Atomic Layer Deposition Coatings on Orthodontic Archwires and Brackets: Resistance to Sliding, Coefficient of Friction, and Mechanical Testing

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Abstract

Objective: To measure the resistance to sliding, coefficient of friction and mechanical properties of atomic layer deposition (ALD) coatings on stainless steel archwires.

Materials and Methods: ALD-coated archwires and brackets were tested along with as-received archwires and brackets to make 4 different groups. A bracket was ligated and pulled parallel to the archwire and force measurements were made to test the resistance to sliding. Nanomechanical testing compared the coefficient of friction between as-received wires and the ALD-coated wires. A scratch test was performed to assess the adherence of the coating to stainless steel and look for signs of delamination. The elastic modulus and elastic limit were tested using a three-point flexure device. Data were analyzed using ANOVA and Student's T-test with $p \leq 0.05$.

Results: The ALD-coated wire and bracket combination had the lowest resistance to sliding and the as-received wire and bracket combination had the highest. The coefficient of friction of the coating was significantly lower than the wire surface and coatings did not delaminate during scratch testing. The elastic modulus of the ALD-coated wire did not differ significantly from the as-received wire.

Conclusions: The ALD-coated wire had lower resistance to sliding and a lower coefficient of friction. The ALD-coating did not significantly alter the elastic modulus of the wire and did not delaminate during nano-scratch testing.

INTRODUCTION

In orthodontics, three components to resistance to sliding (RS) have been recognized: classical friction, elastic binding, and plastic binding or physical notching.[1] Classical friction is a resistance to sliding as two objects move tangentially against each other.[2] With conventional orthodontic appliances, friction results from the interaction of the archwire and any material it contacts such as a bracket or ligation mechanism. This friction, consisting of an initial static zone and subsequently a lower force dynamic zone, forms only a partion of the resistance to movement as a bracket slides along an archwire. [3,4] In contrast, elastic binding is created when the tooth tips or the wire flexes such that there is increased contact between the archwire and the corners of the bracket slot. Plastic binding or physical notching is found when permanent deformation of the archwire takes place at the bracket corner interface. Tooth movement resumes only when the notch is released.[3,4]

Resistance to sliding due to the interaction between the bracket and the archwire adversely affect treatment outcomes and duration.[5,6,7] The portion of the applied force lost to overcome friction can range from 12% to 60%.[6] Decreasing RS reduces the amount of force needed to obtain optimal biological responses, resulting in more predictable and efficient tooth movement.[9,10]

A variety of coated archwires were previously tested in an attempt to reduce the RS, including Teflon;[2,11,12] diamond-like carbon coating (DLC);[13] and plasma immersion ion implantation.[14,15] While these have shown the capacity for reducting coefficients of friction, all have limitations. Teflon coated archwires have regions that peel off during masticatory function testing and thus significantly affect the mechanical properties.[16] Similarly, DLC coating is prone to plastic deformation, cracks and significant delamination.[17] With plasma immersion ion implantation, surface hardness of the wire increases,[18] and results in a higher roughness compared to uncoated samples, thus potentially leading to increased plaque retention.[19] A more ideal coating would reduce the coefficient of friction without delaminating or drastically changing the physical properties of the wire.

Our lab has been investigating a novel method of coating orthodontic archwires using atomic layer deposition or ALD. This is a thin film deposition technique that results in a highly uniform, conformal, pinhole-free coating of highly controllable thickness.[20] The method involves exposing archwires to gaseous precursors in a cyclic manner in order to grow a thin, uniform ceramic coating that is covalently bound to the underlying metal.[20] ALD surface coatings offer some advantages over other coating methods. These include, but are not limited to: accurate and simple thickness control; large area and large batch capability;excellent conformality; good reproducibility; low processing temperatures and the capability to prepare multilayer structures in a continuous process.[20] This unique coating has not been reported in orthodontic literature and only limited research has reported a reduction in friction.[21]

The purpose of this project was to test the hypothesis that this thin, durable coating process on stainless steel archwires and stainless steel brackets will decrease the resistance to sliding (RS) and friction as well as leave the modulus and elastic limit unchanged. We tested this hypothesis by using combinations of coated and uncoated wires and brackets and a mixture of micro and macro scale mechanical testing.

MATERIALS AND METHODS

Stainless steel archwires 0.019" x 0.025" (n=110; Opal Orthodontics, South Jordan, UT) and stainless steel upper premolar brackets with a slot dimension of 0.022" x 0.028" with -7° torque and 0° angulation (n=60; Avex MX, Opal Orthodontics) were provided by the manufacturer from their commercial supply. All archwires were from the same lot. The archwire dimension was chosen as it is a commonly-recommended size for sliding mechanics with an 0.022" appliance.[22] Ten wires and10 brackets were measured before and after the ALD coating process to verify uniform dimensions. The wires were measured with a Mitutoyo digital micrometer with 0.00005" resolution and 0.0001" accuracy.[23] Measurements were made bilaterally at the ends of each wire and also in the midline of the archwires. The cross-section of the bracket slots were imaged viewing the distal surface of the bracket using a Nikon VMR-3020 digital microscope and measured using Nikon VMR digital software. For each bracket, measurements of the height of the archwire slot were made at a distance of 0.0039", 0.0118", and 0.0196" from the base of the wire slot.

ALD Coating

Forty-five stainless steel archwires (cut to a length of 5.5") and 30 brackets were randomly selected. To remove potential surface contaminants, the wires and brackets were ultrasonically cleaned using in sequence acetone, isopropyl alcohol and deionized water before being dried in an oven for 5min at 130°C.

The coating process was performed in a Picosun Sunale R-150B (Picosun, Detroit, MI) atomic layer deposition unit. Wires were supported at their ends to allow uniform deposition along the central region of the wires. Wires were coated with a film of approximately 200 nm Al_2O_3 by reaction of Trimethylaluminum (TMA) and water at 200 °C for 7 hours. Silicon wafers coated alongside the wires and brackets were used to measure the coating thickness by ellipsometry (VASE, J. A Woollam, Lincoln, NE). The thickness of the coatings ranged from 187 nm to 202 nm. Fifteen additional wires underwent the ALD thermal process without receiving a coating to act as thermal processing controls for the coated wires.

