Original Article

Mechanical Properties and Surface Characteristics of Three Archwire Alloys

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Abstract: Recent developments in material science have presented newer archwire materials as well as improvements in the properties of existing ones. Proper selection and understanding of the biomechanical requirement of each case requires proper characterization studies on archwire alloys. The present study characterizes and compares three orthodontic archwire alloys, stainless steel, beta titanium alloy (TMA™), and a newly introduced titanium alloy (TiMolium™), for the parameters (1) ultimate tensile strength (UTS), 0.02% offset yield strength (YS), and modulus of elasticity (E); (2) load deflection characteristics; (3) frictional properties; (4) surface characteristics and (5) elemental analysis for TiMolium™. Seven specimens of each archwire alloy were used for evaluating each parameter. An instron universal testing machine was used for tensile testing, three-point bend testing, and evaluation of frictional characteristics. Scanning electron microscope was used for surface evaluation and X-ray fluorescence for elemental analysis of TiMolium™ wire specimens. Stainless steel was the strongest archwire alloy with high UTS, E, 0.02% offset YS, and less friction at the archwire-bracket interface. TMA™ wires exhibited better load deflection characteristics with less stiffness than the other two wires. The surface of TMA™ appeared rough and exhibited very high values for friction at the archwire-bracket interface. TiMolium™ appeared to be an alpha-beta titanium alloy composed of titanium, aluminum, and vanadium and intermediate in nature for all the parameters evaluated. (*Angle Orthod* 2004;74:825–831.)

Key Words: Archwires; Materials; Characterization; TiMolium™; Titanium

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INTRODUCTION

Over the past 100 years, improvements in both mechanotherapy and treatment philosophy have led to major advancements in orthodontic patient care. Changes in the field of mechanotherapy have largely been made possible with the emergence of newer orthodontic materials. Archwire materials form a large part of this change, and selecting the appropriate archwire requires a thorough knowledge of archwire biomechanical and clinical applications. This knowledge requires proper characterization of archwire alloys to predict their outcome when used clinically.

In the past few decades, a number of wire alloys with a wide spectrum of mechanical properties have been introduced, adding versatility to orthodontic treatment. Two articles reviewing the mechanical properties as well as the clinical applications of archwire alloys have been published recently.[1,2] These articles stressed evaluating tensile properties, bending characteristics, frictional characteristics, and surface properties as part of archwire alloy characterization. They agree that austenitic stainless steel with its good balance of environmental stability, stiffness, resilience, and formability has continued to be the mainstay archwire alloy since its introduction.[1–3]

Titanium-based alloys are slowly gaining popularity in recent years, mainly with the introduction of nickel-titanium[4] and beta titanium,[5] with titanium's superior properties of biocompatibility, corrosion resistance, and low stiffness. TiMolium™ is a recent introduction in the field of titanium-based orthodontic alloy archwire materials,[6] and proper literature regarding the properties of this archwire alloy is lacking. The present study was aimed at characterizing and comparing the mechanical properties and surface characteristics of the two archwire alloys used commonly in orthodontics, ie, stainless steel and TMA™, with the newly introduced TiMolium™.

MATERIALS AND METHODS

Preformed 0.43 × 0.64-mm (0.017 × 0.025 inches) archwires were obtained as stainless steel (Ormco Corpo-

