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Influence of ceramic and stainless steel brackets on the notching of archwires during clinical treatment

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SUMMARY The surface topography of 100 clinically used archwires of stainless steel, beta-, or nickel-titanium were investigated that had contacted either ceramic or stainless steel brackets. One group consisted of two sets: 60 wires with no treatment records accessed to bias analyses, and 40 wires for which extensive clinical records were available, half of which were used with ceramic or stainless steel brackets. A control group consisted of two sets: 30 unused wires comprised of five round and rectangular wires of each alloy, and four wires that were ligated and immediately removed from patients' mouths. After ultrasonic cleaning, each wire was inspected under an optical and/or a scanning electron microscope. Notches were categorized with regard to frequency, patterns, and severity, and mapped as a function of wire aspect (lingual, facial, and occlusal/gingival) and anatomical regions (molar, premolar, canine, and incisor). From these data the average severity of notch patterns and a notching index were derived. Although no recognizable defect patterns were observed in the control group, seven basic patterns were recognized for each wire cross-sectional shape in the clinically used wires. These wires appeared most damaged on their lingual aspect and least damaged on their facial aspect. With regard to anatomical regions, notching was prevalent in the anterior regions and sparse in the molar regions. The notch activity and the severity were nearly three times greater from ceramic brackets than from stainless steel brackets. Over one-third of all notches documented in ceramic bracket cases had severity numbers of 3 and penetrated at least one-quarter of each wire's dimension, However, over two-thirds of all notches documented in stainless steel bracket cases had severity numbers of 1. From these tabulations a theory of notch formation was proposed in which vertical movement from tooth or wire during mastication caused fretting wear, and horizontal movement during orthodontic procedures such as space closure, tipping, or bodily movement caused sliding wear.

Introduction

When sliding mechanics are employed to either close or regain space in the dental arch, mechanical phenomena will resist the applied force (F) used to move the teeth. Three mechanical phenomena are known to cause the resistance to sliding (RS) of a bracket along an archwire (Kusy and Whitley, 1997): classical friction (FR), binding (BI), and notching (NO). Friction (Figure 1, top) and binding (Figure 1, middle) have previously been shown to compromise significantly the efficiency and reproducibility of sliding mechanics (Articolo and Kusy, 1999). Notching, which has largely been overlooked by the profession in the past, is now suspected to cease sliding altogether (Kusy *et al*., 1998). Notching (Figure 1, bottom) may be defined as the observed mechanical damage to an archwire that occurs during the latter stages of binding, which manifests itself as recognizable defects of varying number, pattern, and severity. The relevance of archwire notching regarding tooth movement is two-fold: first, the mere presence

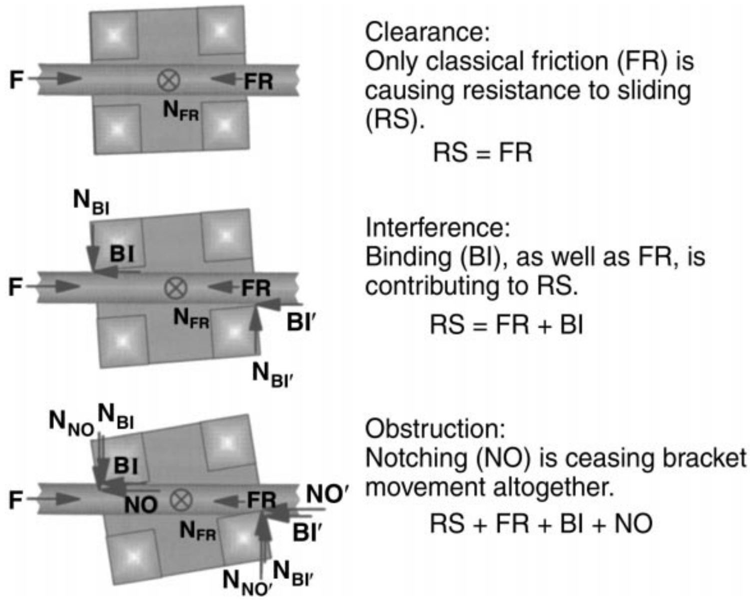

Figure 1 Three frictional phenomena that increase the resistance to sliding (RS) between an archwire and bracket: classical friction (FR), binding (BI), and notching (NO). As the angulation increases, ample clearance gives way to an interference fit until the wire is obstructed by the bracket slot. Note that whether the normal forces of classical friction (N_{FR}), the normal forces of binding (N_{BI} and $N_{BI'}$), or the normal forces of notching (N_{NO} and $N_{NO'}$) are applied into the slot floor or the slot wall in any combination, the classical friction force (FR), binding forces (BI or BI′), and the notching forces (NO and NO′) are parallel to the long axis of the wire and oppose the applied force (F).

of notching is evidence of sluggish movement; second, the resultant notches create 'obstacles' that obstruct further movement.

The surface damage of a material, which is caused by the contact and movement against another material, represents a readily recognizable phenomenon called 'wear' (Czichos, 1986). Tribology, or the science of friction and wear phenomena, has explored the cause and effect of surface damage for a wide range of materials extending from the ball bearings in industrial machinery to the ball-and-socket or sliding joints of medical prostheses (Park and Lakes, 1992). The goal of tribology is to understand such phenomena to lessen the deleterious effects that they may have on the efficiency and longevity of such systems. Types of mechanical wear applicable to orthodontic treatment include fretting, sliding, and galling (these terms will be defined in the Discussion section) that result in fatigue, adhesion, abrasion, and seizure between the wire and the bracket during orthodontic movement (Blau, 1989; Jastrzebski, 1976). Moreover, the nature of mechanical wear is cyclic in that these effects actually cause increased wear. Generally, the volume of material that is worn away as a result of adhesive wear (V) is directly proportional to the applied force (F) and sliding distance of the materials (d), but inversely proportional to the hardness (H) of the softer of the two interacting materials according to the relationship, $V = (k/3)(Fd/H)$, where k equals the wear coefficient (Shackelford, 1996). Note that H is proportional to the yield strength (YS) for not only pure metals (e.g. copper in which $H = 3\ YS$) (Gilman, 1973) and ionic crystals (e.g. titanium carbide in which $H = 35\ YS$) (Gilman, 1973; Rice, 1973), but also for metal alloys such as ductile iron and silicon steel (Abson *et al*., 1973). Correlations also exist between H and elastic moduli (E) for many noble metals and covalent crystals (Gilman, 1973).

The manifestation of mechanical wear in orthodontic appliances was initially noted by Tanne *et al*., 1991) as 'scratches' present on wires 'artificially' sliding within ceramic and metal brackets. Others (Kusy and Whitley, 1990; Saunders and Kusy, 1994; Keith *et al*., 1994) found wire debris in ceramic and metal bracket slots after sliding, citing 'adhesion' and 'abrasion' between the materials as the cause. Although superficially nothing appeared unusual about a wire removed from a patient after canine retraction using stainless steel brackets, Siatkowski (1997) reported 'considerable wear and tear', as well as 'gouging' of the wire upon microscopic examination. Hansen *et al*. (1998) conducted the only *in vivo* study to date that specifically addressed 'notching' damage during orthodontic treatment. They reported that stainless steel wires suffered 'overwhelming damage' when clinically used with ceramic brackets. Moreover, the damage was characterized as a finite series of distinct notching patterns in accordance with the size and shape of an orthodontic bracket. Thus, the present study was undertaken to investigate more extensively the phenomenon of notching, which occurs during orthodontic treatment. The ultimate goal is to elucidate notching, its aetiology, and its effect during clinical treatment.

