to 0.481 mm (0.0185 to 0.0189 inches). This corresponds to a variation in the torsional play of 1° for a 0.018 × 0.025-inch wire and would be even higher for a 0.016 × 0.022-inch wire (Meling, Odegaard et al. 1998). This means that even when using an archwire, whose vertical dimension, or height, is the same nominal value as the height of the bracket slot, there is still 1° of torque loss.

In a study, by Cash et al, five upper left central incisor brackets were selected at random from a total of 11 commercially available conventional, esthetic, and self-ligating orthodontic bracket systems. Brackets were measured on two occasions by two different operators across the top and across the base of the slot. When a metal slot had been incorporated into a bracket base of a different material (Clarity and Elegance Plastic), only the metal slot insert was measured. Measurements were completed after calibration on a one-mm scale, using a single-axis Maxtascan 100 (Graticules, Tonbridge, Kent, UK) producing a digital readout. This study determined that all of the bracket slots examined were oversized, by between 5% and 17%, and that slot walls varied between, parallel, convergent, and divergent, depending on manufacturer. It was reiterated in this study, as with others, that the measurement of the brackets is slightly complicated by the fact that the brackets have rounded or beveled edges in their slots, and the degree to which this rounding is present varies among manufacturers (Cash, Good et al. 2004).

Earlier findings were similar in a study by Kusy and Whitley, who measured 24 brackets from eight manufacturers microscopically, to the nearest .0001”. They found that while three bracket slots were smaller than the stated sizes, 20 others exceeded the stated sizes. The largest .018" slot actually measured .0209", which is nearly .003" oversized, and the largest .022" slot measured .0237", or almost .002" oversized (Kusy and Whitley 1999). Siatkowski noted that maxillary and mandibular incisors may suffer unexpected loss of torque when protracting the buccal segments during space closure with the preadjusted edgewise appliance. These anterior teeth may suffer a loss of torque of 5–10°, and this equates to roughly 1.9 mm of lingual retrusion of incisal edges during space closing protraction. These conclusions are in line with the findings by Kusy and Whitely. Siatkowski also mentions that European orthodontic bracket manufacturers use metric tooling, and, as a result of the difference between this and American tooling based on the imperial system, the 0.022-inch slots in European-made brackets are automatically oversized by 4.22% even before any manufacturing variability is encountered (Siatkowski 1999).

Dellinger presented deviation angles for arch wires in 0.018 and 0.022 inch bracket slots; these were based on both the nominal wire sizes and the worst tolerance conditions associated with the smallest wire sizes allowable by manufacturers. Dellinger’s data was obtained from theoretical calculations using a formula for deviation angle. In Creekmore’s tables the effect on play associated with the range in bracket slot size due to manufacturer tolerance was considered. The values, in degrees, for the deviation angle or play differed from the corresponding values published by Dellinger, who had focused only on manufacturer tolerance for the wire dimensions. For an 0.017 × 0.025 inch wire in an 0.018 inch slot, Dellinger showed a deviation angle of 3.4°, and thus a 3.6° effective torque angle, for a bracket torque angle of 7°. On the other hand, Creekmore indicated a deviation angle of 4.5° or an effective torque angle of 2.5°, for a bracket torque angle of 7°. Hixson and associates used a technique involving a torque-meter assembly to actually measure the values of deviation angle for some of the various rectangular wires used in 0.018 and 0.022 inch bracket slots; their experimental data were different from the results provided by Dellinger and Creekmore. For example, Hixson's group determined a deviation angle or play of 6.8° for an 0.017 × 0.025 inch wire in an 0.018 inch slot (Sebanc, Brantley et al. 1984).

Deviations from the theoretical and measured bracket/archwire play can be caused by intrinsic variations in arch-wire size, arch-wire edge bevel, bracket slot dimension, and bracket deformation, in addition to other aforementioned reasons. The purpose of the study by Badawi et al was to measure the difference in third-order moments that can be delivered by engaging 0.019 × 0.025-in stainless steel archwires in 2 active self-ligating (ASL) brackets (In-Ovation, GAC, Bohemia, NY; Speed, Strite Industries, Cambridge, Ontario, Canada) and 2 passive self-ligating (PSL) brackets (Damon2, Ormco, Orange, Calif; Smart Clip, 3M Unitek, Monrovia, Calif) (Badawi, Toogood et al. 2008). Active self-ligating brackets are designed in order to force the wire against the bottom of the bracket slot when the clip is engaged, whereas with passive self-ligating brackets, even a full-size wire (nominal height of wire is equal to the nominal height of the slot), will not be forced against the bottom of the slot, due to an increased slot depth.

In their study, a bracket/wire assembly torsion device was developed. This apparatus can apply torsion to the wire while maintaining perfect vertical and horizontal alignment between the wire and the bracket. A multi-axis force/torque transducer was used to measure the moment of the couple (torque in Newton-millimeters, or Nmm), and a digital inclinometer was used to measure the torsion angle. The torsion angle is the relative angle of twist of the archwire and is the combination between the angle of the bracket and the angle of twist of the archwire (Badawi, Toogood et al. 2008).

Clinically effective torque has been suggested to be 5 to 20 Nmm. This study determined that the angles of torsion at which the lower limit of that range (5 Nmm) is achieved were 15° for the active self-ligating brackets and 22.5° for the passive self-ligating brackets. For the active self-ligating brackets, the angle of torsion at which the upper limit of that range (20 Nmm) was achieved was 31°, but it was 34.5° for the passive self-ligating brackets (Badawi, Toogood et al. 2008).

The relevant conclusions that can be drawn from these findings are that the torsion angle must be greater than 15° for ASL brackets, and 22.5° for PSL, and that for the majority of bracket prescriptions torque will not be realized unless wires are modified to increase torque where needed, or torqueing auxiliaries are used (Badawi, Toogood et al. 2008). Therefore it is evident that even with ASL brackets, which more closely resemble conventional twin brackets, wherein the archwire is secured into the bracket with an elastomeric or stainless steel ligature, torque realization is limited and the addition of increased torque into the wire is needed.

Major et al.'s study on the accuracy of bracket slot dimensions used a different method from Meling and Odegaard. In their study, Major et al. examined three different types of 0.022 in (0.559mm) slot upper right central incisor stainless steel self-ligating brackets, which included Damon Q, In-Ovation-R, and Speed. Each bracket was photographed through a microscope, and brackets were carefully aligned so that the slots were photographed perpendicularly to the slot. The bracket images were evaluated using a technique that allowed for precise examination of the outline of the bracket slot. This permitted determination of exact heights of the bracket slot throughout the depth of the slot, in addition to bracket shape, as in parallel, divergent, or convergent slot walls (Major, Carey et al. 2010).

This study determined some very specific and pertinent information in regard to slot shape and size among the three different types of brackets analyzed. For example, the Speed brackets in the study had strongly pronounced rounding in the corners where the right and left walls meet the bottom. This has an effect on measurements because the larger the rounding radius of the corners, the less accurate the assumption is that the slots are essentially a trapezoidal shape. The Damon brackets had a slight rounding in the corners at the slot bottom, and In-Ovation appeared nearly square. In Speed brackets, the slot was 0.556 mm at the bottom and 0.547 mm at the top. Compared to the nominal slot size of 0.559 mm, statistically speaking 63% and 95% of Speed brackets are undersized as measured at the bottom and top, respectively. In-Ovation slot size is very near the nominal value at the bottom, but oversized by 2.6 standard deviations at the top of the slot, meaning that over 99.5% of In-Ovation brackets are oversized as measured at the top. Damon brackets are the most rectangular slot, as evidenced by having nearly 90° angles at the bottom corners. But both the top and bottom of the slot are oversized compared to the nominal 0.559mm slot by approximately 1%, on average (Major, Carey et al. 2010).

This study goes on to give a great example about manufacturing tolerances and precision, and the effect it can have in the orthodontic arena. Often tolerances are reported as being ±2 standard deviations since 95% of all data is within 2 standard deviations of the average, therefore the tolerances of the slot heights are 15 μm, 15 μm, and 43 μm for Speed, In-Ovation, and Damon, respectively, as measured at the top of the slot. Damon notably has the highest tolerance in slot height. Using the aforementioned formula presented by Meling et al. to calculate torque play, and assuming a rectangular slot and a nominal 0.483 × 0.635mm (0.019 × 0.025 in) wire, the torque play theoretically changes 4.7° from a 43 μm difference in slot height. Using the same formula, the difference between the average torque play between a Speed and Damon bracket is 2.3°. These torque play differences are an idealized estimate, and actual torque play is dependent on factors such as bracket/wire friction and beveling of wire corners. Using their torque expression data, a torque play of 4.7° could result in variation of torque expression of 5–10Nmm, which is clinically relevant since the ideal torque value for biological movement of teeth is between 5 and 20 Nmm (Major, Carey et al. 2010).

It is clear that bracket slot height inconsistencies are not the only factor that affects torque realization. Another factor is, of course, the archwire. Deviations from the nominal size, the existence of an edge bevel, and variations within, can have a great impact on tooth movement, in general, and torque realization, specifically. In a study by Joch et al. both bracket slot heights (various self-ligating brackets were used in this study) and archwires were evaluated, measured, and effective torque determined for all bracket/archwire combinations. In their study, the slot height of 10 upper right central incisor brackets, with a nominal slot height of 0.022 in, from 5 different bracket systems, as well as 10 archwires from six different types were measured. This study found that orthodontic bracket slot heights were oversized by 1% up to 7% from the nominal size. All measured bracket slot height values were within DIN (German Institute for Standardization) tolerance limits, most of them close to the upper limit. The largest deviation was a bracket slot, which was oversized by 24%. In addition, this investigation of stainless steel archwires with 0.019 × 0.025 and 0.020 × 0.025-inch dimensions showed measurements outside the upper and lower limits in height and width given by DIN. Two-thirds of the examined archwire types exceeded the DIN limits for height, and one-third exceeded the limits for width. This study then used the findings in order to calculate torque play of all combinations of brackets and archwires. The authors combined these into a matrix format in order to determine torque play of all combinations, which can be seen in Figure 4.

Figure 4. Minimum and maximum deviation angle ranges of various combinations of measured).022 inch brackets and 0.019 × 0.025 and 0.020 × 0.025 inch archwires (Joch, Pichelmayer et al. 2010).

The torque play in this analysis ranged from a minimum of 4.5° to a maximum of 11.7°. For example, from the table, it can be appreciated that the maximum torque play for the combination of the SPEED System™ and SPEED Wire™ medium upper is 6.9°. These torque losses can have a significant effect on treatment when the nominal torque in the upper right central incisor for example is 12°, reducing effective torque drastically (Joch, Pichelmayer et al. 2010).

In addition, the roundness, or bevel, of the corners of the wire was not taken into consideration. These factors can have additional influence on torque play (Joch, Pichelmayer et al. 2010). There has been commentary on this factor, as well as numerous studies that determined the extent and effect of this issue on torque realization. As stated by Gioka et al., manufacturers can enlarge the size of the slot and slightly decrease the archwire cross-section relative to the nominal size to exclude the possibility that a wire could not be fully engaged into the bracket slot. Furthermore, they go on to state that another measure taken to prevent this undesirable incident include rounding and beveling the edges of both archwires and brackets; this makes inserting the wire easier. The effect of this being an additional factor that accounts for the difference between incorporated torque, or nominal torque, and effective torque. Additionally, the round edges of an archwire and the bracket slot can account for the difference between theoretical play and actual play (Gioka and Eliades 2004).

