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Frictional characteristics of composite orthodontic archwires against stainless steel and ceramic brackets in the passive and active configurations

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The frictional characteristics of prototype composite archwires were investigated. The resistance to sliding was measured in the dry state for wires with three different volume fractions of fiber reinforcement against stainless steel, polycrystalline alumina, and single crystal alumina orthodontic brackets. Each archwire and bracket combination was tested at 34 °C with twelve different normal forces (from 0–400 g) and six different angulations (from 0°–12.5°). The kinetic coefficients of friction were determined from the slopes of linear regressions through plots of the resistance to sliding versus normal force data. The *y*-intercepts of these regressions were also evaluated as indicators of the binding magnitude. The tested archwire samples were examined for wear using a scanning electron microscope. A fully factorial model analysis-of-variance showed no significant differences in the frictional coefficients for changes in bracket material, reinforcement level, or angulation. Highly significant differences were observed in the *y*-intercepts for changes in the reinforcement level and angulation. Highly significant, positive, and linear correlations between the *y*-intercepts and angulations were also established. Abrasive wear of the composite surface was observed at the archwire–bracket interface, particularly at higher normal forces and angulations. Relative to other frictional studies of metallic archwire materials, the composite archwires had higher kinetic coefficients of friction than stainless steel but lower coefficients than either nickel titanium or beta-titanium archwires against all bracket materials tested. © *1998 Kluwer Academic Publishers*

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1. Introduction

Over the past decade, several investigators have considered the feasibility of fabricating an orthodontic archwire from a unidirectional fiber-reinforced polymer (UFRP) composite material [1–6]. The most obvious advantage of such a wire would be the aesthetic, tooth-colored appearance that is characteristic of select composites. However, a composite archwire would also be favorable because wire stiffness could be varied through the control of reinforcement and matrix composition without changing the wire size or shape [7]. Consequently, the use of variable modulus orthodontics would be accommodated, which would allow good engagement between the archwire and the bracket slot from the initial to the final stages of orthodontic treatment [8].

Early composite archwires were manufactured using conventional pultrusion [1–4]. Most recently, prototype UFRP composite archwires have been fabricated using a novel manufacturing method known as photo-pultrusion [9, 10]. To evaluate the clinical viability of these wires, studies have been conducted to characterize the mechanical properties [11], hydrolytic stability [12], and steady-state sorption characteristics [13] of the photo-pultruded composite materials. Although the results thus far suggest that the prototype wires would function well during the initial and intermediate stages of orthodontic treatment, the frictional characteristics, which should be minimized during sliding mechanics, have not been investigated.

A literature search for frictional studies of fixed orthodontic appliances revealed that the effects of several factors have been considered. Among these, the bracket material, wire material, angulation, and normal (ligation) force were all shown to vary

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TABLE I Archwire and bracket materials

Material	Product	Code	Specifications
Archwires:			
UFRP composite	0.70 $V_f^{a,b}$	C70	0.020 in. diameter wire
	0.59 $V_f^{a,b}$	C59	0.020 in. diameter wire
	0.49 $V_f^{a,b}$	C49	0.020 in. diameter wire
Brackets:			
Stainless steel	Uni-Twin® Dyna-Lock®[c]	SS	0.022 in. slot, 0° angulation, − 7° torque
Polycrystalline alumina	Transcend® Series 6000[c]	PCA	0.022 in. slot, 0° angulation, − 7° torque
Single-crystal alumina	Starfire® TMB[d]	SC	0.022 in. slot, 0° angulation, 0° torque

[a] Volume fraction of reinforcement.
[b] UNC Dental Research Center, Chapel Hill, NC.
[c] Unitek/3M Corporation, Monrovia, CA.
[d] The "A" Company, San Diego, CA.

significantly the resistance to sliding* [14–24]. In particular, the normal force has a fundamental effect on sliding resistance. In the passive configuration, where no binding occurs, the normal force and the resistance to sliding are theoretically proportional, where the constant of proportionality is the coefficient of friction [25]. Thus, the normal force must be carefully controlled in any study of frictional properties.

In this study, the frictional characteristics of photo-pultruded composite archwires were evaluated in the dry state against stainless steel, polycrystalline alumina, and single-crystal alumina brackets. A friction-testing apparatus, which was designed to simulate clinical conditions, was used with a standard mechanical testing machine to measure drawing forces. This apparatus included a closed-loop feedback control system to maintain real-time control over the normal force. From the results, the kinetic coefficients of friction of the composite archwires were higher than archwires made from stainless steel but lower than those made from either nickel titanium or beta-titanium, as determined in previous studies, against the three bracket materials.

2. Materials and methods

Composite archwires were evaluated against stainless steel (SS), polycrystalline alumina (PCA), and single-crystal alumina (SC) bracket materials (Table I). Each of the brackets had a 0.022 in. (0.56 mm) slot and no pre-angulation. Two of the bracket types (SS and PCA) were pre-torqued to − 7°. Composite archwires, having round cross-sectional profiles, were fabricated with a nominal diameter of 0.020 in. (0.51 mm) using a photo-pultrusion manufacturing process, the details of which have been described elsewhere [10]. The wires were manufactured of S2-glass® continuous-fibre yarns (Owens Corning Corp., Toledo, OH, USA) and a glassy copolymer, which consisted of 61 wt% bisphenol-A diglycidyl methacrylate (Nupol 046-4005, Cook Composites and Polymers Co., North Kansas City, MO, USA) and 39 wt% triethylene glycol dimethacrylate (TEGDMA, Polysciences Inc., Warrington, PA, USA). The volume fraction of reinforcement, V_f, and ultimately the stiffness of the wire, was adjusted by changing the number of S2-glass® yarns that were pultruded into the composite profile. The actual V_f was calculated using the cross-sectional area of the composite as determined from a mean of eight diameter measurements (Sony μ-mate® Digital Micrometer, Sony Magnescale America, Inc., Orange, CA, USA). Three different composite archwires were fabricated, such that the mean V_f was 0.70, 0.59, and 0.49 for C70, C59, and C49 archwires, respectively.