Resistance to Sliding

Thirty coated wires and 30 as-received wires (length of 5.5") and 30 coated brackets and 30 as-received brackets were tested, based on a pilot study and power analysis performed prior to this project to determine sample size. Test groups are listed in Table 1. Before testing, the uncoated wires were cleaned and dried following the same protocol as used with the coated wires.

A custom-fabricated friction-testing device, based on that described by Hain,[23] was used to record the force necessary to move the bracket along the archwire (Fig. 2). The lower end of each test unit was attached to a heavy base block on the lower crosshead of the testing machine through a hollow screw. This allowed the wire to freely rotate. The upper attachment apparatus had a soldered wire attached to a free-spinning washer around the load cell attachment. This configuration eliminated the introduction of torque between the archwire and bracket during testing.[24]

The brackets were ligated to the archwire with grey elastomeric ligatures (3M Unitek, Monrovia, CA) 25 mm from the end of the wire. The archwire was insterted into the hollow screw and a 2mm right angle bend was placed. The 0.018" stainless steel wire was attached to the bracket base in a passive configuration.

Testing was performed on an MTS Q Test (MTS Systems, Eden Prarie, MN) with a crosshead speed of 5 mm/min over a 5 cm span.[25] All testing was done by the same experimenter. The bracket was pulled with a force parallel to the archwire. The force required to initiate (static resistance) and continue movement (dynamic resistance) of the bracket was recorded 255 times per minute for the first 12 mm and 40 times per minute thereafter. Static resistance was defined as the highest force experienced during the initial stages and dynamic resistance was the average value across the range from 2.5 cm to 5 cm from the starting point (Fig. 3).

Coefficient of Friction

Nanomechanical scratch testing was performed to determine the coefficient of friction and to test the interaction of the coating with the substrate. The coefficient of friction testing analyzed the surface of the coating and did not penetrate into the substrate. In this way the coefficient of friction between the coating and a common standard material, in this case a diamond tip, was assessed. ALD-coated and as-received archwires were tested using an UBI-1 nanomechanical testing system (Hysitron Inc., Minneapolis, MN). Twelve tests were performed on each group. A constant normal force of 1 mN was applied to the sample and the tip was moved 16 μm along the sample at a rate of 0.5 μm/sec. The normal force, the resistance to the lateral force, and lateral displacement were measured and used to calculate the coefficient of friction as the ratio between the resistance to the lateral force and the normal force.[26]

Scratch Test

Stainless steel sheets were cut into 15.5 mm disks and were coated with 200nm thick Al_2O_3 coating as described above. Disks were used, rather than wires, to allow for a larger surface area for scratch testing. Coated disks were tested with the UBI-1 nanomechanical testing system. Ten scratches were performed. A normal force starting at 0 mN was increased to 3 mN while advancing at a constant rate of 0.5 μm/sec for 16 μm. Scanning probe microscopy (SPM) was performed using the UBI-1 nanomechanical testing system to image the surface after scratch testing and to look at the substrate/coating interface for signs of delamination.

Modulus and Elastic Limit

A 3-point flexure test was performed to measure the elastic modulus and elastic limit of the arch-wires.[27] Coated and as-received wires with a length of 4 inches were placed on a custom fabricated two point 10 mm span flexure apparatus with round ends (Fig. 4). The load was placed using a pin with a ball point that was permitted to roll. Testing was performed on the MTS Q Test with a crosshead speed of 3 mm/min over a 5 mm vertical span.[28] Data was collected every 0.00625 mm and plotted with load versus distance traveled to create a load/distance curve. The elastic modulus was defined as a line tangent to the initial, linear elastic portion of the load/distance curve.[29] The elastic limit was defined where the slope of the tangent to the initial curve changed and began to level (Fig. 5).[29] Additional 3-point tests were performed on wires that were subjected to the ALD thermal process alone to separate the effects of the ALD thermal treatment on the physical properties of the coated wires.

Statistical analysis

A Student's paired t-test was used to examine the differences between dimensions of the as-received and coated wires and brackets. The RS of the coated and as-received wire and bracket combinations were analyzed using ANOVA and a Tukey post-hoc with a 5% level of significance. A Student's t-test was used to analyze differences in the coefficient of friction between the ALD-coated and as-received wires. Wires were also optically examined for evidence of delamination. The elastic modulus and elastic limit of the coated, as-received and thermal treated wires were analyzed using ANOVA.

RESULTS

Wire and Bracket Dimensions

The as-received wire and coated wire dimensions and the as-received bracket and coated bracket dimensions $p<.001$ were not statistically different to 0.01mm.[27]

Resistance to Sliding

Results of the comparisons of the four groups consisting of combinations of coated or as-received with coated or as-received brackets are shown in Table 2 and Figure 6. Table 2 compares the means and standard deviations of the static resistance and dynamic resistance. The ANOVA test revealed significant differences between group 1, group 3 and group 4($p<.05$). The static and dynamic resistance means between the combination without any coating group 1 and the combination of the as-received wire and coated bracket group 2 was not statistically different. ($p=.16$) The combination with both devices coated group 4 had the lowest static and dynamic resistance to sliding means while the combination without any coating group 1 had the highest resistance to sliding.

Coefficient of Friction

The mean value of the coefficient of friction (Fig. 7) for the as-received wires (0.226 ± 0.027) was significantly different from the coefficient of friction for the coating (0.101 ± 0.015; $p<0.0001$).

Scratch Resistance

Images following scratch testing showed no signs of delamination occurring between the coating and the wire substrate.

Modulus and Elastic Limit

The analysis of the 3-point flexure test demonstrated that the elastic modulus of the coated wire did not differ from the as-received wire ($p=.27$). The elastic limit, however, was statistically different ($p<.0001$) between the coated and as-received wires where the elastic limit for the coated wires was higher. The elastic limit for the wires that were heat treated only were not statistically different from the coated wires ($p=.55$; see Table 3, Figs. 8, 9).

