Surface Roughness and Sliding Mechanics of Aesthetic Composites Brackets and Archwires: SEM-Profilometry Study

Sarder Sadique

Arthur Weisberg Family Applied Engineering Complex, Marshall University
One John Marshall Drive, Huntington, WV 25755-2586
sadique@marshall.edu

Abstract - **The purpose of this biomechanical study is to evaluate the surface topography (ST), surface roughness (SR), and hardness of available brackets/archwires including developed aesthetic polymer matrix composites (PMC) archwire and bracket (braided). Those are important determinants for the effectiveness of archwire-guided tooth movement. The present study characterizes and compares stainless steel (SS) & developed PMC archwires and SS, ceramics, composite & developed PMC brackets for ST, SR and hardness with respect to (w.r.t.) frictional force. Archwires are slid against the slots (contact flats) of brackets in tensile tester. Statistical analysis is performed with confidence level (p < 0.05) for frictional force & SR and hardness of SS archwires are analyzed as well. Detailed wear studied were performed by SEM. The roughness average (R_a) and correlation coefficient (r) are expressed as the mean. Significant positive correlations (p < 0.05) are observed. Identical hardness (580-600 kg/mm^2) of SS archwires for different shapes are recorded except composite archwire. SEM results show that the ST of brackets and archwires varies among as-received and after sliding. Transcend (PCA) is the roughest brackets while the SS (SRO-AW) and aesthetic PMC archwires are the roughest archwires.**

Keywords— *Biomechanics (sliding), Aesthetic PMC Composites, Surface Roughness, Surface topography, Surface hardness.*

1. Introduction

Brackets and archwires are the most important parts or appliances commonly used in orthodontic treatment. The ability of orthodontic archwires to slide through brackets slots is essential for a successful orthodontic movement [1]. This is directly related to the sliding resistance, which contributes to sliding mechanism, when two materials touching one another share a contact area tangentially - cause friction, between the bracket slots and archwire [2].

The effects of forces applied by orthodontic treatment appliances are reduced friction that is orthodontist's great concern. Indeed there is a need for increased force and greater anchorage [3]. The maximum force and level of frictional force following the initiation of motion are highly dependent on the relative roughness of the contacting surfaces and the magnitude of the normal force component. Minimizing the frictional force that opposes the instantiation and maintenance of tooth movement will provide a more efficient and reproducible mechanical system [4].

The surface roughness (an indication of surface irregularity measured by the root-mean square (rms) of the surface variations), hardness of orthodontic appliances as well as sliding mechanics are the essential factors determine the effectiveness of archwire-guided tooth movement, surface contact and friction, biocompatibility, aesthetics of archwires and brackets [5]. Enhancing the contact area between the bracket and the archwire due to higher surface roughness can increase frictional forces which, in turn, reduce the orthodontic force by 50% or more thereby the quality of orthodontic treatment diminishing [6]. Considering the fact that surface roughness affects frictional forces, [7] the assessment of surface topography of archwires manufactured is clinically important in terms of both safety and quality of orthodontic treatments.

The surface roughness of orthodontic brackets and archwires have been evaluated previously on popular brands of brackets & archwires. This may prompt orthodontist to use more economical products approximately 5 to 10 times less expensive than the former (renowned companies).

Therefore, assessing the surface roughness of newly introduced and more economical archwires are of great importance and this characteristic is an essential factor influencing the effectiveness of arch-guided tooth movement [8] and also contributes to the biocompatibility and aesthetics of orthodontic appliances. The more commonly used archwire-bracket combinations are investigated by several researches and have focused on their performance. Sometimes potential factors e.g. surface roughness, hardness, stiffness, yield strength, and relative velocity, are acknowledged [9], but minor researches have been done to

__International Journal of Supply Chain Management__
IJSCM, ISSN: 2050-7399 (Online), 2051-3771 (Print)

establish the extent of their influence. Surface roughness can critically affect both the aesthetics and the performance of working orthodontic components [10].

On the other hand, because of increased surface tension in the archwire, saliva may increase the friction and present an adhesive interference. An analysis of the surface roughness of different archwires materials suggests that these results could be related to the coefficient of friction of the material analyzed by Binnig et al. (1986) [11]. However, the results obtained for materials of certain brands may not necessarily be applicable to products of other brands [12], and there have been no studies that have compared new archwires with the more expensive archwires.

A series of studies have been initiated to understand more fully the critical parameters of sliding mechanics [13]. The first study for surface topography considers whether surface roughness affects the dry and wet frictional forces in comparison. In this investigation a comparison is made among the surface texture of seven brackets and five archwires. Frictional characteristics of these products against five archwires will be calculated to determine the effect that roughness has on friction. Using various archwire-bracket combinations from seven brackets and five archwires, a model of orthodontic systems were constructed. By surface roughness and frictional force measurements, the hypothesis that a smoother surface correlates with a lower coefficient of friction was investigated.

2. Methodological Approach

2.1. Specimen Preparation

Seven brackets materials were selected that represented stainless steel (SS), ceramics, PMC - polymer matrix composites (Table 1). Five archwire materials were selected that represented SS, PMC (Table 2). Frictional forces were measured using a device that was designed to simulate orthodontic sliding mechanics.

2.2. Measure Surface Roughness

Bottom contact flats of bracket slot for the SS, alumina/polycrystalline ceramic PMC represented the extent or field of typical bracket finishes, duplicated the finish of a popular bracket and designated the finish of a usual tailored surface finish respectively. The bottom contact flats of brackets (SS, ceramics, PMC) were prepared in the laboratory using standard metallographic specimen preparation techniques. That means, the tie-wings of six as-received brackets and developed bracket were ground down using 400 grit SiC abrasive paper until the bulk metal of the bottom of the slot was readily apparent, unaffected by the grinding operation, for the Talysurf diamond stylus travelling along the length to measure surface roughness data.