Frictional properties were determined using a friction-testing apparatus (Fig. 1), which was mounted to the transverse beam of a mechanical testing machine (Instron Model TTCM, Instron Corp., Canton, MA, USA). This apparatus was similar to that used in previous studies [20–23], but with several design enhancements. These included real-time control of the normal force and the ability to perform tests at discrete archwire–bracket angulations. The normal force was produced by activating a spring with a computer-controlled linear translation motor (A). This force was transferred through a normal force load cell (B) to two 0.010 in. (0.25 mm) SS ligature wires (C) (Item PL1010 Ligature Wire, GAC International, Commack, NY, USA), which applied the normal force directly to the archwire (D). The linear translation motor and the normal force load cell formed a closed-loop feedback control system that maintained a constant normal force. Discrete angulations were obtained by rotating the bracket (E) and ligature wires with respect to the archwire in a plane perpendicular to the normal force vector. Two roller bearings (F) were placed at an inter-bracket distance of 16 mm above and below the archwire-bracket engagement to keep the archwire collinear to the drawing force vector of the tensile load cell during angulation. Each pair of frictionless bearings approximated the leading and trailing slot edges

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*For this study, resistance to sliding is used instead of frictional force because the latter is traditionally defined as being proportional to the normal force. Although this definition is generally satisfied in the passive configuration, binding increases the sliding resistance in the active configuration irrespective of the normal force. Consequently, the definition of resistance to sliding includes both the frictional force and the sliding resistance caused by binding [15].

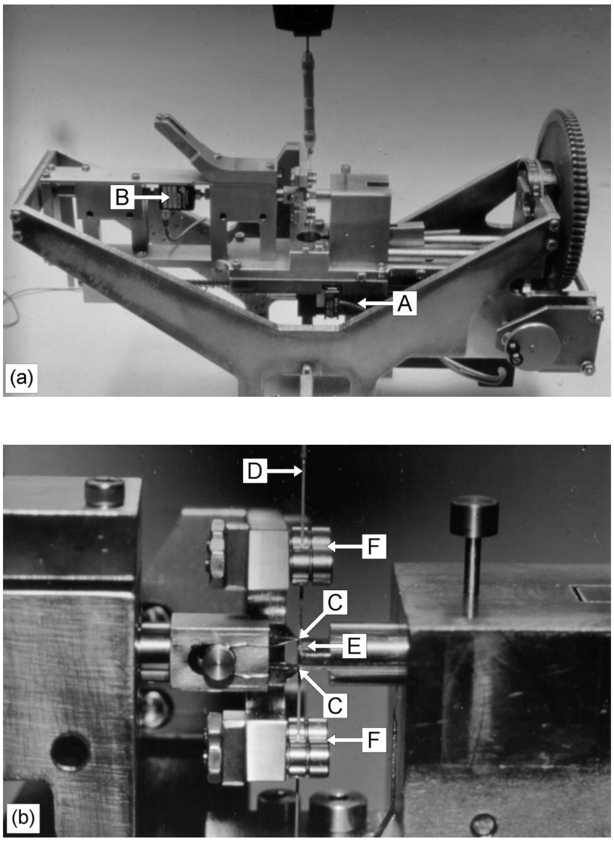

Figure 1 Photographs of the friction-testing apparatus. (a) For clarity, the entire apparatus is shown separate from the universal testing machine and computer interface. (b) A close up view reveals the archwire–bracket–ligature interface in detail.

of adjacent brackets, at a distance far enough away to minimize interactions.

Both load cells (tensile and normal force) were calibrated with standard weights before and after every testing session. Each archwire–bracket combination (couple) was tested in the dry state at 34 °C. All materials were washed in 95% ethanol and air dried prior to testing. Where appropriate, brackets were mounted at a 7° incline, parallel to the slot axis, so that all of the tests were conducted at the equivalent of 0° torque. For each determination, brackets were translated a distance of 5 mm along virgin sections of archwire at a sliding velocity of $1\,\mathrm{cm\,min^{-1}}$ [20]. No more than three tests were conducted on each archwire sample because of limitations on the length of archwire that could be drawn through the friction-testing apparatus. New brackets and ligature wires were used for each angulation. Drawing forces were measured for each of the nine archwire–bracket couples at twelve different normal forces ($N = 50, 100, 150, 200, 250, 300, 75, 125, 175, 225, 275$, and 400 g sequentially) and six different angulations ($\theta = 0°, 2.5°, 5.0°, 7.5°, 10.0°$ and $12.5°$) for a total of 648 individual tests.

Drawing force, P, and distance, δ, data were collected from the mechanical testing machine at a rate of ten points per second using Instron Series IX materials testing software (Version 5.27, Instron Corp., Canton, MA, USA). A $P-\delta$ plot was created for each N tested. The resistance to sliding, RS, corresponding to each N was determined from these plots by averaging the P data in the plateau region and dividing by two [20–23]. Kinetic coefficients of friction, μ_k, were calculated from the slopes of least-squares linear regressions through the data of $RS-N$ plots. These plots each contained at least twelve data points corresponding to different N magnitudes. Additional data points were collected for some samples at $\theta \geqslant 10°$ in order to clarify the higher angulations.

After testing, selected archwire samples were evaluated for effects consequential to sliding using a scanning electron microscope at 15 keV (SEM; Model JSM-6300FV, Jeol USA, Peabody, MA, USA). Representative bracket materials were also examined to identify any unique design or material characteristics. All samples were coated with gold–palladium prior to viewing.

Statistical significance was ascribed to the results when a probability value, p, of less than 0.05 was observed. Highly significant observations, where $p < 0.001$, were noted as such. The significance of each $RS-N$ linear regression was determined using the correlation coefficient, r. A fully factorial model analysis-of-variance (ANOVA) was performed to determine significant differences in μ_k and in the y-intercept data of the $RS-N$ regressions (SYSTAT Version 5, SYSTAT, Inc., Evanston, IL, USA). The effects of bracket material, V_f, and θ were investigated in terms of main effects and two-way interactions. Significant interactions were further investigated with Tukey–Kramer pairwise comparisons of the individual treatment means.