DISCUSSION

A reduction in the resistance to sliding during space closure with sliding mechanics would be a tremendous benefit to the field of orthodontics. Many other coatings have been used to reduce RS. Unfortunately, these coatings have unwanted side effects including peeling or delamination of the coating, change in the modulus of the underlying substrate and an increased roughness of the wire. [16,17,18] A more ideal coating would be able to reduce RS while maintaining the original physical properties of the wire and without delaminating. Our study showed that the ALD coatings were able to reduce RS while maintaining the original physical properties of the wire and without delamination.

The ALD coatings reduced the RS in our system. The RS with the as-received combination, group 1, was 132.85g, which is comparable to previous research.[13] The RS of the coated combination, group 4, was 71.62g which is a 48% reduction in RS. This result is comparable to other coatings that have shown a reduction in RS. Teflon coatings, ion implantation and diamond-like carbon coating have shown frictional losses of 0-45.9%.[12,13,14] This comparison would certainly place ALD coatings as one of the more efficient coatings for reducing RS.

The lower RS from the coated combination could be the result of various factors. An increased hardness has been shown to reduce RS. [5,30] The main contributor to the reduction in RS with the diamond-like carbon coating is it's increased hardness.[13] ALD coatings have been shown to have higher hardness values than stainless steel and could be a contributing factor in the reduction of RS with the ALD coating.[31,32] Another contributor is the roughness of the material. Kusy found that reducing the roughness of the stainless steel wire reduced friction.[33] ALD has been shown to reduce asperities and therefore reduce the roughness of a material.[34] A final contributor is a reduction in the coefficient of friction. Our study also demonstrated a lower coefficient of friction which could also contribute to the reduction in RS.

Our analyses of the RS shows that a key to the reduction of static and dynamic RS is the ALD-coated wire. Coating the bracket alone, group 2, did not differ significantly from the as-received combination whereas coating only the, group 3, wire did provide lower RS values. In theory group 2 and group 3 should not be statistically different. The difference could be the result of the interaction between the ligature and the coated wire in group 3. In group 2 the ligature interacted with the as-received wire and that could have resulted in a higher RS. Therefore, the ALD coating of the archwire is a key in reducing RS with these materials.

It is also interesting to note that the static resistance of the coated wire and bracket combination was significantly lower than both the static and the dynamic resistance of the uncoated pair. Orthodontics is mainly concerned with static friction as teeth do not move in a dynamic manner. This phenomenon could also be used in other fields where a significant reduction in static and kinetic resistance is crucial.

Previous studies have analyzed variables that can affect RS where most of these have attempted to use laboratory models that do not replicate actual tooth movement. Burrow[4], in a review article, concluded that the tooth's resistance to being moved contributes to resistance to sliding, particularly when bodily movement, rather than tipping is desired. During bodily movement, elastic binding and plastic notching contribute to a releasing phenomenon. It is this phenomenon that is the major determinant of how well bracketed teeth move along an archwire.[4] The laboratory model we used was based on Hain's experiment[23] with the addition of an upper attachment that was allowed to freely rotate. This model adheres to Burrows suggestion in that it permits the bracket to undergo a binding and releasing phenomenon and therefore more closely simulates actual tooth movement during sliding mechanics. The data therefore is more relevant to actual clinical practice than a mere analyses of the coefficient of friction. We also ensured consistency of the slot measurements and wire size before and after the coating to reduce the effects of slot size on the reduction of friction.[30]

We chose to use a dry field as opposed to a simulated wet field with either artificial saliva or saliva. This was done as previous research has shown conflicting evidence[36] and to reduce extra variables in our experiment.

The coefficient of friction was also reduced 55% from 0.226 to 0.101. This reduction in the coefficient of friction is comparable to previous research with ALD coatings[37], Many methods have been used to determine the coefficient of friction in the field of orthodontics resulting in various and often inaccurate assessments.[4] We have proposed a reproducible method of determining the coefficient of friction between two surfaces using a nanomechanical testing system. Friction should be calculated between the substrate and one other material with known physical properties. The diamond tip used in nanomechanical testing has well-known physical properties and therefore can be used to compare unknown substrates. The system we used was void of ligation and other variables that can lead to inaccurate results. We also analyzed the coefficient of friction at a material level as opposed to a macromechanical level, thereby permitting the effects of the coating to be directly measured. We propose that this novel method can be used as a universal method to analyze and provide a comparable value for the coefficient of friction of orthodontic materials.

Our study also determined that the ALD coating did not delaminate from the orthodontic wire even after the diamond tip of the nanomechanical test penetrated to a depth that exceeded the coating thickness. This demonstrates that the ALD coating is firmly attached to the wire substrate through covalent bonding. This is a great advantage over other low friction coatings that are prone to delamination and peeling such as Teflon and diamond-like carbon coating.[16,17] This finding also suggests a high wear resistance. Previous research in our lab determined that the ALD coating has a high wear resistance and reduced the wear of a stainless steel substrate by up to 74%[38], and studies have been planned for performance in a clinical orthodontic setting.

The elastic modulus of the coated and as-received wires was not statistically different. The very thin coating did not affect the stiffness of the wire. This is important as many orthodontic systems are based on the stiffness of the stainless steel wire.[22] However, the coated wires did have a higher elastic limit and therefore a greater working range. The coated wires had an elastic modulus and an elastic limit that was the same as the heat treated wires. This is consistent with previous research that concluded that an increased yield strength is the most significant effect of heat treatment.[39] The increase in the elastic limit can be attributed to the heat treatment during the ALD coating. This increase in the working range is a potential side benefit of the ALD coating process.

In summary, the findings of our research have shown that the ALD coating reduces the resistance to sliding and the coefficient of friction, and did not delaminate from the wire. The modulus was unaffected while the working range increased. These findings show there is great potential for the implementation of ALD coatings in the field of orthodontics. Although the test results are promising, future *in-vivo* research will need to be performed to evaluate the clinical effects of ALD coating.

