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Friction Characteristics of Nanocoated Biomedical 316L Stainless Steel with Tantalum, Niobium, and Vanadium Under Wet Conditions

Dhiaa J. Aldabagh [1,*], **Akram F. Alhuwaizi** [1], **Thair L. Alzubaydi** [2]

[1]Department of Orthodontics, College of Dentistry, University of Baghdad, Baghdad. Iraq
[2]Department of Prosthetic Dental Techniques, College of Health and Medical Techniques, Al-Esraa University, Baghdad, Iraq

ABSTRACT

Reducing friction between orthodontic components, such as archwires and brackets, is crucial in contemporary orthodontic treatments. Coating these components is a significant method to achieve this goal. This research is aimed To investigate the tribological performance of nanocoated 316L stainless steel (SS)—one of the most widely used alloys in orthodontic archwire manufacturing—coated with vanadium (V), tantalum (Ta), and niobium (Nb) via plasma sputtering at varying time intervals (1, 2, and 3 hours) under wet conditions simulating an oral in-service environment, which is unexplored previously in the existing literature. Using a computerized tribo-system applying 1 N for 20 minutes on coated SS substrates, the common alloys for orthodontic archwire manufacturing. *Results*: The results indicated that the coefficient of friction (CoF) increased generally under wet conditions as a result of hydrogen bonding and capillary adhesion. Ta emerged as the preferred coating, demonstrating substantial friction reduction compared to Nb and V. V was found to have a negative tribological impact. This work concluded that Coating 316L SS with Ta was identified to improve tribological behavior in wet conditions that simulate an oral environment, potentially minimizing the duration of orthodontic treatment and promoting efficient tooth movement.

Keywords: Coefficient of friction, Nano-coatings, Tribological behavior, Wet frictional conditions, Orthodontic components.

1. INTRODUCTION

Tribology, which means "rubbing" in Greek, is the study of rubbing, friction, and wear on surfaces. It is the science and technology of surfaces interacting with one another and moving relative to one another. It is regarded as an art to offer one-stop shopping for

*Corresponding author
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answers to some economically significant issues, such as equipment wear and dependability **(Meng et al., 2020)**. The field of nanotechnology typically includes materials with sizes no larger than 100 nm. The pharmaceutical and medical sciences, as well as the industrial, commercial, and agricultural sectors, have all rapidly improved thanks to technology **(Ali, 2021; AL-Qaysi and Abbas, 2023)**. It is necessary to explore the tribology of biomedical materials to improve their performance and longevity **(Davim, 2019)**.

The phenomenon of friction is the force that affects an object's movement direction in an opposing direction and makes movement difficult **(Develi and Namdar, 2019)**. Under dry conditions, interactions between the items on the direct contact surface play a significant role in friction on contact sliding. However, in lubricated conditions, a third object, the capillary condensed water bridge, or meniscus, always exists between contact bodies. It combines two nanoscale asperities and significantly influences friction **(Riedo et al., 2002)**. Friction is a major impediment to tooth retraction or alignment during orthodontic treatment. One method to bypass it is to apply more force; however, this could lead to an adverse anchoring loss. Other solutions that might help reduce slide resistance include changing the design of the bracket and the requirements of the archwire and applying different biomaterials to the surfaces of the wire **(Batra, 2016)**. Friction during clinical tooth movement will vary depending on the type of ligation used to secure orthodontic archwires against orthodontic brackets **(Nahidh et al., 2022)**, as well as the materials of the orthodontic brackets and archwires **(Jasim et al., 2020)**. Moreover, the most common stainless steel varieties utilized in the production of orthodontic brackets and archwires are austenitic stainless steels (316–316L) **(Izquierdo et al., 2010)**. The search for materials and combinations of materials that have low coefficients of friction (CoF), minimal wear rates, and long useful lifetimes is the main goal of tribological research. To improve the tribological performance of a material, a variety of surface modification and coating methods have been investigated **(Ren et al., 2023).** Moreover, over the past 20 years, a lot of work has been done to reduce the friction resistance between brackets and archwires. Specifically, it is made clear that one of the best methods for controlling the friction and wear characteristics of the archwire-bracket interface systems is the surface coating procedure **(Bącela et al., 2020).** On the other hand, Friction setup under wet conditions is considered more representative to in-service environment which is the oral cavity **(da Silveira et al., 2022)** and **(Pentagna et al., 2023)**, as the corrosion of archwires and brackets is higher in a wet environment (in the presence of saliva) than in dry air expecting to impair the surface topography of both of them by increasing surface roughness, hence frictional resistance might be impaired significantly **(Nanjundan and Vimala, 2016)**.

To the best of our knowledge, no research has been done on the tribological behavior of 316L SS substrates coated with V, Ta, and Nb using plasma sputtering at different times (1, 2, and 3 hours) under lubricated conditions. Therefore, the objective of this research article is to investigate the tribological behavior of 316L SS substrates (coated with Ta, Nb, and V) under wet conditions, which are the most widely used biomedical alloys for the manufacture of orthodontic archwires.