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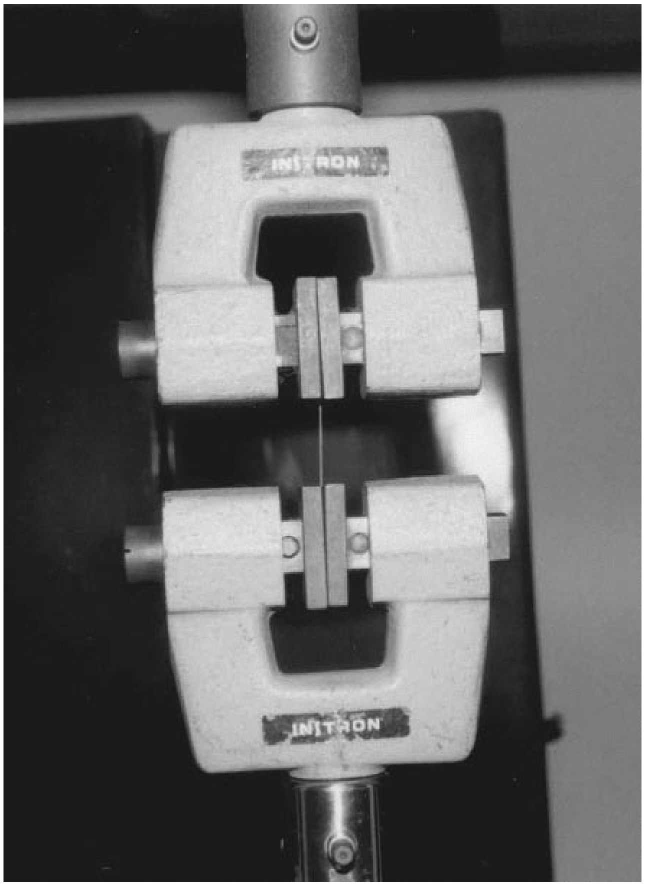

FIGURE 1. Setup for tensile evaluation with specimen in place.

ration, Glendora, Calif), TMA™ (Ormco), and TiMolium™ (TP Labs, Indianapolis, Ill).

The specimens of these three archwires were coded as:

- group I: stainless steel
- group II: TMA™
- group III: TiMolium™.

Seven specimens from each group were evaluated for the parameters:

- ultimate tensile strength (UTS), yield strength (YS), and modulus of elasticity (E);
- load deflection characteristics;
- frictional characteristics;
- surface characteristics;
- elemental analysis for TiMolium™ (as it is a recent introduction).

Ultimate tensile strength, yield strength and modulus of elasticity

A standard tensile test[7] (Figure 1) using each of the archwire alloys from groups I–III were performed in an Instron Universal Testing Machine (Model No. 1195, Instron Corporation, Canton, Mass). A full-scale load of 1000 N was set in the machine with a crosshead speed of one mm/minute. The span of the wire between crossheads was standardized as 40 mm. The load taken to break the wire divided by the cross-sectional area of the wire gave the value for UTS. The load deflection data obtained from the tensile testing were plotted as stress-strain curves from which the E as well as 0.2% offset YS were calculated.

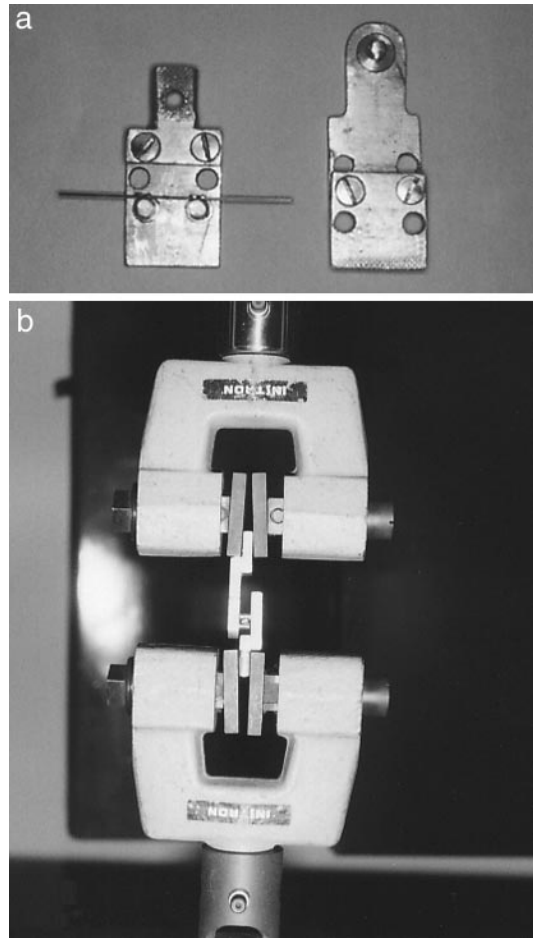

FIGURE 2. (a) Fixture for three-point bend test with wire in place. (b) Setup for three-point bend test.