3. Results

Prior to testing the composite materials, the testing apparatus and operator were validated against previous results by measuring RS for a "standard" couple. A SS archwire (Standard Edgewise 0.021 in. × 0.025 in., American Orthodontics, Sheboygan, WI, USA) was tested at $\theta = 0°$ and $N = 200, 400, 600, 800$, and 950 g against the SS bracket. A linear regression of the results from this test was highly significant at $\mu_k = 0.12$, which compared favorably with previous frictional studies [20, 23].

Representative P–δ traces for each archwire coupled with the PCA bracket material at $N = 150$ g and $\theta = 0°, 5°$, and $10°$ (Fig. 2) showed that a consistent increase in P was associated with increasing θ. A similar increase in the y-intercept with increasing θ was observed from linear regressions of the corresponding $RS-N$ data (Fig. 3). This increase in the y-intercept was invariably observed for all archwire–bracket couples (Tables II–IV). Using r, all but two of the values of μ_k and the y-intercept that were determined from these regressions were significant and most were highly significant.

The ANOVA showed no difference in μ_k with respect to bracket material, V_f, or θ (Tables II–IV). By averaging all of the significant data points, μ_k of the composite archwires equaled 0.25 ± 0.06.

A highly significant interaction between θ and V_f was observed for the y-intercepts. Tukey–Kramer pairwise comparisons showed no difference in the y-intercepts between $\theta = 0°$ and $2.5°$ or between any of

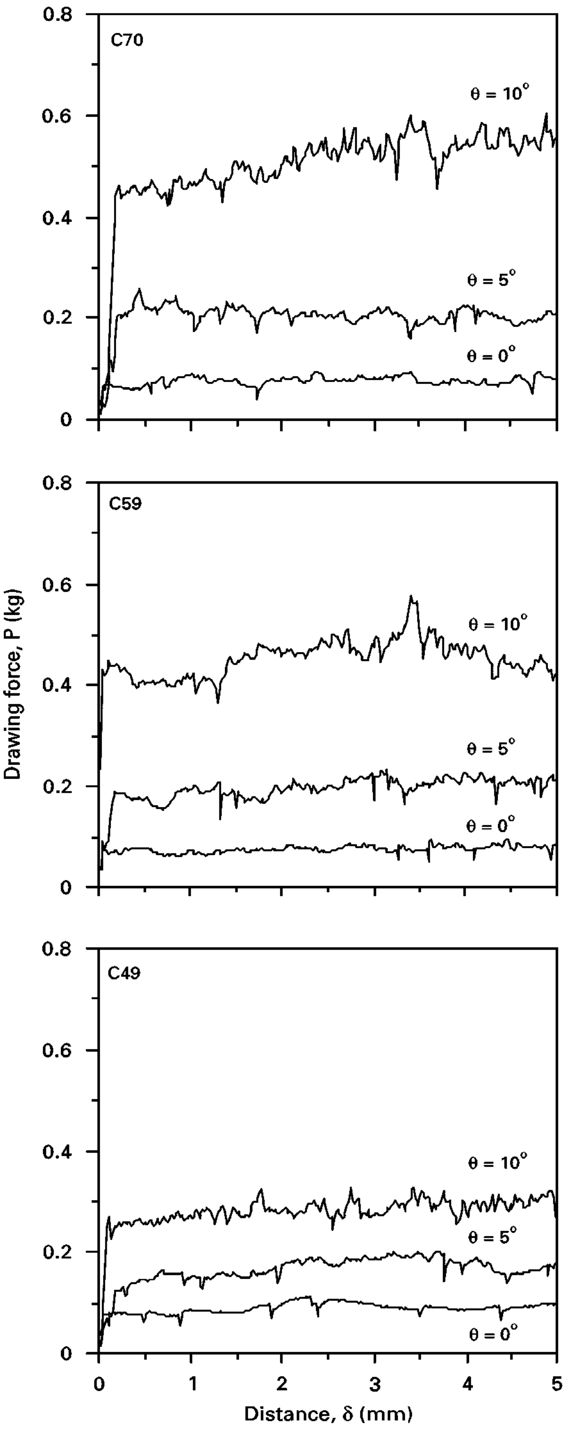

Figure 2 Drawing force, P, versus distance, δ, traces for composite archwires with 0.70, 0.59, and 0.49 volume fraction of reinforcement, V_f (coded C70, C59, and C49, respectively), coupled with the PCA bracket material at a normal force, N, of 150 g and angulations, θ, of 0°, 5°, and 10°.

the bracket materials. However, highly significant differences were observed for all $\theta \geqslant 2.5°$. Significant differences in the y-intercepts were also observed for all V_f.

Scanning electron micrographs of the bracket materials showed the overall design of each bracket as well as the specific appearance of each bracket slot (Fig. 4). Once again, the characteristic rough surface of the PCA bracket can be seen in relation to the smoother surfaces of the SS and SC brackets [21]. The slot edges were also noticeably sharp for each bracket material, but especially for the SC bracket.

Tested samples of the composite archwire showed evidence of wear along the interface between the archwire and the floor of the bracket slot for each bracket material tested (Fig. 5). At $\theta = 0°$, the severity of this wear increased as N increased from 50 g (Fig. 5a) to 400 g (Fig.5b). Wear along the archwire–ligature interface was only visible at the highest levels of N and was much less than the wear observed along the archwire–bracket interface. At $\theta > 2.5°$, wear damage was also observed along the interface between the archwire and the wall of the bracket slot (Fig. 6). Here the severity of the wear increased as θ rose from 2.5° (Fig. 6a) to 12.5° (Fig.6b). No systematic change in the nature or extent of the wear could be detected as a result of the composite archwires bearing against different bracket materials.