- ALD coatings reduce the resistance to sliding
- ALD coatings reduce the coefficient of friction
- The ALD coating does not delaminate from the archwire
- The ALD coating process does not change the modulus of the orthodontic archwire at a 200nm thickness
- The ALD coating process increases the elastic limit similar to a heat treated wire

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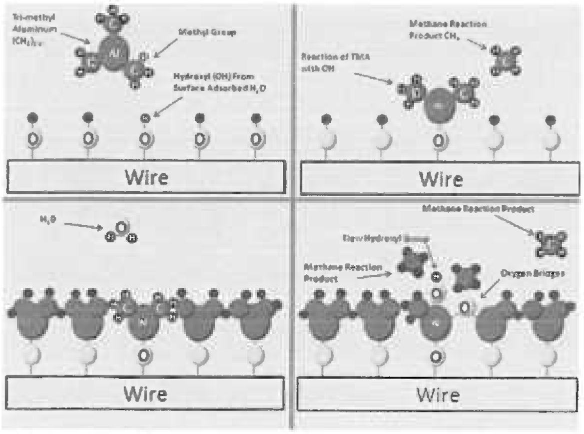

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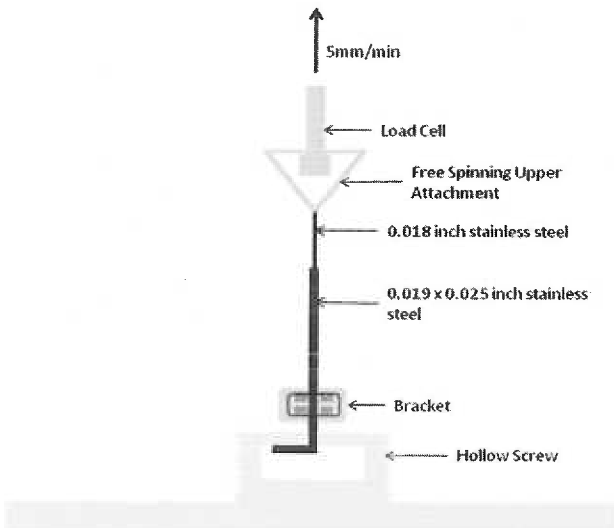