Sebanc et al. thoroughly investigated the function of edge bevel of orthodontic archwires on effective torque. He explains the manufacturing process of archwires, “square or rectangular arch wires are fabricated from round wires by a process of rolling rather than drawing. The round wire is passed through a device called a ‘Turk’s head’, which is a set of two rollers positioned 90° to each other, and rolled to the desired dimensions. The edges of the wire remain rounded after this rolling process, resulting in the edge bevel.” Clearly, this process will yield archwires with an edge bevel, and this roundness will have a great effect on torque expression because it is the edges of the archwire that first engage the bracket slot for delivery of torque (Sebanc, Brantley et al. 1984).

In his study it was determined that the largest percent contribution of the edge bevel to the measured deviation angles (torque play) occurred with the beta-titanium wires. This is attributed to the fact that there is an inability of the manufacturer to better approximate a square corner for the beta-titanium wire during rolling may be due to the mechanical and wear properties of this alloy. Specifically, in the 0.022 inch slots, the 0.019 × 0.025 inch beta titanium segments produced measured deviation angle values of about 22° and an edge bevel contribution to the torque play of about 12.7°. These values are much higher than the average torque of about 12°, with an edge bevel contribution to the torque play of only about 4°, for the stainless steel 0.019 × 0.025 inch wires in the 0.022 inch slots. Beta-titanium being the greatest because with increased edge bevel there is greater torque play (Sebanc, Brantley et al. 1984).

In addition, Gioka et al. commented on the importance of the mechanical properties of the wire material and its effect on torque realization. For example, in the case of a low-modulus alloy such as Ni-Ti, the expression of torque is further decreased because some activation is dissipated as elastic deformation. Furthermore, because there is increased torque play as a function of wire size and edge bevel, lower modulus alloys, Ni-Ti and β-Ti, are unable to apply the amount of torque necessary, 5-20 Nmm, to effectively cause these desired 3rd order movement without incorporated “wire twisting”, or increasing the torsion angle of the wire (Gioka and Eliades 2004).

Meling et al discusses the importance of precision when increasing the torsion angle of the wire, and the difficulty in keeping the angle within the ideal torque moment value (between 5 and 20 Nmm). One of the objectives of their study was to determine the change in the torqueing moment (Nmm) per degree of twist in the wire, calling this torsional stiffness. This study used only stainless steel wires, and only 0.018 in orthodontic stainless steel brackets. It was determined that "the change in torsional stiffness as expressed by the slope of the line, ranged from 2.5 Nmm/degree for a 0.016 × 0.022-inch wire to 3.9 Nmm/degree for a 0.018 × 0.025-inch wire". This means that for 1° of twist a 2.5 Nmm moment is generated with a 0.016 × 0.022-inch wire in an 0.018in bracket slot. Furthermore, if the acceptable working range for a torqueing moment is 15 Nmm (the difference between 20 Nmm – upper limit – and 5 Nmm – lower limit), then this equates to between 6.0° for a 0.016 × 0.022 inch wire and 3.8° for a 0.018 × 0.025-inch wire. Comparing the working range with the observed span of torsional play, it can be seen that the ratio between these two is relatively small. Therefore, it is difficult to apply torque with a desirable degree of accuracy. For example, in this study it was determined that the mean torsional play for a 0.016 × 0.022 inch wire was 18.5°. To obtain a 20 Nmm moment, a mean additional twist of 7.8° must be applied for a total of 26.3°, since with this size wire the torsional stiffness is 2.5 Nmm/degree. However, if the calculations in this example is based on the 0.016 × 0.022 inch wire in the study with the least amount of play (16.6°), and also the highest torsional stiffness (2.9 Nmm/degree) for this size wire, and the same 26.3° of twist is applied, the resulting torque moment is 28.1 Nmm, which is outside of the range for an acceptable torqueing moment (Meling, Odegaard et al. 1997). Therefore it can be seen that applying the same amount of additional twist to one particular wire in one instance can result in a completely different, and ineffective or nonphysiologcal, torqueing moment with another wire of the same nominal size. This study did not take into account variation in bracket slot dimensions.

Meling et al performed a similar study, using the same methods as the aforementioned study, but testing nickel-titanium and beta-titanium wires. Again this study used 0.018 in stainless steel brackets. The general impression from the data for the 0.016 × 0.022-inch nickel-titanium alloy wires is that, for twist angles below 20°, they develop very little torque. Even at 25°, the torque levels were less than 5 Nmm. The torsional stiffness varied from 0.34 to 1.03 Nmm per degree, with a mean of 0.70 Nmm per degree. The beta-titanium alloy wire with these dimensions had a torsional stiffness of 1.15 Nmm per degree, a torque of 6.48 Nmm at 25°. For the 0.017 × 0.025- inch nickel-titanium wires it was demonstrated that torque was exerted at twist angles above 10°. At 25° they developed a mean torque of 13.5 Nmm with a range of 10.13 to 17.99 Nmm. These wires had torsional stiffnesses ranging from 0.79 to 1.45 Nmm per degree, with a mean of 1.04 Nmm per degree. The TMA wires had torsional stiffnesses of 1.15 for 0.016 × 0.022-inch and 1.64 Nmm per degree for the and 0.017 × 0.025-inch wires, thus being 1.6 times stiffer than nickel-titanium. Furthermore, none of the wires that were tested exhibited superelasticity when activated to 25°. Although, when activated beyond 25°, some wires had deactivation plateaus and demonstrated hysteresis. As most torque prescriptions advise less than 25° of torsional twist, the superelasticity of the nickel-titanium wires is of little clinical importance regarding torque effect (Meling and Odegaard 1998).

In addition to the variability found in bracket slot dimensions, archwire material, and edge bevel dimensions there are even other variables that will affect torque realization. In Zinelis et al's study of the "Metallurgical Characterization of Orthodontic Brackets Produced by Metal Injection Molding" some interesting findings in regards to the hardnesses of stainless steel orthodontic brackets were made, in comparison with orthodontic archwires, and the effect of these differences. The Vickers hardness (VHN), a scale which measures the effective hardness of a material, essentially tendency to deformation, of the brackets tested varied from 154 to 287 VHN, which is much lower than the hardness (400 VHN) reported for the wing components of conventional SS brackets. This difference may have significant effects on the wear phenomena encountered during the archwire interaction with the bracket slot. The SS archwires demonstrate a hardness of 600 VHN, whereas the hardness of NiTi archwires range from 300 to 430 VHN. It is desirable to minimize this mismatch in hardness to avoid wear in brackets during orthodontic treatment. The clinical significance of the hardness findings is the fact that low-hardness wing components may affect the force transfer from the archwires to teeth because it may inhibit full engagement of the wire to the slot wall and possible plastic deformation of the wing (Zinelis, Annousaki et al. 2005). In effect this means that the orthodontic bracket slot can plastically deform due to the force applied by the harder orthodontic wire, which can affect the bracket slot dimensions, further complicating torque realization.

In addition, manner of wire ligation can have an effect on torque realization. This is mentioned by Gioka et al, who states "elastomeric ligatures have shown a force degradation pattern characterized by an initial exponential decrease reaching 40% in the first 24 hours" (Gioka and Eliades 2004). This means that the elastomeric ligatures will be unable to seat the archwire against the slot floor, limiting force application and resultant torqueing moment. And furthermore, by Sebanc et al who states "ligation can substantially affect the amount of torque transferred from the arch wire-bracket system to the tooth" (Sebanc, Brantley et al. 1984). Form of ligation and bracket positioning are two variables that are within the control of the practitioner. Therefore placing the brackets in the correct position, and using stainless steel ligation, when torque expression is required and desired, should be performed routinely.

As previously stated, archwires, bracket placement, type of ligation, and tooth morphology, in addition to others, can have a great effect on torque realization. It is important to remove, or account for, as many variables as possible, specifically those that are outside the doctor and patient's control. A potential source of inconsistency is within the manufacturing process. As with any other product, the manufacturing process of brackets results in some variation in sizes and characteristics, including dimensional accuracy and torque prescription consistency. Although brackets are made from several materials, including titanium and ceramics, the focus will be on stainless steel (type 17-4) orthodontic brackets. As Badawai et al stated, various bracket manufacturing processes such as injection-molding, casting, and milling can affect the accuracy of the prescribed torque values, and this has been reported to be about 5% to 10% (Badawi, Toogood et al. 2008). Shortcomings with each of these manufacturing techniques include the fact that the MIM exposes the material to expansion and shrinkage, whereas milling can incorporate a rough grained surface. Furthermore, bracket slot manufacturing introduces metal particles, grooves, and striations, which can preclude the full engagement of the wire in the slot walls. All slot walls have a rough surface with imperfections, porosity, and microstructural defects, which could affect the dimensional accuracy of the slot wall (Gioka and Eliades 2004).

Materials and Methods

In this study two different types of 0.022 in (0.559 mm) slot maxillary right central incisor stainless steel conventional brackets, manufactured with metal injection molding (GAC OmniArch, Bohemia, NY, USA) and computer numerical control milling (OPAL Avex - OPAL Orthodontics, South Jordan, UT, USA) respectively were investigated: and, both brackets with MBT prescription, which is 17° torque for the maxillary central incisors. The MBT prescription was used because of the higher torque of the central incisors which would make the potential difference in deviation angle more apparent. The GAC OmniArch bracket system was chosen for this study as this company utilizes the MIM process exclusively in the manufacturing of its brackets and, therefore increased accuracy in the manufacturing technique could be expected. This investigation used a sample size of 10 brackets for both bracket types. Throughout the imaging and evaluation process the evaluator was blinded to the bracket type.

In order to conduct different measurements of the walls of the bracket slot of both systems studied, the mesial profiles of the brackets were imaged using ZEN imaging software through a Carl Zeiss Stemi508 microscope (Carl Zeiss MicroImaging GmbH, Jena, Germany), at 45x magnification. The setup can be seen in Figure 5. This method has been used in previous studies to measure the bracket slot height (Major, Carey et al. 2010).

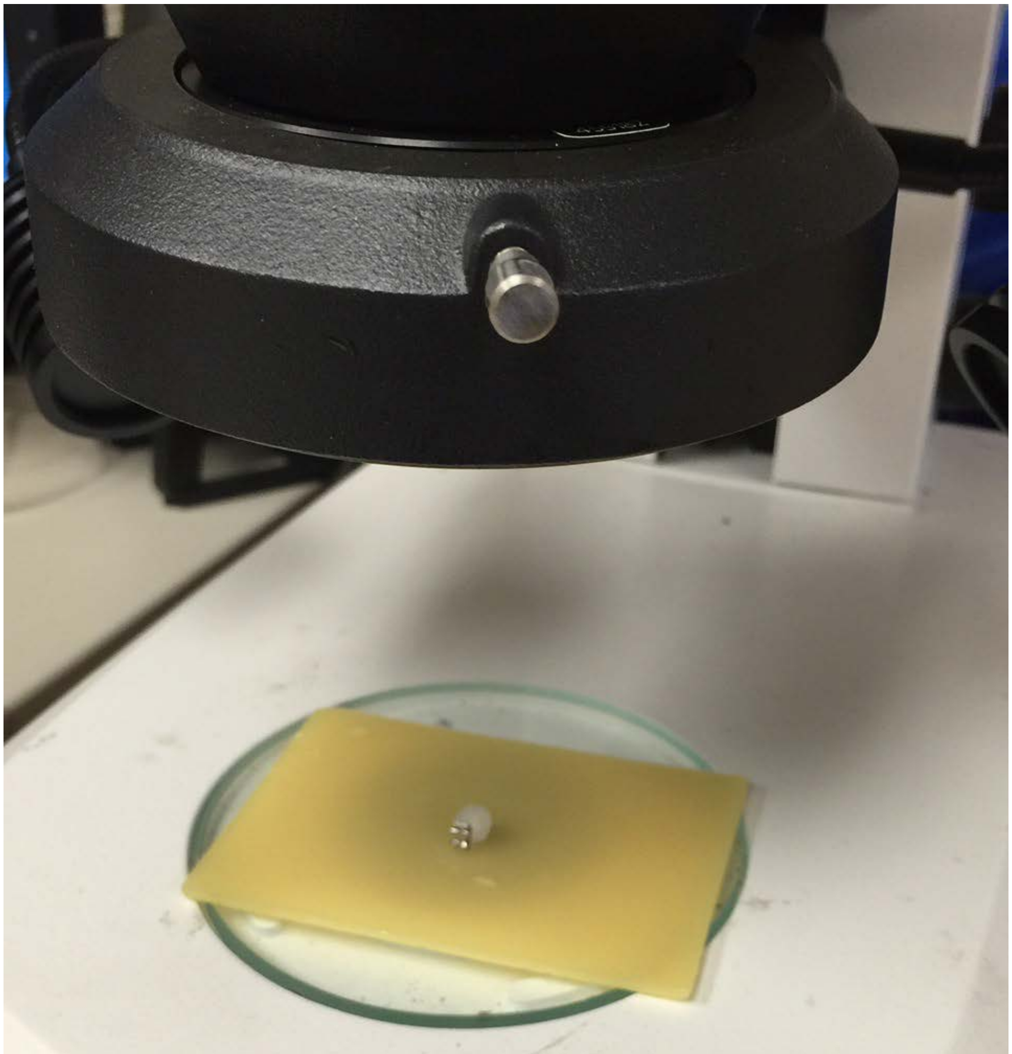

Figure 5. Carl Zeiss stereomicroscope setup for bracket slot imaging

The brackets were carefully aligned so that the slots were photographed perpendicular to the slot. Alignment was confirmed by visually reviewing images to ensure the brackets were not tilted. An example image can be seen in Figure 6.