Materials and methods

Two archwire-bracket groups, which comprised four sets, were evaluated in this study (Table 1). The control group comprised two sets. Control group, set 1 consisted of five round and five rectangular as-received unused archwires each of three alloys [stainless steel (SS), beta-titanium (β-Ti), and nickel titanium (NiTi)] for a total of 30 archwires. Control group, set 2 consisted of two SS–SS archwire-bracket combinations and two SS-ceramic (CER) archwire-bracket combinations. This set was clinically ligated, immediately removed, and visually inspected for iatrogenically induced damage. Likewise, the experimental group comprised two sets. Experimental group, set 1 consisted of a random sampling of 10 round and 10 rectangular clinically used archwires each of three alloys (SS, β-Ti, and NiTi) for a total of 60 archwires with no treatment records to bias them. Experimental group, set 2 consisted of 40 archwires that had been used in initial alignment, levelling, and finishing of patients. These came with complete records, which showed that no premolar extraction cases were included and that elastomeric ligatures dominated these treatments. Following standard orthodontic procedure, half of this set were wires used against CER brackets (primarily in the upper arch from at least 3–3) with the balance being SS brackets. The other half of this set were wires used exclusively against SS brackets in the upper or lower arch. None of the brackets had inserts. All of these archwires were ultrasonically cleaned with a 10:1 non-ionic multi-purpose ultrasonic solution (Health Sonics Corp., Pleasanton, CA), and inspected using an optical macroscope (AO American Optical Corp., Southbridge, MA) and/or a scanning electron microscope (SEM; JEOL JSM-6300, Oberkochen, Germany) without conductive coatings at 15 keV in the secondary electron mode.

Table 1 Number of archwires evaluated for a given bracket within different groups and sets.

Control group		Experimental group	
Set 1 Archwire-bracket	Set 2 Archwire-bracket	Set 1 Archwire-bracket	Set 2 Archwire*-bracket**
10 stainless steel (SS)-none 10 beta-titanium (β-Ti)-none 10 nickel titanium (NiTi)-none	2 SS-SS 2 SS-ceramic (CER)	20 SS-unknown 20 β-Ti-unknown 20 NiTi-unknown	12 SS-CER 13 SS-SS 8 NiTi-CER 7 NiTi-SS

*Only SS and NiTi archwires were considered in this study as they represent the outer bounds of stiffness behaviour.
**All brackets were 0.022-inch edgewise, and the CER brackets were polycrystalline alumina, typically from canine to canine in the maxillary arch.

The notches that were observed for each archwire were mapped with regard to their wire aspects (L, lingual; F, facial; and O/G, occlusal/gingival) and anatomical regions (M, molar; B, premolar; C, canine; and I, incisor). The wire aspect was designated according to its normal intra-oral position. The method of determining the region involved the use of a semi-circular grid composed of 16 segments, each subtending an arc of 11.3 degrees (Figure 2). The archwires were placed on the grid to designate segments that most similarly represented the anatomical characteristics of a typical dental arch. The segments were assigned as follows: M = 6 segments (0–33.8 degrees and >146.3–180 degrees); B = 4 segments (>33.8–56.3 degrees and >123.8–146.3 degrees); C = 2 segments (>56.3–67.5 degrees and >112.5–123.8 degrees); and I = 4 segments (>67.5–112.5 degrees). The number of notches, which were mapped at each specific anatomical region and wire aspect, equalled the notch frequency (NOn) or simply *n*. Notches that occupied contiguous surfaces (e.g. lingual and facial) were mapped as having an $n = 0.5$ for both aspects. For calculations, notches occurring in the premolar and molar regions of the CER bracket cases were attributed to ceramics, although both CER and SS brackets were used on the premolars and SS tubes were exclusively used on the molars.

The most commonly observed notches were classified according to wire cross-sectional shape (round and rectangular), pattern (singular or paired), and severity (relative size and depth; Figure 3). When the notching pattern (NOp) consisted of a single notch, it was classified as the 'S' category; when the NOp consisted of an associated pair of notches, it was classified as the 'P' category. Note that, although both 'S' and 'P' were each a single pattern, their *n* values equalled 1 and 2, respectively. Depending upon the perceived notch severity (NOs), which was based on the relative size and depth of the notch, each NOp was then assigned an NOs number of '1', '2', or '3'. When an NOp appeared as two distinct patterns that overlapped each other (mainly applicable to 'P' category), the category was repeated accordingly. Therefore the notation, 'PP,2', meant that two pairs of notches ('PP') were observed that had moderate severity ('2') (cf. Figure 3, bottom). When a rare or unusual NOp occurred that could not be classified, it was assigned to the 'X' category. These usually consisted of random shallow scratches and scrapes.

After all the archwires were observed, the mappings were analysed according to NOp, NOs,

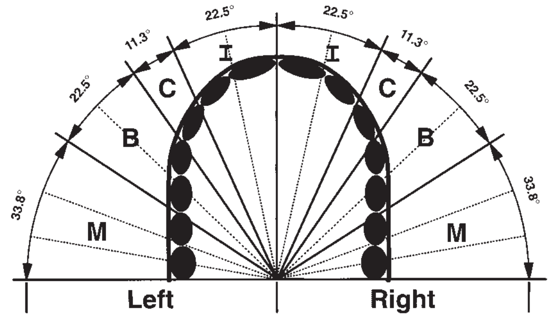

Figure 2 Breakdown of the oral cavity into 16 equal segments and eight anatomical regions per dental arch to facilitate mapping: molar (M), premolar (B), canine (C), and incisor (I). Note that, although this figure contains the teeth corresponding to its given identity, the angular position is independent of upper/lower jaw, arch length, or tooth dimensions.

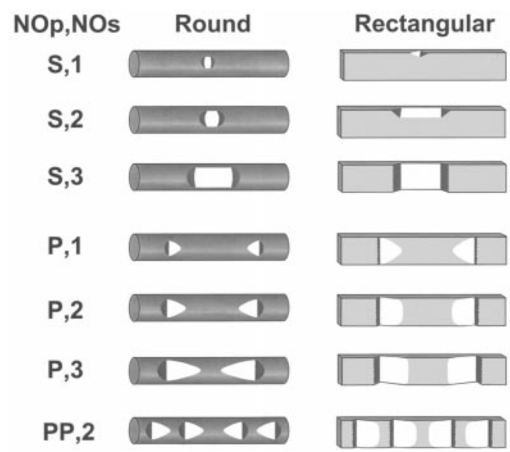

Figure 3 Catalogue of the 14 commonly observed notches according to wire cross-sectional shape (round or rectangular), pattern (NOp: singular, S, or paired, P), and severity (NOs: 1, 2, or 3). Less than 6 per cent of all notches did not coincide with one of the 14 shown.

and NOn. From these raw data several quantities were acquired:

Total number of notch patterns = $(\mathrm{NOp})_{\mathrm{TOTAL}}$ $= n_{S,1} + n_{S,2} + n_{S,3} + n_{P,1} + n_{P,2} + n_{P,3} + n_{X,1}$ (1)