4. Discussion

4.1. Comparison with traditional archwire materials

A search of the literature revealed no other studies on the frictional properties of UFRP composites with which to make a relevant comparison to this study. However, valuable comparisons can be made with frictional studies of conventional archwire materials, because these serve as familiar reference points from which to evaluate composite archwires. Of particular interest is how the frictional properties of composite archwires compare with those of nickel titanium (NiTi) and beta-titanium (β-Ti) archwire materials, because the stiffness limits outlined by NiTi and β-Ti are similar to those outlined by the current generation of composite archwires. Also of interest is how composite archwires compare to SS archwires, which have traditionally demonstrated better frictional properties than other archwire materials.

The standard couple tested in this study confirmed the validity of the frictional data and allowed these results to be compared to previous studies [20 –23]. The average μ_k of the composite archwires was compared to the μ_k values that had been previously determined for NiTi, β-Ti, and SS archwires coupled with SS and PCA brackets [22] and with SC brackets [21] (Fig. 7). This comparison showed that, for all of the bracket materials tested, the composite archwires had a lower μ_k than the NiTi and β-Ti archwires but a higher μ_k than the SS archwire. For the SC bracket this translated into $\mu_k = 0.52$, 0.54, and 0.16 for NiTi, β-Ti, and SS archwire materials, respectively, as compared to $\mu_k = 0.25$ for the composite archwires (cf. Fig. 7).

4.2. Effect of bracket material and V_f on μ_k

Despite the fact that the surfaces of the bracket slots were all different (cf. Fig. 4 and [21]), the frictional characteristics of the composite archwires against each bracket were similar. Ceramic brackets have been shown to have higher friction than their SS counterparts [14, 17–19]. This observation has been associated with structural characteristics, such as the rough surfaces of PCA brackets or the sharp slot edges

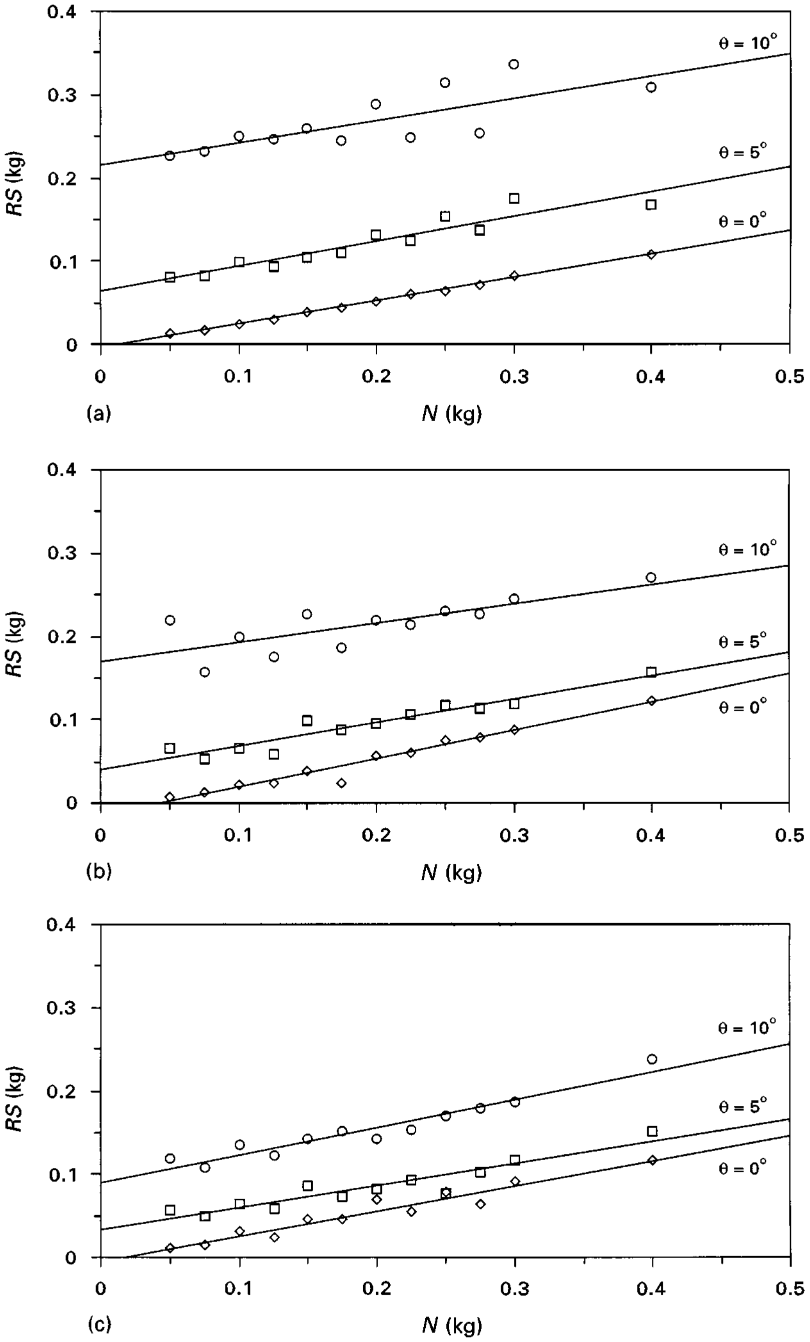

Figure 3 Linear regression plots of the resistance to sliding, *RS*, versus *N* data for the (a) C70, (b) C59, and (c) C49 composite archwires coupled with the PCA bracket material at $\theta = 0°$, $5°$ and $10°$.

of SC brackets. Indeed, these conditions were confirmed in the micrographs of the bracket slots (cf. Fig. 4).

The bracket materials tested in this study were all much harder than the polymeric matrices of the composite archwires. Examination of archwires samples that were tested at $\theta = 0°$ showed that reinforcement was peeled away from the surface of the wire, especially at high *N* (cf. Fig. 5). The frictional mechanism that is associated with this type of abrasive wear, known as plowing, is common in sliding friction when one material is much harder than the other [15, 26, 27]. Consequently, the similar values of μ_k suggested that RS was dominated by plowing of the composite by the edges of the bracket slot. Any contributions that were attributable to the specific characteristics of the brackets were likely eclipsed by this mechanism.