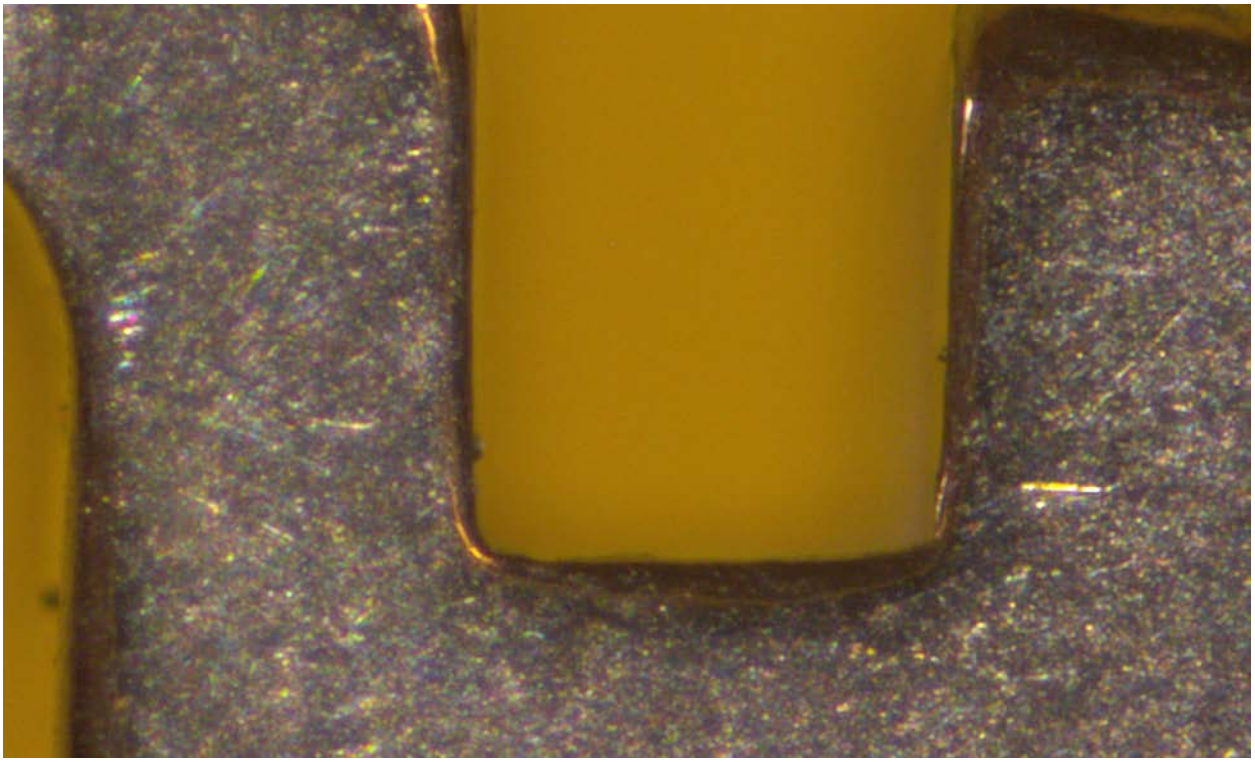

Figure 6. Example photo of the slot.

This process was repeated three times for each bracket. All 20 brackets were imaged on three separate occasions, 7 days apart. This was done in order to verify consistency of imaging perpendicularly to the slot. All of the images were taken using the same magnification. The images were calibrated and evaluated using the GNU Image Manipulation Program (GIMP) software. Using the software, points were selected and transferred for analysis into an Excel spreadsheet. In each photo 3 points were selected on the left (gingival) wall, the right (incisal) wall, and the floor. The points were all plotted on a 2-dimensional Cartesian (x,y) coordinate system, which was given by the GIMP software, and represented pixel coordinates. An example of this analysis can be seen in Figure 7.

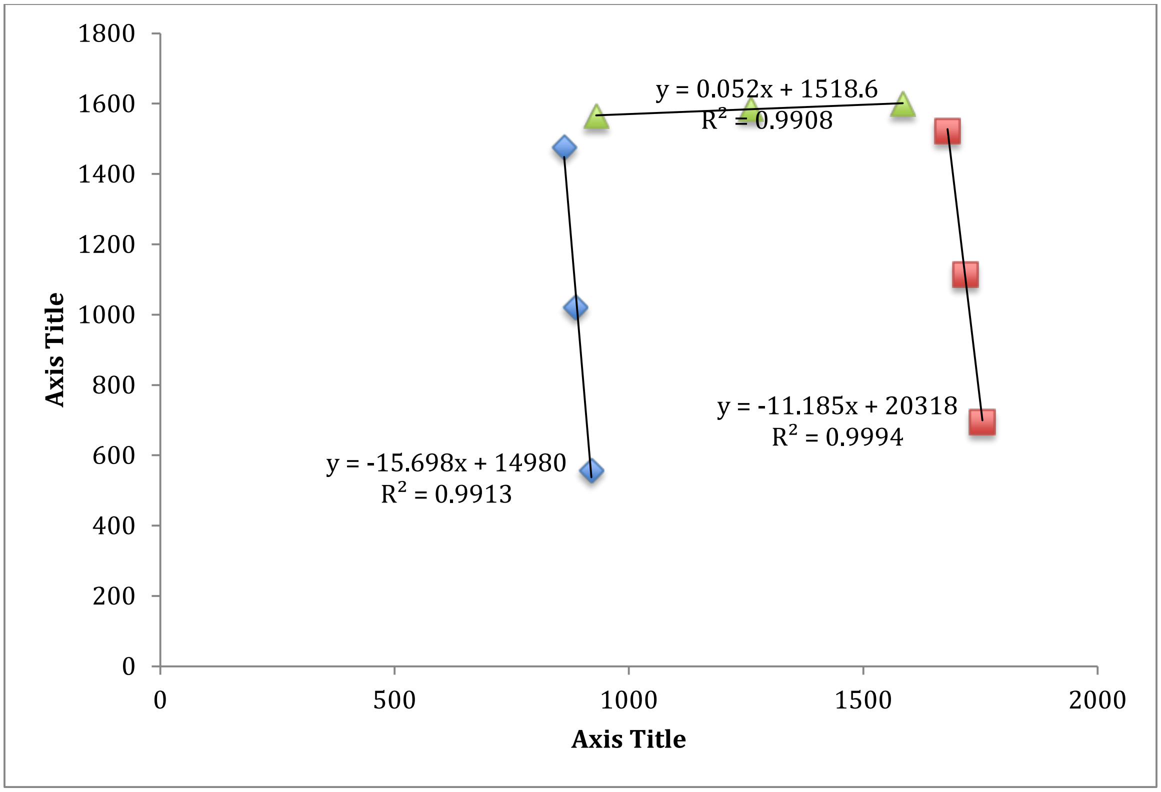

Figure 7. Slot profile evaluation, showing trendlines for the slot floor and walls.

Each corner, where the right and left wall meets the floor, has a radius, therefore points were selected just outside the radius. Along each wall two endpoints were then selected, just before the walls started to round. In order to determine the evaluator's consistency in selecting points along the walls and floor of the slot, the evaluator repeated the process for 20 slot profiles. Then using the distance formula, the midpoint of both walls and the floor of the bracket were identified. Using Excel, a trend-line was generated for the walls and the floor, using linear regression. Therefore there was an output of an equation in the form of $y = mx + b$, and an R^2 for the walls and the floor. The R^2 value for the three lines provides a means to evaluate the linearity of the slot walls.

A total of five measurements are calculated from what is assumed to be a trapezoidal profile of the slot. Then three angles are calculated: the angle between the slot walls, which determines the slot taper (θ_3), and the angles made at the intersection of the slot walls and floor (θ_1 and θ_2).

The distance between any two 2-dimensional Cartesian point is given by Formula 4:

$$Dist = \sqrt{(x_2-x_1)^2 + (y_2-y_1)^2} \tag{4}$$

The bottom distance is calculated as the distance between the points generated by the intersection of the left wall and the bottom line, and the right wall and bottom line. The top distance is calculated by taking the (x,y) coordinates of the highest point plotted on the right wall, generating an equation with the same slope as the floor of the slot, and determining the intersection of that this new line with the equation for the left wall, then taking that (x,y) coordinate and using the distance formula to determine the top slot height. The slot bottom and top distance is the measurements that corresponds to the slot height, nominally 0.022 in. Initially, these measurements are given in pixel length. A gauge block (Mitutoyo Corportation, Kanagawa Japan) of 1mm was imaged using the microscope under the same conditions therefore pixels could be converted to known units of length, millimeters and inches. The gauge block is ASME-1 rated and has an accuracy to within 0.02µm (0.00002 mm). Since the nominal bracket slot dimension is 0.559mm, this level of accuracy is considered sufficient.

The three angles can be determined using the slopes of the three lines, and the following equations:

$$\begin{aligned}
\theta_1 &= \arctan(\text{slope}_{\text{left_wall_line}}) - \arctan(\text{slope}_{\text{bottom_line}}),\\
\theta_2 &= \arctan\left(\frac{1}{\text{slope}_{\text{right_wall_line}}}\right) + \arctan\left(\frac{1}{\text{slope}_{\text{bottom_line}}}\right),\\
\theta_3 &= \arctan\left(\frac{1}{\text{slope}_{\text{right_wall_line}}}\right) - \arctan\left(\frac{1}{\text{slope}_{\text{left_wall_line}}}\right).
\end{aligned} \tag{2}$$

In addition to these measurements, the torque play for each bracket was determined for five different, commonly used rectangular wires. Nominal values for the archwires were used to determine torque play. The archwire dimensions used were: 0.016in × 0.022in, 0.017in × 0.025in, 0.018in × 0.025in, 0.019in × 0.025in, and 0.021in × 0.025in. The torque play is the more clinically applicable information.

The data sets, consisting of the outcome variables for each of the three images (30 OPAL images and 30 GAC images) for each individual bracket were averaged, creating a final data set of ten OPAL and ten GAC. The statistical analysis to determine if there is a statistical difference of the outcome variables will be performed using this data set.