Table 1: Bracket Characteristics and Prescription. [WM - with metal slot; WOM- without metal slot; Monocrystalline alumina (MCA); Polycrystalline alumina (PCA); Polycarbonate (PC); Polymer Matrix Composite (PMC); Braided Glass Fiber (BGF)]

Slot manufacture	**Material composition**	**Torque**	**Tip**	**Slot length**	**Source**	**Slot size**	**Bracket Manufacturer**
Milled	SS	-7°	0°	3.0 mm	USA	0.022″	**Victory 3M Unitek**
Milled	Metal slot ceramic	-7°	0°	3.0 mm	USA	0.022″	**Clarity 3M Unitek**
drag	Sapphire (MCA)	-7°	0°	3.0 mm	USA	0.022″	**Inspire Ormco**
drag	Ceramic (PCA)	-7°	0°	3.5 mm	USA	0.022″	**Transcend 3M Unitek**
Milled	PMC-SS slot	-7°	0°	3.1 mm	USA	0.022″	**Spirit MB Ormco**
Milled	PMC- SS slot	-7°	0°	3.33 mm	USA	0.022″	**Elan GAC**
drag	PMC-BGF Reinforced	-7°	0°	3.4-3.5 mm	Develo -ped	0.022″	**Composite PMC-WOM**

Polished brackets and archwires were embedded in a substrate to hold them for the measurement of roughness. The surface topography (roughness) of each bracket and archwire was measured using a stylus profilometry instrument (Taylor Hobson Ltd, Leicester, Great Britain). The apparatus converts these minute deflections into electrical signals, from which it produces an analogue display of the centerline average of the surface roughness, in micro-mm (microns). The curve produced, took the form of an initial peak followed by a plateau region. The data for the present study included only the maximal static frictional force ($F_{s.max}$) which was determined to be the point at which the archwire first moved in the bracket; namely, the point on the X-Y plot where the trace departed from a vertical direction.

The surface roughness determination protocol used archwire samples 3 cm long. This part of the present study used a total of six or three (for developed one) specimens of each bracket and archwire type and took the mean for surface roughness value. The actual test sampled three areas of each specimen, one area = 1 mm from each end of the specimens and one area at the center. In some cases, the surface roughness of certain specimens was below the resolution of the Profilometer. To permit inclusion in the study, these readings arbitrarily received the minimum value for resolution of the Profilometer, which is 0.01 microns (micro-mm). The roughness average (R_a) and coefficient (r) values of the surface profile were recorded.

Table 2: Names, sources and codes of archwires.

Archwire	**SS, Rectangular**	**SS, Square**	**SS, Round**	**SS, Round**	**Aesthetic PMC (GFR)**
Manufact-urer	ORMCO	ORMCO	ORMCO	Wilcock Australia	Singapore
Source	CA, USA	CA, USA	CA, USA	New Delhi, India	Developed
Code	SRE	SSQ	SRO-OR	SRO-AW	CRO-DEV
Achwire size	0.019″ x 0.025″	0.018″ x 0.018″	0.018″	0.018″	0.018″

2.3. Measurements of Surface Hardness

The operator weighed desired amount of resin (approximately 20g for a 1" high by 1¼" diameter ring form), mixed 100 parts resin with 24 parts hardener, stirred thoroughly with glass rod using a "figure eight" motion for 5-10 minutes, being careful not to introduce many air bubbles. Then he used a swab to spread a thin layer of epoxy release agent on the edge of the ring form(s) and surface of plate which allowed to dry. Slowly poured epoxy over sample to desired height and allowed to set overnight which removed it from the cured mount. The surface hardness of the four types of archwire was measured with a digital Vickers micro hardness tester (MXT 70, Matsuzawa Seiki, Tokyo, Japan) by applying a 100-g force for 20 seconds. The hardness of each archwire was measured twice.

2.4. Mechanical Traction Test

A setup for mechanical test was developed in order to simulate the sliding movement of the archwire through the bracket slots for the orthodontic treatment. The bracket holding vice was labeled in the jig. Both the archwires and flats were cleaned with 95% ethanol immediately before mounting in the double contact friction device. Three (unavailability of developed samples) to six specimens of each archwire and brackets were used for evaluating friction parameter systematically applied at room temperature (22±2°C).

To investigate whether the surface roughnesses of opposing materials influence the frictional characteristics and ultimately the movement of teeth, the contact flats were drawn by the crosshead beam of the screw-driven Instron 4502 testing machine’s past the archwire. The bracket contact flats, which had different roughnesses, were tested in dry and wet conditions against the five-archwire types at a sliding velocity of 0.5 mm/minute for 4 minutes, producing 2 mm of archwire movement. An axial tensile force could be applied at the specified crosshead velocity using a 50 N load cell. For the straight archwires (SS/PMC) new surfaces were tested for each load. The static drawing forces (P) were either read directly from the maximum initial rise on the Instron chart recorder (the static value) or were calculated by averaging the digitally stored plateau region of each force-distance (P-δ) trace (the kinetic value). From the measured frictional force, half of the maximum force is required initiating motion of the archwire and half of the steady state force. Estimation of frictional resistance for each bracket/archwire couple for all trials was determined from an average of the kinetic frictional force encountered during displacement of the archwire relative to the bracket. Kinetic frictional force occurred after 0.3 mm once departed from static frictional force [13]. Subsequently, displacement of the archwire relative to the bracket was another 1.7 mm.

Adequate measures have been taken for the possible reproducibility and associated methodical error of mechanical test in the frictional force during sliding/friction test such as a series of trials were performed to verify the functioning of the testing apparatus to achieve concurrent control of linear and angular bracket displacement while simultaneously acquiring frictional resistance data with temporal integration to archwire.