2. MATERIALS AND METHODS

A series of abrasion cycles utilizing 80-1000 grit paper was used to prepare 316 L SS substrates (15 ×15 mm, 2 mm thickness) according to ASTM E3-95, then polished with a diamond suspension of 1-15 μm to create a mirror surface finish. The coating procedure, which was performed on a DC glow discharge at a low pressure of 6×10^{-2} mbar, employed nano-plasma sputtering. The voltage and discharge current of the DC power source were increased until a plasma was generated with a power rating of 25 watts (7 mA×3. 6 Kv). The selection of targets for the synthesis of nanoparticles included sheets of ultrapure tantalum (Ta), vanadium (V), and niobium (Nb). Structural, elemental, and topographical surface characterizations were accomplished in our earlier study **(Aldabagh et al., 2023)** for the coated samples and untreated SS plates, in which the D8 ADVANCE diffractometer from Bruker Com. (Germany), which produces Cu K-α X-rays, was used to perform XRD. Data were gathered for 787 seconds, λ = 1.5418 Å, spanning a 2θ° angle that ranged from 10° to 80°, with a 5°/min scanning speed. Match!3 software was used to compare the resultant peaks with the standard peaks of the joint indexed on powder diffraction standards and the international center for diffraction data. Moreover, FESEM of the MIRA 3 XMU Type (maker TESCAN, Brno, Czech Republic) in low vacuum (in conjunction with an EDS detector) and an accelerating voltage of 15.0 KV, the shape, arrangement, and characteristics of the nanoparticles were observed. Four magnification powers between 25.0 and 150.0 KX, view fields between 1.38 and 8.30 μm, and scales between 200 and 2000 nm were employed. Furthermore, the energy-dispersive X-ray microanalysis method was used to analyze the percentage of elemental composition. Each examined specimen's X-ray EDS spectra were collected using an area analysis mode at 25 KX magnification, 8×8 μm sampling window, and 100-second acquisition time, under 15 kV accelerating voltage. Using nonstandard analysis and ZAF correction techniques, IDFix -EDAX software was used to do a quantitative examination of the weight concentration percentage.

Surface roughness was analyzed using atomic force microscopy (AFM) with the Brisk model (Ara Research Co., Iran), equipped with an HQ-NSC15-ALBS probe series. The probe features a typical resonance frequency of 325 kHz (ranging from 265 to 410 kHz), a typical spring constant of 40 N/m (ranging from 20 to 80 N/m), and an uncoated silicon tip with an 8 nm radius and aluminum backside coating. As a fundamental component of AFM, the software was used to measure the surface roughness parameters. Non-Contact AFM mode (NC-AFM) was employed to examine the surface roughness by exploiting the attractive interatomic force between the tip and a sample surface of three separate areas, 2×2, 5×5, and 10×10 μm, of each tested specimen from each sample group. After that, the average surface roughness was computed. Further characterization of the nanoparticle size of the coated surfaces was carried out in the our most recent article **(Aldabagh et al., 2023)** in accordance with the methodology presented by **(Farivar et al., 2021)**, using the highest magnification (150.0 KX) of (FESEM), of MIRA 3 XMU (TESCAN, Brno, Czech Republic).

2.1 Friction Test

A key element in the tribological behavior of recently developed biomaterials is the appropriate test methodology. An excellent device for tribology applications is a pin-on-plate mechanical sliding tester, which measures wear and/or friction. A tribo-system designed by Swaminathan and Gilbert **(Swaminathan and Gilbert, 2012)** and modified by the authors was used in accordance with the methodology of **(Menezes et al., 2011)** in compliance with **(ASTM G99-17, 2020)**, using ATID analyzing software representing the wear and friction test of the plate **(Fig. 1)** to measure Cof (μ), executed under wet conditions (lubricated) at room temperature 25º C **(Gracco et al., 2019)**. Using a specific pin, the procedure involves making friction tracks on hard plates (untreated 316L SS substrate and those coated with V, Ta, and Nb) in order to measure tangential and normal forces**.**

The following components contribute to the tribo-system:

1. HTIMS 301 three-axis manual translation stage (Technic Assembly Company, China), with a sensitivity of 0.002 mm and a minimum scale reading of 0.005 mm, allows us to precisely alter the tested specimen's position and the amount of normal load given to it in the manner described below:
A-Vertical Z direction: Modify the load that the pin applies to the specimen being tested. The specimen is often attached to a 2-D load cell that holds and measures the normal and frictional forces.
B-Horizontal X direction: Modify where the friction track's beginning point is on the tested plate (316LSS nanocoated).
C-Horizontal Y direction: Maintain parallel alignment among multiple friction tracks in the X-horizontal direction by adjusting the spacing between them.