Total severity of notch patterns = $(\mathrm{NOs})_{\mathrm{TOTAL}} = n_{S,1} + 2n_{S,2} + 3n_{S,3} + n_{P,1} + 2n_{P,2} + 3n_{P,3} + n_{X,1}$ (2)

Total number of notches = $(\mathrm{NOn})_{\mathrm{TOTAL}} = n_{S,1} + n_{S,2} + n_{S,3} + 2n_{P,1} + 2n_{P,2} + 2n_{P,3} + n_{X,1}$, (3a)

or equivalently as

$= n_{L,M} + n_{L,B} + n_{L,C} + n_{L,I} + n_{F,M} + n_{F,B} + n_{F,C} + n_{F,I} + n_{O/G,M} + n_{O/G,B} + n_{O/G,C} + n_{O/G,I}$ (3b)

Average number of notches per pattern = $(\mathrm{NOn})_{\mathrm{TOTAL}}/(\mathrm{NOp})_{\mathrm{TOTAL}}$

= [eqn (3a)]/[eqn (1)], (4a)

or equivalently as

= [eqn (3b)] / [eqn (1)] (4b)

Average severity of notches per pattern = $(\mathrm{NOs})_{\mathrm{TOTAL}}/(\mathrm{NOp})_{\mathrm{TOTAL}}$ = [eqn (2)]/[eqn (1)] (5)

Notching index = ν

= (average no. of notches per pattern) • (total severity of notch patterns)

$= [(\mathrm{NOn})_{\mathrm{TOTAL}}/(\mathrm{NOp})_{\mathrm{TOTAL}}] \bullet (\mathrm{NOs})_{\mathrm{TOTAL}}$

= [eqn (3a)] • [eqn (5)], (6a)

or equivalently as

= (average severity of notches per pattern) • (total no. of notches)

$= [(\mathrm{NOs})_{\mathrm{TOTAL}}/(\mathrm{NOp})_{\mathrm{TOTAL}}] \bullet (\mathrm{NOn})_{\mathrm{TOTAL}}$

= [eqn (5)] • [eqn (3b)] (6b)

Results

Although the control group of as-received but unused archwires and clinically ligated but immediately removed archwires (cf. Table 1, control group, sets 1 and 2, respectively) had no consistently recognizable defect patterns, 14 different NOp's were classified from the two sets of the experimental group (Table 1), seven for each wire cross-sectional shape (Figure 3). The seven patterns were readily placed into just two types (S and P), since they appeared to differ in severity by a number from '1' to '3' or, as in the last wire, by an overlap of two similar patterns (PP,2). Each of the seven NOp's observed on the round wires (Figure 3, left-hand side) had analogous NOp's on the rectangular wires (Figure 3, right-hand side). These NOp's accounted for approximately 90 per cent of all perceived defects on the archwires. The remaining 10 per cent, which were deemed notable, was placed into the miscellaneous 'X' type of severity '1' (Figure 4, right canine, C, and right premolar, B).

When clinically used SS, β-Ti, and NiTi archwires were viewed at the four anatomical regions, notches were observed that varied in frequency, pattern, and severity. These wires (Table 1, experimental group, sets 1 and 2) appeared most damaged on their lingual aspects and least damaged on their facial aspects. Most often notching was noted in the canine region and least often in the molar region. Stiffer wires, whether from an inherently larger elastic modulus (e.g. an 0.018-inch SS versus an 0.018-inch NiTi wire) or a larger geometric effect (e.g. an 0.018-inch versus an 0.016-inch SS wire), suffered most when bearing against the universally harder CER brackets. The photomicrographs of the round and rectangular arches illustrate the influence of wire aspect and anatomical region (Figures 4 and 5). When β-Ti and Ni-Ti patterns were compared with SS patterns, no noteworthy differences were seen between these wire alloys except for a slightly softer or burnished appearance in the two Ti alloys over the SS.

Having qualitatively evaluated many archwires, detailed notch mapping (Tables 2 and 3) from 40 clinically used archwires (Table 1, experimental group, set 2) showed the wide range of notching activity observed. Using the NOp of a given NOs as the basis, all three S- and P-type notching patterns were seen, four of which were quite

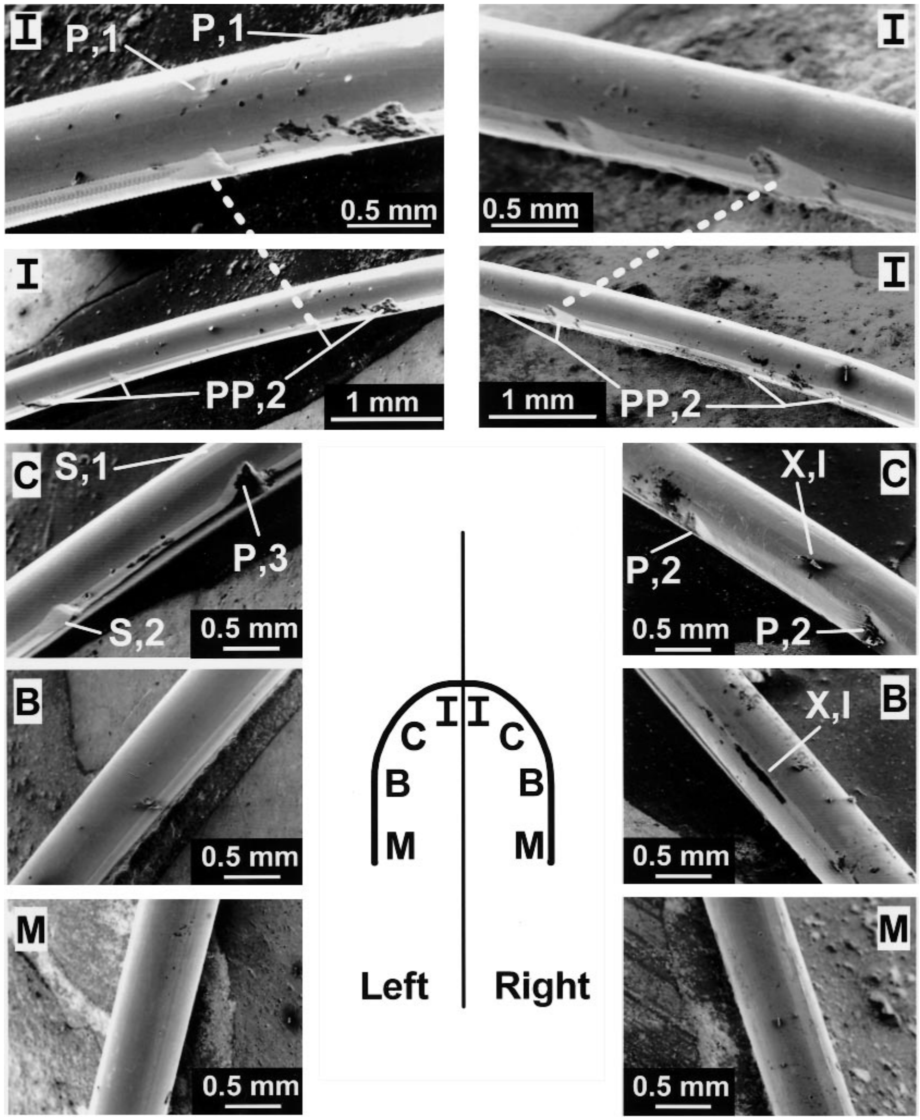

Figure 4 Ten scanning electron photomicrographs of a clinically used 0.018-inch stainless steel (SS) wire at its eight anatomical regions (Figure 2). In the M region, this wire is typical of as-received wires and is relatively free of build-up (BU) of plaque, calculus, food debris, or gross oxidation. In the B and C regions tears in the surface (X,1) are shown, one of which is still partially attached. In the C regions, one P,3 notch is seen on the lingual aspect, which penetrates nearly half way through the wire. Also seen at C and I regions are less numerous and less severe notches (e.g. S,1) on the occlusal-gingival aspect. The wire was examined without any coating preparation in the secondary electron mode at a voltage potential of 15 keV.