Furthermore, all of the brackets evaluated in the study were additionally imaged using scanning electron microscopy (SEM) allowing for more precise subjective evaluation of the bracket slots, in addition to the objective forms of evaluation previously mentioned. The SEM images revealed any surface inconsistencies within the bracket slots, that could affect bracket-wire interaction, and therefore tooth movement.

Statistical Analysis

Intraclass Correlations Coefficients (ICC) were used to test for agreement because of the continuous nature of the data. The ICC is a general measurement of agreement or consensus. The coefficient represents agreements between two or more raters or evaluation methods on the same set of subjects multiple times. The ICC was determined for the perpendicularism of the bracket slot image acquisition as well as the consistency of point selection within the bracket slot walls. An ICC of 1 represents perfect agreement.

P-values for comparing Opal and GAC were determined based on the outcome variables, bottom dimension, top dimension, divergence angle of slot walls, linearity of slot walls and floor, as well as torque play for 5 commonly used rectangular arch-wires. P-values were obtained using a Wilcoxon Signed Rank test since the distributions for the variables were not normal. In addition, summary statistics for each outcome by group, OPAL and GAC, were determined in terms of mean, median, standard deviation, and minimum and maximum. Furthermore, P-values were obtained, using a Wolcoxon Signed Rank test, to determine if there was a significant difference in the deviation from the mean for all of the outcome variables. This was done in order to determine if there is a difference in precision between the manufacturing methods.

Results

The Intraclass correlations for perpendicularism of bracket slot image acquisition were determined between all the groups simultaneously and then pairwise. The ICC for all groups was 0.95248, therefore consistency of image acquisition shows very high agreement. In addition, the ICC for point selection within the slot, is 0.99735, therefore it is shown that points are selected consistently between images.

Summary statistics for the outcome variables can be seen in the Table 1. In the table the outcome variables are listed on the left, and include the bottom and top dimensions in both inches and millimeter units, as well the divergence angle of the slot walls. Furthermore, the deviation angles for the five selected archwire sizes are listed as well. For each outcome variable, the mean, standard deviation, and minimum and maximum value is listed. This table serves as an overview of the samples from each group, for the outcome variables. In the following, more specific data is shown that includes the values for each bracket from both groups.

	Group	N	Mean	Standard Deviation	Minimum	Maximum
Bottom (mm)	MIM	10	0.5852	0.0082	0.5746	0.5953
	Milled	10	0.5476	0.0040	0.5432	0.5557
Top (mm)	MIM	10	0.6109	0.0104	0.5966	0.6256
	Milled	10	0.5658	0.0036	0.5625	0.5728
Bottom (in)	MIM	10	0.0230	0.0003	0.0226	0.0234
	Milled	10	0.0216	0.0002	0.0214	0.0219
Top (in)	MIM	10	0.0241	0.0004	0.0235	0.0246
	Milled	10	0.0223	0.0001	0.0221	0.0226
Divergence	MIM	10	2.2847	0.6925	0.6760	3.1029
	Milled	10	2.1627	0.4231	1.4428	2.9262
16x22	MIM	10	21.8763	1.2847	20.2510	23.4577
	Milled	10	16.4025	0.5475	15.7980	17.5167
17x25	MIM	10	15.4392	0.9483	14.2324	16.6047
	Milled	10	11.2775	0.4273	10.8043	12.1463

18x25	MIM	10	12.6602	0.9077	11.5045	13.7756
	Milled	10	8.6643	0.4115	8.2086	9.5008
19x25	MIM	10	9.9698	0.8700	8.8614	11.0386
	Milled	10	6.1292	0.3965	5.6899	6.9352
21x25	MIM	10	4.8558	0.8023	3.8328	5.8412
	Milled	10	1.2972	0.3690	0.8882	2.0471
Left wall	MIM	10	0.9419	0.0821	0.7247	0.9947
	Milled	10	0.8941	0.0901	0.7318	0.9860
Right Wall	MIM	10	0.9130	0.0957	0.7095	0.9983
	Milled	10	0.9633	0.0479	0.8662	0.9988
Floor	MIM	10	0.6378	0.1897	0.2850	0.9822
	Milled	10	0.7169	0.1827	0.3444	0.9396

Table1. Outcome statistics

Comparison of the CNC milled (AVEX OPAL) and metal-injection molded (GAC OmniArch) brackets for the outcome variables with the specific P-values can be found in Table 2. The statistically significant p-values are those highlighted below.

	p-value
Bottom (mm)	0.0002
Top (mm)	0.0002
Bottom (in)	0.0002
Top (in)	0.0002
Degrees R/L	0.3075
16x22	0.0002
17x25	0.0002
18x25	0.0002
19x25	0.0002
21x25	0.0002
Left wall	0.1859
Right Wall	0.3075
Floor	0.3475

Table 2. P-values for outcome statistics. Statistically significant variables are highlighted

From the above table it is evident that statistically significant differences were found between the two groups in bottom and top slot height, as well as deviation angle for the five archwires selected and used in the mathematical model.

The bottom slot dimension for the OPAL sample had a mean of 0.0216in, with a standard deviation of 0.0002in, and a maximum of 0.0219in. The entire sample being below the nominal slot height of 0.022 in. The GAC bracket had a mean of 0.0230in, with a standard deviation of 0.0003in, and a maximum of 0.0234in. The entire sample of GAC brackets evaluated had a bottom slot height above 0.022in. On average, the AVEX OPAL bracket slot heights were 2% below the nominal value, whereas the GAC OmniArch brackets were 4.5% oversized. The bottom slot height dimension for the entire sample from each group can be seen in Figure 8.

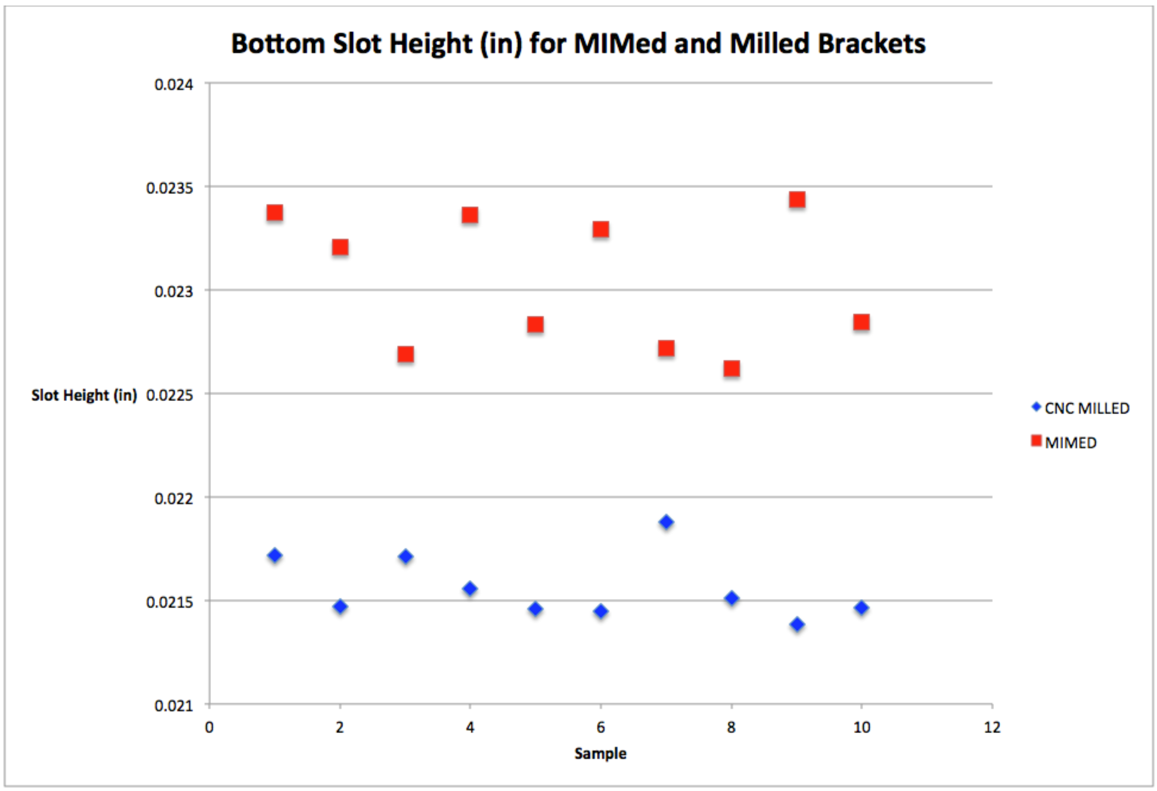

Figure 8. Scatter plot of the bottom slot height for the samples of the CNC milled (OPAL) and MIMed (GAC).

All of the brackets in both groups had slot walls that were divergent, meaning that the top height of the bracket slot was greater than the bottom height. There was no statistical difference found between the two groups when considering divergence angle of the slot walls. Furthermore, there was a statistically significant difference found between the top slot height for the two groups.

No difference was found in the linearity of the slot walls and floor of the bracket slots between the two groups, based on the R^2 values of the trendlines.

There was a statistical difference found for the deviation angles for wires of commonly used nominal sizes. For a 0.016in × 0.022in nominally sized archwire in an OPAL bracket the average deviation angle is 16.40°, with a standard deviation of 0.55°, with a minimum and maximum of 15.80° and 17.52°, respectively. For GAC brackets with the same sized archwire, the average deviation angle is 21.88°, with a standard deviation of 1.28°, with a minimum and maximum of 20.25° and 23.46°, respectively. The differences in deviation angle for the two groups can be seen in Figure 9.

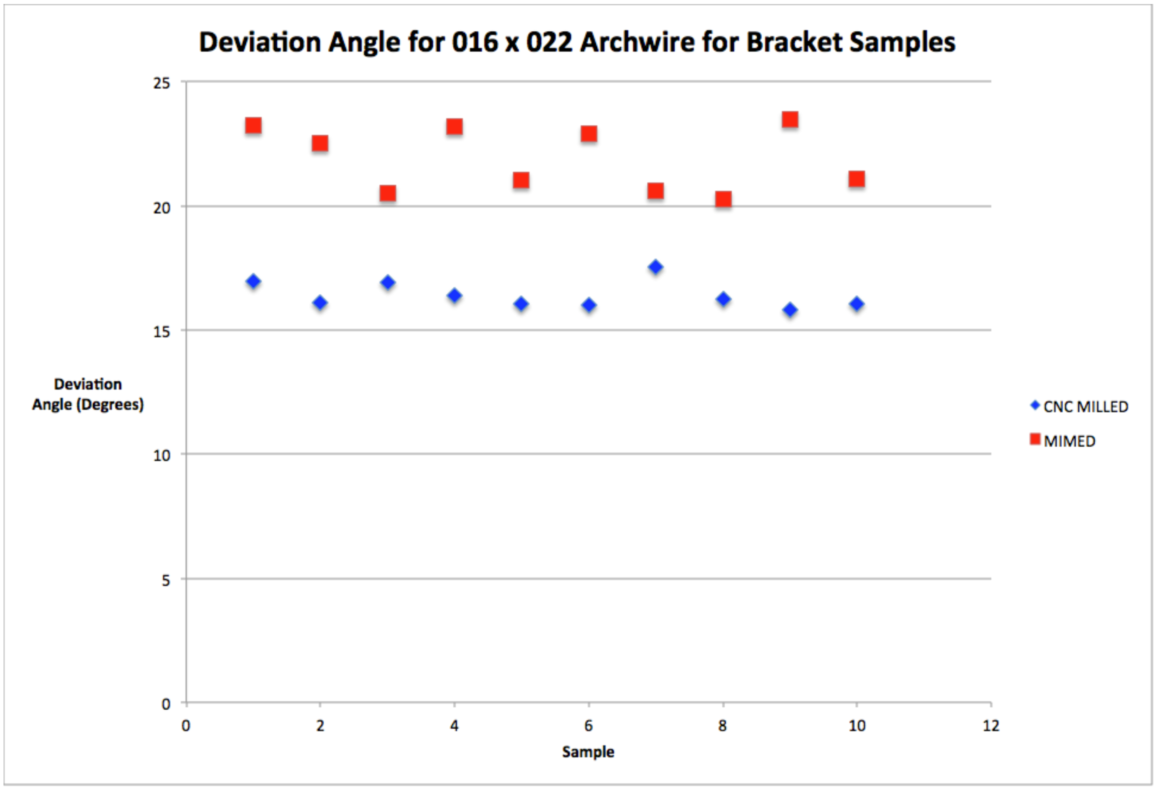

Figure 9. Scatter plot of the deviation angle for an 0.016in × 0.022in archwire for the samples of the CNC milled (OPAL) and MIMED (GAC).

