Original Article

Evaluation of surface roughness of orthodontic wires by means of atomic force microscopy

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ABSTRACT

Objective: To compare the surface roughness of different orthodontic archwires.

Materials and Methods: Four nickel-titanium wires (Sentalloy®, Sentalloy® High Aesthetic, Titanium Memory ThermaTi Lite®, and Titanium Memory Esthetic®), three β-titanium wires (TMA®, Colored TMA®, and Beta Titanium®), and one stainless-steel wire (Stainless Steel®) were considered for this study. Three samples for each wire were analyzed by atomic force microscopy (AFM). Three-dimensional images were processed using Gwiddion software, and the roughness average (Ra), the root mean square (Rms), and the maximum height (Mh) values of the scanned surface profile were recorded. Statistical analysis was performed by one-way analysis of variance (ANOVA) followed by Tukey's post hoc test ($P < .05$).

Results: The Ra, Rms, and Mh values were expressed as the mean ± standard deviation. Among as-received archwires, the Stainless Steel (Ra = 36.6 ± 5.8; Rms = 48 ± 7.7; Mh = 328.1 ± 64) archwire was less rough than the others (ANOVA, $P < .05$). The Sentalloy High Aesthetic was the roughest (Ra = 133.5 ± 10.8; Rms = 165.8 ± 9.8; Mh = 949.6 ± 192.1) of the archwires.

Conclusions: The surface quality of the wires investigated differed significantly. Ion implantation effectively reduced the roughness of TMA. Moreover, Teflon®-coated Titanium Memory Esthetic was less rough than was ion-implanted Sentalloy High Aesthetic. (*Angle Orthod.* 2012;82:922–928.)

KEY WORDS: Orthodontic archwire; Surface roughness; Surface treatment; Atomic force microscopy

INTRODUCTION

The availability of different alloys for orthodontic archwires has been one of the main breakthroughs in orthodontic materials research, leading to key improvements in the field of mechanotherapy.[1] New materials are constantly being proposed to the orthodontists, and this sometimes increases confusion about the actual characteristics of the wires. In fact, the ubiquitous claims of improved performance are not always supported by accurate information. Thus, the characterization of archwire alloys can be considered an initial step in understanding wire behavior in the clinical context.[2]

Several properties should be considered in the search for the ideal archwire: esthetics, biostability, friction, formability, weldability, resilience, and springback.[3] Moreover, among the alloy's characteristics that alter the behavior of the archwires, the surface roughness plays an important role. Studies[4] have shown that the surface characteristics influence both the performance and the biocompatibility of orthodontic archwires. In addition, surface topography can critically modify the esthetics, corrosion, and efficiency of orthodontic components.[5] Furthermore, plaque accumulation is affected by surface roughness variation, and this, in turn, has a key role on the other properties previously described.[4] Above all, surface roughness may modify the friction coefficient.[6–8] Friction is a dissipative force that resists the relative motion of two

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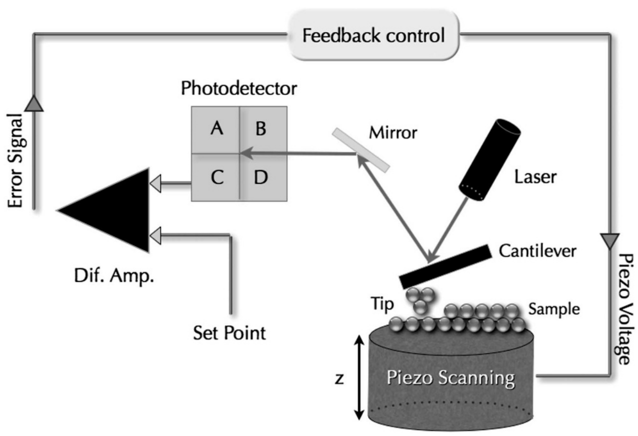

Figure 1. Atomic force microscope (AFM) diagram of operation: The AFM consists of a cantilever, the end of which is fitted with a tip, typically composed of silicon or silicon nitride, which has a radius of curvature on the order of nanometers. Attraction and repulsion forces between the tip and the sample depend on Van der Waals forces, which cause a deflection of the cantilever (the elastic constant of which is known), in accordance with Hooke's Law. The deflection is measured using a laser light reflected from the top of the micro-lever, which will be detected by a four-quadrant photodiode. A feedback loop adjusts the distance between the tip and the sample in order to keep the force acting between them constant, which in turn allows for perfect scanning of all the surface asperities. The sample is placed on a piezo-electric tube that can move it perpendicularly (z direction) to maintain a constant force in the plane (x and y directions) to analyze the surface. The resulting map (x, y) represents the topography of the surface sample.