prevalent for CER brackets (S,1; S,3; P,2; and P,3; cf. Table 2) and one of which was quite prevalent for SS brackets (S,1; cf. Table 3). The $(NOp)_{TOTAL}$ ranged from 3 to 39 for the CER bracket cases and from 0 to 13 for the SS bracket cases. The average number of NOp per wire was 14.5 (= 289/20) versus 5.5 (= 110/20) for CER and SS bracket cases, respectively; whereas, the average severity of the NOp per case were 29.6 (= 591/20) and 8.1 (= 161/20) for CER and SS bracket cases,

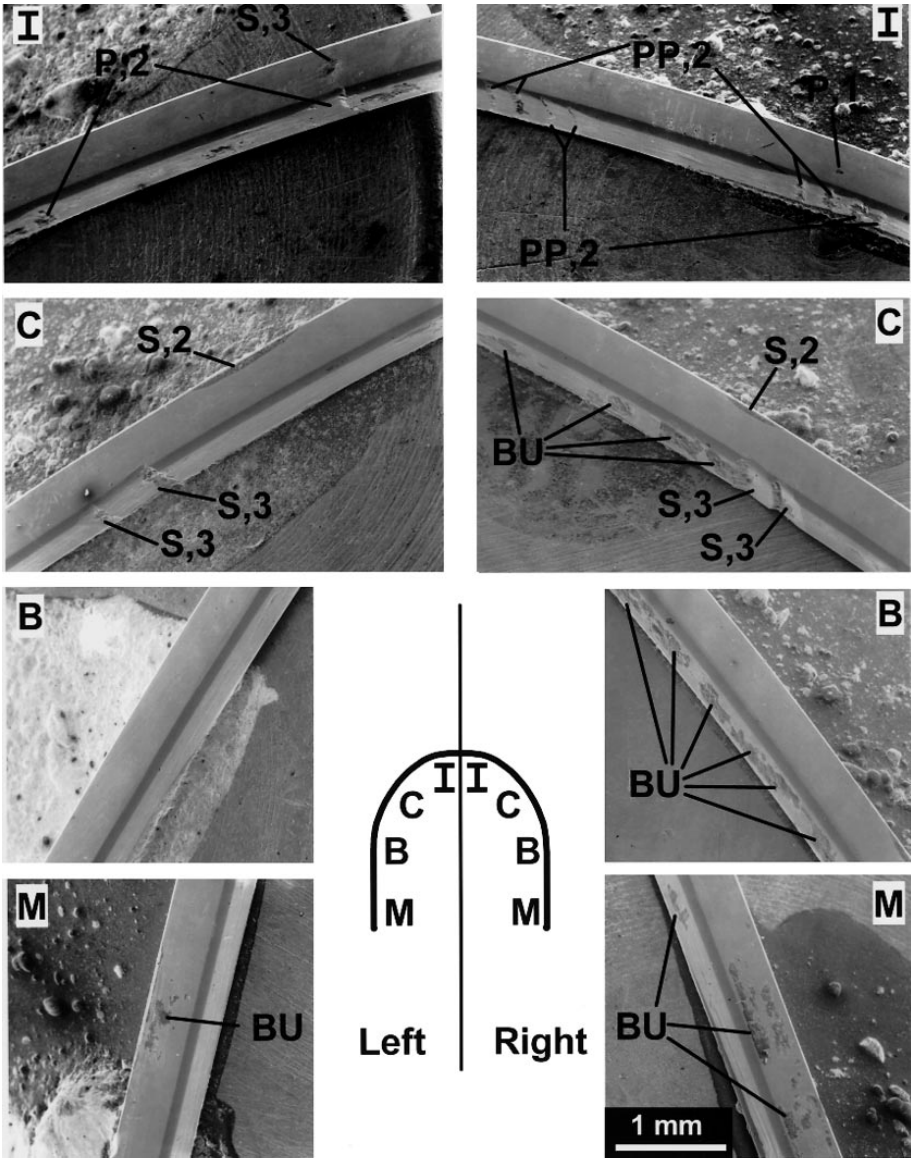

Figure 5 Eight scanning electron photomicrographs of a clinically used 0.019 × 0.025-inch SS wire against a 0.022-inch polycrystalline alumina ceramic (CER) bracket at its eight anatomical regions (cf. Figure 2). Although some BU is occasionally noted in the M and B regions, mechanical archwire damage (e.g. S,2) is infrequent. In the C and I regions many severe notches (S,3 and PP,2) are identified along with some less severe notches (e.g. S,2 and P,1). Note that, like many rectangular archwires (Meling *et al*., 1998), the edges are rounded or (as in this case) have flat bevels, rather than sharp corners, which are the result of manufacturing processes. The wire was examined without any coating preparation in the secondary electron mode at a voltage potential of 15 keV.

respectively. From among 399 patterns observed, less than 6 per cent did not fit the standard form and subsequently were placed in the miscellaneous or 'X,1' category.

Much of the notching from CER bracket cases was quite severe as reflected by 38 per cent of NOp's with severity numbers of '3' (Table 4). This typically indicated notches that penetrated

Table 2 Notch mapping of archwires for ceramic (CER) bracket cases using the number of notching patterns (NOp) of a given notch severity (NOs) as the basis.

Archwire designation	Archwire alloy	Archwire size (inch)	NOp,NOs							$(NOp)_{Total}$*	$(NOs)_{Total}$**
			S,1	S,2	S,3	P,1	P,2	P,3	X,1		
a	NiTi	0.016U	3	4	9	8	10	5		39	81
b***	SS	0.019 × 0.025U	19	2	3	1	6	7		38	66
c	SS	0.017 × 0.025U	9	7	3		8			27	48
d	SS	0.018U			3		1	7		11	32
e	SS	0.018U		1	2		1	7	1	12	32
f	NiTi	0.016U	3	3	2	4	5	1		18	32
g	SS	0.016U	1		2		1	7		11	30
h***	SS	0.018U		1	3		1	5	2	12	30
i	SS	0.018U	4	5	4	2	2		1	18	33
j	NiTi	0.016U	5		6		4			15	31
k	SS	0.016U					4	4		8	20
l	SS	0.016U			2		2	3	1	8	20
m	SS	0.019 × 0.025U	4	5	1	4			4	18	25
n	NiTi	0.016U	4	2	1		5			12	21
o***	SS	0.019 × 0.025U	4	1	7				2	14	29
p	SS	0.018U		1	3			3	1	8	21
q	NiTi	0.016U	1		2			3	1	7	17
r	NiTi	0.016L	1		5					6	16
s	NiTi	0.019 × 0.025U	1			3				4	4
t	NiTi	0.016U	2						1	3	3
		$(NOp)_{Total}$	61	32	58	22	50	52	14	289	
		$(NOs)_{Total}$	61	64	174	22	100	156	14		591