For a 0.017in × 0.025in nominally sized archwire in an OPAL bracket the average deviation angle is 11.28°, with a standard deviation of 0.43°, with a minimum and maximum of 10.80° and 12.15°, respectively. For GAC brackets with the same sized archwire, the average deviation angle is 15.44°, with a standard deviation of 0.95°, with a minimum and maximum of 14.23° and 16.60°, respectively. The differences in deviation angle for the two groups can be seen in Figure 10.

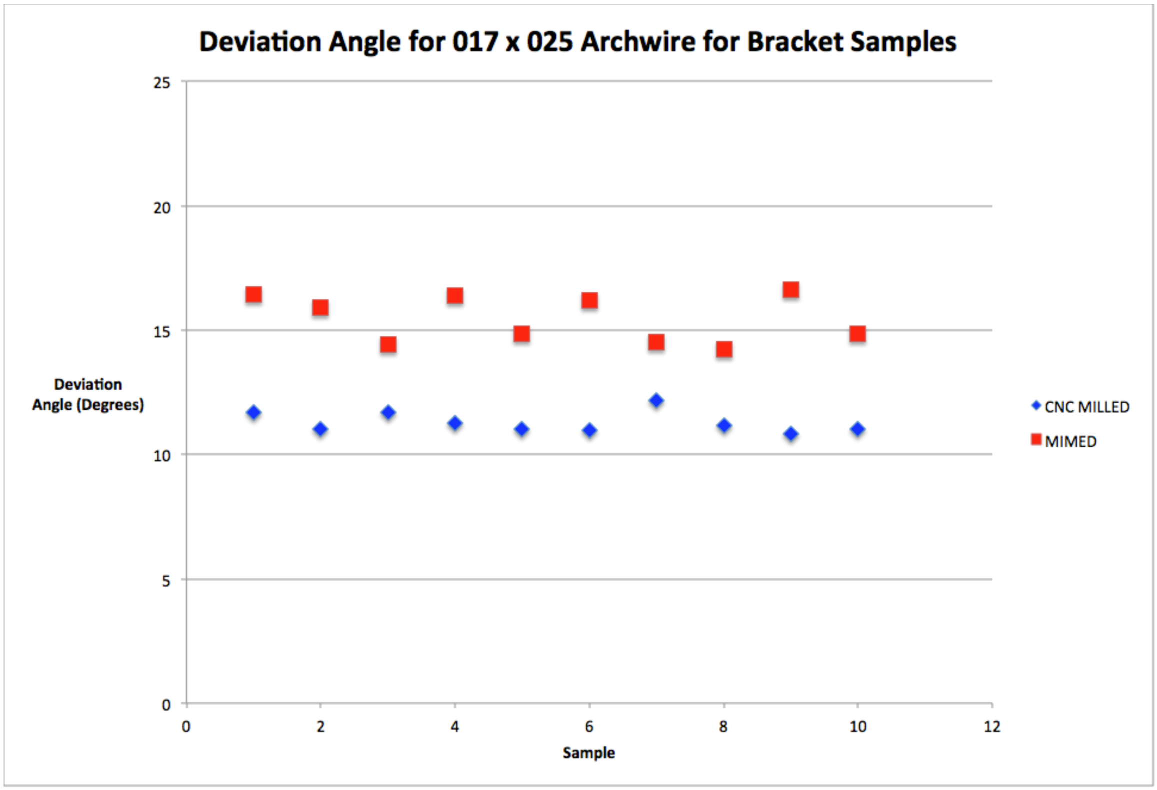

Figure 10. Scatter plot of the deviation angle for an 0.017in × 0.025in archwire for the samples of the CNC milled (OPAL) and MIMED (GAC).

For a 0.018in × 0.025in nominally sized archwire in an OPAL bracket the average deviation angle is 8.66°, with a standard deviation of 0.41°, with a minimum and maximum of 8.21° and 9.50°, respectively. For GAC brackets with the same sized archwire, the average deviation angle is 12.66°, with a standard deviation of 0.91°, with a minimum and maximum of 11.50° and 13.78°, respectively. The differences in deviation angle for the two groups can be seen in Figure 11.

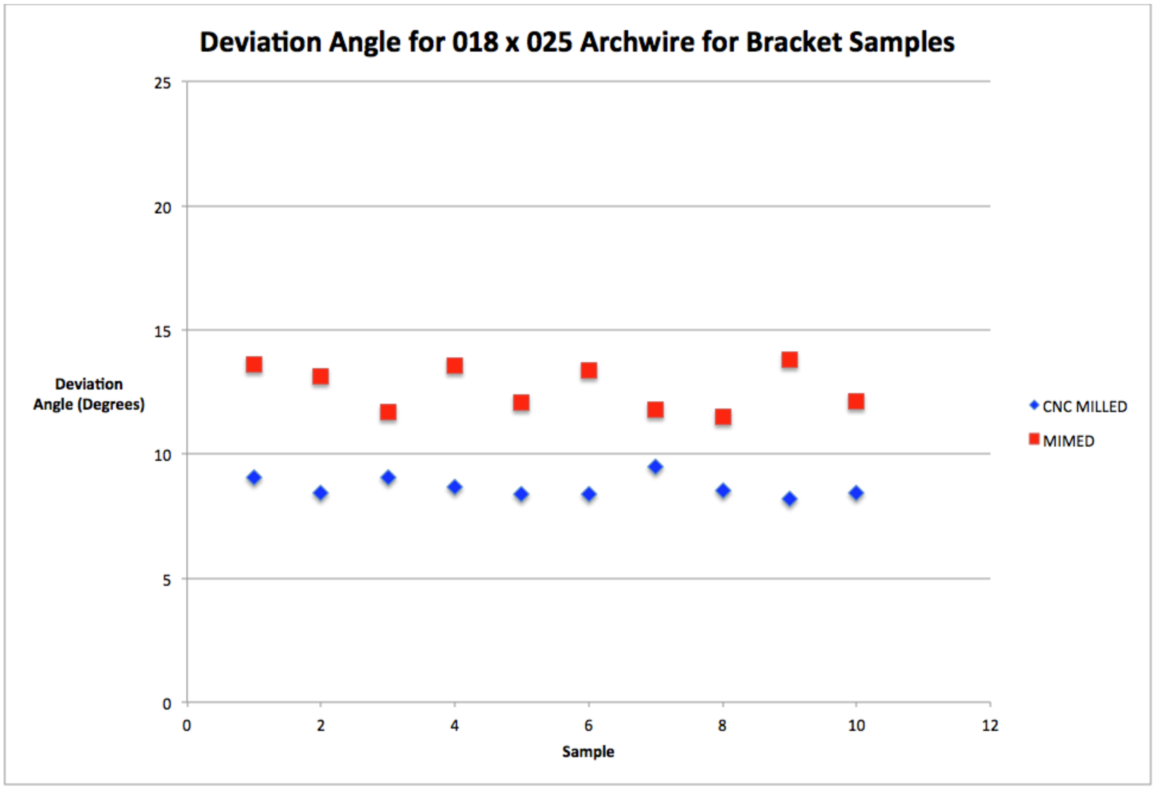

Figure 11. Scatter plot of the deviation angle for an 0.018in × 0.025in archwire for the samples of the CNC milled (OPAL) and MIMED (GAC).

For a 0.019in × 0.025in nominally sized archwire in an OPAL bracket the average deviation angle is 6.13°, with a standard deviation of 0.40°, with a minimum and maximum of 5.69° and 6.93°, respectively. For GAC brackets with the same sized archwire, the average deviation angle is 9.97°, with a standard deviation of 0.87, with a minimum and maximum of 8.86° and 11.03°, respectively. The differences in deviation angle for the two groups can be seen in Figure 12.

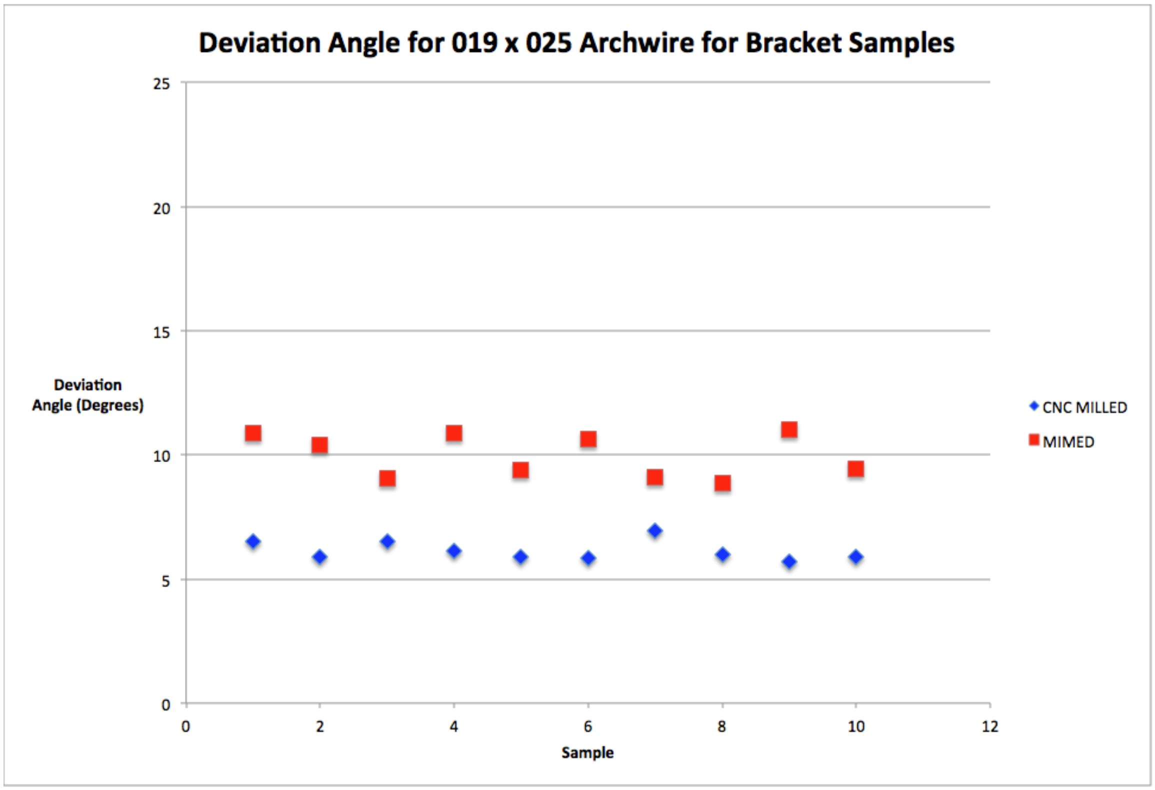

Figure 12. Scatter plot of the deviation angle for an 0.019in × 0.025in archwire for the samples of the CNC milled (OPAL) and MIMED (GAC).