The statistical analysis showed no difference in μ_k between the three composite archwires. Considering that the observed abrasive wear ensured that the contact surface of the archwire with the bracket slot consisted of both reinforcement and matrix materials, the differences in the reinforcement–matrix composition suggest that μ_k should vary. The results can be explained by the non-homogeneity of the reinforcement fiber distribution, however, as the photo-pultrusion manufacturing method tended preferentially to position the reinforcement fibers toward the perimeter of each composite's cross-section [11]. As V_f was increased, the additional reinforcement displaced the

TABLE II Summary of normal force, N, versus resistance to sliding, RS, regression data for the C70 composite wire

Bracket	Angulation, θ (deg)	Coefficient of friction, μ_k	y-intercept (kg)	Correlation coefficient, r[a]
SS	0	0.24	−0.01	0.97
	2.5	0.21	0.00	0.99
	5.0	0.21	0.04	0.95
	7.5	0.41	0.07	0.86
	10.0	0.10	0.21	0.22[b]
	12.5	0.30	0.23	0.63[c]
PCA	0	0.28	0.00	1.00
	2.5	0.31	0.01	1.00
	5.0	0.30	0.06	0.94
	7.5	0.34	0.09	0.91
	10.0	0.27	0.22	0.77[d]
	12.5	0.13	0.28	0.34[b]
SC	0	0.28	−0.01	0.99
	2.5	0.30	0.00	0.98
	5.0	0.24	0.06	0.96
	7.5	0.31	0.10	0.90
	10.0	0.23	0.22	0.60[c]
	12.5	0.33	0.22	0.61[c]

[a] $p < 0.001$ except where indicated.
[b] Not significant.
[c] $p < 0.05$.
[d] $p < 0.01$.

TABLE III Summary of normal force, N, versus resistance to sliding, RS, regression data for the C59 composite wire

Bracket	Angulation, θ (deg)	Coefficient of friction, μ_k	y-intercept (kg)	Correlation coefficient, r[a]
SS	0	0.22	−0.01	1.00
	2.5	0.24	−0.01	0.99
	5.0	0.22	0.03	0.88
	7.5	0.17	0.08	0.79[b]
	10.0	0.24	0.14	0.84
	12.5	0.22	0.22	0.54[c]
PCA	0	0.34	−0.02	0.98
	2.5	0.27	0.00	1.00
	5.0	0.28	0.04	0.96
	7.5	0.17	0.10	0.96
	10.0	0.23	0.17	0.77[b]
	12.5	0.26	0.17	0.88
SC	0	0.23	0.00	0.99
	2.5	0.27	0.01	0.99
	5.0	0.27	0.06	0.87
	7.5	0.26	0.09	0.98
	10.0	0.16	0.16	0.65[c]
	12.5	0.30	0.21	0.81[b]

[a] $p < 0.001$ except where indicated.
[b] $p < 0.01$.
[c] $p < 0.05$.

polymer-rich region that existed at the center of the composite, but the reinforcement concentration at the perimeter remained the same (Fig. 5 of [11]). Thus, the composite surface that was in sliding contact with the bracket was virtually identical for all three archwires, despite the overall difference in V_f.

4.3. Effect of θ and V_f on the y-intercept

The $P - \delta$ traces showed that increases in P were associated with increases in θ (cf. Fig. 2). This relationship was indicative of the active configuration and resulted from binding between the archwires and the walls of the bracket slots. Articolo and Kusy [28] reported that increases in RS that were associated with binding did not effect μ_k (cf. Fig. 11 of [28]). Instead, they observed that binding caused the height of the $RS - N$ linear regression lines to increase. These same observations were made here for composite archwires from the $RS - N$ data plots and were confirmed by the statistical analysis (cf. Fig. 3 and Tables II–IV, respectively). In the RS–N plots, the linear regression for $\theta = 0^\circ$, 5°, and 10° were all nearly parallel and increased in height with increasing θ. For convenience, the increase in regression line height was evaluated in terms of the y-intercept.

When composite archwire samples that had been tested for $\theta = 2.5°–12.5°$ were examined, notching was noted for $\theta > 2.5°$ (cf. Fig. 6). In addition, the pairwise comparisons of the individual treatment means showed that the y-intercept was different for all $\theta > 2.5°$, but that no significant difference existed between $\theta = 0°$ and 2.5° (cf. Tables II–IV). These observations indicated that the passive configuration existed for $\theta \leqslant 2.5°$. Thus, the effects of binding were present only when the active configuration existed for $\theta > 2.5°$. (This value of $\theta = 2.5°$ was specific to this study and could shift $\pm$ 2.5°, depending upon the relative geometry of the archwire–bracket couple tested [29].)

TABLE IV Summary of normal force, N, versus resistance to sliding, RS, regression data for the C49 composite wire

Bracket	Angulation, θ (deg)	Coefficient of friction, μ_k	y-intercept (kg)	Correlation coefficient, r^a
SS	0	0.27	− 0.01	0.99
	2.5	0.28	− 0.02	0.98
	5.0	0.24	0.02	0.98
	7.5	0.24	0.06	0.96
	10.0	0.19	0.11	0.81^b
	12.5	0.23	0.12	0.76^b
PCA	0	0.30	− 0.01	0.97
	2.5	0.22	0.01	0.98
	5.0	0.27	0.03	0.94
	7.5	0.17	0.09	0.80^b
	10.0	0.33	0.09	0.96
	12.5	0.17	0.15	0.51^c
SC	0	0.26	− 0.01	0.97
	2.5	0.25	0.00	0.96
	5.0	0.21	0.04	0.88
	7.5	0.18	0.09	0.84
	10.0	0.20	0.11	0.74^b
	12.5	0.08	0.18	0.65^c

[a] $p < 0.001$ except where indicated.
[b] $p < 0.01$.
[c] $p < 0.05$.