*Calculated using equation (1).
**Calculated using equation (2).
***Active space closure with elastomeric chain occurred with this archwire.

at least one-fourth of the wire's dimension, often involved an area greater than approximately 0.1 mm^2, and were readily seen with the unaided eye. The notching from SS bracket cases was relatively less severe in that 69 per cent of the NOp's were assigned a severity number of '1' (Table 4). These notches were usually characterized by recognizable 'nicks' (which barely penetrated the surface of the wire), often involved an area less than approximately 0.01 mm^2, and required the aid of a microscope. By patterns (Table 4), the S patterns greatly outnumbered the P patterns in the SS bracket cases by 2:1 (60 and 32 per cent), but had only a slight advantage in CER bracket cases by 6:5 (52 and 43 per cent). Overall, the S patterns outnumbered the P patterns 4:3 (54 and 40 per cent). Examples of these various notch patterns are annotated on a wire of round and rectangular cross-sections in Figures 4 and 5, respectively.

When the wire aspects and their corresponding anatomical regions of notches were mapped using n as the basis, between 3 and 62 notches per archwire were mapped in CER bracket cases (Table 5), and 0–20 notches in SS bracket cases (Table 6). On average, the notch frequency was nearly three times greater for CER bracket cases than for SS bracket cases at 20.7 (= 413/20) and 7.3 (= 145/20), respectively (Tables 5 and 6). From the frequency of entries, the lingual aspect received great damage in the I, C, and B anatomical regions. As the lingual aspect was subjected to the preponderance of the damage, its counterpart (the facial aspect) was relatively free of notches.

As was qualitatively observed via scanning electron microscopy (Figures 4 and 5), notches were most prevalent (72 per cent) on the lingual aspect of each wire as it contacted the floor of its bracket slot and least prevalent (5 per cent) on

Table 3 Notch mapping of archwires for stainless steel (SS) bracket cases using the number of notching patterns (NOp) of a given notch severity (NOs) as the basis.

Archwire designation	Archwire alloy	Archwire size (inch)	NOp,NOs							$(NOp)_{Total}$*	$(NOs)_{Total}$**
			S,1	S,2	S,3	P,1	P,2	P,3	X,1		
A	SS	0.016U			2	6	1		1	10	15
B	SS	0.016L	1				6			7	13
C	SS	0.018U	8	2	1		2			13	19
D	SS	0.016U				7	1		4	12	13
E	NiTi	0.016U			2	3				5	9
F	SS	0.017 × 0.025U	3	1	1	2			1	8	11
G	SS	0.018L	8	2					1	11	13
H	NiTi	0.016U			4					4	12
I	NiTi	0.016U			1	3				4	6
J	SS	0.021 × 0.025U			3				1	4	10
K	SS	0.018L	3			3				6	6
L***	SS	0.017 × 0.025L	6	1						7	8
M	SS	0.018L	2		1				1	4	6
N	NiTi	0.018U	6							6	6
O	SS	0.016U	1	1	1					3	6
P	SS	0.017 × 0.025L	1		1					2	4
Q	SS	0.018U	1			1				2	2
R	NiTi	0.016L	2							2	2
S	NiTi	0.016U								0	0
T	NiTi	0.016U								0	0
		$(NOp)_{Total}$	42	7	17	25	10	0	9	110	
		$(NOs)_{Total}$	42	14	51	25	20	0	9		161

*Calculated using equation (1).
**Calculated using equation (2).
***Active space closure with elastomeric chain occurred with this archwire.

Table 4 Overall notch pattern (NOp) summary of archwires against various brackets (cf. Tables 2 and 3).

	CER brackets		SS brackets		All brackets	
	$(NOp)_{Total}$	%	$(NOp)_{Total}$	%	$(NOp)_{Total}$	%
Severity						
1	97	34	76	69	173	43
2	82	28	17	15	99	25
3	110	38	17	15	127	32
$(NOp)_{Total}$	289		110		399	
Pattern						
S	151	52	66	60	217	54
P	124	43	35	32	159	40
X	14	5	9	8	23	6
$(NOp)_{Total}$	289		110		399	

Table 5 Notch mapping of archwires for ceramic (CER) bracket cases using notch frequency (n) as the basis.

Archwire designation	Archwire alloy	Archwire size (inch)	Lingual				Facial				Occlusal/ gingival				$(NOn)_{Total}$*
			M	B	C	I	M	B	C	I	M	B	C	I	
a	NiTi	0.016U	2	14	12	18					5	9	2		62
b**	SS	0.019 × 0.025U	3.5	1.5	14	19	2				5.5	1.5	2	3	52
c	SS	0.017 × 0.025U	4.5	3	7	13		1			2.5	3		1	35
d	SS	0.018U	2	4	5	7						1			19
e	SS	0.018U	2	5	4	6						1	1	1	20
f	NiTi	0.016U	4	9	4	6	2				1	2			28
g	SS	0.016U	2	4	5	6					1		1		19
h**	SS	0.018U		4	5	6		1			1		1		18
i	SS	0.018U	5	2	4	6	2					2	1		22
j	NiTi	0.016U		3	5	4					1	3		3	19
k	SS	0.016U	2	4	4	6									16
l	SS	0.016U		2	2	6					1	1		1	13
m	SS	0.019 × 0.025U	1.5	2.5	3	4.5	1	3	1		1.5	0.5	1	2.5	22
n	NiTi	0.016U		1	4	6						2	4		17
o**	SS	0.019 × 0.025U		2	5	2		2				2	1		14
p	SS	0.018U		3.5	2	3						1.5		1	11
q	NiTi	0.016U		2	2	4					1		1		10
r	NiTi	0.016L				1					2	1	2		6
s	NiTi	0.019 × 0.025U		3	2	2									7
t	NiTi	0.016U		1		1						1			3
		$(NOn)_{Total}$	28.5	70.5	89	126.5	7	7	1	0	22.5	31.5	17	12.5	413
															Average: 21

*Calculated using equation (3a) or (3b).
**Active space closure with elastomeric chain occurred with this archwire.

the facial aspect of the wire as it contacted its ligature (Table 7). Overall, most notching was observed in the incisor region (34 per cent); whereas, the least activity was seen in the molar regions (14 per cent). The notching on wires that involved CER bracket cases tended to be higher than SS bracket cases, as they generally had a greater total number of notches ($(NOn)_{TOTAL}$ = 413 versus 145).

Discussion

The presence of clinically induced notching on archwires could be classified by a few distinct patterns (Figures 3–5), some of which were consistent with the patterns observed by Hansen *et al.* (1998). Notch formation is caused by mechanical damage that results from the forced contact and relative movement between each bracket and its archwire. The direction and amount of movement determines the type of damage and subsequent appearance of the NOp, the magnitude of NOs, and the frequency of NOn (cf. equations (1)–(3), respectively).

Theory of notch formation

A predominantly vertical movement, specifically tooth movement within the periodontal ligament during mastication, would result in a form of wear called fretting. Fretting wear is characterized by oscillatory motion that leads to the generation of surface cracks followed by the formation and rupture of adhesive bonds between opposing materials. The fatigue failure and plastic deformation of the surface creates wear particles that oxidize and cause further abrasion of the material via three-body wear (Czichos, 1986).