2.5. Statistical Analysis

The surface roughness values of the five types of archwire were initially analysed using a one-way analysis of variance (ANOVA) with a 5% level of significance. All statistical analyses for surface roughness were performed using the SPSS 2000 (University of Strathclyde, Glasgow) software package. In contrary, statistical analyses of the surface hardness values of the four types of SS archwires were accomplished by SAS (Cary, NC, USA) for mean and standard deviation.

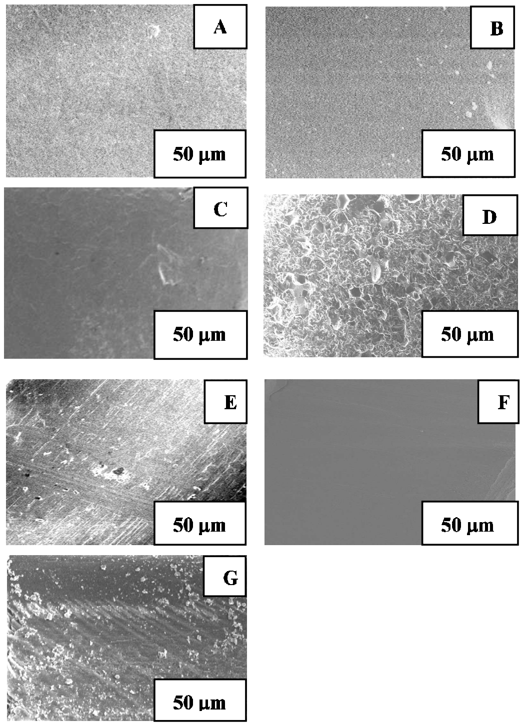

Figure 1. SEM of contact flat morphologies of brackets before testing: [**A**] Victory, [**B**] Clarity, [**C**] Inspire, [**D**] Transcend, [**E**] Spirit MB, [**F**] Elan and [**G**] Braided PMC (developed). Slots were cleaned with 95% ethanol before viewing.

One-way ANOVA analysis was used to identify any significant differences among groups. With frictional force data sampling functioning continuously at 2 samples per second, each trial (ANOVA) of yielded 1644 measures of the frictional force. A complete plan was drawn up, assessing three factors: (i) degree of the malalignment, (ii) diameter of the archwire, (iii) design of the slot, and (iv) bracket / ligature combination for a regression analysis. A p of ≤ 0.05 was considered significant.

2.6. Surface Topography by Scanning Electron Microscopy (SEM)

The orthodontic brackets and archwires were randomly selected, and sectioned for analysis of their surface with a JEOL scanning electron microscope (2000 FX, Tokyo, Japan). The samples were separately washed with alcohol before SEM observation.

Next, the orthodontic bracket and archwires were positioned on a double-faced adhesive tape whose sequence was carefully recorded. The samples were then placed in the sample chamber of the microscope for visualization of the surfaces of the bracket slots and archwires. A Scanning electron microscope (SEM) was used for surface evaluation of archwire and bracket specimens before and after the sliding tests. The appearances of the surfaces for as received bracket slots and archwires before the test are shown in Figures 1 and 2 respectively.

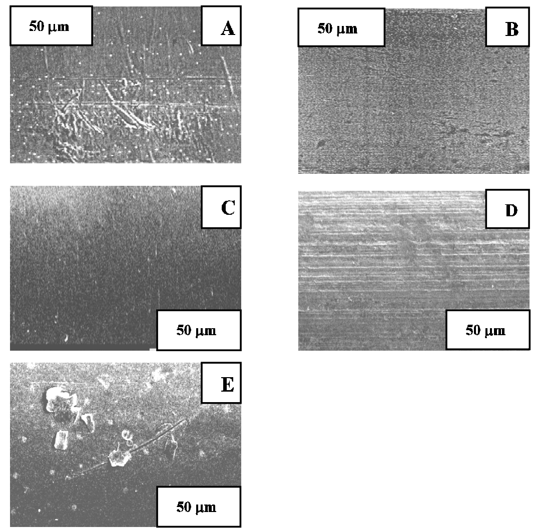

Figure 2. SEM images of as-received archwire morphologies: [**A**] a SS (Rectangular), [**B**] a SS (Square), [**C**] a SS (OR), [**D**] a SS (AW) and [**E**] an aesthetic PMC) archwires. All archwires were cleaned with 95% ethanol before observation.

3. Results

3.1. Surface Roughness and Mean Frictional Forces

As will be seen, neither the loading sequence nor the ceiling values had any apparent effects on the results.

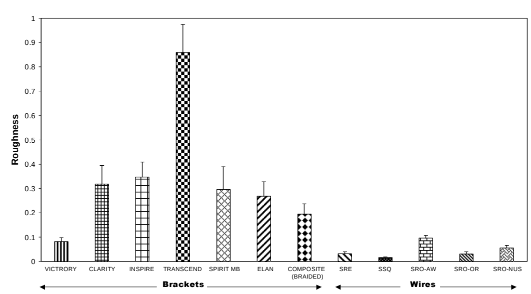

Figure 3. The roughness data illustrating the surface roughness of various brackets & archwires used for friction test. Shows how the surface roughness varies on the properties of brackets and archwires as well as surface coating/soft matrix. (SRE, SSQ, SRO-AW, SRO-OR & CRO-DEV)

It is evident from Figure 3 that the SS bracket (Victory) has the lowest surface roughness followed by the composite bracket - without metal (WOM) slot, Clarity - ceramic with metal (WM) slot, Inspire-ceramic without metal (WOM) slot) and

Transcend - ceramic without metal (WOM) slot brackets (Table 3).

Table 3. Mean surface roughness values for various brackets and archwires [based on six or three (developed) samples].