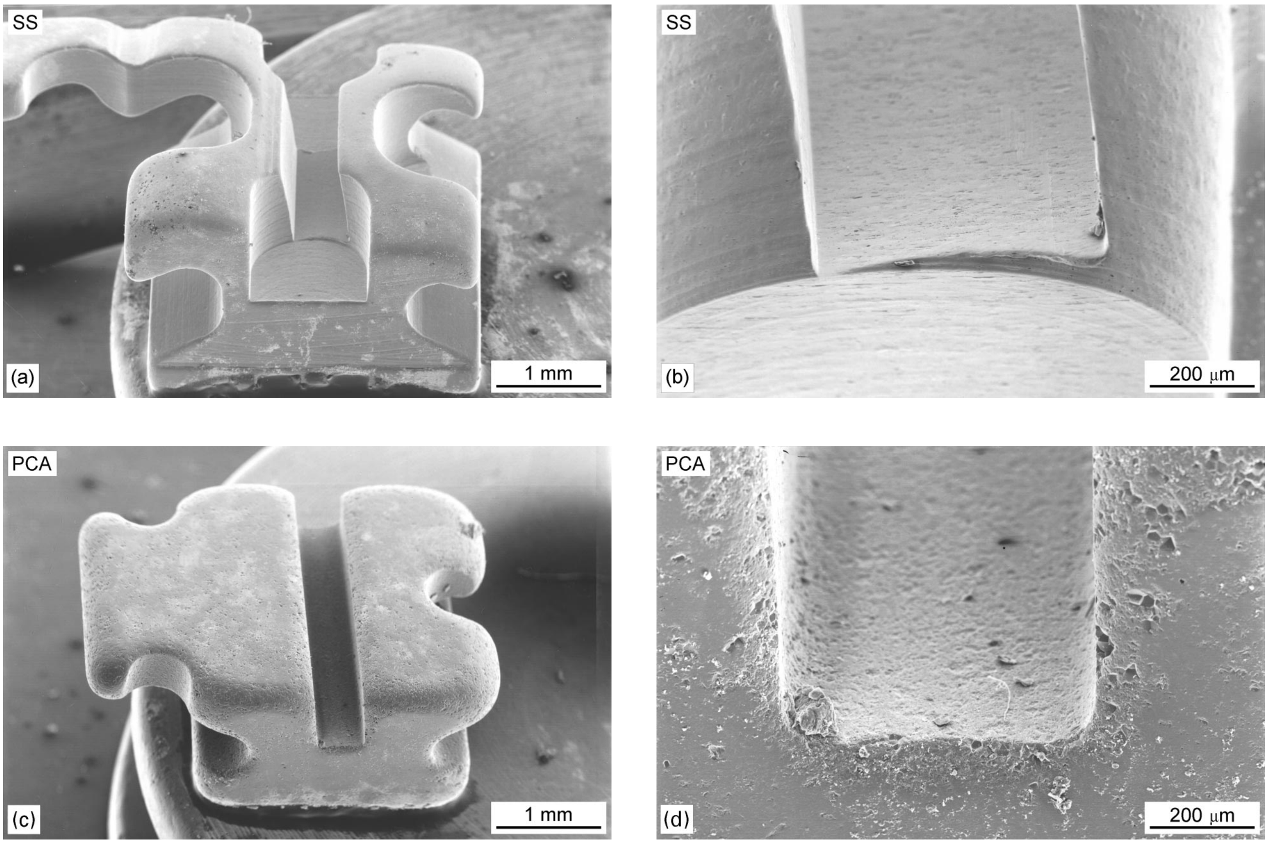

Figure 4 Scanning electron micrographs of (a, b) stainless steel (SS), (c, d) polycrystalline alumina (PCA), and (e, f) single-crystal alumina (SC) brackets. For each bracket material, the entire bracket and details of the edges and floor of the bracket slot are shown.

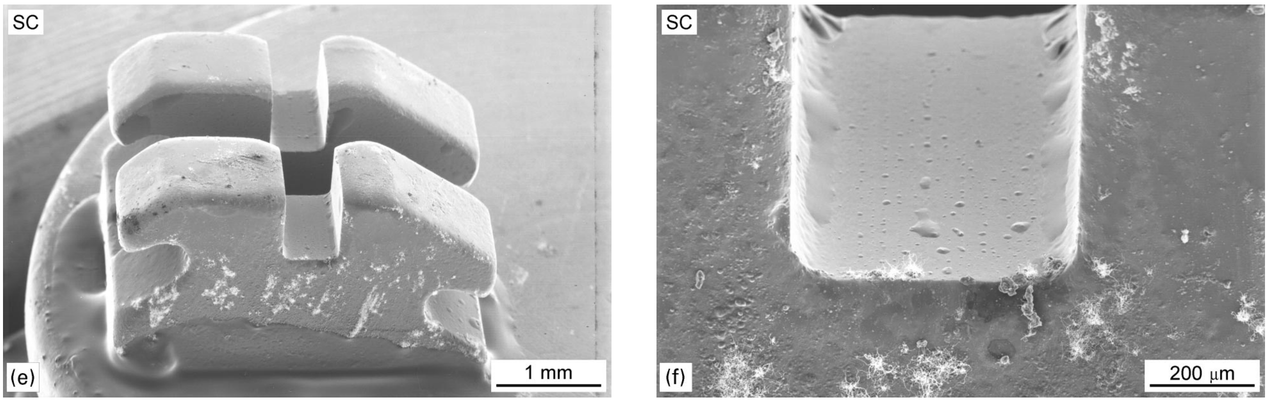

Figure 4 (Continued).