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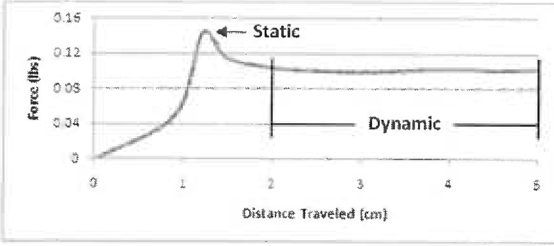
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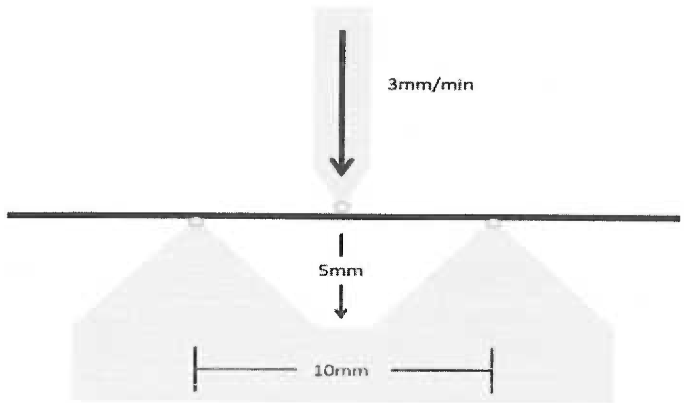
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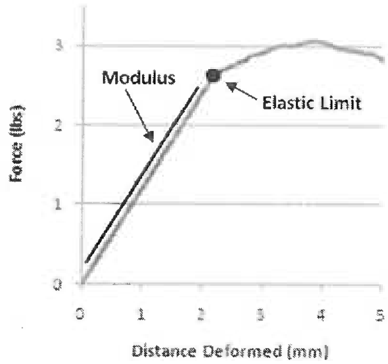
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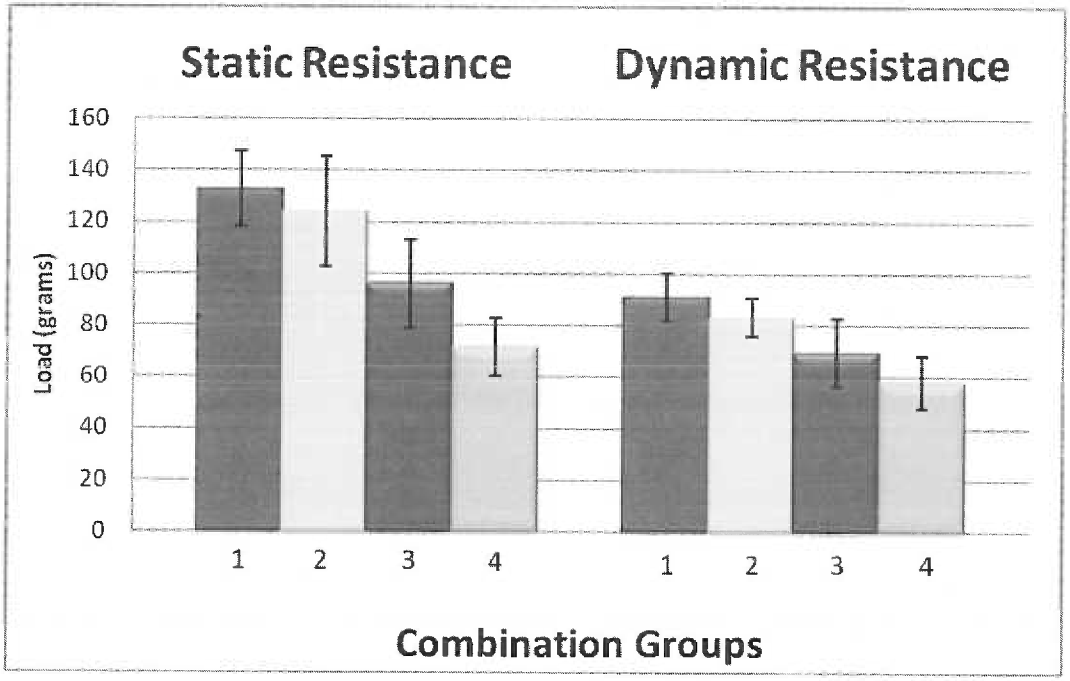
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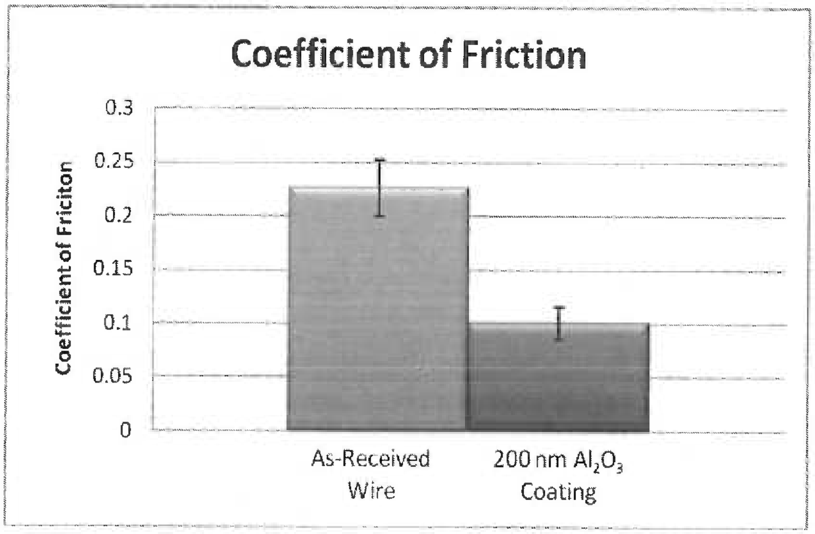
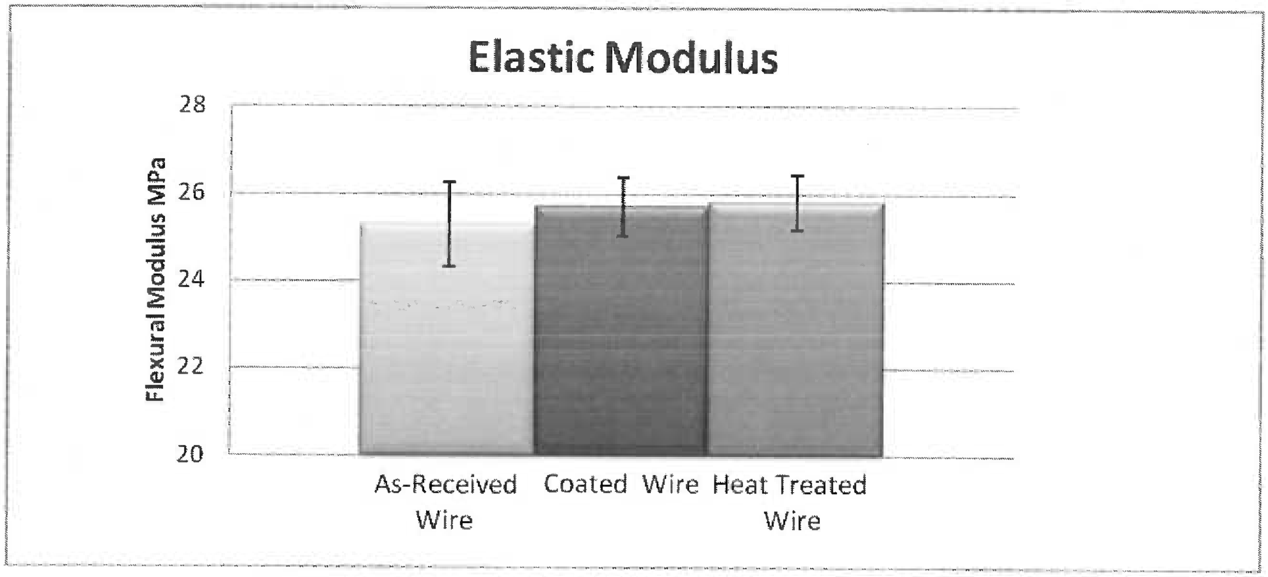
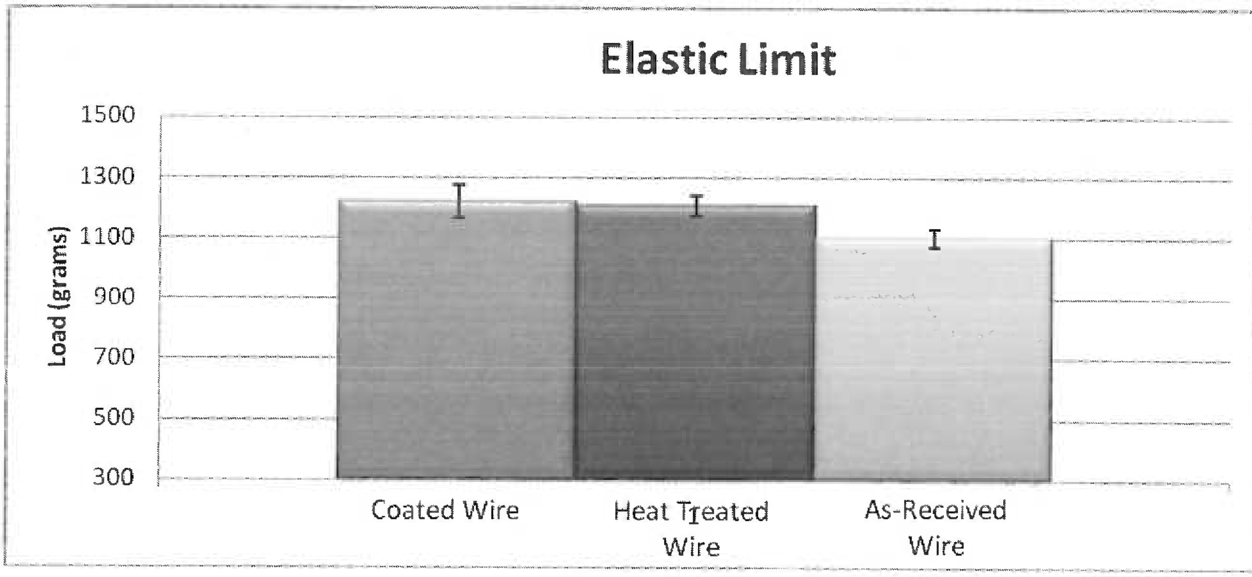
4
Combination Groups