	Material	R_a (µm)	Coeff ®	P value
A. Brackets				
Victory	SS	0.0818	0.944	0.000
Clarity	Ceramic WM slot	0.3183	0.914	0.001
Inspire (SCA)	Ceramic WOM slot	0.3466	0.996	0.000
Transcend (PCA)	Ceramic WOM slot	0.8594	0.998	0.010
Spirit MB	Comp WM slot	0.2956	0.993	0.030
Elan	Comp WMslot	0.2679	0.936	0.010
Braided PMC	Comp WOM slot	0.1945	0.986	0.000
B. Archwires				
SS (USA)	0.019 × 0.025″	0.0317	0.987	0.001
SS (USA)	0.018 × 0.018″	0.0162	0.989	0.001
SS (India)	0.018″	0.0959	0.980	0.001
SS (USA)	0.018″	0.0309	0.990	0.001
PMC-DEV (Aesthetic)	0.018″	0.0563	0.998	0.001

The surface roughness values of archwires have complex behavior with ascending order:

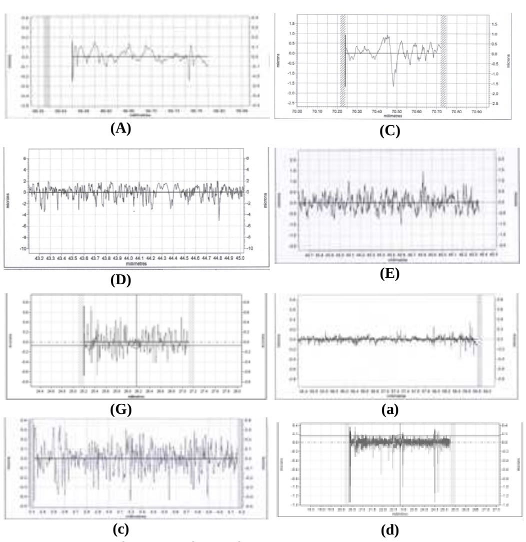

Figure 4. Surface profile of brackets: (**A**) Victory (SS) [R_a (surface roughness) = 0.0798 μm], (**C**) Inspire (ceramic WOM) (R_a = 0.3085 μm), (**D**) Transcend (ceramic WOM) (R_a = 0.8348 μm), (**E**) Spirit MB (composite WOM) (R_a = 0.2784 μm), (**G**) Aesthetic braided composite (WOM) (R_a = 0.1696 μm); archwires: (**a**) SS rectangular (SRE) (R_a = 0.0353 μm), (**c**) SS round (SRO-AW, R_a = 0.0979 μm), Aesthetic composite (CRO-DEV) (R_a = 0.0647 μm).

Square (Ormco), Round (Ormco), Rectangular (Ormco), Round (aesthetic) and Round (Australian Wilcock). Sample surface topography (roughness) of bracket and archwire measured using a stylus profilometry instrument is shown in Figure 4. The regressions produced straight lines from which the roughness of the contact flats and archwires varied for the SS, ceramics, PMC.

The sequence for increasing frictional resistance for composite round archwires ranged from composite bracket - without metal slot, Victory (SS) and Transcend (ceramic without metal slot) with elastomeric ligatures, respectively. It is noted that frictional forces increases with increased roughness values and also represented a complex behavior, specifically, for ceramic brackets without metal slots i.e. behaved inversely. Multiple regression analysis was carried out using the probabilities (*p*) associated with the correlation coefficients (*r*) and significant differences were observed in terms of surface roughness of brackets and archwires ($p < 0.001$, Table 3).

The surface roughness of the brackets in the range of 0.08 to 0.83 µm and archwires varied from 0.03 to 0.09 µm (Figure 3). The regression results were highly significant indicating that frictional forces increase with increased roughness values ($p < 0.001$, $r = 0.914 - 0.998$; Table 3).

Table 4. Mean frictional force (newtons) and standard deviation (SD) for bracket/archwire combinations under elastomeric ligatures (based on 6 observations per entry; based on 3 observations per entry for PMC bracket/archwire combinations)

Bracket	***Aarch - wire***	***Dry Condition***		***Wet Condition***	
		Mean	*(SD)*	*Mean*	*(SD)*
Victory	SRE	1.23	0.21	1.55	0.16
	SSQ	1.21	0.16	1.48	0.13
	SRO-AW	1.44	0.18	1.62	0.18
	SRO-OR	1.15	0.22	1.35	0.13
Clarity	SRE	1.36	0.15	1.60	0.15
	SSQ	1.32	0.11	1.47	0.10
	SRO-AW	1.55	0.14	1.69	0.15
	SRO-OR	1.33	0.18	1.38	0.21
Inspire	SRE	1.67	0.12	1.80	0.18
	SSQ	1.62	0.07	1.71	0.15
	SRO-AW	1.67	0.19	1.82	0.28
	SRO-OR	1.53	0.16	1.53	0.20
Trans -cend	SRE	1.56	0.10	1.74	0.12
	SSQ	1.42	0.10	1.58	0.10
	SRO-AW	1.59	0.13	1.72	0.11
	SRO-OR	1.38	0.17	1.56	0.10
Spirit MB	SRE	1.15	0.17	1.31	0.11
	SSQ	1.09	0.14	1.29	0.13
	SRO-AW	1.28	0.21	1.48	0.07
	SRO-OR	1.18	0.07	1.39	0.20
Elan	SRE	1.37	0.12	1.56	0.14
	SSQ	1.39	0.09	1.60	0.10
	SRO-AW	1.41	0.27	1.66	0.12
	SRO-OR	1.19	0.21	1.45	0.26
PMC (braided)	CRO-DEV	1.25	0.20	1.41	0.29

Representative traces of the frictional force or load (N) vs. displacement (MM) for the seven brackets and the five archwires are measured. It shows that the frictional forces have the lower mean for aesthetic braided composite brackets without metal slot with aesthetic composite archwires under dry and wet conditions with elastomeric ligatures for 0 degree angulation.