Table 6 Notch mapping of archwires for stainless steel (SS) bracket cases using notch frequency (n) as the basis.

Archwire designation	Archwire alloy	Archwire size (inch)	Lingual				Facial				Occlusal/ gingival				$(NOn)_{Total}$*
			M	B	C	I	M	B	C	I	M	B	C	I	
A	SS	0.016U		5	4	6						1	1		17
B	SS	0.016L		4	4	4						1			13
C	SS	0.018U	3	1			1				2	1	1	6	15
D	SS	0.016U	2	4	4	6		1				2		1	20
E	NiTi	0.016U		3	2	2					1				8
F	SS	0.017 × 0.025U	0.5			4	1.5	0.5			2	0.5	1		10
G	SS	0.018L		1		1				1	1	1	4	2	11
H	NiTi	0.016U		1	0.5	0.5					0.5	1	0.5		4
I	NiTi	0.016U		2	2	2		1							7
J	SS	0.021 × 0.025U						0.5	0.5	0.5	1	0.5	0.5	0.5	4
K	SS	0.018L		3	2	2				2					9
L**	SS	0.017 × 0.025L				2		0.5	0.5			1.5	0.5	2	7
M	SS	0.018L				1					1	1		1	4
N	NiTi	0.018U			0.5	1.5	0.5	0.5			0.5	1	0.5	1	6
O	SS	0.016U		3											3
P	SS	0.017 × 0.025L			0.5					0.5			0.5	0.5	2
Q	SS	0.018U				3									3
R	NiTi	0.016L		2											2
S	NiTi	0.016U													0
T	NiTi	0.016U													0
		$(NOn)_{Total}$	5.5	29	19.5	35	3	4	1	4	9	11.5	9.5	14	145
															Average: 7

*Calculated using equation (3a) or (3b).
**Active space closure with elastomeric chain occurred with this archwire.

Table 7 Overall notch frequency (n) summary of archwires against various brackets (cf. Tables 5 and 6).

	Area (%)	CER brackets		SS brackets		All brackets	
		$(NOn)_{Total}$	%	$(NOn)_{Total}$	%	$(NOn)_{Total}$	%
Aspect							
L	25	314.5	76	89	61	403.5	72
F	25	15	4	12	8	27	5
O/G	50	83.5	20	44	30	127.5	23
$(NOn)_{Total}$		413		145		558	
Location							
M	37.5	58	14	17.5	12	75.5	14
B	25	109	26	44.5	31	153.5	28
C	12.5	107	26	30	21	137	25
I	25	139	34	53	37	192	34
$(NOn)_{Total}$		413		145		558	

The resultant notches appear as shallow parabolic or triangular defects, with their bases perpendicular to the wire's long axis (cf. Figure 3, P-type patterns; Figure 5, right incisor). Although S-type patterns appear anywhere, P-type patterns occur mainly on the lingual surfaces. They may be solitary, but are usually isolated *pairs* or 'mirror images' of each other that correspond to the mesial and distal edges of a single opposing bracket. The internal walls of the defect are square-like due to the acute angle of contact between the wire and the slot floor of the bracket during its vertical movement, which moves in a direction perpendicular to the wire. Consequently, both bracket ends contact the wire at the same time. Although each pair is commonly separated by a tooth's distance, which corresponds to the regular positioning of a bracket along an archwire, pairs often overlap creating PP,2-type patterns (cf. Figure 3, bottom, and Figures 4 and 5, incisors). This appearance occurs when the vertical fretting wear is interrupted by horizontal or translational tooth movement. Once this translatory movement ceases, a new pair of notches is established in close proximity to the first pair as fretting resumes.

Horizontal or translational movements, such as those that occur during sliding mechanics, can also create defects via sliding wear. Sliding wear is characterized by the scratching, scoring, and galling (extensively penetrating surface damage) of one material when a harder material is ploughed into its surface (Jastrzebski, 1976). When a bracket slides along an archwire and depending on the degree of angulation or torque, the leading edge contacts the wire surface, digs in, and then releases, often leaving solitary elliptical or polygonal defects (Figure 3, S-type patterns; Figure 4, left canine; Figure 5, left and right canines). If this jig-jog movement is repeated in concentrated areas, this may mimic the appearance of a PP,2-type pattern with one exception: the markings all point in the same direction. The internal walls of the defect are more obtuse due to the movement of the bracket edge during either tipping or translational tooth movement. Via the yield strength and stiffness, the contact stress (which is directly proportional to contact load and contact angle but inversely proportional to contact area) and the relative hardness of the materials are the principal material characteristics that determine the severity of these notch patterns.

Theory within present context

Most of the S versus P patterns (217 versus 159; Table 4) had an appearance consistent with sliding wear—that is, solitary defects with an elliptical or polygonal surface, and angular depth (cf. Figure 3, S-type patterns; Figure 5, left and right canines). However, this is not a wide margin, when taking into account the nature of the patterns. Since the P pattern actually involves twice as many notches (two parabolic or triangular defects mirroring one another), it could be argued that fretting wear actually dominates with more notches [217 versus 318 ($= 2 \times 159$)]. We submit that both fretting and sliding wear routinely occur simultaneously. Thus, vertical tooth movement or vertical wire movement that is caused by mastication is at least as important as translational tooth movement that is caused by orthodontic procedures. Indeed, when Jost-Brinkmann and Miethke (1991) compared the frictional forces that occur *in vivo* and *in vitro*, they found that the physiological tooth mobility had a profound influence on lowering frictional forces during mastication. Consequently, the impact that these two types of patterns may have on clinical treatment warrants further investigation.

A substantially larger proportion of notches occurred on the lingual aspect of the archwire, regardless of which bracket was employed (Figure 6, top). This was expected due to the nearly constant contact of the bracket floor with the archwire in fixed appliances. Since most of these notches were in the form of P patterns, these notches were likely caused by fretting wear created by the vertical movement of the bracket floor during mastication. Notches that occurred on the occlusal-gingival aspect of a wire revealed that the bracket slot was not always parallel to the wire during use of the appliance. Consequently, the sides of the bracket slot gouged the wire due to this lack of clearance. Under typical clinical conditions, this binding

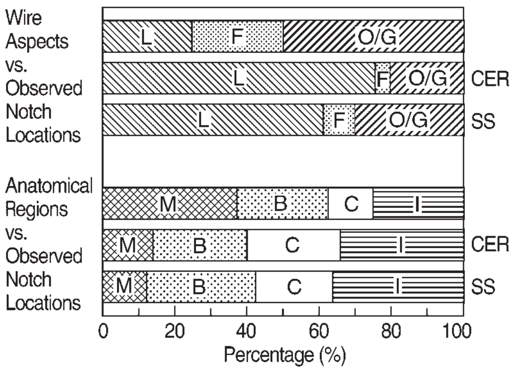

Figure 6 Relative comparisons of wire aspects and anatomical regions versus observed notch locations, after archwires were clinically used in CER and SS bracket cases. Considering the relative size of the lingual (L) aspect and the canine (C) region, many more notches were observed for both bracket cases. For the facial (F) aspect and molar (M) region, the concentration of notches was proportionally less. Recalling that, in the so-called CER bracket cases, CER brackets were never placed beyond the most notch-prone regions from 4 to 4 (cf. Materials and Methods section), the relative damage from either CER or SS brackets is actually quite similar. However, the number of notches per wire aspect or per anatomical region is greater, when CER bracket cases versus SS bracket cases are considered (Tables 5 and 6).