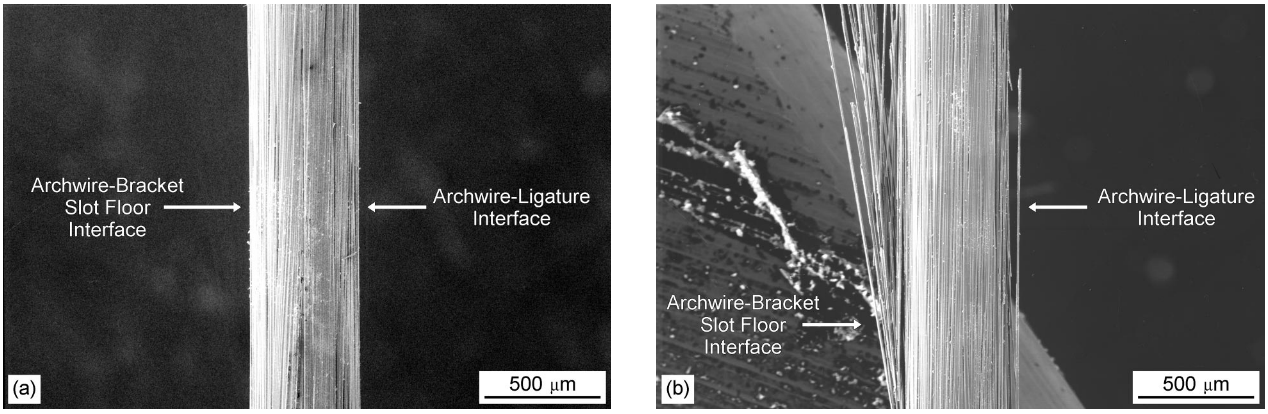

Figure 5 Scanning electron micrographs of C59 composite archwires tested in the passive configuration at $\theta = 0°$, when $N =$ (a) 50 g and (b) 400 g.

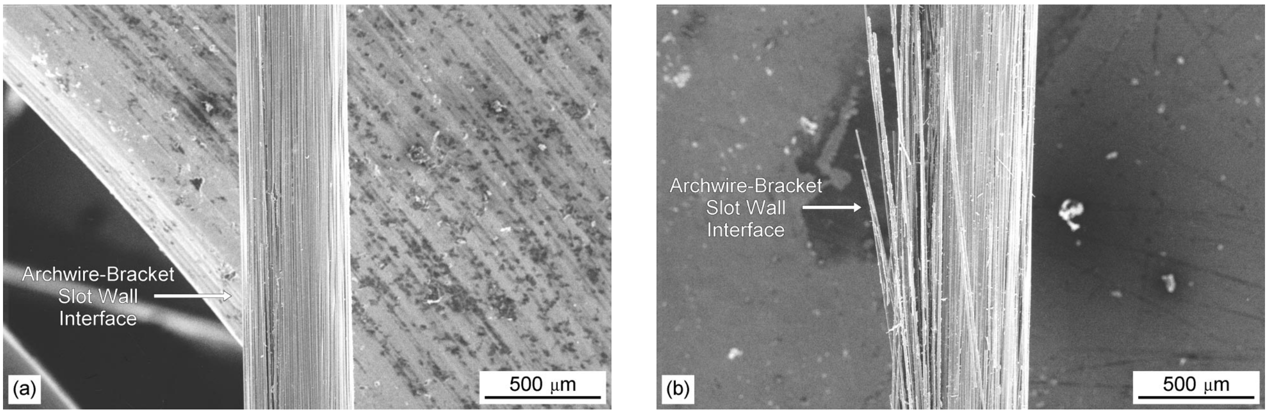

Figure 6 Scanning electron micrographs of C59 composite archwires tested at $N = 100$ g, when in the active configuration at $\theta =$ (a) 2.5° and (b) 12.5°.

In the active configuration, a highly significant positive correlation between the y-intercept and θ was revealed from a least-squares linear regression of the data at each V_f (Fig. 8). This regression was similar to the $RS - N$ linear regressions that were used to determine μ_k.

Specifically, the y-intercept was correlated with the RS due to binding, and θ was indicative of the force between the wall of the bracket slot and the archwire. The mechanics that related θ to the force between the wall of the bracket slot and the archwire is beyond the scope of this discussion. Nevertheless, the slopes of these regressions (Fig. 8) were useful indicators of the binding sensitivity of the composite archwires. These slopes equalled 0.015, 0.021, and 0.025 for the C49, C59, and C70 composite archwires, respectively. The differences in these slopes were attributable to the fact that, as V_f increased, the stiffness of the archwires also increased. Based on the results of a prior study, the stiffness of the present composites nominally varied