In general, quantitatively, a comparatively lesser frictional force was elicited by Spirit MB bracket (composite with metal slot). Then, the frictional force is progressively increased for Victory, Clarity, Elan (composite with metal slot), Transcend (ceramic without metal slot) and Inspire (ceramic without metal slot) bracket against the rectangular, square and round SS archwires respectively under dry and wet conditions for elastomeric ligatures (Table 4) with the effect of surface roughness.

3.2. Archwire and Bracket Surface Roughness

By plotting the frictional forces against surface roughnesses of four SS archwires one observes that frictional force (N) is not always systematically dependent on the surface roughness (σ_0) of the archwires and the brackets (Figures 5-6).

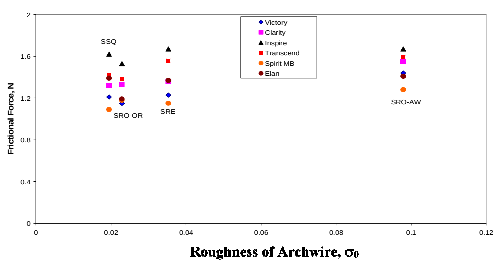

Figure 5. Influence of surface roughnesses of the archwire (σ_0) on the frictional force (N) for elastomeric ligatures. The plot shows that N is not systematically dependent on σ_0. [SRE: Rectangular; SSQ: Square; SRO-OR: Round (Ormco) and SRO-AW: Round (A. Wilcock)]

Overall, the SS couples have the lowest surface roughnesses and friction, regardless of whether a surface finish is comparable to a SS bracket or SS slot or the alumina itself. Among the five SS archwires, the rectangular one displayed the most damage within the bracket slots, which is supportive of increased frictional force.

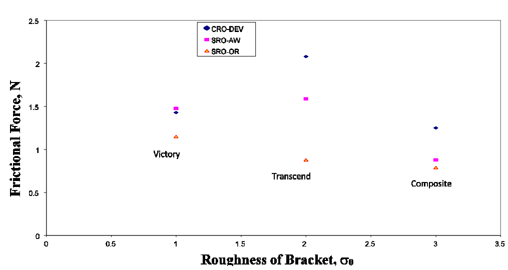

Figure 6. Influence of surface roughnesses of the archwire (σ_0) on the frictional force (N) for elastomeric ligatures. The plot shows that N is not systematically dependent on σ_0. [CRO-DEV: Round (developed), SRO-OR: Round (Ormco) and SRO-AW: Round (Australian Wilcock)]

3.3. Surface Hardness of Archwires

The hardness values of SS archwires with respect to different shapes [rectangular, square, round (coated), round respectively] Vickers and Rockwell hardness was almost identical (Table 5). On the other hand, a composite archwire (PMC-Metafil reinforced with GF) was not possible to measure by the micro-hardness. It was not possible to measure the micro-hardness of this small diameter composite rod. The bundle of fibers comprising the rod moved or separated under the load applied by the hardness indenter which prevented an indention from being made.

3.4. Wear Study

The orientation of the brackets on the SEM images is displayed in Figures 7 for various brackets with archwire combinations.

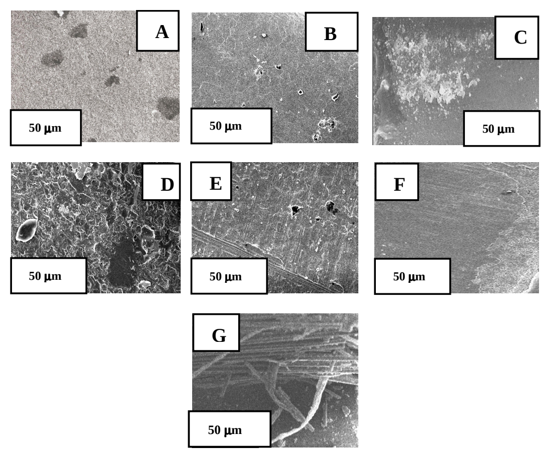

Figure 7. Scanning electron micrographs (SEM) (15 kV: 2.5 amp) of contact flats of brackets after testing. [**A**] Victory (stainless steel), [**B**] Clarity (ceramics - with metal slot), [**C**] Inspire (ceramics - without metal slot), [**D**] Transcend (without ceramics - metal slot), [**E**] Spirit MB (composite - with metal slot), [**F**] Elan (composite - with metal slot), [**G**] Braided composite (developed - without metal slot), after testing against, proved that most of them showed either evidence of galling or attached debris so well that the general shape of the particles could be discerned. Flats were not coated prior to viewing.

The bracket wear patterns varied with the different bracket archwire combinations, bracket materials and archwire alloys. The composite bracket (Spirit MB) with metal slot was associated with mild and moderate abrasive wear. Ceramic brackets without metal slot show higher abrasive wear with the different wire alloys. SS brackets shows galling of the surfaces from the bracket slots and produces spots.

Table 5. Surface roughness and surface hardness of five types of orthodontic archwire.

Archwire type	Vickers Hardness (kg/mm^2) Mean±SD	Rockwell Hardness, R_c Mean±SD
Stainless steel (Ormco, USA)	582.50±16.26	52.15±1.20
Stainless steel (Ormco, USA)	590.50±27.58	52.55±1.90
Stainless steel (AW, India)	590.50±27.58	52.60±1.84
Stainless steel (Ormco, USA)	597.50±17.68	53.20±0.99
PMC (Aesthetic; Developed)	It was not possible to measure the micro-hardness of this small diameter composite rod.	

In contrast, the SEM images are demonstrated in Figures 8 for various archwire combinations with brackets. SS archwire (SRO-AW) produces white specks of matrix and fibers distorting during sliding while broken fibers with damaged corner predominant. It is evident that matrix depleted with opening the fibers with for composite (SRO-DEV) archwire.