Load deflection rate

The load deflection characteristics of specimens from each group were evaluated with the help of the three-point bend test as described by Miura et al.[8] The test was performed on a specially designed fixture (Figure 2a) comprising two poles placed 14 mm apart on a stage to obtain the values at loading as well as unloading (0.5 mm and one mm of loading and 0.5 mm of unloading). The test wire specimen was secured on brackets fixed on the poles using 0.012-inch elastomeric ligatures. The stage was attached to the upper movable head of the Instron machine. A single pole, fixed to a stage was attached to the lower head of machine in such a manner that the tip of the pole was on the center of the test-wire span (Figure 2b). The mid portion

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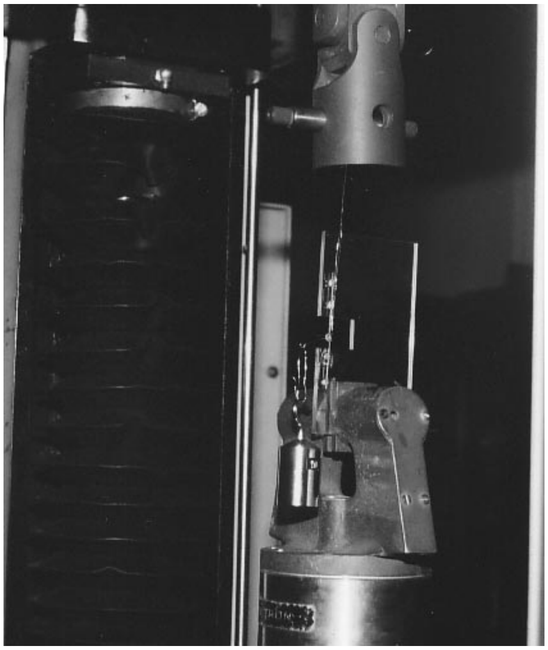

FIGURE 3. Setup for evaluation of frictional characteristics.

of the wire was then deflected one mm with a crosshead speed of one mm/minute and a full-scale load of 10 N. The load values were noted at 0.5 mm loading (0.5 L), one mm loading (1 L), and 0.5 mm unloading (0.5 UL).

Frictional characteristics

Evaluation of the friction produced at the archwire-bracket interface was done following a test protocol described by Tidy.[9] This test consisted of a simulated half-arch fixed appliance with archwire ligated in position (Figure 3). Four 0.022- × 0.028-inch edgewise brackets with zero torque and zero angulations were bonded into a rigid Perspex sheet at eight-mm intervals. A 16-mm space was left at the center for sliding the canine bracket to simulate canine retraction. The archwires were secured using 0.012-inch elastomeric ligatures. The movable canine bracket was soldered with a 12-mm power arm from which weights of 0.05 N/0.1 N were hung to represent the single equivalent force acting at the center of resistance of the tooth root.

All tests were conducted in dry condition with an Instron universal testing machine. The movable bracket was suspended from the load cell of the testing machine, whereas a base plate (Perspex sheet) was mounted on the crosshead below. The full-scale load was set at 5 N with a crosshead speed of 10 mm/minute. At the start of each test, a trial run was performed with no load on the power arm to check whether there was any binding between the archwire and bracket. Then a 0.05-N followed by 0.1-N weight was suspended from the power arm, and the load needed to move the bracket across the central span in apparatus was recorded separately. The load cell reading represented the clinical force of retraction that would be applied to a canine, part of which would be critical friction whereas the rest would be the translation force on the tooth. The difference between the load cell reading and load on the power arm represented frictional resistance. The coefficient of friction, both static and kinetic, at the archwire-bracket interface was calculated using appropriate formulae.[9]

Statistical analysis

All the data obtained from the three parameters described above were tabulated and entered into SPSS (ver. 10), a computer-based statistical program. Means and standard deviations were calculated, and analysis of variance (ANOVA) test was performed to find out the level of significance between the values obtained from archwire alloy specimens in groups I–III. In addition, repeated-measures ANOVA was performed on values obtained through the three-point bend test. This was performed to verify whether there is any significant difference when the same archwire alloy is subjected to continuous loading and unloading and measured repeatedly.

