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Comparison of surface topography of low-friction and conventional TMA orthodontic arch wires using atomic force microscopy

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Abstract:

OBJECTIVE: To evaluate the surface topography and roughness of orthodontic arch wire materials, including low-friction titanium molybdenum alloy (TMA), conventional TMA, and stainless-steel arch wires.

MATERIALS AND METHODS: The surface topography was evaluated using atomic force microscopy (AFM). A total of 24 wire specimens were used for the AFM scans {8 low-friction TMA (TMA-Low), 8 conventional TMA (TMA-C), and 8 stainless steel (SS)} (Ormco, Orange, CA, USA), measuring 0.016 × 0.022 inches. The conventional and low-friction TMA arch wires served as the test groups, while the stainless-steel arch wire served as the control group.

RESULTS: Surface roughness evaluation using AFM revealed that the highest mean of all three roughness parameters was found in the TMA-C group followed by the TMA-Low and SS arch wires in descending order. Pairwise comparison of the mean values showed that the mean value of the SS arch wire material is statistically significantly lower than the mean values of the other two arch wire materials (TMA-C and TMA-Low). However, there was no statistically significant difference in the mean values of TMA-C and TMA-Low arch wires.

CONCLUSION: The SS arch wire showed the smoothest surface topography among the alloys and had statistically significantly lower roughness values than the TMA-C and TMA-Low groups. Low-friction TMA arch wire is still considered to be inferior to stainless steel arch wire.

Keywords:

Friction, in vitro, steel, surface roughness, titanium molybdenum alloy, wire

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Introduction

The topography of a given surface has a significant impact on its functional properties despite the complexity of its physical nature. Additionally, the topography of a surface defines the current carrying capacity, which means that the functional properties, such as friction and wear, are determined by the topography.[1] The macrostructure of a surface is determined by its microstructure and roughness. Altering the surface topography by modifying the surface, for example, via ion implantation, can alter the physical properties of the surface area.[1]

Roughness is considered a main factor of the surface topography, and the term can be used interchangeably with surface texture. It represents the finest closely spaced irregularities of the surface, appears as peaks (asperities) and valleys, and is a result of the material production process that comprises grinding or cutting tools.[2] Therefore, comprehensive analysis of surfaces' microtopographic features is

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key to improving the product quality characteristics of a given material.[3]

The measurement of surface topography was first made possible by the development of precision stylus profiling instruments in the late 1920s to comprehensively evaluate the fine structure of surface topography. The need to detect atomic scale features at a nanoscale level and on an extensive range of insulating surfaces led to the development of atomic force microscopy (AFM) in 1986 by Binning, Quate, and Gerber.[4] Since the invention of AFM, it has become the most common technique among scanning probe microscopies to be utilized in the fields of physics, biology, and material science. AFM provides valuable images down to the atomic level by utilizing noninvasive probes.[5] Nanoscale science is now an emerging field, as it studies the phenomena and features at a very small scale and shows how nanoparticles exhibit different properties than large particles of the same material.[6] Among the scanning microscopies, AFM provides a three-dimensional analysis of the scanned surface. It also provides a qualitative and quantitative measurement of surface roughness.[7-9]

Conventionally, the use of a combination of SS arch wires and brackets has been the gold standard for orthodontists to utilize during sliding mechanics.[10] Beta-titanium alloy, also called titanium molybdenum alloy (TMA), arch wires were first introduced in 1979 by Goldberg and Burstone.[11] Recently, these arch wires have gained popularity because of their favorable characteristics, including low stiffness, high formability, and efficient working range for tooth movement.[12] However, TMA wires have some disadvantages, including a high surface roughness, which increases friction at the wire-bracket interface during sliding mechanics.[13] Manufacturers have introduced different TMA arch wires with different surface treatments, attempting to reduce their frictional characteristics and improve their surface topography.[14] However, despite the manufacturers' efforts to improve the surface properties, TMA arch wires are still considered to be inferior to SS arch wires.[8] Low-friction TMA arch wires were introduced in 2014 by the Ormco company to improve the properties of the conventional TMA wires. The company claimed that they refined the TMA manufacturing process by changing the processing at the vendor to improve the surface finish and reduce the frictional properties. These low friction arch wires seem to be beneficial to minimize the amount of friction in specific clinical applications if proven to have lesser effect on frictional properties. However, the cost of these materials is still considerably higher than the traditionally used materials and their real cost to benefit remains scientifically questionable.