2. Zaber automation stage, Type x axis T-I 13m has a speedy resolution of 0.0099 mm/s and an accuracy of 29 µm (Zaber Technologies, Vancouver, Canada). Automating sub-micrometer positioning can be done quickly, easily, and affordably with a computerized positioner. These positioners are typically operated by Zaber Console software, which allows us to adjust the friction track's length as well as the motion's speed and duration during each oscillating friction cycle (Zaber script), which in turn determines the cycle's collected distance.

Figure 1. Tribo-system designed by **(Swaminathan and Gilbert, 2012)** and modified by **(Aldabagh et al., 2023)**

3. A load cell that detects all six components of force and torque is the multi-axis force/torque sensor, type-Mini45 F/T transducer six-axis load cell, manufactured by ATI Measurement Inc., USA. The loading cell's sensitivity is 0.001 N, and its maximum force measurement is 16 N. It has hardware temperature adjustment features that optimize the accuracy of the transducer over a range of approximately ±25ºC over ambient temperature and stabilize its sensitivity over temperature.
4. Pin: A 316L SS rod with an 8 mm diameter ends in the shape of a sphero-cone **(Beake and Liskiewicz, 2013).**
The following vital points need to be verified before each friction cycle settling:
a- Firm securing of the pin to the loading cell equipment, which is connected to the manually controlled Z-direction portion of the tribo- system.
b- A plastic holder that has been particularly manufactured utilizing computer numerical control (CNC) technology to secure the tested plate (specimen) to the sliding stage firmly.
c- Use a dry cloth and acetone to clean the pin and plate.

d- Setting the following parameters that specify Zaber console-script adjustment, which applied certain criteria for each oscillating wear cycle, comparable to Grieseler et al.'s nano-tribological test **(Grieseler et al., 2022)**, a sliding setup of 3 mm distance (which represents the average orthodontic bracket width) and 100 sliding oscillating cycles with a total distance of 600 mm were conducted for 20 minutes at a speed of 0.5 mm/sec.. The normal load (friction force-Fn) placed on the nanocoated sample was 1 N, which was similar to the in service load equal to the optimal orthodontic force generated by the orthodontic appliance during the course of orthodontic treatment course **(Theodorou et al., 2019)**.

To minimize methodological variations and enhance the validity of the results, a tribological friction test was conducted on 30 specimens. A total of 150 cycles were done under wet (lubricated). Of the 30 samples, 3 belong to untreated 316L SS, and 27 samples belong to coated with V, Nb and Ta (3 × 9) corresponding to varying sputtering times (1, 2, and 3 hours), 5 friction tracks (cycles) were implemented for each sample under wet condition, their average was taken. CoF was computed using Fr/Fn, where Fn represents the normal force, while Fr is the tangential (frictional) force.

It is crucial to underline the following during wet friction conditions, the firmly secured nanocoating sample was immersed in artificial saliva to simulate an in-service oral environment during the orthodontic treatment course, which should be replaced by a new artificial saliva solution at the beginning of each 5 tracks corresponding to a specific specimen to reduce the effect of wear debris on the constituency of artificial saliva and improve the validity of the results gained. The chemical composition of artificial saliva is listed in **Table 1.**

Table 1 . Chemical composition of artificial saliva according to **(Alfonso et al., 2013).**

Chemical product	Concentration (g/dm^3)
K_2HPO_4	0.20
KCI	1.20
KSCN	0.33
Na_2HPO_4	0.26
NACL	0.70
$NaHCO_3$	1.50
Urea	1.50
Lactic acid	Until pH = 6.7

5. The collected data was dealt within two forms:

A. Average CoF along the 20 minutes friction cycle of each subgroup and 316L SS.
B. Average CoF every 0.5 minutes along the friction cycle of each subgroup and 316L SS to explore their tribological behavior.

3. RESULTS AND DISCUSSIONS

3.1 Normality and Homogeneity of Data.

Table 2 presents the normality test of CoF variables. All the tested variables were normally distributed using the Shapiro-Wilk test, as all the tested subgroups did not violate the assumption of normality (P > 0.05), therefore ANOVA statistical test was used to compare the mean differences among them. Moreover, in **Table 3**, Levene's test was used to test the homogeneity of CoF variances, a significant difference was found between some groups, therefore, Welch test was used (in case of significant difference) in addition to ANOVA which shows similar results, hence Post HOC-Tukey test was used for multiple comparisons among subgroups of homogenous types of variances, while Post HOC- Games Howell test was used when the assumption of homogeneity is violated (non-homogenous types of variances).

Table 2. Shapiro-Wilk Test to test the normality of CoF under wet conditions.