Coefficient of Friction
Coefficient of Friciton
0.3
0.25
0.2
0.15
0.1
0.05
0
As-Received Wire
200 nm Al_2O_3 Coating


Elastic Modulus
Flexural Modulus MPa
28
26
24
22
20
As-Received Wire
Coated Wire
Heat Treated Wire



Elastic Limit
1500
1300
1100
900
700
500
300
Load (grams)
Coated Wire
Heat Treated Wire
As-Received Wire

LIST OF TABLES

Table 1		
Wire and Bracket Combinations for RS Testing		
Groups	***Condition of Wire***	***Condition of Bracket***
Group 1	*As-Received Wire (ARW)*	*As-Received Bracket (ARB)*
Group 2	*As-Received Wire (ARW)*	*Coated Bracket (CB)*
Group 3	*Coated Wire (CW)*	*As-Received Bracket (ARB)*
Group 4	*Coated Wire (CW)*	*Coated Bracket (CB)*

Table 2					
Resistance to Sliding Results					
No	Group	Variable	Mean (grams)	Variable	Mean (grams)
1	ARW ARB	Static	132.85 (14.59)	Dynamic	91.0 (9.12)
2	ARW CB	Static	123.99 (21.24)	Dynamic	83.12 (7.45)
3	CW ARB	Static	96.2 (17.16)	Dynamic	69.48 (13.25)
4	CWCB	Static	71.62 (11.3)	Dynamic	58.23 (9.95)

Table 3			
Flexural Modulus and Elastic Limit			
	Coated Wire	**Heat Treated Wire**	**As-Received Wire**
Flexural Modulus			
Mean	25.7MPa	25.8MPa	25.3MPa
SD	$0.61e^6$	$0.56e^6$	$0.88e^6$
Elastic Limit			
Mean	1220.7 grams	1209.6 grams	1102.63 grams
SD	55.2	34.8	28.4

Literature Review

RESISTANCE TO SLIDING

In orthodontics, there are three components to resistance to sliding: classical friction, elastic binding and plastic binding or physical notching.[1] Kusy and Whitley[2] further defined these three components.

Friction

Friction is a resistance to sliding as two objects move tangentially against another.[3] In orthodontic tooth movement with conventional appliances, friction results from the interaction of the archwire and any material it contacts such as the orthodontic bracket or a ligature. It is not a fundamental force but occurs because of the electromagnetic forces between charged particles which constitute the surfaces in contact. Because of the complexity of these interactions friction cannot be calculated from first principles, but instead must be found empirically.[4] Friction can be divided into two categories, static and dynamic.

Static Friction

Static friction is friction between two solid objects that are not moving relative to each other. The static friction force must be overcome by an applied force before an object can move. The maximum possible friction force between two surfaces before sliding begins is the product of the coefficient of static friction and the normal force: $f = \mu_s F_n$. When there is no sliding occurring, the friction force can have any value from zero up to F_{max}. Any force smaller than F_{max} attempting to slide one surface over the other is opposed by a frictional force of equal magnitude and opposite direction. Any force larger than F_{max} overcomes the force of static friction and causes sliding to occur. The instant sliding occurs, static friction is no longer applicable—the friction between the two surfaces is then called kinetic friction.[4]

Kinetic Friction

Kinetic (or dynamic) friction occurs when two objects are moving relative to each other and rub together (like a sled on the ground). The coefficient of kinetic friction is usually less than the coefficient of static friction for the same materials.[5] Kinetic friction is now understood, in many cases, to be primarily caused by chemical bonding between the surfaces, rather than interlocking asperities;[6] however, in many other cases roughness effects are dominant, for example in rubber to road friction.[7] Surface roughness and contact area, however, do affect kinetic friction for micro- and nano-scale objects where surface area forces dominate inertial forces.[4]

Coefficient of Friction

The 'coefficient of friction' (COF), also known as a 'frictional coefficient' or 'friction coefficient' and symbolized by the Greek letter μ, is a dimensionless scalar value which describes the ratio of the force of friction between two bodies and the force pressing them together. The coefficient of friction depends on the materials used. For instance, a large aluminum block has the same coefficient of friction as a small aluminum block. However, the magnitude of the friction force itself depends on the normal force, and hence the mass of the block.[4]

For surfaces at rest relative to each other $\mu = \mu_s$, where μ_s is the coefficient of static friction. This is usually larger than its kinetic counterpart.

For surfaces in relative motion $\mu = \mu_k$, where μ_k is the coefficient of kinetic friction. The Coulomb friction is equal to F_f, and the frictional force on each surface is exerted in the direction opposite to its motion relative to the other surface.[4]

Rougher surfaces tend to have higher effective values. Both static and kinetic coefficients of friction depend on the pair of surfaces in contact; for a given pair of surfaces, the coefficient of static friction is usually larger than that of kinetic friction; in some sets the two coefficients are equal, such as teflon-on-teflon.[4]

While it is often stated that the COF is a "material property," it is better categorized as a "system property." Unlike true material properties (such as conductivity, dielectric constant, yield strength), the COF for any two materials depends on system variables like temperature, velocity, atmosphere and also what are now popularly described as aging and deaging times; as well as on geometric properties of the interface between the materials.[4]

Friction is only a part, and usually a small part, of the resistance to movement as a bracket slides along an archwire.[8]

Binding

Binding is created when the tooth tips or the wire flexes so that there is contact between the wire and the corners of the bracket.[2]

Notching

Notching occurs when permanent deformation of the wire occurs at the wire-bracket corner interface. Tooth movement stops when a notched wire catches on the bracket corner and resumes only when the notch is released. Binding and notching account for most of the resistance to sliding.[8, 9]

Effects on Orthodontic Treatment

High frictional forces due to the interaction between the bracket and the archwire adversely affect treatment outcomes and duration.[10,11,12] Up to 60% of the orthodontic forces applied to a tooth are used to overpower friction resistance.[10] Controlling frictional resistance can reduce the applied force during orthodontic treatment to obtain an optimal biological response for effective tooth movement.[13,14]

The contributions of friction, binding, and notching to resistance to sliding can be understood best by considering the 3 stages in the active phase of moving teeth.