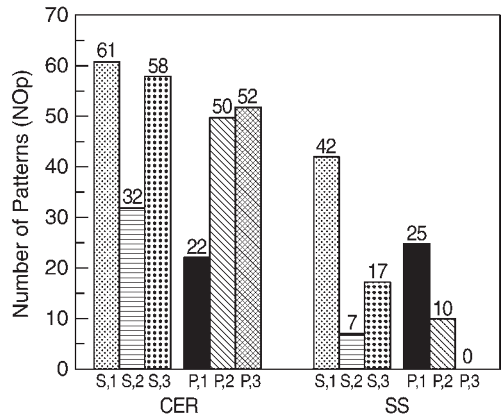

Figure 7 Number of notching patterns of a given notch severity after archwires were clinically used in CER and SS bracket cases. For all (NOp, NOs) categories, not only are the total number of notches greater, but also the relative proportion of severe defects are greater (Tables 2 and 3).

should create a couple, which would upright and release the bracket from the notch, allowing movement to occur. Excessive angulation can ultimately lead to the cessation of bracket movement due to the bracket being mechanically locked in the notch (Kusy *et al.*, 1998).

The concentration of notching in the canine region was also expected, independent of which bracket was employed (Figure 6, bottom). Although the canine region constitutes only 12.5 per cent of the archwire, 25 per cent of the notching occurred in this region. Two possible reasons are postulated. First, this region represents the greatest curvature in the dental arch and, consequently, causes the bracket edges to contact the wire at a sharper angle. Second, more space closing or space regaining procedures are performed in this region, which results in more sliding wear (Figures 4 and 5).

Generally, CER bracket cases cause more archwire damage than SS bracket cases (Figure 7). Not only were more NOp's observed, but many more patterns of higher severity were seen in CER than SS bracket cases. This is also reflected by comparing the notching data in which CER bracket cases scored higher than SS bracket cases in both NOs (Tables 2 and 3) and NOn (Tables 5 and 6). This outcome may be due to the high relative hardness and stiffness of ceramic compared with stainless steel. For CER brackets the hard asperites cause a rasp-like action that lead to P-type pattern formation during fretting wear, and any sharp corners create high contact stresses that lead to S-type pattern formation during sliding wear.

Defining a notching index (ν)

An attempt to quantify notching was sought that would encompass both the notch frequency and notch severity. The rationale was that the integration of the two parameters would facilitate the characterization of a particular archwire using a single value—the notching index (ν). The development of ν requires at least an intuitive understanding of the clinical relevance of notching, since the relative importance of frequency and severity in orthodontic treatment has yet to be established. Notwithstanding this limitation, provisional formulae were derived [equations (6a) and (6b)] that incorporated

Table 8 Determination of the notching index (ν) of archwires for ceramic (CER) bracket cases* using $(NOn)_{Total}$, $(NOs)_{Total}$, and $(NOp)_{Total}$.

Archwire designation	Archwire alloy	Archwire size (inch)	Duration of use (days)	$(NOn)_{Total}$**	$[(NOs)_{Total}/(NOp)_{Total}]$***	ν****
a	NiTi	0.016U	128	62	2.1	129
b*****	SS	0.019 × 0.025U	441	52	1.7	90
c	SS	0.017 × 0.025U	63	35	1.8	62
d	SS	0.018U	74	19	2.9	55
e	SS	0.018U	128	20	2.7	53
f	NiTi	0.016U	236	28	1.8	50
g	SS	0.016U	52	19	2.7	52
h*****	SS	0.018U	42	18	2.5	45
i	SS	0.018U	63	22	1.8	40
j	NiTi	0.016U	173	19	2.1	39
k	SS	0.016U	57	16	2.5	40
l	SS	0.016U	239	13	2.5	33
m	SS	0.019 × 0.025U	28	22	1.4	31
n	NiTi	0.016U	133	17	1.8	30
o*****	SS	0.019 × 0.025U	152	14	2.1	29
p	SS	0.018U	55	11	2.6	29
q	NiTi	0.016U	43	10	2.4	24
r	NiTi	0.016L	173	6	2.7	16
s	NiTi	0.019 × 0.025U	56	7	1.0	7
t	NiTi	0.016U	35	3	1.0	3
						Average: 43

*All archwires were rank-ordered by ν.
**Calculated using equations (3a) and (3b).
***Calculated using equation (5).
****Calculated using equations (6a) or (6b).
*****Active space closure with elastomeric chain occurred with this archwire.

these two parameters using the definitions of NOp, NOs, and NOn [cf. equations (1)–(3), respectively].

The data acquired via these formulae (Tables 8 and 9) magnified the disparity between archwires used in CER and SS bracket cases. The mean of ν was five times larger for CER (42.9 ± 28.3, Table 8) than SS (10.6 ± 7.9, Table 9), as well as the range (3–129 for CER versus 0–26 for SS). This outcome underscores the fact that notching was more frequent, as well as more severe, in CER than in SS bracket cases. Future studies, which analyse different archwire-bracket combinations, may reveal various trade-offs between materials. For example, although one material may be more prone to a high NOn, another material may compensate via a low NOs [cf. equations (6a) or (6b)]. In such cases, ν will be able to distinguish the better compromise. Therefore, as the experimental evidence accumulates and the theoretical arguments mature, clinicians may increasingly find ν valuable for selecting archwire-bracket combinations.

The ν suggested another interesting finding: namely that, with the exception of two wires (‘a’ and ‘b’), the level of notching appears independent of the duration that the wire was in use (Figure 8). In an earlier unpublished bench-top investigation that used a wax dentiform, it was shown that no notching was created by fully-engaging an archwire in CER brackets. Only when the dentiform was submerged in an ultrasonic bath to simulate tooth movement during mastication and/or sliding did damage occur to the archwire. Having clinically confirmed that such notching was not iatrogenically induced during the initial engagement of a wire into a bracket (cf. Table 1, control group, set 2), it would appear that most notches developed during the first month of use (when the opposing forces

Table 9 Determination of the notching index (ν) of archwires for stainless steel (SS) bracket cases* using $(NOn)_{Total}$, $(NOs)_{Total}$, and $(NOp)_{Total}$.

Archwire designation	Archwire alloy	Archwire size (inch)	Duration of use (days)	$(NOn)_{Total}$**	$[(NOs)_{Total}/(NOp)_{Total}]$***	ν****
A	SS	0.016U	152	17	1.5	26
B	SS	0.016L	168	13	1.9	24
C	SS	0.018U	94	15	1.5	22
D	SS	0.016U	135	20	1.1	22
E	NiTi	0.016U	182	8	1.8	14
F	SS	0.017 × 0.025U	65	10	1.4	14
G	SS	0.018L	94	11	1.2	13
H	NiTi	0.016U	280	4	3.0	12
I	NiTi	0.016U	138	7	1.5	11
J	SS	0.021 × 0.025U	91	4	2.5	10
K	SS	0.018L	173	9	1.0	9
L*****	SS	0.017 × 0.025L	85	7	1.1	8
M	SS	0.018L	63	4	1.5	6
N	NiTi	0.018U	149	6	1.0	6
O	SS	0.016U	131	3	2.0	6
P	SS	0.017 × 0.025L	315	2	2.0	4
Q	SS	0.018U	203	3	1.0	3
R	NiTi	0.016L	99	2	1.0	2
S	NiTi	0.016U	61	0	–	(0)
T	NiTi	0.016U	31	0	–	(0)
						Average: 11

*All archwires were rank-ordered by ν.
**Calculated using equations (3a) or (3b).
***Calculated using equation (5).
****Calculated using equations (6a) or (6b).
*****Active space closure with elastomeric chain occurred with this archwire.