objects in contact.[9] In orthodontics it interferes with the correct sliding of the bracket along the wire.[5] Friction depends on the following factors: (1) molecular adhesion (ie, the electromagnetic forces between atoms), (2) the interlocking produced by surface roughness, and (3) the plowing effect.[10] It is interesting to note that if the surface can be deformed plastically the coefficient of friction (μ) is independent from the contact visible area, as determined by the second law of friction.[10,11] Nevertheless, a basic premise of the theory of friction is that apparently flat and smooth surfaces are not smooth when analyzed on a microscopic scale.

The surface of metals is actually rough, and the asperities determine this roughness.[12] Microscopically, the effective interface area (Σ_{eff}) between two solids is a very small part of the nominal interface area Σ_0. The effective area is defined as the summed area of contact between the microscopic irregularities of surfaces;[13] these points, called asperities, bear the entire load between the surfaces.[12]

Therefore, a critical step in the evaluation of archwire performance is the analysis of the surface roughness of different wires available in the market. In past years, the main technique with which to determine surface roughness was the surface profilometry,[14] in which a thin tip was used to scan the topography in a single line of a preselected area. The main drawback of this method was the impossibility of measuring surface defects adjacent to the scan line; furthermore, the profilometry was invasive, and damage to the surface was possible during scanning. Thus, the increasing demand for nondestructive and noninvasive techniques has enhanced new methods of analysis, based on optical methods[15] and on a developed scanning tunneling microscope.[16] With these methods it is possible to scan a preselected surface area of a model without direct interaction. The scanning probe microscopy includes different types of scanning tunneling microscopes, the atomic force microscope (AFM),[17] and the magnetic force microscope. The AFM is considered the most appropriate tool for measuring surface topography because it can provide three-dimensional information on surface morphology.[18]

The aims of this study were to compare the surface roughness of eight types of as-received archwires by means of AFM and to evaluate the advantages of AFM in the analysis of orthodontic materials.

MATERIALS AND METHODS

Three orthodontic archwire alloys were considered for this study: stainless-steel (SS), β-titanium (β-Ti), and nickel-titanium (NiTi) alloys. In order to ensure wide availability of data, four NiTi round wires (0.016 inches; Sentalloy® and Sentalloy® High Aesthetic, GAC International, Bohemia, NY; Titanium Memory ThermaTi Lite® and Titanium Memory Esthetic®, AO, Sheboygan, Wisc); three β-Ti rectangular wires (0.016 $\times$ 0.022 inches; TMA® and Colored TMA®, Ormco, Glendora, Calif; Beta Titanium®, AO); and one SS rectangular wire (0.016 $\times$ 0.022 inches; Stainless Steel®, AO) were selected.

In order to analyze approximately straight specimens, three samples of each wire product (5 mm) were cut from the end of three different preformed archwires and were observed with an AFM (AFM Perception, Assing, Italy) (Figure 1) operating in contact mode under ambient conditions. The samples were attached to a metal holder using a rapid-drying cyanoacrylate glue, and then, for each specimen, 20 areas (15 $\times$15 μm) of the surface were randomly selected and analyzed ($N = 60$). AFM probes (curvature radius <10 nm) mounted on cantilevers (250 μm), with a spring constant of 0.1 N/m, were used. Three-dimensional images (400 $\times$ 400 lines) were processed using Gwyddion software 2.9 (http://www.gwyddion.net), and average roughness (Ra), mean square roughness (Rms), and maximum value height (Mh) were recorded. The Ra and Rms represent the arithmetical mean of the absolute values and the root mean square value of the scanned surface profile, respectively; Mh is the maximum height of a