1. The first is the early stage of sliding as the tooth tips and contact of the wire with the corner of the bracket begins to occur; both friction and binding contribute to resistance to sliding.

2. In stage 2, the contact angle increases between the bracket and the wire, when binding is the major source of resistance and friction becomes inconsequential.

3. In stage 3, if the contact angle becomes steep enough, notching of the wire occurs, and both friction and binding become negligible. In clinical treatment, tooth movement stops from notching, until elastic deformation of the wire occurs as bone remodeling and bone bending during mastication displace the teeth, and the notch is released from contact with the bracket. Further permanent deformation of the wire (another notch) is likely to occur from contact with the corner of the bracket after the first notch is released.**Error! Bookmark not defined.**

A series of studies in the late Robert Kusy's laboratory established the basis for binding and notching as the primary components of resistance to sliding. Articolo and Kusy[9] studied resistance to sliding as a function of 5 angulations of .021 3 .025-in steel, nickel-titanium, and beta-titanium alloy wire to conventionally ligated edgewise brackets (0°, 3°, 7°, 11°, and 13°), using various combinations of archwires and brackets. They noted that the binding influence became greater as the wire-bracket angulation increased. With a 7° angulation, the binding made up 80% of the resistance to sliding; when the angle was increased to 13°, binding produced 99% of the resistance to sliding, and friction was not an influence.[8]

Mechanisms Used to Reduce Friction

Friction during clinical tooth movement depends on the size and shape of the wire, [15] the bracket type,[16,17] the bracket and wire materials,[18] the angulation of the wire relative to the bracket,[19] the type of ligation,[9] surface roughness[20] and whether the environment is wet or dry.[21]

Size and Shape of Wire

It has been shown that smaller wires produce less friction because of the resulting additional space in the slot and their greater elasticity.[22] Kusy and Whitley[23] described the effects of wire size on friction by describing the critical contact angle between the wire and bracket slot. They have found that the amount of friction significantly increases at the critical contact. Larger wires will have a smaller critical angle. The smaller the critical angle the more frequently the critical contact will affect friction. Therefore, a larger the wire will generate more friction.

Archwires come in two typical configurations; round and rectangular. Several studies show that rectangular wires produce greater friction than round wires in certain circumstances.[24,25] Drescher et al.[24] found that the occluso-gingival dimension of the wire was the most critical dimension affecting friction. They found that a 0.016 round stainless steel wire produced the same amount of friction as a 0.016 x 0.022 stainless steel wire.

Self-Ligation

Thorstenson and Kusy[26, 27] compared a series of self-ligating brackets with conventionally ligated brackets in a similar but more extensive way, studying the effect of friction to binding on resistance to sliding in a steadystate laboratory model under both dry and wet (saliva) conditions. They reported that, with both conventional and self-ligating brackets, binding also increased as the wire-bracket angulation increased. When the bracket was held steady the resistance to sliding was lower for all the self-ligating brackets than for a conventional bracket tied in with a wire or an elastomeric ligature, and lower for brackets with a passive clip than an active one.[28] This condition never occurs clinically, however. Unless the bracket is held steady as it moves along the archwire (which cannot be done under clinical conditions), it tips relative to the wire when a force is applied to move it. As soon as the corners of the bracket contact the wire, binding occurs, and this contributes most of the resistance to sliding. Data was collected for binding using the same brackets and the researchers concluded that "binding does not appear to be affected by the ligation method"; ie, binding is similar with conventional and self-ligating brackets. 8, 28

Several clinical studies have investigated this. In a prospective clinical trial with 54 subjects who had nonextraction treatment, Pandis et al[29] investigated the time needed to correct mandibular crowding with conventional vs Damon2 self-ligating brackets. They concluded that "there was no difference in the time required to correct mandibular crowding between self-ligating Damon2 and conventional edgewise brackets." In a similar study, Miles et al[30] concluded that the Damon2 bracket "was no more effective at reducing irregularity than the conventional twin bracket with elastometric ligation." Miles[31] also did a limited clinical trial comparing SmartClip to conventional brackets, with the same conclusion.[8]

Bracket Materials

Stainless steel has been one of the most popular material in orthodontics. New "esthetic" brackets have been developed as the demand has increased. Because these materials have different coefficients of friction than stainless steel it is important to assess how these different bracket materials can affect friction. Pratten et al.[32] compared the frictional resistance of two ceramic brackets, Transcend (Unitek; 3M, Monrovia, CA) and Allure (GAC International; Central Islip, NY) with stainless steel brackets. They found that both ceramic brackets produced nearly twice as much friction compared to the stainless steel brackets. Similarly, several other studies support the conclusion that frictional resistance is significantly higher in ceramic brackets in any wire sizealloy combination.[33,34] To overcome the increased friction of ceramic brackets some manufacturers have inserted a stainless steel slot into the ceramic bracket in order to reduce friction. Loftus et al.[35] compared ceramic brackets (Transcend, 3M Unitek, Monrovia, CA), ceramic brackets with a stainless steel slot (Clarity, 3M Unitek, Monrovia, CA), and stainless steel brackets (Victory, 3M Unitek, Monrovia, CA; Damon SL, A-Company, San Diego, CA) to assess how the addition of a stainless steel slot affects friction. They found that the ceramic brackets produced significantly more friction than both the ceramic bracket with the stainless steel slot and the stainless steel bracket. No significant difference was found between the stainless steel brackets and the ceramic bracket with a stainless steel slot.