	Shapiro-Wilk Test		
	Statistic	**df**	**Sig.**
SS	0.929	15	0.263
Nb 1h	0.934	15	0.316
Nb 2h	0.957	15	0.633
Nb 3h	0.928	15	0.25
Ta 1h	0.902	15	0.101
Ta 2h	0.914	15	0.156
Ta 3h	0.967	15	0.811
V 1h	0.913	15	0.148
V 2h	0.941	15	0.392
V 3h	0.941	15	0.395

Table 3 . Homogeneity of variances of coF under wet condition

Coefficient of friction		**Levene Statistic**	**df1**	**df2**	**Sig.**
1h	Based on Mean	4.153	3	56	0.01
2h	Based on Mean	4.544	3	56	0.006
3h	Based on Mean	2.489	3	56	0.07
Nb	Based on Mean	3.004	3	56	0.038
Ta	Based on Mean	7.188	3	56	0
V	Based on Mean	2.976	3	56	0.039

3.2 Wet Friction Behavior

Fig. 2 shows a wet friction behavior of coatings and their 316L SS substrates, it is clearly seen that the coefficient of friction was reduced only in Ta group (at 1, 2, and 3 hrs) and Nb 2hrs subgroup. Moreover, other coatings showed either comparable results (Nb 3hrs subgroup) or deteriorations in frictional behavior in comparison to their 316L SS substrates (Nb 1hr subgroup, and V group of coatings).

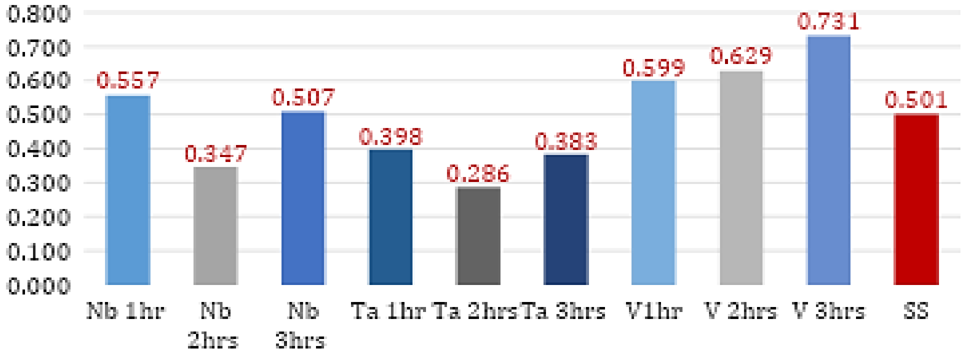

Figure 2. Comparison of Friction behavior of Nb, Ta, and V under wet condition

Table 4 presents the average CoF of all coating materials and their substrates; the least friction was seen in Ta 2 hours (0.286), while the highest friction was related to V 3 hours (0.731) compared to their SS substrate friction (0.501). Furthermore, the mean times difference using ANOVA/ Welch statistical tests exhibited substantial variances between subgroups coated with Nb, Ta and V at different sputtering times and their SS substrates. However, the mean difference in the coating materials showed a significant difference at sputtering times of 1, 2, and 3 hours between each coating (Nb, Ta, and V) and their untreated substrates.

Table 4 . A Comparison of the friction coefficient of 316L SS and various coating materials (Ta, Nb, and V) at different sputtering times, using one-way ANOVA (homogeneous variables) and the Welch test (non-homogeneous variables) under wet friction conditions.

	Mean of CoF	**SD±**	**ANOVA / Welch**
Nb-1hr	0.557	0.184	Statistic = 4.174 P≤0.001
Nb-2hrs	0.347	0.170	
Nb-3hrs	0.507	0.181	
SS	0.501	0.077	
Ta-1hr	0.398	0.180	Statistic= 15.993 P≤0.001
Ta-2hrs	0.286	0.090	
Ta-3hrs	0.383	0.104	
SS	0.501	0.077	
V-1hr	0.599	0.163	Statistic= 13.772 P≤0.001
V-2hrs	0.629	0.150	
V-3hrs	0.731	0.117	
SS	0.501	0.077	
ANOVA/ Welch	**1hr (Nb,Ta,V) and SS**		Statistic = 3.926 P≤0.001
	2hrs (Nb,Ta,V) and SS		Statistic = 24.640 P≤0.001
	3hrs (Nb,Ta,V) and SS		F= 20.119 P≤0.001

The mean difference is significant at the 0.05 level.
Number of friction cycles =15, F=ANOVA test value, Statistic =Welch test value

Tables 5 and 6 present multiple comparisons among nano-coatings sputtered at different sputtering times using) using Tukey Post Hoc (homogenous variables) and Games -Howell tests (non-homogeneous variables), revealing a significant statistical difference between the Nb (2 hours) and Ta (2 and 3 hours) subgroup and their SS substrates, indicating the ability of these coatings to enhance the tribological features of their substrates, while a significant difference was observed between V 2 and 3 hours and their SS substrates, indicating the ability of these coatings to deteriorate the tribology of their substrates. Furthermore, the sputtering time of 2 hours of Nb and Ta significantly improved the tribology of their SS substrates.