This study aims to evaluate the surface topography and roughness of orthodontic arch wire materials, including low-friction TMA, conventional TMA, and stainless-steel arch wires, using noncontact mode atomic force microscopy. This will help orthodontists know the surface properties of these new products and fully understand the impact of the material characteristics on their applied biomechanics in the clinic. The null hypothesis tested was that there is no difference in the surface topography and roughness of low-friction TMA, conventional TMA, and SS arch wires.

Materials and Methods

Ethical approval was obtained from King Saud University, College of Dentistry Research Center, (PR 0073).

A. Sample description

A total of 24 arch wire specimens were used as received for the AFM scans {8 low-friction TMA (TMA-Low), 8 conventional TMA (TMA-C), and 8 stainless steel (SS)} (Ormco, Orange, CA, USA), measuring 0.016 × 0.022 inches. The TMA-C and TMA-Low arch wires served as the test groups, while the SS arch wire served as the control group.

B. Experimental setup

Measuring tool

A MicroGlider® with a highly precise positioning stage on air bearings with excellent running accuracy and an individual sensor setup was used [Figure 1]. It comprises two mounted sensors in one machine: a chromatic white sensor (CWS) and an atomic force microscope (AFM sensor). The air bearings are firmly placed on a granite base and depressurized during the AFM scan to reduce the amount of resulting vibration.

AFM measuring head and sample calibration

Noncontact AFM mode and high aspect ratio nanosensor tips were used (The Art of Metrology, Bergisch Gladbach, Germany). These nanosensor tips (NANOSENSORS™ AR5-NCLR AFM tips were essentially developed for the tapping or noncontact AFM mode, and the length of the HAR portion of the tip was more than 2 µm. The probe of this system necessitates a minimum cantilever length of more than 125 µm or a resonance frequency of less than 400 kHz, which makes the cantilever feature a high operational stability along with a fast scanning ability and outstanding sensitivity. The tip used has a curvature radius of less than 15 nm and is made of highly doped silicon to dissipate static charge, acting as a scanning probe. The tip was attached to a cantilever with the following properties: 227 µm in length, 7 µm in thickness, and 38 µm in width with a spring constant of 21 to 98 N/m and a resonance frequency of 190 kHz. Both sensors were calibrated separately. The AFM sensor was calibrated according to the known AFM standards, which include a coordinate system-like grid with a 10 μm spacing to calibrate the AFM xy-scanner and determine the offset between the AFM scan area and the spot of the optical sensor. The chromatic sensor was calibrated using an interferometer, which is usually performed once by the manufacturer and periodically checked using a specified gauge block or height calibration standards.[15]

Sample placement on the stage

The arch wire specimen was placed with 45° rotation on a highly precise positioning stage on air bearings with three translational degrees of freedom, enabling it to move perpendicularly (z direction) to maintain a constant force (in both the x and y directions) for analyzing the surface [Figure 2]. The measuring field rotation of 45° produced the largest possible AFM measuring field of 100 × 100 μm². Approach of the measuring field was first performed using a chromatic white light sensor (CWL 600 μm) to ensure a centered AFM measuring field [Figure 3]. Then, scanning of the AFM measuring field (100 × 100 μm²) was carried out to analyze the surface. The tip was placed against the specimen surface (at approximately 10–100 nm) to produce a force constant of 49 N. The presence of this force expresses the interaction between the specimen surface and tip, causing the cantilever to bend; a deflection sensor recorded this vertical deflection. The rougher the surface, the longer the scan time was. The scan time was in the range of 20 minutes for each SS specimen and 60 minutes for each low-friction and conventional TMA specimen, respectively.