Ligation

Friction can also vary depending on the type of ligation used. Frank and Nikolai compared the two ligation mechanisms and found that frictional resistance increased as the ligature applies greater force to the wire.[36] They found that there was an insignificant difference between elastomeric ligation and a stainless steel ligature tied with a force of 225 grams. Khambay et al.[37] tested elastomeric ligation and stainless steel ligation to determine their differences in tension, seating force, and their contribution to frictional resistance. It was found that all the elastomeric ligatures had significantly different frictional resistance values and did not correspond with the archwire seating force levels. Stainless steel ligatures produced the greatest amount of archwire seating yet had the least amount of frictional resistance. The authors concluded the surface characteristics of the ligatures may play a greater role than the force of ligation.

Archwire Surface Texture

The basic laws of friction state that friction is independent of the surface area between the two objects in contact. Yet studies evaluate the effect of surface roughness on friction. It has been shown via laser spectroscopy that different archwire alloys have significantly different surface textures.[38] Stainless steel appears the smoothest, followed by Elgiloy, TMA, and NiTi. Kusy evaluated these wires and found that the surface roughness of the stainless steel had very little effect on the coefficient of friction and it was concluded that surface roughness does not affect friction.[39] This is a finding that agrees with the classical laws of friction.

Saliva

Many of the in vitro studies assessing friction are done under dry conditions and do not fully recreate the clinical situation. To address this, some studies have introduced human saliva or artificial saliva to assess their effect on friction. Baker et al.[40] measured the static frictional resistance of several stainless steel wires as they were drawn through an edgewise bracket under three conditions: dry brackets, brackets bathed in artificial saliva (glycerin), and brackets bathed in human saliva. They found no significant reduction in friction with the artificial saliva, but did find that human saliva significantly reduced the static frictional force by 16.5%. Other studies provide evidence that the presence of fluid media can affect the amount of friction generated as a wire slides across an orthodontic bracket.[41] As for human saliva, there is conflicting evidence as to the effectiveness of human saliva as a lubricant to reduce orthodontic friction.[42]

ATOMIC LAYER DEPOSITION

Coatings

Coated archwires to reduce RS are becoming increasingly popular in orthodontics. Many types of archwires have been coated to try and reduce the coefficient of friction including Teflon,**Error! Bookmark not defined.**,[43,44] diamond-like carbon coating (DLC)[45] and plasma immersion ion implantation.[46,47] All coating methods have shown a reduction in the coefficient of friction. Unfortunately the Teflon coated archwires have regions that peel off during masticatory function testing and it affects the mechanical properties drastically.[48] Although the (DLC) coating also demonstrated a reduction in the resistance to sliding by reducing binding and notching, it is prone to plastic deformation, cracks and significant delamination.[49] Plasma immersion ion implantation increases the hardness of the material[50] and resulted in a higher roughness compared to uncoated samples.[51]

Atomic Layer Deposition

ALD is a thin film deposition technique that deposits a highly uniform, conformal, pinhole-free coating of highly controllable thickness. This is accomplished by exposing the wire to gaseous precursors repeatedly in order to grow a thin uniform coating that is covalently bound to the underlying metal. ALD surface coatings have not been reported in the application of orthodontics nor for the reduction of friction.

ALD surface coatings offer some advantages. These unique advantages include, but are not limited to, accurate and simple thickness control, large area and large batch capability, excellent conformality, good reproducibility, capability to produce sharp interfaces and superlattices, low processing temperatures and the capability to prepare multilayer structures in a continuous process. [52] ALD also has increases the hardness of the material.[53] Articolo and Kusy[5] found that harder materials had a lower RS in a passive configuration and a very high RS when the bracket was tipped. They also found that sliding efficiency appeared to be greater in couples made of a hard wire in a relatively softer bracket; and smoother materials performed better than rougher materials. Although studies have been performed testing the hardness of ALD coating and stainless steel materials, none have used the same testing method to be able to compare. Future studies should be performed to analyze the difference.

ALD Process

The film growth occurs in a cyclic manner. A brief overview shows that there are four steps in one cycle: (1) exposure of the first precursor, (2) purge or evacuation of the reaction chamber, (3) exposure of the second precursor and (4) purge or evacuation. The cycle is repeated as many times as is necessary to create a desired thickness of the coating.[52]

An example of this process would be to react Al_2O_3 with a substrate. The first precursor, water vapor is added to the chamber. The water vapor reacts with the substrate to form hydroxyl groups at the surface. Tri-methyl aluminum is added to the chamber and reacts with the hydroxyl groups and releases methane as a bi-product. Excess tri-methyl aluminum and methane are evacuated from the chamber and water vapor is added again. H_2O reacts to form (Al-O) bridges and hydroxyl groups that can react with the next pulse of tri-methyl aluminum. One H_2O pulse and one tri-methyl aluminum form one cycle.

ALD Uses

Atomic Layer Deposition has many different application due to it's ultrathin and conformal film structure. Different reactants are used for different applications. Metal nitrides are used in wear-resistant coatings, diffusion barriers and as superconductors.

Metal oxides provide a coating against corrosion and act as diffusion barriers, gas sensors, capacitors for integrated circuits and thin films for optics. Metals are used as electrical conductors, nucleation and adhesion layers, metallization in integrated circuits. Metal sulfides are used in light emitting materials.[54]

FUTURE RESEARCH

Results from this study are promising. Continued opportunities to expand the function of ALD coatings in the field of orthodontics are great. The following is a list of future research opportunities:

1) Various ALD coating thicknesses could be evaluated. This would determine at what thickness level the coating would affect the physical properties and what thickness is ideal to protect against wear.

2) The coating could be evaluated with a pigmented layer. Using the same material and methods this could evaluate the potential of using ALD coatings to create esthetics wires.

3) A ion solubility test could be performed. The ALD coating shows promise in the field of corrosion and a study could investigate the ion permeability of the coating at rest, under flexure and after a plastic deformation of the wire has occurred.

4) Different ALD coatings could be studied. There are several different types of ALD coatings including metal, metal oxides, metal sulfides and metal nitrides. Each could be examined to determine the beneficial effects in the field of orthodontics.

5) A clinical study could be performed to analyze the effectiveness of the ALD coating during space closure. This would allow for an in-vivo experiment to evaluate the in-vitro findings.

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