Table 5. Multiple comparisons of the friction coefficient of 316L SS substrates and other coating materials (Ta, Nb, and V) at different sputtering times (1, 2, and 3 hours) using Tukey Post Hoc (homogeneous variables) and Games-Howell tests (nonhomogeneous variables) under wet friction conditions.

Depend. variables	Independ. variables		Wet friction	
			Mean Differ.	Sig.
Nb	SS	Nb1	0.05667-	0.694
		Nb2	*15413.	P≤0.001
		Nb3	0.00647-	0.999
	Nb1	Nb2	*21080.	P≤0.001
		Nb3	0.0502	0.875
	Nb2	Nb3	0.1606-	0.081
Ta	SS	Ta1	0.10267	0.212
		Ta2	*21487.	P≤0.001
		Ta3	*11740.	P≤0.001
	Ta1	Ta2	0.1122	0.169
		Ta3	0.01473	0.993
	Ta2	Ta3	*09747.-	P≤0.001
V	SS	V1	0.09873-	0.178
		V2	*12880.-	P≤0.001
		V3	*23067.-	P≤0.001
	V1	V2	0.03007-	0.952
		V3	0.13193-	0.075
	V2	V3	0.10187-	0.188

*The mean difference is significant at the 0.05 level.

Table 6 . Multiple comparisons of the friction coefficient of 316L SS substrates and various coating materials (Ta, Nb, and V) at each sputtering time (1, 2, and 3 hours) using Tukey Post Hoc (homogeneous variables) and Games-Howell tests (non-homogeneous variables) under wet conditions.

Depend. variables	Independ. variables		Wet friction	
			Mean Differ.	Sig.
1hr	SS	Nb	0.05667-	0.694
		Ta	0.10267	0.212
		V	0.09873-	0.178
	Nb	Ta	0.15933	0.102
		V	0.04207-	0.91
	Ta	V	*20140.-	P≤0.001
2hrs	SS	Nb	*15413.	P≤0.001
		Ta	*21487.	P≤0.001
		V	*12880.-	P≤0.001
	Nb	Ta	0.06073	0.62
		V	*28293.-	P≤0.001
	Ta	V	*34367.-	P≤0.001
3hrs	SS	Nb	0.00647-	0.999
		Ta	0.1174	0.062
		V	*23067.-	P≤0.001

	Nb	**Ta**	*12387.	P≤0.001
		V	*22420.-	P≤0.001
	Ta	**V**	*34807.-	P≤0.001

* The mean difference is significant at the 0.05 level.

Fig. 3 presents the average friction behavior of Ta, Nb, and V under wet conditions along the whole friction cycle (20 min,) measured each o.5 min, it is clear that the best friction behavior was seen in the Ta group while the worst was seen in the V group in comparison to their SS substrate, however, the Nb group was comparable to the untreated SS substrate.

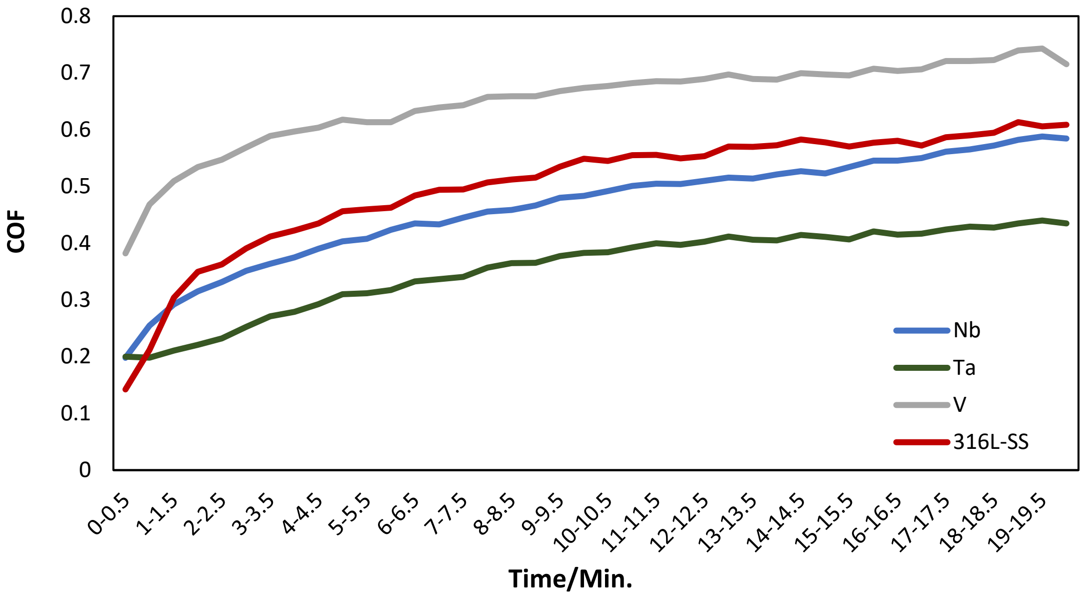

Figure 3 . The average coefficient of wet friction of 316L SS substrate compared to the Nb, Ta, and V coatings (every 0.5 min during the 20 min friction cycle)

