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. 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.

Several properties should be considered in the search for the ideal archwire: esthetics, biostability, friction, formability, weldability, resilience, and spring-back. Moreover, among the alloy’s characteristics that alter the behavior of the archwires, the surface roughness plays an important role. Studies 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. Furthermore, plaque accumulation is affected by surface roughness variation, and this, in turn, has a key role on the other properties previously described. Above all, surface roughness may modify the friction coefficient. Friction is a dissipative force that resists the relative motion of two
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b H Microscopically, It is interesting to note that if the
and Titanium Memory Esthetic, High Aesthetic,
With these methods H and Colored TMA
and Sentalloy in 923 S b 13 H 14 m
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asperities determine this roughness. When analyzed on a microscopic scale.
Nevertheless, a basic premise of the theory of friction is
that apparently flat and smooth surfaces are not smooth
to maintain a constant force in the plane (x and y directions) 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.9 Friction
depends on the following factors: (1) molecular adhe-
sion (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
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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 (Σeff) between two solids is a
very small part of the nominal interface area Σ0. The
effective area is defined as the summed area of contact
between the microscopic irregularities of surfaces;13
de this area, 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

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.

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 × 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 × 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

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
× 0.022 inches; TMA® and Colored TMA®, Ormco,
Glendora, Calif; Beta Titanium®, AO); and one SS
rectangular wire (0.016 × 0.022 inches; Stainless
Steel®, AO) were selected.

In order to analyze approximately straight specimens,
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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 \( \times \) 15 \( \mu \text{m} \)) 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 2. Representative three-dimensional AFM topography images (15 \( \times \) 15 \( \mu \text{m} \)) 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).*
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*

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

* SD indicates standard deviation.
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 \(\beta\)-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.\(^{22}\) \(\beta\)-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 friction generated by this material.\(^{26,27}\) 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 \(\beta\)-Ti alloy. Colored TMA was less rough than were nontreated \(\beta\)-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.,\(^30\) and Ghaafari\(^34\) 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 \(\beta\)-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 \(F_r = \mu \times F_n\), where \(\mu\) (friction coefficient) depends on the roughness of the wires and on its physical characteristics,\(^1,37\) and where \(F_n\) (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 (\(\sim\)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 \(\beta\)-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.

REFERENCES