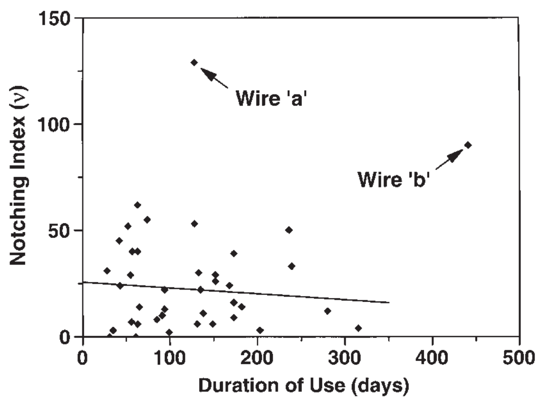

Figure 8 Independence of notching index (ν) with duration of use that an appliance was inserted. With the exception of two CER bracket cases involving wires ‘a’ and ‘b’, the plot suggests two possibilities: first, that notching occurs predominantly within the first month of use (after which notching is independent of duration of use). Alternatively, that comparable amounts of notching occur at any time following initial activation or subsequent adjustment (unless sliding or other problems occur).

from the malocclusion were greatest) or that comparable amounts of notching occurred at any time following initial activation or subsequent adjustment. Thus, notching was not exacerbated by the duration that the wire was in use; that is to say, if notching was going to occur, the worst damage occurred soon after activation or adjustment. This interpretation correlates well with the passive and active configurations of an orthodontic archwire during treatment. Such conventional straight wire appliances are usually only active during the first month of placement or for about a month after each adjustment. Consequently, as the applied forces relax (as co-ordinated movement of the teeth and stress relaxation of the materials occur) and the passive configuration is approached, mechanical damage diminishes. As treatment goals are realized then notching would be lessened as the normal forces and wire activations would be decreased. This interpretation does not dismiss the fact that other factors may be involved, which also exacerbate archwire damage, for example, patient parameters (bite forces), parafunctional habits (bruxing or clenching), and/or treatment parameters (single-tooth retraction or the wearing of elastics).

Although the notching phenomenon has been identified and detailed, more information is needed to determine the practical significance of these notches. Do they demonstrate a hindrance to treatment progression or are they a normal occurrence that is necessary for tooth movement? If they are a necessary occurrence, are notches obstacles to further treatment? Further analyses of the treatment records of these and other cases may elucidate such questions.

Conclusions

1. Notches appear only on clinically used archwires, and may be categorized by their frequency, pattern, and severity.
2. Fourteen distinct defect patterns are only required to describe notching.
3. Specific wire aspects (e.g. lingual) and anatomical regions (e.g. canine and incisor) are more prone to notching.
4. Two mechanisms of notch formation are suggested: (1) fretting, in which tooth movement in the vertical plane often causes pairs of shallow parabolic or triangular defects; and (2) sliding, in which translational movement in the horizontal plane often leaves a solitary elliptical or lunar-like defect.
5. Expressions for the total number of notch patterns $(NOp)_{TOTAL}$, the total severity of notch patterns $(NOs)_{TOTAL}$, and the total number of notches $(NOn)_{TOTAL}$ may be described in terms of the notch frequency (n).
6. The values of $(NOp)_{TOTAL}$, $(NOs)_{TOTAL}$, and $(NOn)_{TOTAL}$ provide a fundamental basis by which the notching index (ν) may be described, as the product of either the average number of notches per pattern × the total severity of notch patterns, or as the average severity of notches per pattern × the total number of notches.

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References

Abson D J, Kosik O, Uvira J L, Jonas J J 1973 Correlation between room-temperature hardness and flow stress in hot worked metals. In: Westbrook J H, Conrad H (eds) The science of hardness testing and its research applications. American Society for Metals, Metals Park

Articolo L C, Kusy R P 1999 Influence of angulation on the resistance to sliding in fixed appliances. American Journal of Orthodontics and Dentofacial Orthopedics 115: 39–51

Blau P J 1989 Friction and wear transitions of materials: break-in, run-in, wear-in. Noyes, Park Ridge

Czichos H 1986 Tribology: a systems approach to the science and technology of friction, lubrication and wear. Elsevier Scientific, Amsterdam

Gilman J J 1973 Hardness—a strength microprobe. In: Westbrook J H, Conrad H (eds) The science of hardness testing and its research applications. American Society for Metals, Metals Park

Hansen J D, Kusy R P, Saunders C R 1998 Archwire damage from ceramic brackets via notching. Orthodontic Reviews 11: 27–31

Jastrzebski Z D 1976 The nature and properties of engineering materials, 2nd edn. Wiley & Sons, New York

Jost-Brinkmann P, Miethke R-R 1991 Einfluß der physiologischen Zahnbeweglichkeit auf die Friktion zwischen Bracket und Bogen. Fortschriftte der Kieferorthopädie 52: 102–109

Keith O, Kusy R P, Whitley J Q 1994 Zirconia brackets: an evaluation of morphology and coefficients of friction. American Journal of Orthodontics and Dentofacial Orthopedics 106: 605–614

Kusy R P, Whitley J Q 1990 Coefficients of friction for arch wires in stainless steel and polycrystalline alumina bracket slots: I. The dry state. American Journal of Orthodontics and Dentofacial Orthopedics 98: 300–312

Kusy R P, Whitley J Q 1997 Friction between different wire-bracket configurations and materials. Seminars in Orthodontics 3: 166–177

Kusy R P, Articolo L C, Kusy K, Saunders C R 1998 *In vivo* notching on arches by ceramic brackets. Journal of Dental Research 77: 696 (Abstract)

Meling T R, Odegaard J, Segner D 1998 On bracket slot height: A methodologic study. American Journal of Orthodontics and Dentofacial Orthopedics 113: 387–393

Park J B, Lakes R S 1992 Biomaterials: An introduction, 2nd edn. Plenum, New York

Rice R W 1973 Correlation of hardness with mechanical effects in ceramics. In: Westbrook J H, Conrad H (eds) The science of hardness testing and its research applications. American Society for Metals, Metals Park

Saunders C R, Kusy R P 1994 Surface topography and frictional characteristics of ceramic brackets. American Journal of Orthodontics and Dentofacial Orthopedics 106: 76–87

Shackelford J E 1996 Introduction to materials science for engineers, 4th edn. Prentice Hall, Upper Saddle River

Siatkowski R E 1997 Wear and tear from sliding mechanics. Journal of Clinical Orthodontics 31: 812–813

Tanne K, Matsubara S, Shibaguchi T, Sakuda M 1991 Wire friction from ceramic brackets during simulated canine retraction. Angle Orthodontist 61: 285–290