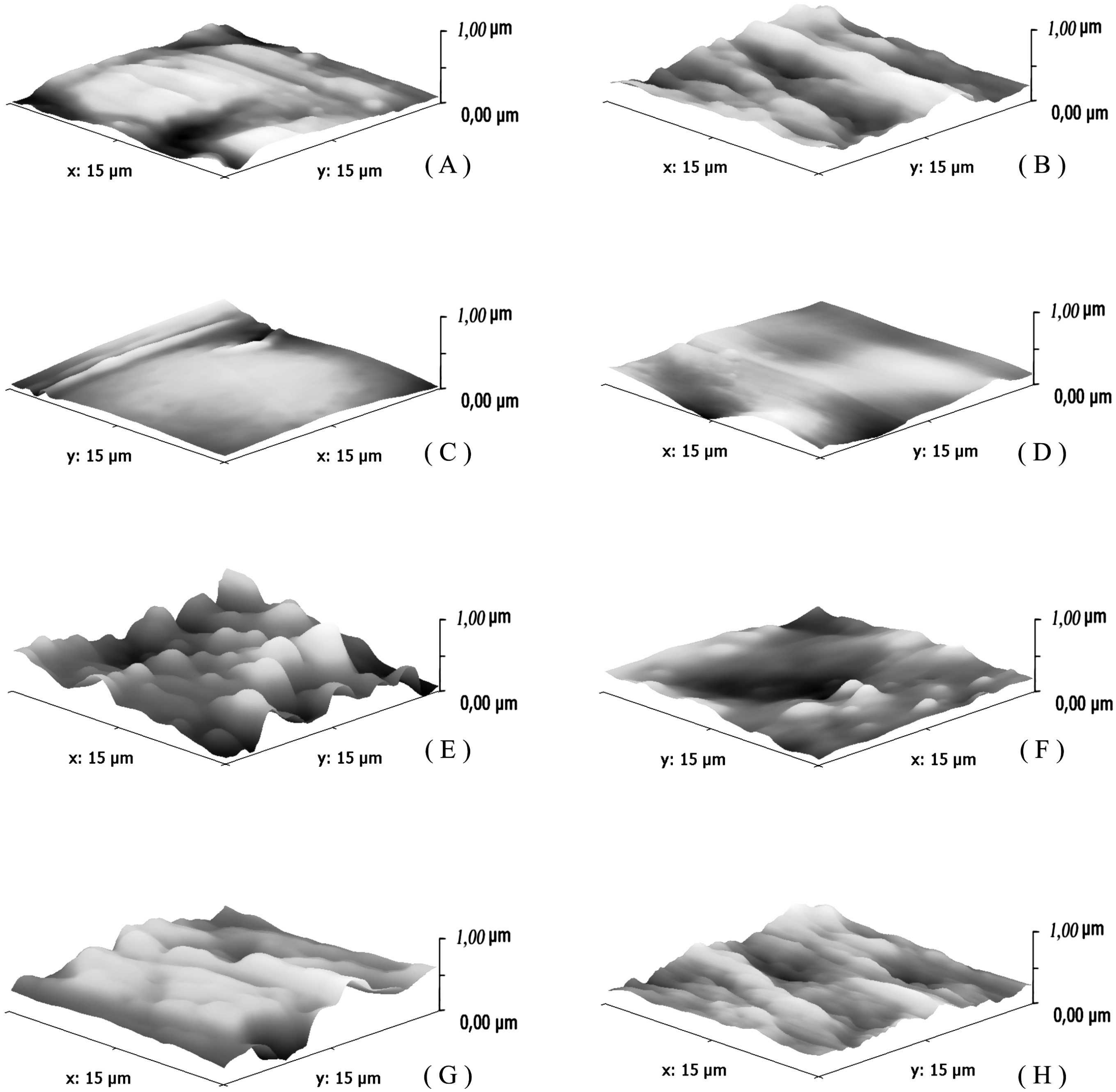

Figure 2. Representative three-dimensional AFM topography images (15 × 15 μm) of the eight samples of orthodontic archwires: Stainless Steel (A), Beta-Titanium (B), Titanium Memory Esthetic (C), Titanium Memory ThermaTi Lite (D), Sentalloy High Aesthetic (E), Sentalloy (F), TMA (G), and Colored TMA (H).

profile peak. Statistical analysis of the data was performed by means of one-way analysis of variance (ANOVA) followed by a Tukey's post hoc test. The level of significance was set at $P < .05$.