Surface characteristics

Surface characteristics of each of the specimens of wires from groups I–III were studied with the help of a scanning electron microscope (SEM) (JEOL JSM 5600LV). A one-cm-long specimen of each alloy wire was mounted on studs, which were later placed in the vacuum chamber of the SEM. The accelerating voltage, angle of fit, and the aperture was adjusted to optimize the quality of the micrograph. The surface was scanned and viewed on the monitor at different magnifications and representative micrographs (500×) of each alloy were obtained.

Elemental analysis

The group III wire specimens were examined using X-ray fluorescence (XRF) to evaluate the composition of the alloy because it forms a new introduction to orthodontic specialty. The wire was wound over the stud, and fluorescent X-ray was passed over it to identify the alloying components.

RESULTS

Ultimate tensile strength, yield strength and modulus of elasticity

The value obtained through tensile testing of archwire alloys indicated clearly superior strength for stainless steel (group I), followed by TiMolium™ (group III), and TMA™ (group II). The group I wire was significantly greater than group II and III wires ($P < .05$), but the difference between groups II and III was statistically insignificant.

The load deflection curves obtained through tensile tests

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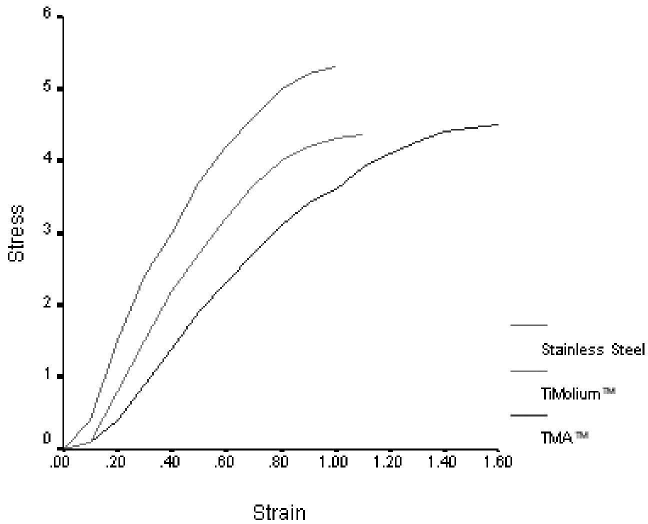

FIGURE 4. Stress-strain curve for the archwire alloys evaluated.

TABLE 1. Mechanical Properties of Orthodontic Wires in Group I–III

Wire Type[a]	Modulus of Elasticity (× 10^3 MPa)	0.2% Offset Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
Group I	170	1640	2100
SD[b]	(20)	(70)	(40)
Group II	70	1010	1250
SD	(10)	(90)	(70)
Group III	90	1090	1280
SD	(20)	(90)	(90)

[a] Group I, stainless steel; group II, TMA™; group III, TiMolium™.
[b] SD indicates standard deviation.

were plotted as stress-strain curves (Figure 4) for each archwire alloy. The slope of the curves, representative of 0.2% offset YS and E, were determined. The values for the mechanical properties of alloy archwires obtained through tensile testing are summarized in Table 1.

Load deflection rate

The load deflection values obtained through three-point bend testing of wire specimens from groups I–III (Table 2), when analyzed statistically (ANOVA at 95% confidence level, significant at $P < .05$) were highly significant for 0.5 and one mm loading and 0.5 mm unloading. The only exception to this was the statistical value comparing the group I specimen with group III on 0.5 mm unloading, which was statistically insignificant. The rank order of wires according to load deflection characteristics can be summarized as (Figure 5):

- 0.5 mm loading: stainless steel > TiMolium™ > TMA™;
- one mm loading: stainless steel > TiMolium™ > TMA™;
- 0.5 mm unloading: TMA™ > TiMolium™ > stainless steel.