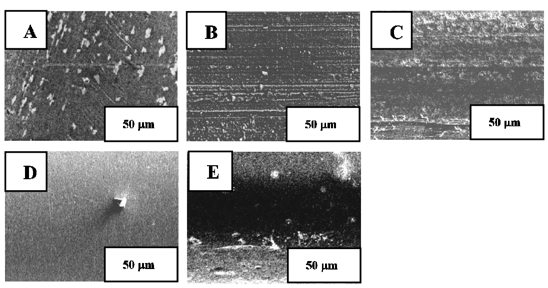

Figure 8. Scanning electron micrographs (15 kV; 2.5 amp) of archwire morphologies: [**A**] a stainless steel (Rectangular), [**B**] a SS (Square), [**C**] a SS (Round, Ormco), [**D**] a SS (Round, Australian Wilcock) and [**E**] a PMC archwires (developed) after testing against bracket slots. It proved that only three showed any evidence of galling.

4. Discussion

It is presumed that the exact composition and manufacturing process of the archwires generally are not disclosed by the manufacturers of orthodontic archwires [15]. The archwires as-received demonstrated an inhomogeneous surface with different patterns of surface irregularities, which may be attributable to the manufacturing process i.e. the complex manufacturing processes, the surface finish treatments, and the alloy used [16] - [17]. Further, the coefficients were identical in most cases although some inhomogeneities were observed in the extent of surface roughness. Surface roughness analysis is represented a complex behavior, specifically, for ceramic brackets without metal slots i.e. behaved inversely.

In addition, the statistically significant results obtained indicate that the number of the specimens was sufficient. From the surface profiles (Figure 4), it can be observed that Victory brackets (SS) have lower surface roughness ($p < 0.05$), which may cause high friction values. The static friction coefficient (μ), increases exponentially with decreasing surface roughness [18]. The roughness for the brackets and archwires behaved similarly i.e. a wide range of variation to those results reported earlier [19].

The wear pattern reveals from SEM images that abrasive wear is possibly due to the rough surface. The high magnification of SEM confined the investigation and interpretation of the surface topology of a smaller area of the archwires and bracket slot flats which is a point of consideration in this regard. Moreover, The SEM comparisons with other interpretations render difficulties as SEM images provide poorly reproducible subjective interpretations. Therefore, the objective technique of profilometry additionally employed [19].

Ref. [20], stated that asperities do not have to cold weld, argued it but that interfacial adhesion between asperities is sufficient to account for friction of metal slots [cf. Figures 1 and 7; (A-B, E-F)]. The factors responsible for low friction include: (i) the oxide film, which effectively separates the two metal surfaces (SS), thus no true metallic contact; (ii) the oxide film has low shear strength. For most engineering surfaces, like SS, the angles of asperities with the horizontal surface (roughness angles) are very small and the plowing component of friction is correspondingly small. The nature of solid contact in sliding, even at low sliding speeds, (fretting) the contact mechanics during sliding was very different from static contact. It has been shown that, between rough surfaces, contact and contact pressure could exist outside the Hertz contact region calculated for smooth surfaces [21] - [22].

In the case of ceramic pairs with two rough surfaces and/or trapped wear particles, the deformation term constitutes the force needed for the plowing, grooving, or cracking of surfaces. The deformation is generally dominant compared to the adhesion component. In addition, interact-tion of two rather rough surfaces may result in mechanical interlocking on a micro or macro scale. Ceramic materials consist of rough surfaces and/or trapped wear particles and hence [cf. Figures 1 and 7; (C-D)], extra force needed to overcome plowing, grooving or cracking of surfaces. Enhancing the surface finish of the polycrystalline alumina (Transcend), refining its grain size, or using a single crystal (monocrystal) material (without the curved surfaces of the vertical sides of the slot parts; Inspire (MCA): Ormco Corp., Orange, CA, USA) may improve these frictional values.

During contact of two elastic-plastic bodies at small loads, the surface is deformed elastically with the maximum shear stress occurring at the surface, some distance below the center of the contact region. The deformation grows from purely elastic to elastic-plastic (contained) followed by fully plastic (uncontained) common for most engineering material combinations.

The substrate surface roughness has an almost negligible influence on friction if the surface roughness is considerably smaller than the thickness of the soft coating/soft matrix, and if the coating is stiff enough to carry the load [cf. Figures 1 and 7; G & cf. Figures 2 and 8; D-E). However, when the roughness of the slider is higher than the coating/matrix thickness, coating/matrix penetration will take place and the friction is considerably increased due to scratching of the substrate material. In addition, interaction of two rather rough surfaces may result in mechanical interlocking on a micro or macro scale. During sliding, interlocking would result in plowing of one of the surfaces. Because of plowing displacement, a certain lateral (friction) force is required to maintain the motion. This also provides more resistance during angulation of the bracket to the archwire, and causes the highest friction for composite brackets.

In orthodontics, surface roughness of orthodontic archwires additionally may affect the aesthetics of the appliance and the performance of sliding mechanics by its influence on the coefficient of friction (cf. Figures 2 and 8). Whether sliding mechanics are used to align irregular teeth at extraction sites, frictional forces dictate the present efficiency and future reproducibility of the clinician's activation force. This discussion shows that a clear relationship does not always exist between surface roughnesses (σ_0) and the frictional force, when adhesive or abrasive mechanisms are present. Moreover, the present studies show that dry frictional forces can exceed those values reported in the orthodontic literature [23].

To investigate further the apparent anomalous behavior of Australian Wilcock (Figure 8 D) and aesthetic developed archwires (Figure 8 E), all contact flat surfaces were examined with a scanning electron microscope. After drawing an equal amount of the five archwires through a unique set of contacts [cf. Figures 2 & 8 (C, E)] showed some damage as the archwires gouged long channels across an otherwise rather featureless surface. The relationship between the above mentioned three parameters will result in a number of different contact conditions characterized by specific contact mechanisms. If one considers such a contact on a microscale, there is effectively a soft coating on a hard substrate, although now the coating plays the role of hard substrate, and the soft microfilm formed plays the role of a coating. The friction usually increases with coating thickness for soft coatings, due to plastic or elastic deformation of the film and to the increased contact area at the interface between the sliding counterface and the coating where the shear takes place [24].