For a 0.021in × 0.025in nominally sized archwire in an OPAL bracket the average deviation angle is 1.30°, with a standard deviation of 0.37°, with a minimum and maximum of 0.89° and 2.04°, respectively. For GAC brackets with the same sized archwire, the average deviation angle is 4.86°, with a standard deviation of 0.80°, with a minimum and maximum of 3.83° and 5.84°, respectively. The differences in deviation angle for the two groups can be seen in Figure 13.

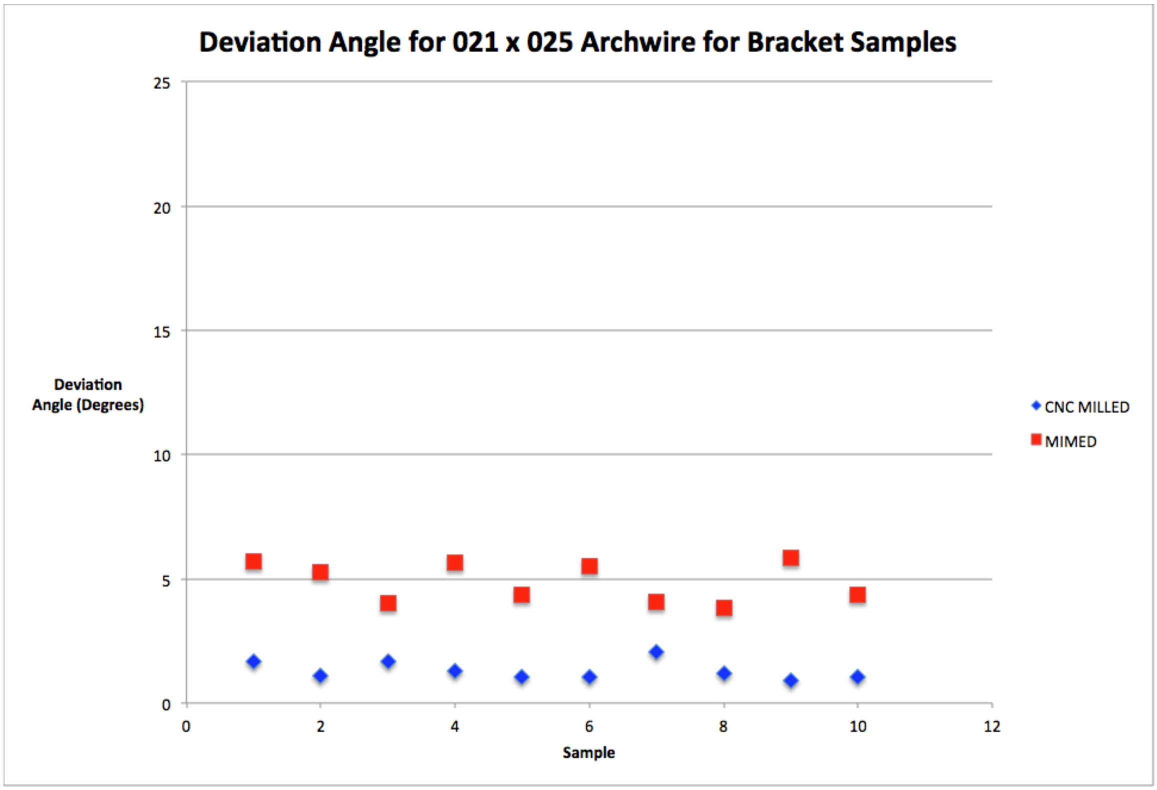

Figure 13. Scatter plot of the deviation angle for an 0.021in × 0.025in archwire for the samples of the CNC milled (OPAL) and MIMED (GAC).

Furthermore, comparison of the two groups was performed to determine if there was a statistical difference in the deviation from the mean for each individual sample. This data is presented in Table 3.

	Group	N	Average Deviation from the mean
Bottom (mm)	GAC	10	0.0075
	OPAL	10	0.0032
Top (mm)	GAC	10	0.0083
	OPAL	10	0.0029
Bottom (in)	GAC	10	0.0003
	OPAL	10	0.0001
Top (in)	GAC	10	0.0003
	OPAL	10	0.0001
Divergence	GAC	10	0.4614
	OPAL	10	0.3264

16x22	GAC	10	1.1756
	OPAL	10	0.4371
17x25	GAC	10	0.8675
	OPAL	10	0.3411
18x25	GAC	10	0.8303
	OPAL	10	0.3284
19x25	GAC	10	0.7958
	OPAL	10	0.3165
21x25	GAC	10	0.7338
	OPAL	10	0.2945
Left wall	GAC	10	0.0554
	OPAL	10	0.0741
Right Wall	GAC	10	0.0746
	OPAL	10	0.0357
Floor	GAC	10	0.1432
	OPAL	10	0.1401

Table 3. Outcome statistics for deviations from the mean

The two groups, GAC and OPAL, were compared and p-values were determined for the outcome variables, based on deviation from the mean. These values can be seen in Table 4. It is evident from this table that the deviations are statistically significant for the bottom slot height and all of the deviation angle values for each of the five wire sizes.

	p-value
Bottom (mm)	0.0010
Top (mm)	0.0640
Bottom (in)	0.0010
Top (in)	0.0640
Degrees R/L	0.9982
16x22	0.0006
17x25	0.0006
18x25	0.0006
19x25	0.0006
21x25	0.0006
Left wall	0.2413
Right Wall	0.1405
Floor	0.8501

Table 4. P-values for outcome statistics for deviations from the mean. Highlighted p-values are statistically significant.

Discussion

The bottom slot height is the outcome variable with the greatest significance, because it is the basis of the comparison between the two bracket types and manufacturing methods. It also determines the torque realization for each of the archwire sizes used in the mathematical model. The mean bottom slot height for the MIM sample is 0.023in, and for the CNC milling sample it is 0.0216in. The MIM sample being 4.5% greater than the nominal size, and the CNC milling sample 2% below the nominal size. Therefore there is a clear difference between the two samples on the basis of dimensional accuracy. The CNC milled brackets would be preferable and be more likely to deliver the nominal torque value due to the size of the bracket slot.

This difference is apparent when the deviation angle for the combination nominally sized archwires for the bracket samples are examined. There is a clear and statistically significant difference between the two samples. The clinically significant aspect of this can be seen especially when examining the torque play for the 0.019in × 0.025in and 0.021in × 0.025in for the two different samples. These archwires are commonly used archwires for torque realization during treatment. It is evident that with MIM brackets a clinician would need to use an archwire with a nominal dimension of 0.021in × 0.025in to achieve the same deviation angle within a degree, as an CNC milled bracket with a wire of nominal dimension 0.019in × 0.025in. This is significant to treatment because the smaller arch wire is more versatile in the clinician's hands, and some detailing can be done with this arch-wire. In addition, from a practice management standpoint, it could represent a need for increased inventory of archwires.

If an orthodontic provider uses MIM manufactured brackets, using a higher torque prescription may be needed, in order to clinically realize the desired torques of the dentition. Alternatively, the clinician can use a larger sized archwire, routinely add torque to the archwire, or use torqueing auxiliaries. All of these will in the least, increase chair time required to treat patients. But furthermore, due to the overall decreased precision and increased range of bracket slot size, compared to the CNC milled brackets, it is still difficult to consistently account for the increased slot height, which will have an effect on torque realization. For MIM manufactured brackets, as seen in Table 3, the average deviation from the mean for bottom slot height is three times larger than the average deviation for the CNC milled brackets. The effect of this is seen when examining the deviations from the mean for torque realization for the different sized archwires, also presented in Table 3. It can bee seen that the deviation from the mean for the MIM sample in effective torque is two to three times greater than it is for the CNC milled sample. For example, the deviation from the mean for an 0.019in × 0.025in, a commonly used archwire for torque realization clinically, for the MIM sample of brackets was 0.80, whereas for the CNC milled sample it was 0.32, roughly 2.5 times greater for the MIM sample.

This statistically significant different deviation could potentially affect treatment, from case to case, and even tooth to tooth within a patient, due to inconsistently oversized bracket slots. Since there is a significant range of deviation from the mean for the MIM brackets studied one could expect to see a range from bracket to bracket within the patient. Using this sample of brackets, it is seen that the range of bottom bracket slot height for the MIM sample is from 0.0226in to 0.0234in. In this case, the largest slot height is 3.5%

greater than the smallest slot height. When comparing these in the mathematical model to determine effective torque, this can lead to a difference of 3.2° in an 0.016in × 0.022in archwire, to 2° in an 0.021in × 0.025in. Therefore, if there was this amount of deviation among brackets within a complete set for a patient, there could be a two to over three degrees difference for torque realized between the maxillary central incisors. Conversely for the sample of the CNC milled brackets the potential differences are 1.7° in an 0.016in × 0.022in archwire, to 1.1° in an 0.021in × 0.025in. This difference is clinically significant and could potentially make finishes more difficult and less predictable for the clinician.

To account for torque play, or deviation angle, increasing torque within the archwire is common practice. However, outinely adding the appropriate torque to a wire can be time consuming and difficult. As previously stated, there is window between 5 and 20 Nmm for physiological torqueing moment for a tooth, and small discrepancies can have an effect on realizing the appropriate torque, and potentially exceeding the physiological appropriate forces on teeth. It is generally acknowledged that application of high force levels is more likely to induce root resorption and possible loss of tooth vitality. Reitan showed that increased forces will lead to hyalinization of the periodontal ligament and subsequent undermining resorption (Reitan 1951). Therefore, if there is a large range in bracket slot height among brackets on the same patient, it will be difficult to consistently add the appropriate torsion to the wire, which will achieve the appropriate torqueing moment, to achieve both consistency and symmetry, and maintain that moment within what is physiologically appropriate.

In addition, due to the fact that there is a clear difference in the accuracy and precision of the brackets there could be in an increase in treatment time. This is because there could be a clinically significant difference in deviation angle from one bracket to the other on the contralateral side within the same patient. This would require bends in the wire in order to make the tooth torques symmetrical. Moreover, the greater deviation angle alone found in the MIM brackets would require adding torque to the archwire or using torqueing auxiliaries. These additional treatment needs could potentially increase treatment time.

The SEM images offer more insight into the shape of the bracket slot and surface appearance of the brackets, and verification of what is seen using the Carl Zeiss STEMI508. There were many findings that are consistent within each group, MIM and CNC milled. Overall, the corners, where the walls meet the floor, of the MIM brackets are very rounded and uneven. There are many surface blemishes, and in many cases, blemishes, and or protrusions, in the bracket slot. In one bracket there appeared to be a large particle slightly protruding into the slot, although this may not have an effect on torque realization, it could potentially do so in other brackets produced by the MIM process. Large protrusions into the slot could actually increase torque realization, but since this is inconsistent among brackets, it can not be accounted for by the clinician and could negatively affect forces and moments delivered to the dentition, and therefore outcomes. The floors of the MIM brackets appeared generally straight, especially when compared to the CNC milled brackets. An example of an SEM image of a MIM bracket that shows these findings can be seen in Figure 14.