TABLE 2. Mean Values for Load Deflection Rate of Wire Specimens in Group I–III

Sample[a]	Mean (g)	Standard Deviation
0.5 mm Loading		
Group I	2100	170
Group II	1300	100
Group III	1700	60
1 mm Loading		
Group I	3100	50
Group II	2300	160
Group III	2700	120
0.5 mm Unloading		
Group I	850	100
Group II	1200	80
Group III	940	50

[a] Group I, stainless steel; group II, TMA™; group III, TiMolium™.

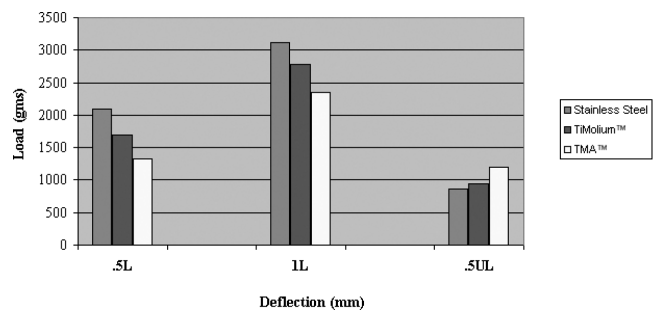

FIGURE 5. Load deflection rate of alloys from groups I–III.

Repeated-measures ANOVA comparing values from same archwire alloys on loading and unloading revealed highly significant statistical differences.

Frictional characteristics

The load values for frictional resistance obtained were substituted in the equation for determining the coefficient of friction (μ).[9] The values were tabulated, and the means and standard deviations were calculated (Table 3). The ANOVA (at 95% confidence level, significant at $P < .05$) values obtained on comparison of the values of archwire specimens from groups I–III were highly significant except when the static friction of group I was compared with group III, which was statistically insignificant. The rank order of the wires in descending order of frictional properties can be summarized as (Figure 6):

- static friction (0.05 and 0.1 N weight)—TMA™ > TiMolium™ > stainless steel;
- kinetic friction (0.05 and 0.1 N weight)—TMA™ > TiMolium™ > stainless steel.

Surface characteristics

The scanning electron micrographs of the archwire alloy specimens from groups I–III in 500× magnifications are

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TABLE 3. Mean Values for Coefficient of Static and Kinetic Friction of Wire Specimens in Group I–III

Sample[a]	Mean	Standard Deviation
Static friction (μ_s) at 0.05 N		
Group I	0.43	0.08
Group II	0.84	0.04
Group III	0.48	0.10
Static friction (μ_s) at 0.1 N		
Group I	0.22	0.03
Group II	0.77	0.08
Group III	0.33	0.06
Kinetic friction at (μ_k) 0.05 N		
Group I	0.43	0.04
Group II	0.90	0.04
Group III	0.69	0.14
Kinetic friction at (μ_k) 0.1 N		
Group I	0.27	0.03
Group II	0.87	0.03
Group III	0.49	0.05

[a] Group I, stainless steel; group II, TMA™; group III, TiMolium™.

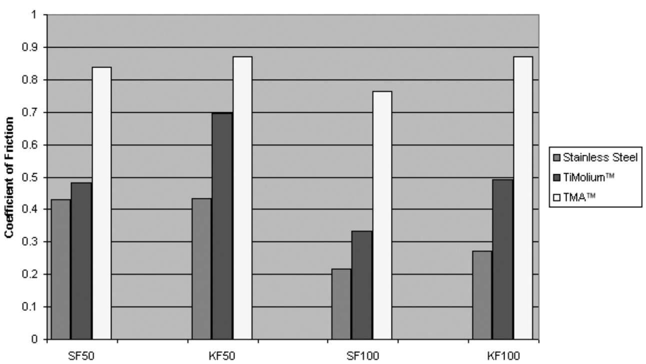

FIGURE 6. Frictional characteristics of alloys from groups I–III.

shown in Figure 7. Group III wires (TiMolium™) exhibited a relatively smooth surface when compared with the other two alloys evaluated, with horizontal wire drawing lines clearly evident on its surface (Figure 7c). The group I (stainless steel) wire exhibited an almost smooth surface with some vertically oriented cracks (Figure 7a). Group II (TMA™) wire exhibited a rough surface with many pores and was ranked as the wire with poorest surface characteristics (Figure 7b).