Analysis of the scanned samples

After obtaining the scanned images for the samples, as shown in Figure 4, the FRT MARK III program (FRT GmbH, Germany) was used to analyze the profile and surface area measurement data. This software is capable of analyzing the common formats of 2D and 3D files of various scanning probe microscopes (SPM). Three surface topography parameters were examined: the arithmetic average height (i.e., average roughness; sRa), root mean square (sRq), and ten-point height (sRz).

Statistical analysis

Statistical analysis was performed using SPSS software (IBM SPSS Inc., version 20, Chicago, IL, USA), and the level of significance was set at $P < 0.05$. Assuming an effect size of $f = 0.7$, with $\alpha = 0.05$ and $\beta = 0.20$ (power of 80%), the required sample size is 8 samples in each of the 3 groups. Normal distribution of the data was tested for each group comparison using Shapiro-Wilk test. Results showed that data were normally distributed and accordingly parametric tests were used for analysis. Descriptive data, including the means, standard deviations, and minimum and maximum readings, were calculated for comparison of all groups. The differences between the weighted means of surface roughness were analyzed using one-way ANOVA, and group differences were further analyzed with Tukey's post hoc comparison test.

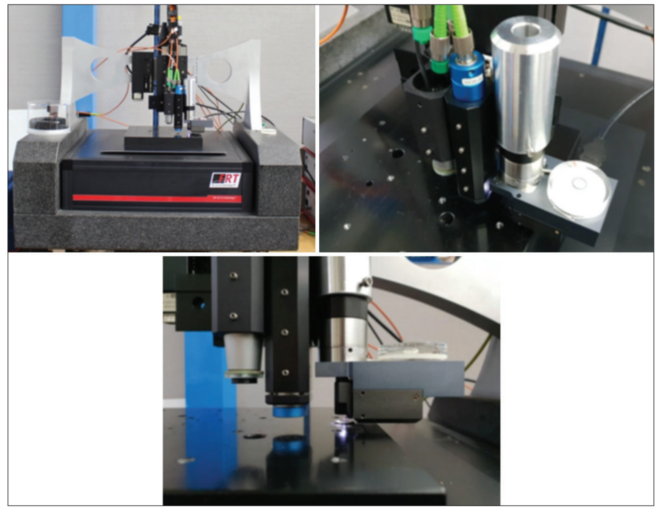

Figure 1: Photograph showing the AFM measurement tool

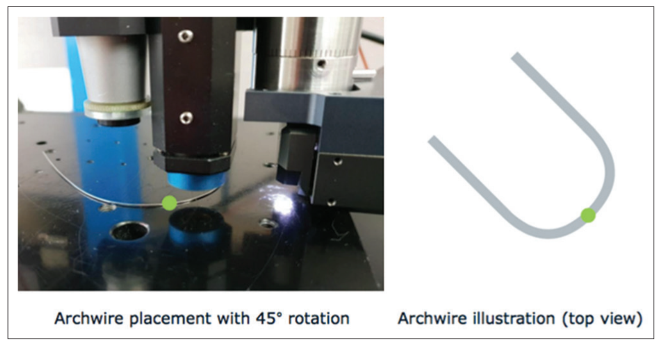

Figure 2: Sample placement with 45° rotation

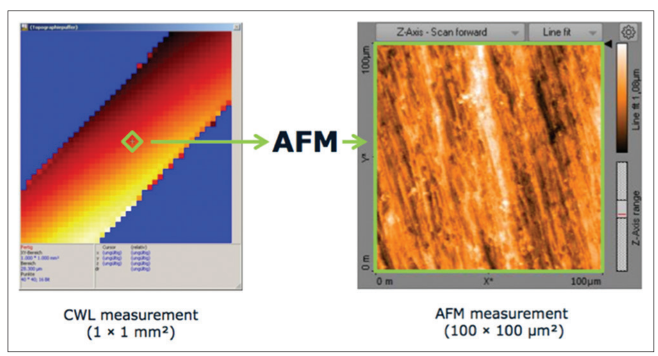

Figure 3: Approach of the measurement field

Results

Three roughness parameters were obtained, and comparisons between each arch wire type for each parameter were performed. Descriptive statistics showed that the highest mean of all three roughness parameters was found in the TMA-C group, followed by the TMA-Low and SS arch wire groups in descending