RESULTS

Topographic irregularities were observed in all of the wires tested. Figure 2 shows representative three-dimensional AFM topography images (15 × 15 μm) of the eight wires analyzed, while Figure 3 shows the two-dimensional images in order to better evaluate the dimension of nanodomains. As shown in Figures 2 and 3, the surface morphologies of the archwires differed from one another based on their composition. The three roughness parameters were used to quantitatively evaluate the surface topography of each archwire and are shown in Table 1 as mean ± standard deviation in nanometers. Statistically significant differences between different types of alloys were found

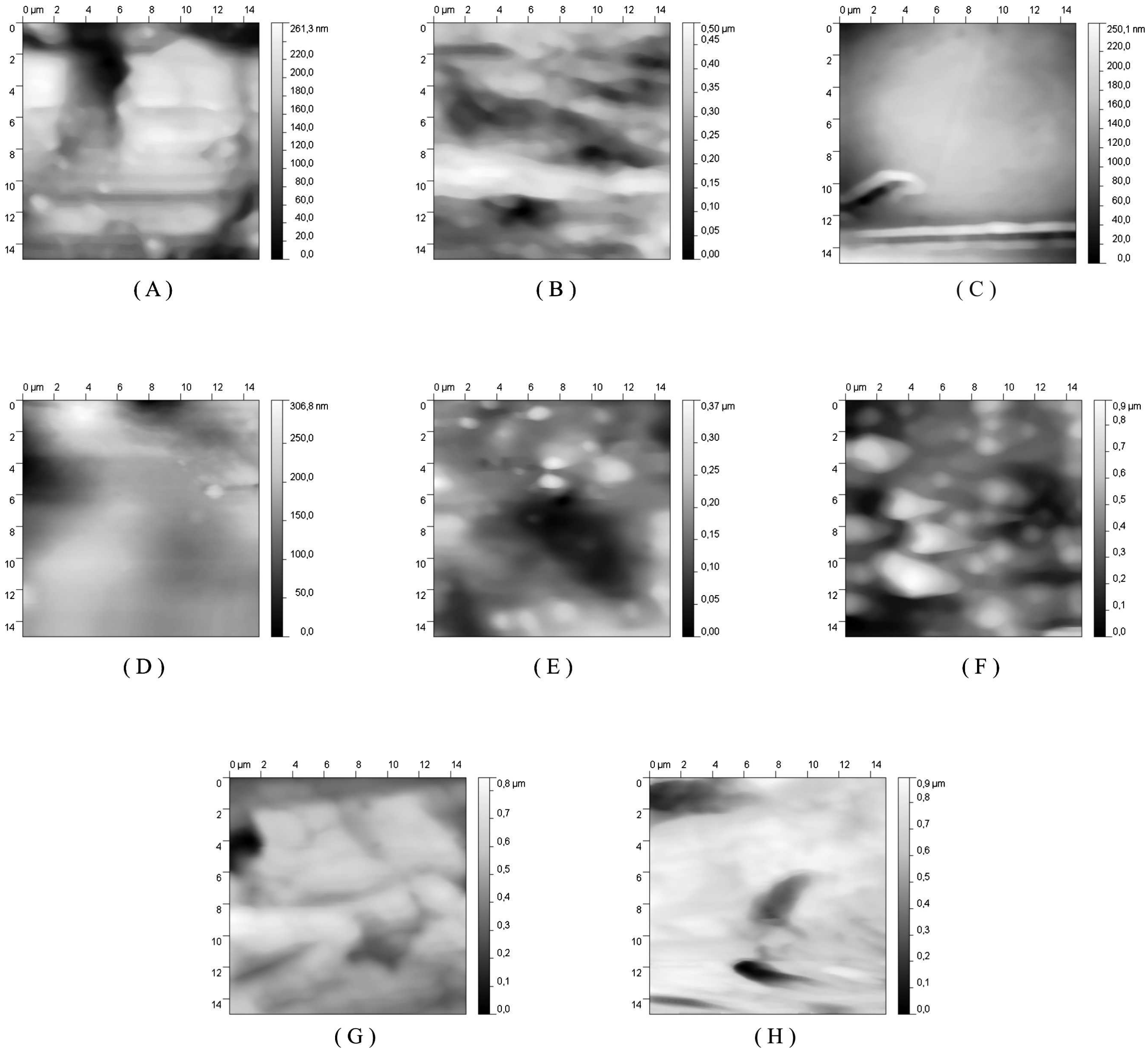

Figure 3. Representative AFM topography images (15 × 15 µm) of the eight samples of orthodontic archwires: Stainless Steel (A), Beta-Titanium (B), Titanium Memory Esthetic (C), Titanium Memory ThermaTi Lite (D), Sentalloy High Aesthetic (E), Sentalloy (F), TMA (G), and Colored TMA (H).