Friction in orthodontics is considered one of the main issues, although it is usually considered a deterrent to the required movement of the teeth, sometimes it is considered advantageous, especially in the case of increasing the anchorage requirement of the posterior teeth during the retraction of the anterior teeth, hence evaluation of the friction behavior of orthodontic components, namely archwires, is recommended to ensure proper and successful treatment. Too many strategies were used to reach this vital goal; nanocoating of archwire could be the best one, depending on the selection of coatings of suitable friction behavior. Moreover, friction is a highly complex physical phenomenon that affects the tribological properties of coatings and cannot be explained by a straightforward model. Almost all straightforward claims about frictional resistance can be refuted with particular instances of opposing interpretation. Furthermore, the amount of friction produced by two mating sliding surfaces that are experimentally determined is represented by the coefficient of friction of the material, which is a dimensionless property.
Stainless steel orthodontic archwires (manufactured mainly from 316L SS) is usually used in the treatment phase of orthodontic treatment, mostly associated with sliding of the teeth over these wires, therefore coating them with a material of low friction may improve orthodontic treatment and reduce its time.

The primary objective of this research is to coat 316L SS substrates—representative of orthodontic archwires—with various nanomaterials (vanadium, tantalum, and niobium) using a DC plasma sputtering system at different sputtering durations (1, 2, and 3 hours), in order to identify the optimal coating material and sputtering time for enhanced performance. Although multiple techniques are available for coating bulk materials, physical vapor deposition (PVD), particularly plasma sputtering, is favored due to its precise control over coating properties and thickness through the adjustment of sputtering parameters **(Zeng et al., 2022)**. Moreover, it is a physical process that does not impact the structural properties of the bulk material **(Bairam et al., 2021)**. In addition to that, the possibility of coating delamination is greatly reduced by this technique **(Ng et al., 2020)**.

It is important to emphasize that, to imitate the in-service state during orthodontic tooth movement, an oscillating sliding setup was used for the current study rather than a linear unidirectional one, since the continuous and dynamic movement (oscillating) is predicted rather than a linear and continuous one **(Resendiz-Calderon et al., 2022)**. In the wet environment (such as the oral cavity), it has been found that the sputtering time of some coatings significantly affects CoF, which could be explained by interaction of other factors, such as capillary adhesion or hydrogen bonding that are associated with the effect of lubricant particles between the two sliding mating surfaces. Hence it is vital issue to test each coating at specific sputtering time which may has a different friction behavior that differs significantly from other different sputtering times of the same coating material, the present finding revealed that 2 hours sputtering time (for both Ta and Nb) provided a better tribological behavior than others, hence, the CoF of all coatings (V, Nb, and Ta) does not affect significantly by sputtering time variations, which is in line with the findings of **(Ma et al., 2022)** who discovered no discernible linear relationship between sputtering time and CoF.

Meanwhile, coating material selection has a more crucial effect on the tribological behavior of nanocoated specimens, since there was a significant statistical difference between subgroups of each coating regarding sputtering times, an average of CoF of each coating could not be taken, hence the best tribological behavior was observed in the Ta -2 hour sputtering time (43% improvement), followed by Nb- 2 hours (31% improvement), while the worst behavior was seen in the V-3 hour sputtering time (45% deterioration) in comparison to their SS substrates (**Table 7**).

Table 7 . Amount of change in CoF of all coatings under wet conditions

Coatings	Wet friction in comparison to wet SS
Nb 1h	%0.11---------%100.11
Nb 2hrs	%31-----------%69
Nb 3hrs	%1------------%101
Ta 1h	%21------------%79
Ta 2hrs	%43-----------%57
Ta 3hrs	%24------------%76
V1h	%12-----------%112
V 2hrs	%26-----------%126
V3hrs	%45-----------%145

Black percentages indicate the amount of CoF of the selected coating compared to CoF of its SS substrate; red percentages indicate improvement; blue percentages indicate deterioration under wet conditions compared to their corresponding substrates.