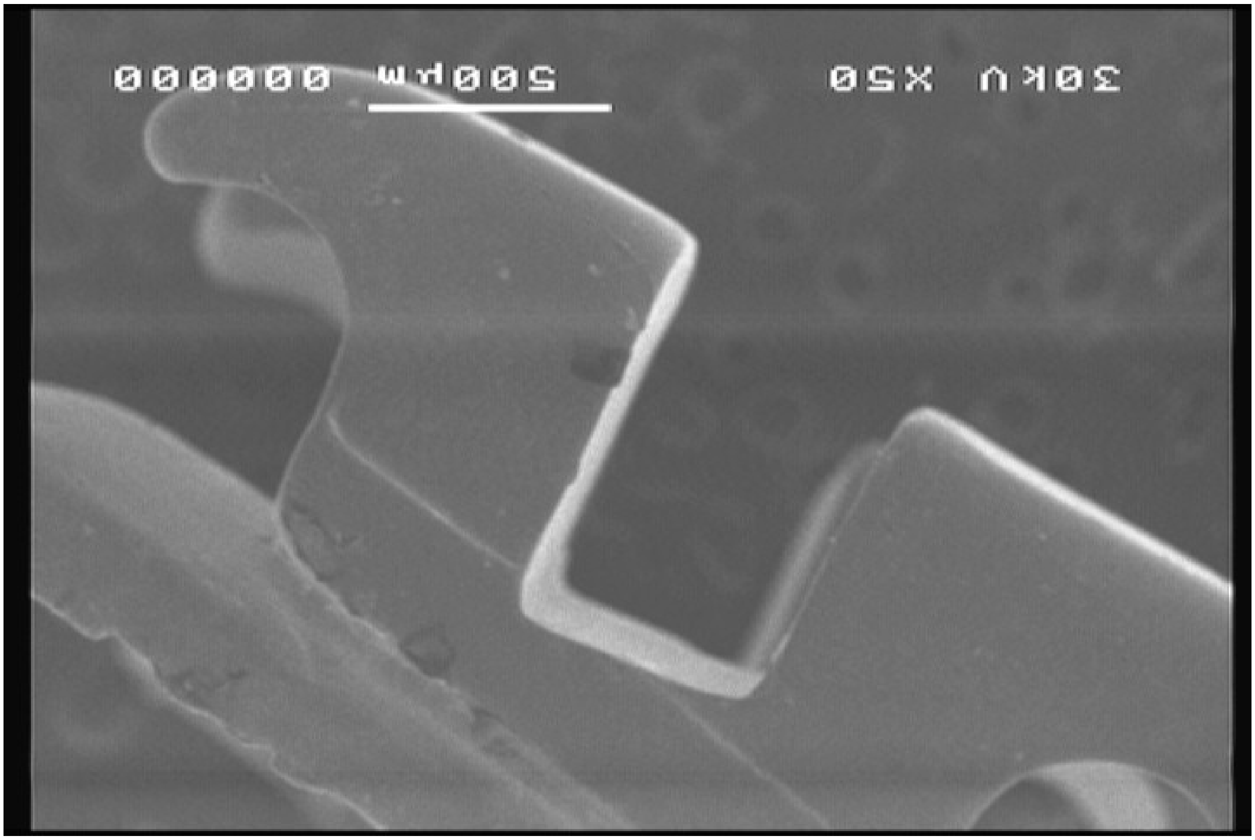

Figure 14. SEM image of bracket produced by the MIM process. Inconsistent rounding of corners, uneven floor, and large particle slightly protruding into the slot can be seen.

The CNC milled brackets were overall very clean and had consistent surfaces. The corner where the left wall meets the floor is very slightly rounded, and the corner where the right wall meets the floor is nearly a perfect corner. The floor of the brackets is consistently is slightly rounded and is not a straight line, which is reflected in the R^2 value for the trendline of the floors for the CNC milled brackets. Only one of the brackets had a slight protrusive blemish that went into the bracket slot. Aside from what is specifically mentioned, overall both bracket types had relatively straight walls. An example of an SEM image of a CNC milled bracket that shows these findings can be seen in Figure 15.

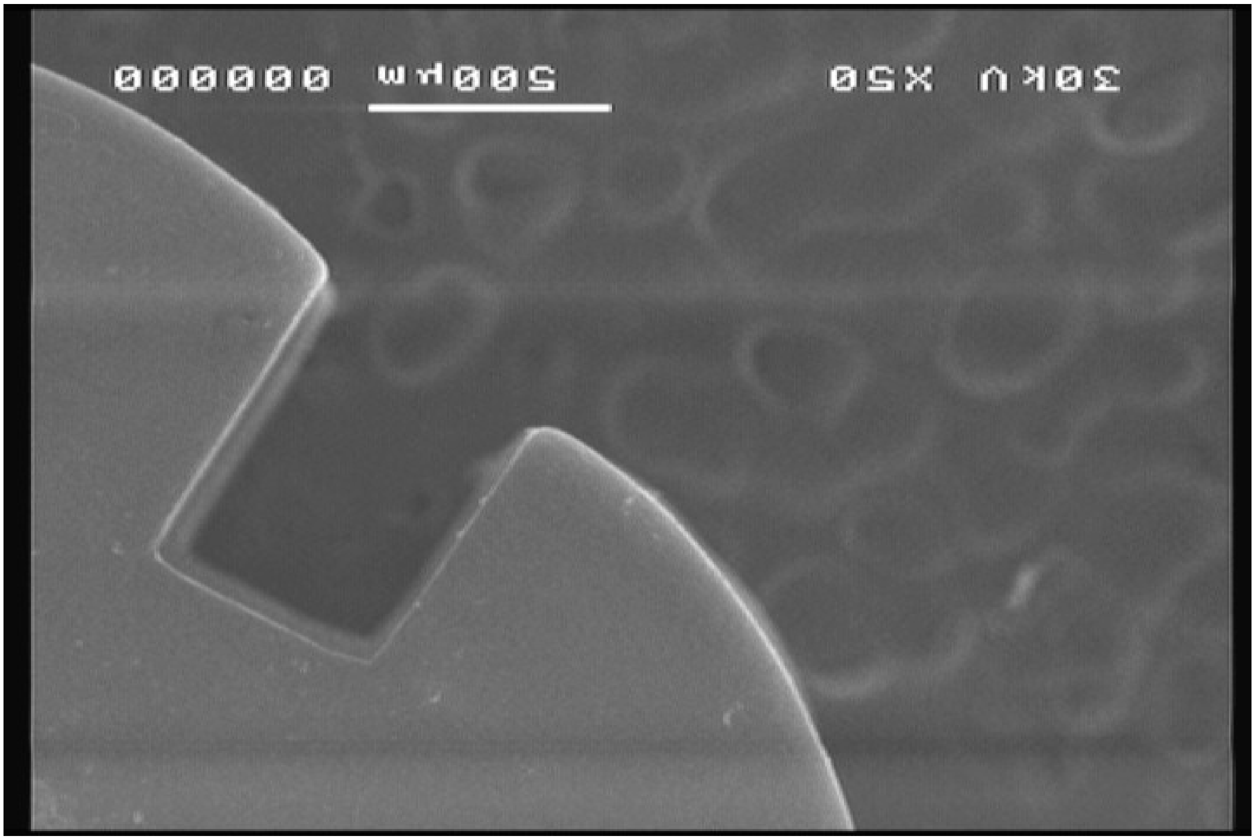

Figure 15. SEM image of bracket produced by the CNC milling process. Consistently sharp corners, floor and walls can be seen.

From the outcome data it is evident that there is not a difference between the two samples in divergence angle of the slot walls. Therefore, when archwires are placed in the bracket slot complete seating of the archwire will occur, and the archwire will make contact with the floor of the bracket slot, therefore, any inconsistencies in the floor could be significant. From the SEM images it is evident that generally, the MIM sample has a floor that is inconsistent, with the middle of the floor being slightly higher than points closer to the corners, outside of the corner radius. This bracket feature could potentially effect seating of the archwire into the smallest dimension of the bracket slot height, therefore, decreasing the effective slot height, and increasing the deviation angle between archwire and bracket slot. This feature differs from that of the CNC milled sample of brackets. There is a consistent, yet slight, concavity on the floor of the slot. This feature would not prevent seating of the archwire into the smallest dimension of bracket slot height. Furthermore, as seen in the SEM image one of the MIM bracket slots, there is a large particle visible, slightly protruding into the slot. In its existing location, there would most likely not be an effect on torque realization for that bracket, but if that particle were located in the floor of the slot, and prevented complete seating of the archwire into the smallest dimension of slot height, there could be an increase in deviation angle between the bracket slot and archwire. Particles of this type were not seen in any of the CNC milled brackets. It is most likely a component of the MIM process.

During the evaluation process for this study, one difficulty was with identifying the points on the slot profile that were marginally outside the rounded corners. This was especially difficult with the MIM brackets, wherein the corners were rounded to a much greater degree. This begins to complicate the assumption that the slot is trapezoidal in shape, as Major et al. discussed in their study on bracket slot tolerances. Knowing exactly where the edges of different size wires engaged the slot, would allow for precise location of points, and therefore permit more accurate objective evaluation of bracket slot dimensions.

Although this is a thorough analysis of the bracket slots, there are some limitations. Ensuring that the pictures are taken from a direct perpendicular viewpoint is difficult. In this study, this was accounted for by imaging the bracket slots in a perpendicular orientation on three separate occasions, comparing the three based on interclass correlations, and then averaging the measurements for the three images together. Selecting three points along the slot walls will yield an accurate representation of the slot profile. If there is an area of irregularity large enough to greatly affect the R^2, but is not in a position where the edges of the arch-wire would engage, then it wouldn't have an effect on torque realization. From both the stereomicroscope images and SEM analysis of the brackets it is apparent that the most irregularity is found in the middle of the floor of the bracket slot, and as previously stated, for the MIM sample could affect seating of the archwire, therefore increase deviation angle between the bracket slot and the archwire. In future studies, if it were possible for a computer program to select an infinitesimal number of points along the walls and floor of the slot, a more accurate model could be created (Major, Carey et al. 2010). The effective height of the bracket slot is the more important outcome, because this will take into account the divergence of the bracket slots. In this study, the bracket slot height used in order to determine the torque play was the bottom dimension, therefore not taking into account the convergence of the slot. This means that the deviation angle values presented may not be the exact angles that will be encountered in treatment, given a wire of the exact nominal dimension. However, since the divergence angle values for the two bracket types are similar, one would expect to see essentially the same change in deviation angle clinically.

Future studies could potentially evaluate if there is any difference in plastic deformation, during treatment, between milled brackets and brackets produced by the MIM process. In addition, since this study and others have only imaged the bracket from the mesial aspect, future studies could evaluate the distal aspect. Another future study could compare the MIM process of two manufacturers and determine if the decreased dimensional precision and accuracy is a function of the manufacturing process itself. Another important factor to consider is the potential difference in bracket dimensions among production lots, which is another topic for a future study. This is a quality control issue within the manufacturing process, but since variation could potentially exist knowledge of this would aid the orthodontic clinician in producing the most accurate forces and moments to the dentition, which in turn would allow for an anticipated outcome, and potentially optimal result (Meling, Odegaard et al. 1998).

Conclusion

In conclusion, it was determined that there was a statistically significant difference between the two samples of brackets, MIM (GAC OmniArch) and CNC milled (AVEX

OPAL), in the outcome variables of bottom slot height, top slot height, and deviation angle for the five nominally sized archwires used in the mathematical model, which effects torque realization. In addition, it was determined that there is a statistically significant difference between the two samples, in terms of deviation from the mean, for those outcome variables. Therefore it can be concluded that there is a statistically significant difference between the two samples in terms of both accuracy and precision. Future studies will have to determine if this difference can be attributed to the manufacturing processes in general, or if there is a difference among manufacturers, but a difference between these two samples was noted nonetheless. These differences are clinically significant for two main reasons. Firstly, a clinician using the MIM manufactured GAC OmniArch would have to use an 0.021in × 0.025in archwire to be able to achieve the same deviation angle as an 0.019in × 0.025in archwire in the CNC Milling AVEX OPAL bracket sample, within a degree. And secondly, because there is overall lack of precision for the MIM sample, compared to the CNC milling sample, there is a clinical inability to predict how much torque is being expressed from bracket to bracket. Precision in the slot dimension, is nearly as important as accuracy to the clinician. It is essential for the clinician to know as much about the bracket slot dimensions, and arch-wire dimensions for that matter, as possible, because this allows the clinician to be able to account for discrepancies during treatment.