Table 1. Roughness Average (Ra), Root Mean Square (Rms), and Maximum Height (Mh) Values of Atomic Force Microscope (AFM) Topography Images[a]

Tested Archwires	Ra, Mean ± SD	Rms, Mean ± SD	Mh, Mean ± SD
Sentalloy®	71.1 ± 15.4	86.9 ± 18.4	497.3 ± 142.8
Sentalloy® High Aesthetic	133.5 ± 10.8	165.8 ± 9.8	949.6 ± 192.1
Titanium Memory ThermaTi Lite®	82 ± 27.3	115.5 ± 40.5	727.5 ± 256.8
Titanium Memory Esthetic®	44.9 ± 17	55.3 ± 20.6	306.7 ± 130.2
Stainless Steel®	36.6 ± 5.8	48 ± 7.7	328.1 ± 64
TMA®	120 ± 38.7	155.1 ± 46.9	876.6 ± 401
Colored TMA®	69.5 ± 25.1	88.8 ± 33.2	540.9 ± 118
Beta Titanium®	77.9 ± 22.4	95.7 ± 26.4	580.4 ± 286.3

[a] SD indicates standard deviation.

Table 2. *P*-Values from Statistical Analysis of Archwire Roughness Parameters (Analysis of Variance [ANOVA] with Tukey's Post Hoc Test)[a]

Tukey's Multiple Comparison Test	Ra	Rms	Mh
Sentalloy® vs Sentalloy® High Aesthetic	***	***	***
Sentalloy® vs Titanium Memory Esthetic®	**	*	ns
Sentalloy® vs TMA®	***	***	***
Sentalloy® vs Colored TMA®	ns	ns	ns
Sentalloy® vs Beta Titanium®	ns	ns	ns
Sentalloy® vs Stainless Steel®	***	**	ns
Sentalloy® vs Titanium Memory ThermaTi Lite®	ns	ns	ns
Sentalloy® High Aesthetic vs Titanium Memory Esthetic®	***	***	***
Sentalloy® High Aesthetic vs TMA®	ns	ns	ns
Sentalloy® High Aesthetic vs Colored TMA®	***	***	***
Sentalloy® High Aesthetic vs Beta Titanium®	***	***	***
Sentalloy® High Aesthetic vs Stainless Steel®	***	***	***
Sentalloy® High Aesthetic vs Titanium Memory ThermaTi Lite®	***	**	ns
Titanium Memory Esthetic® vs TMA®	***	***	***
Titanium Memory Esthetic® vs Colored TMA®	*	*	**
Titanium Memory Esthetic® vs Beta Titanium®	***	***	**
Titanium Memory Esthetic® vs Stainless Steel®	ns	ns	ns
Titanium Memory Esthetic® vs Titanium Memory ThermaTi Lite®	***	***	***
TMA® vs Colored TMA®	***	***	*
TMA® vs Beta Titanium®	***	***	***
TMA® vs Stainless Steel®	***	***	***
TMA® vs Titanium Memory ThermaTi Lite®	**	*	ns
Colored TMA® vs Beta Titanium®	ns	ns	ns
Colored TMA® vs Stainless Steel®	**	**	*
Colored TMA® vs Titanium Memory ThermaTi Lite®	ns	ns	ns
Beta Titanium® vs Stainless Steel®	***	***	*
Beta Titanium® vs Titanium Memory ThermaTi Lite®	ns	ns	ns
Stainless Steel® vs Titanium Memory ThermaTi Lite®	***	***	***

[a] ns indicates not significant.

* $P < .05$; ** $P < .01$; and *** $P < .001$ indicate statistically significant differences between the two archwires.

(Table 2). Among the NiTi archwires, Titanium Memory Esthetic was determined to be the least rough (ANOVA, $P < .05$), followed by Sentalloy and ThermaTi. Sentalloy High Aesthetic, an ion-implanted wire, was the roughest (ANOVA, $P < .05$). Among the β-Ti archwires, Colored TMA showed the lower parameter values, while nontreated Beta Titanium and TMA presented a rougher surface. Stainless Steel (Ra $= 36.6 \pm 5.8$; Rms $= 48 \pm 7.7$; Mh $= 328.1 \pm 64$) was determined to be significantly less rough than the other alloys (ANOVA, $P < .05$).