Furthermore, the surface of coating was very rough. At the beginning of the fretting movements, only a few large asperities came into contact with the counterface. Due to the high pressure applied on the specimen, plastic deformation would occur at the tips of these asperities. Because of the relative movement of the two counterfaces, some of the asperities were fractured and formed the debris, while the others could move back and forth to take up some tangential movement by elastic deformation. Much debris formed escaped from the contact areas in the surrounding hollows or holes in the coating. With the increasing number of oscillatory cycles, a large amount of debris was formed, and some of the asperities of the coating were gradually worn flat [25]. This debris played a dual role in controlling wear and friction: the formation of the compacted layer and the abrasive action before their compaction and after the delamination of the compacted layers. The wear process is thus governed by the plasticity and fracture of this debris and the possibility of their ejection from the contact area. The debris was spherical in shape with a typical diameter of several microns.

The first reason could be the different fretting wear mechanisms. Work hardening was likely to prevent these deformed asperities from being completely flattened so that the sharper asperities on a rough surface would be able to accumulate more of the tangential movement by elastic deformation. During fretting, a lot of debris accumulated on the contact surface and caused severe ploughing, but on the rough surface of the coating, there were greater chances, that wear debris escaped from the contact areas into the adjacent hollows or depressions, instead of ploughing the wearing surfaces. The porous and lamellar structure of the coatings appeared to promote the delamination wear and more and more debris generated could then plough the two counterfaces. Under lubricated conditions, all the typical gross-slip is indicating the occurrence of wear. It can be observed that for coatings under unlubricated conditions, the coefficient of friction is stable. For the lubricated conditions, the coefficient of friction is much lower and is stable at a constant value around. This probably can be attributed to the lamellar structure of coating which facilitates the generation of debris. Existence of the pores and micro-cracks in the deposited coating can promote the propagation of cracks and delamination processes [26]. In contrast, the surface roughness of the identical shape and size of archwire has given a more or less normal trend to increased or decreased frictional force and shown a positive correlation with frictional forces. The three round archwires surface characteristics are in different manner.

However, categorized the archwire as aesthetic composite (CRO-DEV: PMC), SRO-AW (A. Wilcock): SS (Martensitic soft coated), and SRO-OR; Ormco: SS) which is an evidence of increasing frictional force with higher surface roughness [Table 4; cf. Figures 2 & 8; (E, D, C)]. More friction ($p < 0.05$) is found with the aesthetic composite archwire (glass fiber) compared to SS archwire (Ormco). In the wear tests, a ball-on-flat wear test on composite resin (Metafil) demonstrates high friction coefficient and brittle fracture by debonding of fillers and matrix. The reason is that Metafil has lower hardness and fracture toughness, and therefore, frets heavily in the abrasive process [27].

Whether sliding mechanics are used to align irregular teeth or to close space at extraction sites, frictional forces must be overcome. The magnitude and variability of the frictional forces dictate the present efficiency and future reproducibility of the clinician’s activation force. This discussion shows that a clear relationship does not always exist between surface roughnesses and the coefficients of friction, when adhesive or abrasive mechanisms are present. Moreover, the present measure-ments show that the dry frictional coefficients can exceed those values reported in the orthodontic literature.

The occurrence of adhesive wear in the form of cold welding is not surprising in the soft coatings/soft matrices, since both can be quite reactive [28] and can display poor wear properties [29]. If cold welding should persist and “stick-slip” occur when in contact with human saliva or at velocities less than 1 cm min^{-1}, this archwire alloy should not be considered for sliding mechanics [cf. Figures 2 & 8 (D, E)].

5. Conclusion

In this study surface topography (ST) and surface roughness (SR) of the brackets and archwires investigated which differed significantly in terms of frictional resistances. The main finding of this research is that dissimilar material contacts at the interface between bracket slots and archwires (like metal/ceramics, polymer/ceramics, polymer/SS etc.) produced more frictional force. However, there is an exception in frictional force for the developed aesthetic composite bracket and SRO-OR/SRO-AW archwires combinations which challenges the characteristics of dissimilar material contacts. Less depletion of soft matrix for aesthetic PMC-BGF brackets against the SRO-OR archwires might be due to its low surface roughness and mild peaks. Whereas, soft matrix might be depleted severely for SRO-AW (Australian Wilcock) archwires due to high surface roughness and sharp peaks. It would contribute further in the periodic orthodontic treatment for the better selection of aesthetic bracket and archwires combinations and impetus for the new researcher or practitioner. A clear concept of the friction parameter especially SR would be possible when these results on the sliding resistance are focused with future investigation.

Acknowledgments

The authors would like to thank Mechanical Engineering, Arthur Weisberg Family Applied Engineering Complex, Marshall University, USA for the provided support to study a problem (surface roughness and hardness) that is of such fundamental importance to the orthodontic profession. Also we are thankful to Mr. Bill Mankins, P.E., FASM, President, Metallurgical Services, Inc./Level 1 Fasteners (17283), 777 Tenth Avenue West, Huntington WV 25701, USA and High Performance Heat Treating, Inc.; 300 3rd Avenue, Huntington, WV 25701, USA to provide the opportunity for micro hardness test.

References

[1] Brady MN. Frictional Forces of a Fixed, Esthetic Orthodontic Appliance System. University of Nevada, USA, M. Sc. Thesis in Oral Biology, 2012.