As a summary, in wet conditions, the Ta subgroups had an improving frictional behavior effect, while V subgroups had a deterioration effect. These variations in the tribological behavior of coatings could be discussed depending on several interacting factors, Surface roughness is considered as one of the fundamental tenets of friction theory, which states that smooth and flat surfaces may not be so smooth when examined microscopically or may even appear unexpectedly rough. As a result, surface roughness is believed to have a significant impact on the tribological behavior of coatings **(Patel et al., 2022).** Metal surfaces are usually rough; asperities often describe how rough they are. They are often able to withstand the entire frictional force between mated surfaces. formed, in a microscopically valuable way, the interface region between two sliding solid surfaces that make up a very small portion of the entire mating surfaces. Kim **(Kim, 2022)** suggested two main friction theories, the abrasive (interlocking) theory, which is usually detected at a microscopic level, and the adhesive one (detected at an ultramicroscopic level, when mating surfaces are extremely polished, adhesion between them may occur). The optimal roughness of a surface region is typically the area where the noticeable friction reduction effect is observed **(Zhou et al., 2015)**, but it does not pertain to smoother surfaces. As a result, the traditional theory that smoother surfaces are generally associated with lower friction is no longer valid; instead, extremely rough or smooth surfaces generally correspond with greater friction than intermediate ones **(Kailasam, 2016)**. In the surface characterization phase of the same coated specimens that were published previously **(Aldabagh et al., 2023),** the surface roughness of the 316L SS substrates was reduced after coating by V, Ta and Nb, with the least roughness related to V coating surfaces, which may be in the extreme smoothness region. However, Nb and Ta coating surfaces were in the intermediate zone of surface roughness (optimal surface roughness region), which is where interlocking fiction typically occurs, which improves the tribological behavior of their SS substrates by reducing CoF to half. This finding is consistent with Menezes and Kailas **(Menezes and Kailas, 2016)** who found that adhesion forces typically dominate at low surface roughness values (highly polished smooth surfaces), increasing CoF; however, at higher roughness amounts, interlocking or abrasion presumes a more significant role, improving the CoF of their sliding mating surfaces. This finding coincides with the finding of Shen et al. **(Shen et al., 2022)**, which highlights the importance of the optimal region of a surface's roughness (intermediate zone), instead of extreme smoothness, in enhancing the frictional behavior of mating sliding surfaces.

Moreover, the Nanoparticle dimension is considered a keystone in determining their performance and properties. Because of its higher nanometric resolution, which enables precise measurement of nanometric scale structures, electron microscopy remains one of the main analytical techniques available for characterizing and studying nanoparticles. However, sample preparation procedures continue to be a crucial component of this process **(Garcia-Gutierrez and Garcia-Gutierrez, 2023).** Furthermore, our previously published work **(Aldabagh et al., 2023)** done on the same specimens, revealed that the dimensions of the nanoparticles in the Nb and Ta coatings were similar and almost half that of the V coatings, which may indicate their influence on the tribological characteristics since both decrease the friction of their SS substrate by almost half. In contrast, V coatings did not positively affect the friction coefficient of their SS substrate, which may be associated to their smaller nanoparticles that can form tribo-films with stronger intrinsic mechanical properties or because their ability to pass through the contact is increased, therefore Ta and Nb coatings expected to have better tribological behavior than V coating, of Nb and Ta

coatings, were found to be in parallel to the findings of **(Buranich et al., 2020)**, but counteracted by the findings of **(Zou et al., 2022)**, who explored that 30 % of friction reduction may take place via increasing nanoparticle dimensions.
Finally, surface binding energy (SBE) plays a substantial role in the surface composition of the coatings (via conditioning the ion sputtering process) is the SBE of the nanocoating material. The SBE of the V metal has the highest value (521.3 eV), followed by the Nb metal (202.4 eV), and the Ta metal (21.8 eV) has the lowest value among the targets used (Transition Metal Elements | XPS Periodic Table | Thermo Fisher Scientific - IQ), which is consistent with our previous findings **(Aldabagh et al., 2023)**, since we found that the V group had the lowest elemental composition and thickness, while the Nb coating had moderate thickness, furthermore, Ta had the highest thickness, In parallel to the findings of Arjunan et al.**(Arjunan et al., 2021),** who highlighted the impact of the surface binding energy and the elemental composition (wt.%) on the characteristics of the coating microstructure, which is suggested to be the most vital aspect that influences the tribological behavior of the coating surface layer's tribological behavior **(Lorenzo-Martin et al., 2013)**. Hence, the V coat either did not affect the tribological behavior of the 316L SS substrate or could potentially worsen it, while both the Nb and Ta coatings were improved.