DISCUSSION

In the present study, topographic surface characteristics of orthodontic as-received archwires were evaluated by means of AFM. The AFM belongs to the family of scanning probe microscopes, a class of tools that, using interatomic interactions, acquires information on detected surfaces; this microscope obtains the images by sensors, consisting of sharp points interacting with the specimen surface. The AFM is considered a promising technique for the evaluation of surface qualities of dental materials.[19–21]

Our results showed that the least rough wire was the Stainless Steel wire. It has been demonstrated that SS shows the lowest frictional coefficient and the lowest sliding resistance, when used in passive configuration, because of its combination of low roughness, high hardness, and high strength.[22] β-Ti archwires were the roughest, which could be associated with the great friction generated by this material.[23,24] These data are consistent with those from the study of Doshi and Bhad-Patil,[25] which showed higher values of surface roughness for TMA, but they are in contrast with the results of several studies[5] in which NiTi wires were considered the roughest. Titanium Memory Esthetic, a Teflon-coated wire, was the least rough among the NiTi archwires, being slightly rougher than Stainless Steel. On the other hand, the Sentalloy High Aesthetic, which is produced by ion implantation of rhodium, showed the highest values of roughness. The ion implantation and the Teflon coating are the most common archwire surface treatments.[26,27] These procedures should decrease the surface roughness of the materials and should improve the sliding of the wire.[4,26,28]

Although further studies should be conducted to assess the deterioration of the coating during clinical practice, in evaluating the properties of Teflon-coated as-received archwires Husmann et al.[26] and Farronato et al.[29] found that in vitro, the coating reduced the friction between wires and brackets. Furthermore, our study showed that not only did ion implantation of rhodium fail to drastically reduce the surface roughness of NiTi wires, it even increased it.[4,14] Ion implantation decreased the roughness of β-Ti alloy. Colored TMA was less rough than were nontreated β-Ti wires.[30] Burstone and Franzin-Nia[30] stated that ion implantation increased archwire hardness, reduced flexibility, and improved surface finish; to obtain the maximum reduction on frictional force, ion implantation should be used on brackets and on archwires over and over again.[25]

An important factor that influences the surface topography of orthodontic wires is, therefore, the production technique; this hypothesis was confirmed by the fact that the roughness measured for various products from the same batch was quite homogeneous.

Opposite opinions exist about the influence of surface quality of wires and bracket slots on the production of friction. Frictional force between wires and brackets is considered a harmful factor that influences the normal movement of the teeth during sliding mechanics.[31] Many studies[6–8,32] confirm that a correlation exists between surface roughness and friction, but tooth orthodontic movement is a very complex process, correlated with a number of critical factors. In fact, Kusy et al.,[5] Prososki et al.,[33] and Ghafari[34] found that low wire-surface roughness is not a sufficient condition for low frictional coefficients.

Among the selected alloys, TMA generally exhibits maximum frictional force, probably as a result of the adhesive and abrasive wear produced with the slot of the bracket as a result of the high reactivity of the wire's surface.[22,35] The NiTi wire, on the other hand, creates lower friction than do the SS and β-Ti wires; in fact, its stiffness and flexibility improve the performance of the archwire.[5,36]

The first law of friction, the Amontons-Coulomb Law, states that $Fr = \mu \times Fn$, where μ (friction coefficient) depends on the roughness of the wires and on its physical characteristics,[10,37] and where Fn (normal force) is the force that keeps adhering the two surfaces (wire and bracket). In active configuration,[3] normal force, which binds the two surfaces, is greater for the stiffer wires, like SS wires, which are less flexible and impact hard against the bracket, developing a stronger contact force. In contrast, more flexible wires, like NiTi wires, although more wrinkled, impact less on the surface of the bracket and develop a lighter normal force. Finally, it should be noted that surface roughness also modifies other characteristics of the wires in addition to friction: the esthetics of the product, the corrosion, the biocompatibility, and the performance.[4,5,14,26]

In conclusion, our investigation demonstrated the potential use of an AFM for the study of surface properties of orthodontic materials. In particular, the AFM has many advantages, such as the production of topographical three-dimensional images in real space with a very high resolution (~10 A). The samples do not require any special treatment, such as metallization, and the AFM can provide quantitative values for the investigated parameters. The most important AFM drawback is the small scan size, which, in association with the slow velocity of scanning, often impedes a complete analysis of the sample.[38] Therefore, there might be some unselected regions with surface defects, and thus with much greater roughness, that would be of clinical importance.

CONCLUSIONS

- This study showed great variability in the surface roughness of wires, with Stainless Steel turning out to be the least rough. The ion-implantation technique was advantageous for β-Ti wires.
- The clinical relevance of this study should be considered in light of all the other factors that contribute to sliding resistance, and further studies must be undertaken to assess the variation of surface roughness that follows the clinical use and its correlation with the friction.

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