Elemental analysis

When subjected to XRF, group III alloy revealed a composition mainly consisting of titanium with aluminum and vanadium as stabilizing elements. The composition was indicated as:

- Titanium: more than 85%
- Aluminum: 6.8%
- Vanadium: 4.2%

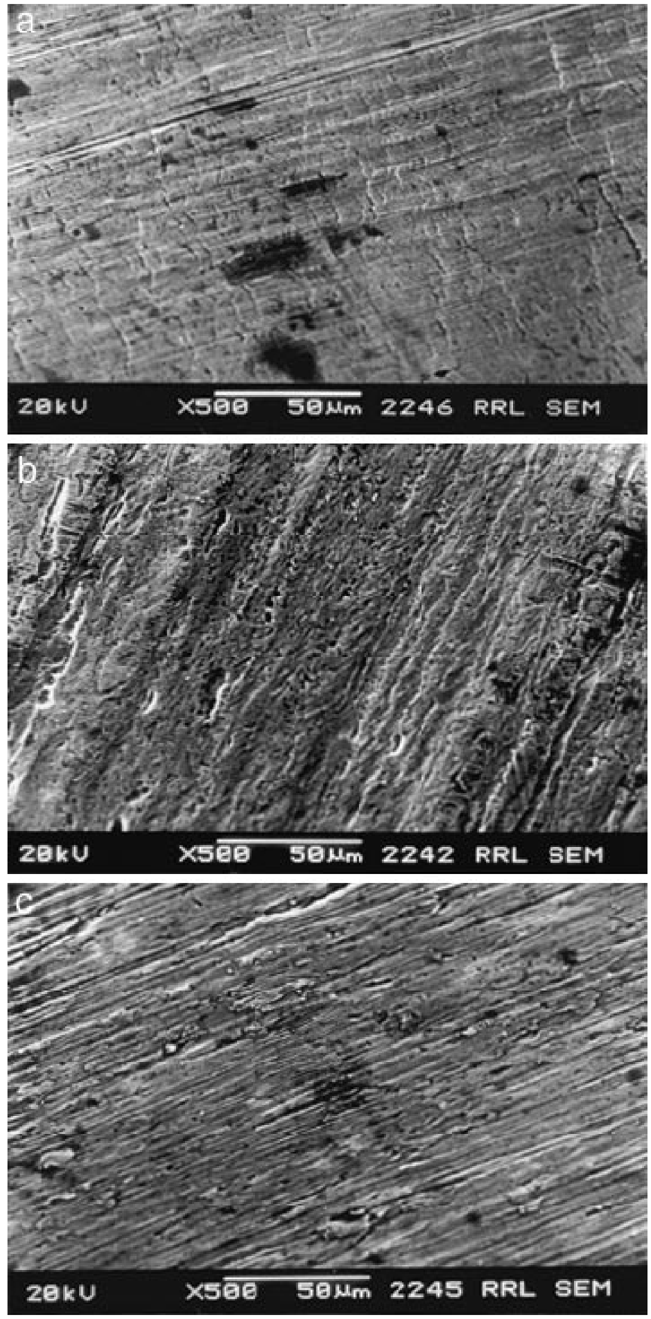

FIGURE 7. Scanning electron micrograph: 500× magnification; (a) Stainless steel, (b) TMA™, (c) TiMolium™.

DISCUSSION

Characterization of archwire alloys forms an initial step toward understanding archwire behavior in clinical situations. This will help the clinician to select an appropriate archwire on the basis of the biomechanical requirement of the clinical situation from the plethora of materials available. The present study was aimed at characterizing the two most commonly used archwire alloys in orthodontics—stainless steel and beta titanium (as exemplified by TMA™) and the newly introduced TiMolium™—for their mechan-

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ical as well as surface characteristics. A comparison between the properties was also performed to provide an insight into their use in each stage of orthodontic mechanotherapy.