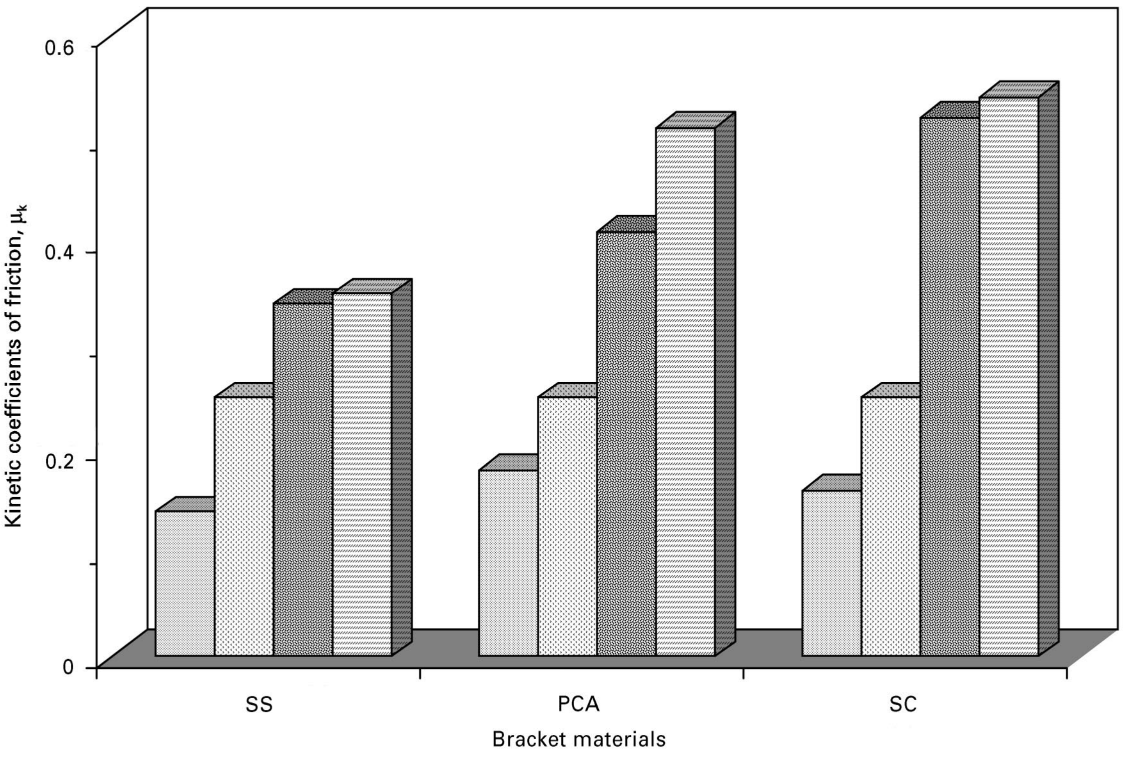

Figure 7 Mean kinetic coefficients of friction, μ_k, for all composite archwires (░) compared to values for (▒) stainless steel, (▓) nickel titanium, and (▤) beta-titanium archwires as determined from previous studies [18–20].

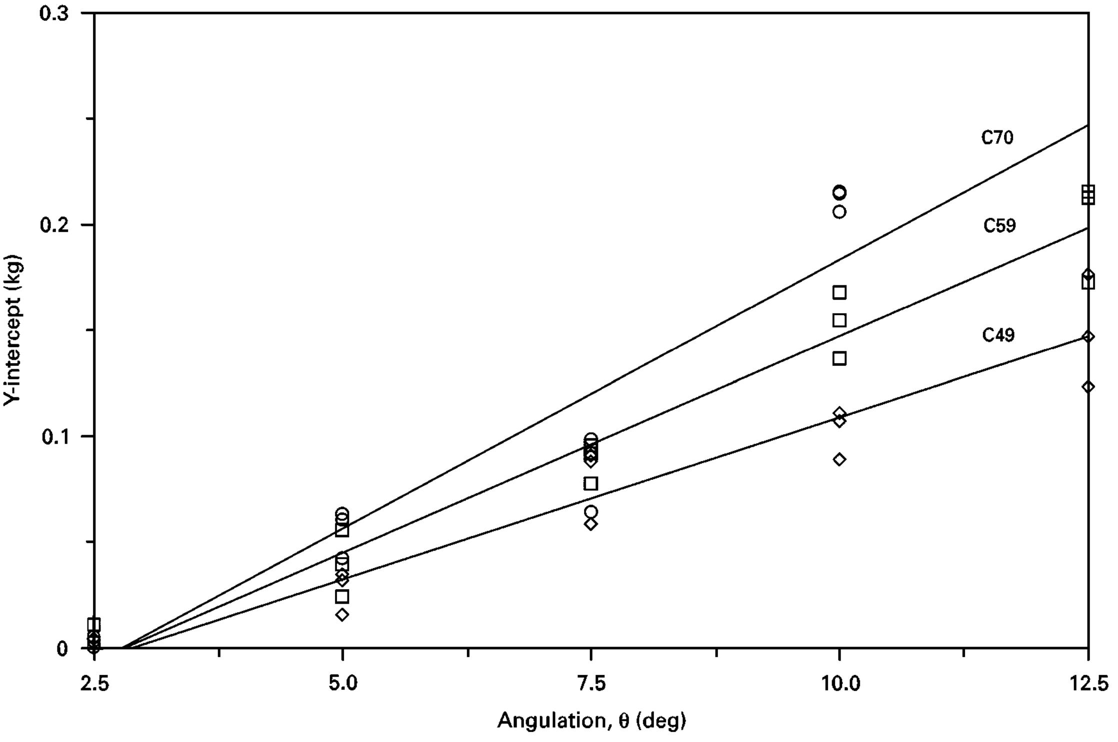

Figure 8 Linear regression plots of y-intercept versus θ data for the (○) C70, (□) C59, and (◇) C49 composite archwires.

from 36 – 60 GPa [11]. For a given θ, this increase in the stiffness with V_f caused an increase in the binding force and a corresponding increase in the y-intercept. Similar results were observed previously for metallic archwire materials [28].

4.4. Reducing composite archwire wear

The scanning electron micrographs of the tested composite archwires showed extensive surface wear for the higher levels of N and θ (cf. Figs 5b and 6b). Although this wear is not likely to alter the mechanical integrity of the archwire in the single-pass scenario that is typical of sliding mechanics, the liberation of the reinforcing fibers within the oral cavity is unacceptable. A possible solution to this problem is to place a thin protective coating on the archwires. The ideal coating would protect the archwires from wear, while reducing μ_k and the binding sensitivity. The reduced wear that was observed at the ligature–archwire interface suggested that improvements could also be made to the bracket design. Smoother surfaces and contoured slot edges would limit plowing and the resulting abrasive wear damage to the composite's surface.

5. Conclusions

The frictional characteristics of prototype composite archwires have been investigated. From $RS - N$ linear regressions, the μ_k values and the y-intercepts were evaluated as functions of bracket material, V_f, and θ. The following conclusions were drawn.

1. The overall μ_k for the composite archwires was greater than SS but less than either NiTi or β-Ti archwire materials, as determined from previous studies of metallic archwires.
2. In both the passive and active configurations, the μ_k values of the composite archwires were unaffected by bracket material, V_f, or θ.
3. In the active configuration, the y-intercepts increased with respect to V_f and θ due to increased binding.
4. The slopes of y-intercept versus θ plots were indicative of the binding sensitivity of the composite archwires. These slopes increased with V_f because of the corresponding increase in wire stiffness.
5. Abrasive wear of the composite archwire increased with N because of plowing and, in the active configuration, with θ because of notching.
6. Further research into methods of reducing abrasive wear could improve the sliding mechanics of composite archwires.

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