Bibliography

(2011). "sinter". American Heritage® Dictionary of the English Language, Fifth Edition, Houghton Mifflin Harcourt Publishing Company.

Andrews, L. F. (1972). "The six keys to normal occlusion." Am J Orthod **62**(3): 296-309.

Andrews, L. F. (1976). "The straight-wire appliance, origin, controversy, commentary." J Clin Orthod **10**(2): 99-114.

Badawi, H. M., et al. (2008). "Torque expression of self-ligating brackets." Am J Orthod Dentofacial Orthop **133**(5): 721-728.

> INTRODUCTION: The labiolingual inclination of maxillary and mandibular incisors is considered by many orthodontists to be an important determinant of pleasing dental esthetics and ideal stable occlusion. In contemporary fixed appliances, attaching a rectangular orthodontic archwire to a bracket with a rectangular slot makes third-order control possible. The purpose of this study was to measure the difference in third-order moments that can be delivered by engaging 0.019 x 0.025-in stainless steel archwires to 2 active self-ligating brackets (In-Ovation, GAC, Bohemia, NY; Speed, Strite Industries, Cambridge, Ontario, Canada) and 2 passive self-ligating brackets (Damon2, Ormco, Orange, Calif; Smart Clip, 3M Unitek, Monrovia, Calif). METHODS: A bracket/wire assembly torsion device was developed. This novel apparatus can apply torsion to the wire while maintaining perfect vertical and horizontal alignment between the wire and the bracket. A multi-axis force/torque transducer was used to measure the moment of the couple (torque), and a digital inclinometer was used to measure the torsion angle. Fifty maxillary right central incisor brackets from each of the 4 manufacturers were tested. RESULTS: There was a significant difference in the engagement angle between the 2 types of brackets; on average, torque started to be expressed at 7.5 degrees of torsion for the active self-ligating brackets and at 15 degrees of torsion for the passive self-ligating brackets. The torque expression was higher for the active self-ligating brackets up to 35 degrees of torsion. Torsion of the wire past this point resulted in a linear increase of the measured torque for the Damon2, the Smart Clip, and the In-Ovation brackets. The torque was relatively constant past 35 degrees of torsion for the Speed bracket. CONCLUSIONS: We conclude that active self-ligating brackets are more effective in torque expression than passive self-ligating brackets.

Cash, A. C., et al. (2004). "An Evaluation of Slot Size in Orthodontic Brackets— Are Standards as Expected?" Angle Orthodontist **74**: 450-453.

Gioka, C. and T. Eliades (2004). "Materials-induced variation in the torque expression of preadjusted appliances." Am J Orthod Dentofacial Orthop **125**(3): 323-328.

> The purpose of this article is to comprehensively investigate the sources of variation in the expression of torque in preadjusted appliances. Variables related to properties of materials were systematically analyzed, including (1) the inability to fill the slot

because of the size difference of archwires and bracket slot, (2) irregularities from the manufacturing process of brackets precluding proper engagement, (3) differences in the stiffness of wire alloys engaged to the bracket slot, (4) variations between actual and reported bracket torque values, and (5) ligation modes, all of which might account for increased third-order clearance or bracket-archwire "play." The effect of these variations on the expression of torque is discussed, and the net buccolingual inclinations are provided as a function of wire size and composition for common bracket slot-archwire combinations. Most reports published on this issue indicate a loss of torque control as high as 100% of the prescribed value. Furthermore, the fallacy of transferring the ideal crown inclination to the torque prescribed in the bracket is illustrated, along with the underestimation of the prescribed torque relative to the proper tooth crown. The realistically required torque is analyzed to its constituent components, involving tooth inclination, compensation for the slot-wire play, and incomplete ligation with elastomeric ligatures. Based on the evidence available, it is proposed that a high-torque prescription should be selected to account for the lack of full expression of the prescribed torque that occurs clinically.

Joch, A., et al. (2010). "Bracket slot and archwire dimensions: manufacturing precision and third order clearance." J Orthod **37**(4): 241-249.

OBJECTIVE: To determine the accuracy of different manufacturer's dimensions of bracket slots and stainless steel archwires and compare these against the tolerance limits given by DIN 13971 and 13971-2. Further to calculate torque play and effective torque and to compare the results to nominal torque. DESIGN: A laboratory investigation. SETTING: The Department of Orthodontics and Dentofacial Orthopedics at Medical University of Graz, Austria. MATERIALS AND METHODS: Ten upper central incisor brackets (0.022 inch) from five different bracket systems were investigated. Bracket slot height was measured with leaf gauges. The height and width of 10 stainless steel archwires with dimensions either 0.019x0.022 or 0.020x0.025 inch were measured using a micrometer. RESULTS: All measured bracket slot heights were within the upper and lower tolerance limits given by DIN 13971-2. Archwires showed measurements outside the upper and lower tolerance limits given by DIN 13971. The smallest effective torque loss (4.5 degrees) resulted from the combination of the 0.022-inch SPEED System bracket with the 0.020x0.025-inch SPEED Wire small upper. The highest torque loss (11.7 degrees) was found with the 0.022-inch Damon 2 bracket and the 0.019x0.025-inch ECO Charge 1 archwire. CONCLUSION: The accuracy of the manufacturers dimension is not to be taken for granted. A perfect 'finishing' still requires correction bends put in by the orthodontist.

Kusy, R. P. and J. Q. Whitley (1999). "Assessment of second-order clear- ances between orthodontic archwires and bracket slots via the critical contact angle for binding." Angle Orthodontist **69**: 71-80.

Major, T. W., et al. (2010). "Orthodontic Bracket Manufacturing Tolerances and Dimensional Differences between Select Self-Ligating Brackets." Journal of Dental Biomechanics **2010**.

Margetts, D. (2016). General overview of the CNC milling process for stainless steel orthodontic brackets. M. Angeloni.

Meling T, et al. (1998). "A formula for the displacement of an arch wire when subjected to a second-order couple." Am. J. Orthod. Dentofac Orthopod **113**: 632-640.

Meling, T. R. and J. Odegaard (1998). "On the variability of cross-sectional dimensions and torsional properties of rectangular nickel-titanium arch wires." Am J Orthod Dentofacial Orthop **113**(5): 546-557.

> Twenty-five rectangular superelastic or conventional work-hardened nickel-titanium alloy wires, commonly used in the 0.018-inch edgewise technique, supplied by seven different manufacturers, along with one braided nickel-titanium and two beta-titanium wires, were studied with respect to wire dimensions, edge bevel, and mechanical properties in longitudinal torsion at 37 degrees C. The wires were twisted 25 degrees and studied in deactivation, simulating application of torque to an individual tooth. Standard Siamese brackets. with stated slot heights of 0.018 inches and measured slot heights of 0.0187 inches, were used. Most wires were within +/-0.0005 inches of the stated dimensions, but had more edge bevel than previously reported for stainless steel and chrome-cobalt alloy wires. Variations in wire dimensions and edge bevel led to variable torsional (third-order) clearance. The torsional stiffness varied among manufacturers within the various wire sizes, this being the result of differences in actual cross-sectional geometry and material properties. None of the tested wires exhibited superelastic properties under the current conditions, and only one wire had a superelastic tendency.

Meling, T. R., et al. (1997). "On mechanical properties of square and rectangular stainless steel wires tested in torsion." Am J Orthod Dentofacial Orthop **111**(3): 310-320.

> Forty different sizes and types of square and rectangular stainless steel wires, supplied by five different manufacturers, were tested in torsion. The study simulated the situation occurring when torque is applied to an individual tooth. We used standard brackets with 0.018-inch slot heights, with an interbracket distance of 4 mm. The results show that variation in cross-sectional dimension and edge bevel leads to variable torsional play (third-order clearance). As an example 0.016 x 0.022-inch wires have a mean torsional play of as much as 18.5 degrees, with a range of 16.6 degrees to 20.4 degrees. We have shown that when 0.016 x 0.022-inch wires are used, one must apply from 24.6 degrees to 29.2 degrees of twist to get 20 Nmm of torsional moment. This variation is mostly due to a rather wide range in torsional play. As a result, the prediction by which a predetermined torsional moment can be delivered becomes uncertain. The results show that because the working range in torsion of stainless steel wires is somewhat limited, precise delivery of torsional moment, based on the condition present in the oral cavity, is difficult. Torsional stiffness varies considerable within the various

dimensional groups, this being the result of variation in cross-sectional geometry and material properties.

Meling, T. R., et al. (1998). "On bracket slot height: a methodologic study." Am J Orthod Dentofacial Orthop **113**(4): 387-393.

Effective bracket slot height is estimated by using a formula that describes the relationship between bracket slot height, wire dimensions, wire edge bevel, and torsional play (third-order clearance). With a torque measuring instrument, the torsional play was estimated for 10 different brackets (0.018-inch stated slot) of the same manufacturer and type. One arch wire with known dimensions and edge bevel was used for all the measurements. With known torsional play, wire dimensions and edge bevel, the bracket slot height could be calculated. This was performed five times for each bracket and the method error for estimation of torsional play for a single measurement was 0.04 degrees, corresponding to 0.36 mm in slot height. The brackets tested had a mean slot height of 0.476 +/- 0.003 mm, with a range of 0.470 to 0.481 mm (0.0187 +/- 0.0001 inches, range 0.0185 to 0.0189). The variation in bracket slot height was much greater than the method error. The method used to measure bracket slot height seems to have a high degree of accuracy and is easier to implement than conventional methods.

Nguyen, Q. L., et al. (2013). "Mathematical Prediction of Torque Loss for Different Archwire Dimensions and Shapes in Different Bracket Slots
." Retrieved 2/3/16, 2016.

Reitan, K. (1951). "The initial tissue reaction incident to orthodontic tooth movement as related to the influence of function; an experimental histologic study on animal and human material." Acta Odontol Scand Suppl **6**: 1-240.

Sebanc, J., et al. (1984). "Variability of effective root torque as a function of edge bevel on orthodontic
arch wires." Am. J. Orthod. **86**(1): 43-51.

Siatkowski, R. E. (1999). "Loss of Anterior Torque Control Due to Variations in Bracket Slot and Archwire Dimensions." Journal of Clinical Orthodontics **33**(9): 508-510.

Zinelis, S., et al. (2005). "Metallurgical characterization of orthodontic brackets produced by Metal Injection Molding (MIM)." Angle Orthod **75**(6): 1024-1031.

The aim of this study was to investigate the bonding base surface morphology, alloy type, microstructure, and hardness of four types of orthodontic brackets produced by Metal Injection Molding technology (Discovery, Extremo, Freedom, and Topic). The bonding base morphology of the brackets was evaluated by scanning electron microscopy (SEM). Brackets from each manufacturer were embedded in epoxy resin, and after metallographic grinding, polishing and coating were analyzed by x-ray energy-dispersive spectroscopic (EDS) microanalysis to assess their elemental composition. Then, the brackets were subjected to metallographic etching to reveal their metallurgical structure. The same specimen surfaces were

repolished and used for Vickers microhardness measurements. The results were statistically analyzed with one-way analysis of variance and Student-Newman-Keuls multiple comparison test at the 0.05 level of significance. The findings of SEM observations showed a great variability in the base morphology design among the brackets tested. The x-ray EDS analysis demonstrated that each bracket was manufactured from different ferrous or Co-based alloys. Metallographic analysis showed the presence of a large grain size for the Discovery, Freedom, and Topic brackets and a much finer grain size for the Extremo bracket. Vickers hardness showed great variations among the brackets (Topic: 287 +/- 16, Freedom: 248 +/- 13, Discovery: 214 +/- 12, and Extremo: 154 +/- 9). The results of this study showed that there are significant differences in the base morphology, composition, microstructure, and microhardness among the brackets tested, which may anticipate significant clinical implications.