The elastic behavior of any material is defined in terms of stress-strain response to an external load, both of which correspond to the internal state of the material being studied. A tensile test is recommended for evaluation of stress-strain behavior, where an entire piece of alloy archwire reaches the elastic limit at the same time. Upon tensile evaluation, stainless steel was the strongest alloy with high values for UTS, E, and 0.02% offset YS. This was followed by TiMolium™ and TMA™, respectively. The ratio YS/E is considered to be a very useful index of wire performance.[10] This ratio indicates the clinical performance of wire in terms of load deflection rate, working range, stiffness, and resilience. In the present study, TMA™ with the value of 0.014 was less stiff than other two archwire alloys, TiMolium™ (0.011) and Stainless steel (0.009).

A modified version of the three-point bend test by Miura et al[8] was performed to evaluate the load deflection properties, the most important parameter determining the biologic nature of tooth movement.[11] This test was chosen mainly because of its close simulation to clinical application, reproducible results, and the ability to differentiate wires with superelastic properties. The results of present study clearly indicated the kinder nature of beta titanium archwires to tooth as well as supporting tissues, as evidenced from the low values needed to deflect the wire and simulate engagement of the wire in the bracket of a misaligned tooth. Evaluation of unloading characteristics revealed a resilient as well as a consistent nature of TMA™ wires when compared with the other two archwire alloys. Stainless steel was the more rigid among three archwire alloys with very high loading values and less spring back properties. TiMolium™ was intermediate in nature, and TMA™ with its low stiffness characteristics showed statistically insignificant values in comparison with the other two alloys. On repeated-measure ANOVA, all three groups revealed statistically significant results. This indicates that the hysteresis (energy loss upon unloading) is associated with all three archwire alloys and is higher with stainless steel followed by TiMolium™ and TMA™, respectively.

Frictional force has long been an important consideration in orthodontic mechanotherapy. It is a well-known fact that any force needed to retract teeth must overcome friction.[1] Various methods have been used in vitro to evaluate the frictional resistance of archwires against brackets with the most accepted one being the method proposed by Tidy.[9] The test closely simulates the clinical retraction of a canine and was used in this study. This can only be taken as a means of comparing the frictional characteristics of different alloy archwires in similar testing conditions, because this does not replicate the exact intraoral environment.

The present study evaluated static as well as dynamic friction, and the values clearly indicated greater friction at the archwire-bracket interface when TMA™ wires are used in comparison with the other two alloy archwires. The finding appeared to be consistent for both static and dynamic friction and with dead weights of 0.05 and 0.1 N. The least archwire-bracket interface friction was observed with stainless steel archwires. TiMolium™, with an intermediate nature can be considered superior to TMA™ but inferior to stainless steel in its frictional characteristics. Clinically, this means that the net force required for translatory movement will be lower for stainless steel and higher when TMA™ wires are used.

Surface evaluation of an archwire alloy is important because of its influence on working characteristics as well as corrosion potential.[12] Scanning electron microscopy evaluation of surface characteristics revealed a smooth surface with little surface irregularity and horizontal wire drawing lines for TiMolium™ archwires. Stainless steel wires exhibited vertically oriented cracks, which can act as stress raisers making the alloy more brittle. TMA™, with a large number of uniformly distributed pores exhibited a very rough surface as reported extensively in the literature.[1,5,12,13] These findings agree with the frictional characteristics observed in the present study.

Elemental analysis of TiMolium™ with the help of XRF revealed titanium as the major constituent of the alloy, with both aluminum and vanadium as stabilizing agents. Aluminum is the element commonly used to stabilize the α phase of titanium to room temperature, whereas vanadium stabilizes the β phase. This alloy contains both stabilizing elements and could be a combination of both the α and β phases of titanium alloy exhibiting an unusual combination of strength and surface smoothness.

CONCLUSIONS

It is clearly evident from the data that stainless steel with high values for strength, low friction, and an almost smooth surface continues to be the mainstay archwire in orthodontic mechanotherapy. TMA™ appears to be kinder to tissues by a generating low, consistent force, when compared with other two alloys for load deflection characteristics. Friction at archwire-bracket interface appears to be higher, when TMA™ wires are used. TiMolium™ with its smooth surface, reduced friction, low modulus, and better strength can be considered an introductory breakthrough in clinical orthodontic practice.

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