[2] Fidalgo da Silva TK, Pithon MM, Maciel JVB, Bolognese AM, “Friction between different wire bracket combinations in artificial saliva - in vitro evaluation”, J Appl Oral Sci. Vol 19, No. 1, pp. 57-62, 2011.

[3] Provoski RR, Bagby MD, Erickson LC, “Static frictional force and surface roughness of nickel-titanium arch-wires”, Am J Orthod Dentofacial Orthop, Vol 100, pp. 341-48, 1991.

[4] Saunders CR, Kusy RP, “Surface topography and frictional character-istics of ceramic brackets”, Am J Orthod Dentofacial Orthop, Vol 106, pp. 76-87, 1994.

[5] Daems J, Celis JP, Willems G, “Morphological characterization of as-received and in vivo orthodontic stainless steel archwires”, Eur J Orthod, Vol 31, pp. 260-65, 2009.

[6] Elayyan F, Silikas N, Bearn D, “Ex Vivo Surface and Mechanical Properties of Coated Orthodontic Archwires”, Eur J Orthod, Vol 30, pp. 661-7, 2008.

[7] Faccioni F, Franceschetti P, Cerpelloni M, Fracasso ME, “In vivo study on metal release from fixed orthodontic appliances and DNA damage in oral mucosa cells”, Am J Orthod Dentof Orthop, Vol 124, pp. 687-93, 2003.

[8] Huang HH, “Variation in surface topography of different NiTi orthodontic archwires in various commercial fluoride-containing environments”, Dent Mater, Vol 23, pp. 24-33, 2007.

[9] Garner LD, Allai WW, Moore BKA, “Comparison of frictional forces during

simulated canine retraction of a continuous edgewise archwire", Am J of Orthod Dentofacial Orthop, Vol 90, pp. 199-03, 1986.
[10] Kusy RP, Whitley JQ, Mayhew MJ, Buckthal JE, "Surface roughness of orthodontic archwires", The Angle Orthod, Vol 61, pp. 33-45, 1988.
[11] Binnig G, Quate CF, Gerber C, "Atomic force microscope", Phys Rev Lett., Vol 56, pp. 930-33, 1986.
[12] Khosravanifard B, Nemati-Anaraki S, Nili S, Rakhshan V, "Assessing the effects of three resin removal methods and bracket sandblasting on shear bond strength of metallic orthodontic brackets and enamel surface", Orthod Waves, Vol 70, pp. 27-38, 2011.
[13] Michael JC, "The Effects of Third-Order Torque and Self-Ligating Orthodontic Bracket Type on Sliding Friction: A Comparative Study", Saint Louis University, M. Sc. Thesis in Dentistry, 2007.
[14] Kamelchuk L, "Quantified simulation of canine retraction for frictional resistance evaluation of sliding mechanics", Univ. of Toronto: Dip. In Orthod Thesis, 1998.
[15] Verstrynge A, Van Humbeeck J, Willems G, "In-vitro evaluation of the material characteristics of stainless steel and beta-titanium orthodontic wires", Am J Orthod Dentofacial Orthop, Vol 130, pp. 460-70, 2006.
[16] Neumann P, Bourauel C, Jäger A, "Corrosion and permanent fracture resistance of coated and conventional orthodontic wires", J Mater Sci Mater Med, Vol 13, pp. 141-47, 2002.
[17] Pernier C, Grosgogeat B, Ponsonnet L, Benay G, Lissac M, "Influence of autoclave sterilization on the surface parameters and mechanical properties of six orthodontic wires", Eur J Orthod, Vol 27, pp. 72-81, 2005.
[18] Karpenko YA, Akay AA, "Numerical model of friction between rough surfaces", Trib Intl, Vol 34, pp. 531-45, 2001.
[19] Amini F, Rakhshan V, Pousti M, Rahimi H, Shariati M, Aghamo-hamadi B, "Variations in surface roughness of seven orthodontic archwires: an SEM-profilometry study", The Korean Journal of Orthodontics (KJO), Vol 42.3, pp. 129-37, 2012.
[20] Bhushan B, "Principles and applications of tribology", New York: John Wiley and Sons, Inc. 1999.
[21] Johnson KL, "Contact mechanics", Cambridge: Cambridge University Press, 1987.
[22] Ogilvy JA, "Numerical simulations of friction between contacting rough surfaces", J of Physics D: Applied Physics, Vol 24, pp. 2098-109, 1991.
[23] Yu J-H, Wu L-C, Hsu J-T, Chang Y-Y, Huang H-H, Huang H-L, "Surface roughness and topography of four commonly used types of orthodontic archwire" J. Med. Biol. Eng., Vol 31, No. 5, 2011.
[24] D'Anto` V, Rongo R, Ametrano G, Spagnuolo G, Manzo P, Martina R, Paduano S, Valletta R, "Evaluation of surface roughness of orthodontic wires by means of atomic force microscopy", Angle Orthodontist, Vol 82, No. 5, 2012.
[25] Fu YQ, Batchelor AW, Khor KA, "Fretting wear behaviour of thermal sprayed hydroxyapatite coating lubricated with bovine albumin", Wear, Vol 230, pp. 98-02, 1999.
[26] Fu YQ, Batchelor AW, Wang Y, Khor KA, "Fretting wear behaviour of thermal sprayed hydroxyapatite (HA) bioceramic coating under unlubricated conditions", Wear, Vol 217, pp. 132-39, 1998.
[27] Ren J, Kim K, Kim SS, "Fracture and Tribological Evaluation of dental composite resins containing pre-polymerized particle fillers", J of Mat Sci Tech, Vol 19, pp. 249-52, 2003.
[28] Duchcyne P, Hastings GW, "Metal and Ceramic Biomaterials", Structure, Vol 1, pp. 99, 1984a.
[29] Duchcyne P, Hastings GW, "Metal and Ceramic Biomaterials", Strength and Surface, Vol 2, pp. 106, 1984b.