3.3 Differences between Dry and Wet (Lubricated) Frictional Behavior

The aim of this study is to characterize the tribological behavior of coated SS substrate with Nb, Ta, and V to be applied on the coated SS orthodontic archwires with the same nanoparticles , hence, conducting frictional testing that evaluates orthodontic archwires in a setting that is comparable to the oral environment as feasible; as a result, wet friction data may be more valid and reliable than dry friction data. The tribological behavior, namely friction under dry and wet conditions, is still a controversial subject, routinely most people propose that, generally CoF in dry conditions is higher than in wet conditions, this is exactly explained by **(Shen et al., 2022)**, who explored the mechanism of friction in both dry and wet conditions, he believed that in the dry field, the friction coefficient does not decrease almost with a reduction in surface roughness, the matter associated mostly with a threshold of roughness (optimal roughness value) below it, it is found that friction is usually increased as a result of modification that occurs in the friction behavior from abrasion to adhesion; hence, CoF is usually increased in extreme smooth dry surfaces, while under wet conditions, he believed that lesser surface roughness is usually linked with a lesser CoF, attributed mainly to the presence of a lubricant thin film between two mating sliding surfaces that prevent intimate contact between them; hence, getting rid of adhesion friction may occur; furthermore, a reduction in asperity contact area may be expected; both reasons reduce friction. However, this may be counteracted by three well-known phenomena: the first is the licking of a finger while reading a book to help turn the pages more easily; the second is that a wet floor poses a risk of slipping; and in certain cases, water added to a surface can increase friction, is partly explained by hydrogen bonds between water and the surface, an effect that was not previously thought to play an important role **(Peng et al., 2022)**. Moreover, the third well-known phenomenon is the ability of the insect to walk vertically, explained mainly by the formation of a Laplace pressure differential between the fluid contained within the bridge and its surrounding gas (capillary adhesion), which consequently causes the surfaces to attract one another, resulting in capillary bridges often showing negative curvature in the direction that corresponds to the interface **(Hsia et al., 2022)**.

4. CONCLUSIONS

Nanocoated 316L SS substrates (the alloy commonly used to manufacture SS orthodontic archwires) by V, Nb and Ta, were investigated for evaluation of tribological behavior under wet conditions using a computerized tribo-system. The following conclusions were made:

1- The wet friction behavior declares an obvious enhancement of frictional behavior via Ta coatings, a negligible effect via Nb coatings, and a worsening effect via V coatings.

2- Ta coating in the selected sputtering times (especially 2-hour) under wet conditions could be the nanocoating of choice that improves the tribological behavior, namely friction of 316L SS substrate, which is the most popular alloy of metal orthodontic archwires.

3- The sputtering time affects the frictional behavior of some coating group or subgroups, and a specific sputtering time must be considered in the wet tribological behavior of coated 316L SS substrate.

Credit Authorship Contribution Statement

All the authors contributed equally to the preparation of this article

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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خصائص الاحتكاك للفولاذ المقاوم للصدأ L316 المطلي بالنانو مع التنتالوم والنيوبيوم والفاناديوم في ظل الظروف الرطبة

ضياء جعفر الدباغ [1,*]، اكرم فيصل الحويزي[1]، ثائر لطيف الزبيدي[2]

[1]قسم تقويم الاسنان، كلية طب الاسنان ، جامعة بغداد، بغداد، العراق

[2]قسم تقنيات صناعة الاسنان، الكلية التقنية الصحية والطبية، جامعة الاسراء، بغداد، العراق

الخلاصة

يعد تقليل الاحتكاك بين مكونات تقويم الأسنان ، مثل الأسلاك المقوسة والأقواس ، أمرا بالغ الأهمية في علاجات تقويم الأسنان المعاصرة. طلاء هذه المكونات هو وسيلة مهمة لتحقيق هذا الهدف. يهدف هذا البحث إلى استكشاف الأداء القبلي للفولاذ المقاوم للصدأ L316 المطلي بالنانو (SS) مع الفاناديوم (V) والتنتالوم (Ta) والنيوبيوم (Nb) باستخدام رش البلازما على فترات زمنية مختلفة (1 و 2 و 3 ساعات) في ظل ظروف رطبة تحاكي بيئة فموية أثناء الخدمة ، والتي لم يتم اكتشافها سابقا في الأدبيات الحالية. باستخدام نظام tribosystem المحوسب الذي يطبق 1 N لمدة 20 دقيقة على ركائز SS المطلية ، وهي السبائك الشائعة لتصنيع الأسلاك المقوسة التقويمية ، أشارت النتائج إلى أن معامل الاحتكاك (CoF) زاد بشكل عام في ظل الظروف الرطبة نتيجة الترابط الهيدروجيني والالتصاق الشعيرات الدموية. ظهر Ta كطلاء مفضل ، مما يدل على انخفاض كبير في الاحتكاك مقارنة ب Nb و V. وجد أن V له تأثير قبلي سلبي. في الختام ، تم تحديد طلاء SS316 L ب Ta لتحسين السلوك القبلي في الظروف الرطبة التي تحاكي بيئة الفم ، مما قد يقلل من مدة علاج تقويم الأسنان ويعزز حركة الأسنان الفعالة.

الكلمات المفتاحية: معامل الاحتكاك. طلاء نانو. السلوك القبلي .ظروف الاحتكاك الرطب .مكونات تقويم الأسنان