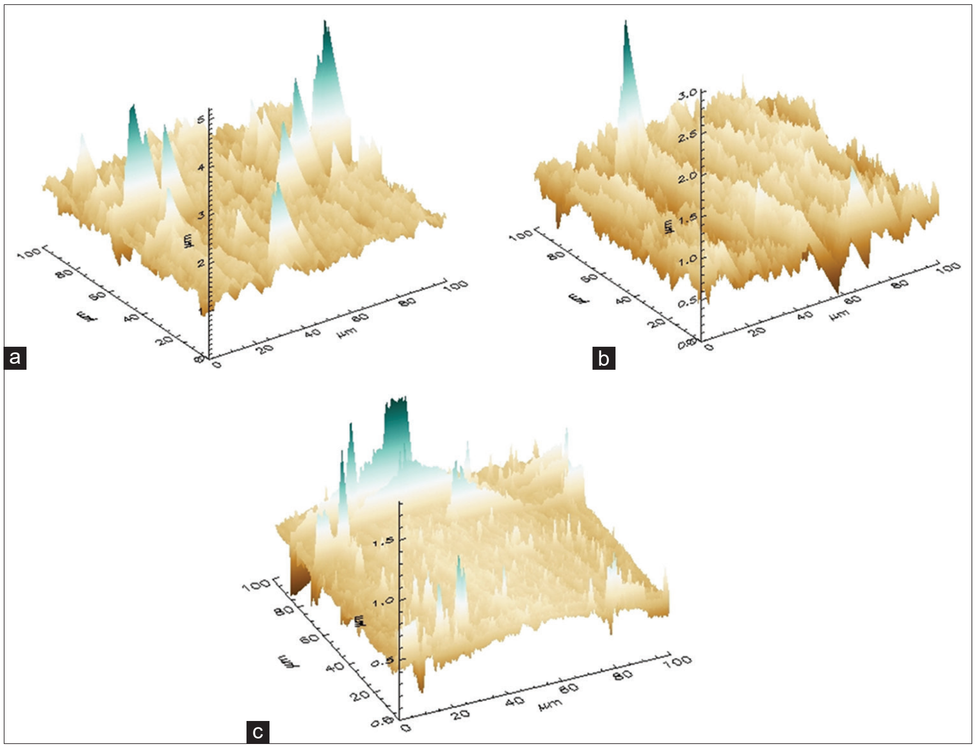

Figure 4: Surface topographical images of the arch wire surfaces obtained by atomic force microscopy. a: (TMA-C), b: (TMA-Low), c: (SS) arch wire

order [Figure 5]. The mean values of the roughness parameters across the three types of wires were compared [Table 1] and are shown below.

A. Arithmetic average height (average roughness, sRa)

There was a statistically significant difference in the mean values of the average roughness (sRa) parameter among the three types of arch wires (TMA-C: sRa = 0.084 ± 0.018 µm, TMA-Low: sRa = 0.076 ± 0.006 µm and SS: sRa = 0.020 ± 0.005 µm; $P < 0.0001$; see Table 2). The pairwise comparison of mean values showed that among the three materials, the (sRa) mean value of the SS arch wire material was statistically significantly lower than the mean values of the other two arch wire materials (TMA-C and TMA-Low; $P < 0.001$ and $P < 0.001$). However, there was no statistically significant difference in the mean values of the (sRa) of the TMA-C and TMA-Low arch wires ($p = 0.346$; Table 3).

B. Root mean square (sRq)

There was a statistically significant difference in the mean values of the root mean square (sRq) parameter among the three types of arch wire (TMA-C: sRq = 0.111 ± 0.032 µm, TMA-Low: sRq = 0.095 ± 0.008 µm and SS: sRq = 0.035 ± 0.010 µm; $P < 0.0001$; see Table 2). The pairwise comparison of mean values showed that among the three materials, the (sRq) mean value of the SS arch wire material was statistically significantly lower than the mean values of the other two materials (TMA-C and TMA-Low; $P < 0.001$ and $P < 0.001$). However, there was no statistically significant difference in the mean values of (sRq) of the TMA-C and TMA-Low arch wire materials ($p = 0.265$; Table 3).

C. Ten-point height (mean peak to valley height) (sRz)

There was a statistically significant difference in the mean values of the ten-point height (sRz) parameter among the three types of arch wire (TMA-C: sRz = 0.998 ± 0.464 µm, TMA-Low: sRz = 0.786 ± 0.121 µm and SS: sRz = 0.530 ± 0.135 µm; $P < 0.0001$; see Table 2). The pairwise comparison of mean values showed that among the three materials, the sRz mean value of the SS arch wire material was statistically significantly lower than the mean value of the TMA-C material ($p = 0.010$) but was not significantly different from the mean value of the TMA-Low material ($p = 0.199$). Additionally, there was no statistically significant difference in the sRz mean values of the TMA-C and TMA-Low arch wire materials ($p = 0.326$; Table 3).

Discussion

The surface roughness and topography of an alloy are especially important because of their contributions to the surface contact area and their effect on the biocompatibility and corrosion behavior of the alloy.[7] The production technique of dental materials is an important contributing factor to the final surface finish

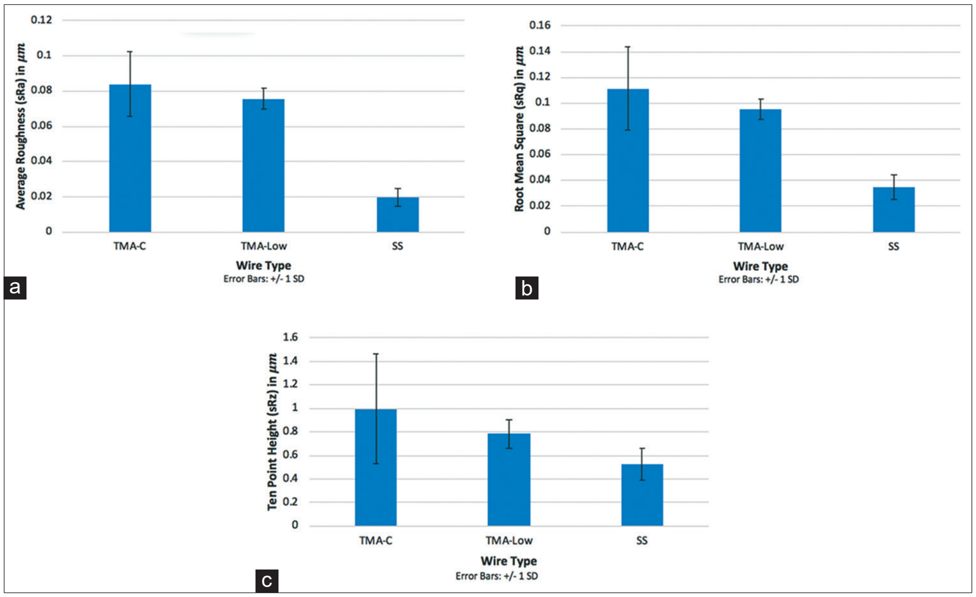

Figure 5: Bar graphs comparing the average mean values of the average roughness (sRa, a), root mean square (sRq, b), and ten point height (Srz, c) parameters obtained using AFM among the three arch wire groups

Table 1: Descriptive statistics of outcome variables

		N	Mean	Std. Deviation	Minimum	Maximum
Average roughness (sRa) in µm	Conventional TMA	8	0.083	0.018	0.056	0.108
	Low TMA	8	0.075	0.005	0.070	0.085
	Stainless steel	8	0.019	0.004	0.013	0.029
	Total	24	0.059	0.031	0.013	0.108
Root mean square (sRq) in µm	Conventional TMA	8	0.111	0.032	0.072	0.171
	Low TMA	8	0.095	0.008	0.089	0.110
	Stainless steel	8	0.034	0.009	0.020	0.048
	Total	24	0.080	0.038	0.020	0.171
Ten point height (sRz) in µm	Conventional TMA	8	0.997	0.464	0.531	1.914
	Low TMA	8	0.786	0.120	0.606	0.997
	Stainless steel	8	0.529	0.135	0.296	0.677
	Total	24	0.771	0.337	0.296	1.914

Table 2: One-way analysis of variance to compare the mean values of outcome variables among the three types of material

		Sum of Squares	df	Mean Square	*F*	*P*
Average roughness (sRa) in µm	Between Groups	0.019	2	0.010	72.806	0.000
	Within Groups	0.003	21	0.000		
	Total	0.022	23			
Root mean square (sRq) in µm	Between Groups	0.026	2	0.013	32.961	0.000
	Within Groups	0.008	21	0.000		
	Total	0.034	23			
Ten point height (sRz) in µm	Between Groups	0.878	2	0.439	5.307	0.014
	Within Groups	1.738	21	0.083		
	Total	2.616	23			

*Significant at $P<0.05$, *** Significant at $P<0.001$

and topography. It should be noted that on a molecular level, there is technically no machining method that can provide a very smooth surface finish, and all produced materials exhibit some roughness features on the nanoscale.[3] Therefore, a noncontact AFM mode device was used to comprehensively analyze the surfaces' microtopographic features and obtain a 3D quantitative and qualitative evaluation of the scanned samples.

In the present study, surface topographical roughness features of orthodontic as received arch wires were evaluated by the AFM. Our findings showed that the SS

Table 3: Multiple comparison of mean values of outcome variables among the pairs of the three types of materials

Dependent Variable	(I) Category	(J) Category	Mean Difference (I-J)	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Average roughness (sRa) in µm	Conventional TMA	Low TMA	0.008	0.346	-0.006	0.022
		Stainless steel	0.064*	0.000	0.049	0.078
	Low TMA	Conventional TMA	-0.008	0.346	-0.022	0.006
		Stainless steel	0.055*	0.000	0.041	0.070
	Stainless steel	Conventional TMA	-0.064*	0.000	-0.078	-0.049
		Low TMA	-0.055*	0.000	-0.070	-0.041
Root mean square (sRq) in µm	Conventional TMA	Low TMA	0.016	0.265	-0.009	0.041
		Stainless steel	0.076*	0.000	0.051	0.101
	Low TMA	Conventional TMA	-0.016	0.265	-0.041	0.009
		Stainless steel	0.060*	0.000	0.035	0.085
	Stainless steel	Conventional TMA	-0.076*	0.000	-0.101	-0.051
		Low TMA	-0.060*	0.000	-0.085	-0.035
Ten point height (sRz) in µm	Conventional TMA	Low TMA	0.211	0.326	-0.151	0.573
		Stainless steel	0.467*	0.010	0.105	0.830
	Low TMA	Conventional TMA	-0.211	0.326	-0.573	0.151
		Stainless steel	0.256	0.199	-0.105	0.619
	Stainless steel	Conventional TMA	-0.467*	0.010	-0.830	-0.105
		Low TMA	-0.256	0.199	-0.619	0.105

*Significant at $P<0.05$, ***Significant at $P<0.001$

arch wire is the smoothest among the alloys. Our results are in agreement with numerous previous studies that have shown that SS arch wires have a smoother surface than TMA arch wires.[7-9,16,17] In 1988, Kusy investigated the surface topography of different orthodontic arch wires and concluded that the SS material showed the lowest surface roughness, followed by cobalt-chrome (Co-Cr), beta-titanium (Beta-Ti), and NiTi.[16] In addition, recent studies utilizing AFM for surface roughness evaluation of different alloys concluded that SS arch wires showed the least roughness values among the other materials.[9,18]

The AFM scans of the present study revealed that the TMA-C arch wire exhibited the roughest surface topography compared to the TMA-Low and SS arch wires, which can be associated with the high frictional values produced by this alloy. Conventional TMA arch wires are generally known to exhibit higher friction values than other alloys.[19] The surface of TMA arch wires exhibits high reactivity and produces adhesive and abrasive wear, which increases the surface roughness values.[19] These findings are in accordance with earlier studies that have shown that the TMA arch wire is the roughest.[9,13,20] Also, evaluation of surface roughness via AFM, laser specular reflectance, and profilometry have shown that the SS arch wire had the smoothest surface among the investigated alloys and the TMA arch wire exhibited greater roughness values when compared to SS material.[7] Additionally, the data obtained by Doshi and Bhad-Patil (2011) indicated higher roughness values for TMA arch wires.[21]

The modified TMA arch wire (TMA-Low) showed intermediate roughness values compared to the other alloys (SS and TMA-C). The difference in roughness values was statistically significantly higher than that for the SS arch wire, which makes the modified TMA material still considered to be inferior to the SS material. Additionally, the difference was not statistically significantly lower than that for the TMA-C, which indicates that the surface finish of this new product is not as the company has claimed. These findings are consistent with multiple studies that investigated different modified products of TMA arch wires with enhanced surface finish and concluded that these modified TMA materials had no advantage over the SS material.[8,14] The investigated TiMolium TMA alloy, which contained aluminum and vanadium as stabilising agents, was found to have a smoother surface finish than the conventional TMA arch wire but still a rougher surface finish than the SS arch wire.[8] This is also similar to what was concluded by Burstone and Farzin-Nia in which coloured TMA arch wires treated by ion implantation showed lower roughness values than non-treated TMA arch wires, yet still inferior to SS arch wire.[22] Those researchers indicated that ion implantation improved the surface finish of the modified TMA arch wire by increasing its hardness and decreasing its flexibility.[22] Generally, the most common types of surface treatments to improve materials properties are ion implantation and Teflon coating. These procedures generally are performed to decrease surface roughness and improve the sliding of the arch wire.[23-25] However, in order to get the maximum benefit of reducing the frictional forces, ion implantation should be used repeatedly.[21]

It was noted from our results that the ten-point height (sRz) parameter analysis showed that the mean value of the SS arch wire material is statistically significantly lower than the mean value of the TMA-C material but not significantly different from the mean value of the TMA-Low material. The insignificant statistical difference between SS and TMA-Low for this parameter, in contrast to the other parameters that showed significant differences, could be explained by the sensitivity of the sRz parameter to occasional high peaks or deep valleys compared to the sRa parameter.[26,27]

In the previous discussion, the null hypothesis was rejected because there were significant differences in the surface topography and roughness between the SS and TMA-Low arch wires and between the SS and TMA-C arch wires.

Many reported studies have correlated the amount of surface roughness with the resulting friction, but it should be acknowledged that tooth movement is a complex process influenced by several factors. In fact, in 1988, Kusy *et al*. found that TMA arch wires had a smoother surface than NiTi arch wires but generated higher friction values, suggesting that friction is not only influenced by the nature of the surface roughness.[16] This is in accordance with Prososki *et al.* who concluded a similar finding that decreased values of surface roughness are not entirely sufficient to ensure low friction values.[28] In addition to the roughness of the material, the molecular adhesion between atoms and the plowing effect that results from the deformation of soft materials under pressure have a great influence on the amount of resulting friction.[29] Nevertheless, the surface roughness of an arch wire is an important factor affecting the functional properties; it contributes to the surface contact area and, thus, has a great impact on the corrosion behavior, aesthetics, and biocompatibility of the material.[7]

Conclusion

- The highest means of all three roughness parameters were found in the TMA-C group, followed by the TMA-Low and SS arch wire groups in descending order.
- The TMA-C arch wire showed the highest roughness value, which was not statistically significantly different from the TMA-Low arch wire roughness value.
- The SS arch wire showed the smoothest surface topography among the alloys.
- The TMA-Low arch wire is still considered to be inferior to the SS arch wire, and the SS arch wire remains the mainstay of orthodontic mechanotherapy.

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Conflicts of interest

There are no conflicts of interest.

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