

RANYA RAFA SALEH ALGADHY

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YEDİTEPE UNIVERSITY

INSTITUTE OF HEALTH SCIENCES

DEPARTMENT OF ORTHODONTICS

**EFFECT OF DIFFERENT pH LEVEL OF
DRINKS ON THE SURFACE
TOPOGRAPHY OF ORTHODONTIC
WIRES**

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RANYA RAFA SALEH ALGADHY

SUPERVISOR
Prof. Dr. Derya ÇAKAN

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THESIS APPROVAL FORM

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	Title, Name-Surname (Institution)	
Chair of the Jury:	PROF. DR. DERYA ÇAKAN YEDİTEPE UNIVERSITY	
Supervisor:	PROF. DR. DERYA ÇAKAN YEDİTEPE UNIVERSITY	
Member/Examiner:	PROF. DR. FULYA ÖZDEMİR MARMARA UNIVERSITY	
Member/Examiner:	PROF. DR. SENEM SELVİ KUVVETLİ YEDİTEPE UNIVERSITY	
Member/Examiner:	ASSOC. PROF. DR. FEYZA ERAYDIN KENT UNIVERSITY	
Member/Examiner:	ASSOC. PROF. DR. SEDEN AKAN YEDİTEPE UNIVERSITY	

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DECLARATION

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree except where due acknowledgment has been made in the text.

14/12/2021

Ranya Rafa Saleh Algadhy

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LIST OF SYMBOLS AND ABBREVIATIONS

AFM	Atomic Force Microscopy
ANOVA	Analysis of Variance
AO	American Orthodontics
B.C.	Before Christ
BCC	Centered cubic structure
C	Carbon
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CGP	Ceramic with gold-palladium slot
CoCr	Cobalt-chrome
Cu	Copper
E-arch	Expansion arch (Arnold expander)
g	Gram
g/l	Gram per liter
GPa	Gigapascal (pressure unit)
H₂O	Water
H₃PO₄	Phosphoric Acid
HCP	Close packed structure
Hz	Hertz (frequency unit)
Kcal	Kilocalorie (energy unit)

KHz	Kilo Hertz (frequency unit)
KJ	Kilojoules (energy unit)
KOH	Potassium Hydroxide
LASER	Light amplification by simulated emission of radiation
LFM	Lateral Force Microscopy
LSR	Laser specular reluctance
mg	Milligram
MgCl₂	Magnesium Chloride
Mh	Maximum height
mm	millimeters (distance unit)
N	Newton (force unit)
NaCl	Sodium Chloride
NiTi	Nickel-titanium
°C	Degree Celsius (temperature unit)
pH	power of Hydrogen (Acidity unit)
Ra	Roughness average
Rq/ Rms	Roughness root mean square
Rz	Mean roughness depth
Sdq	Root mean square gradient
SEM	Scanning Electron Microscope
SS	Stainless steel
Sv	Arithmetical mean height
TEM	Transmission Electron Microscopy
TIG	Tungsten inert gas
TMA	Titanium-molybdenum alloy (beta-titanium)

TTR	Transition temperature range
UHV	Ultra-High Voltage



ABSTRACT

Algadhy, Ranya Rafa Saleh, 2021. Effect of Different pH Level of Drinks on the Surface Topography of Orthodontic Wires. Yeditepe University Institute of Health Sciences, Department of Orthodontics, PhD Thesis, İstanbul.

The aim of this study was to evaluate and compare the changes in surface roughness of three different orthodontic wire types after their immersion in different soft drinks with dissimilar pH levels. A total of 90 samples, 30 stainless steel (SS), 30 nickel titanium (NiTi) and 30 titanium molibdenium alloy (TMA) wire sections were immersed in Coca Cola (pH:2.2), iced tea (pH:3.1), kefir (pH:4.3), coffee (pH:6.8) and artificial saliva (pH:7.1) as the control group. The duration of immersion was 60 minutes in each liquid. Then the samples were rinsed with deionized water and preserved in artificial saliva for 28 days at 37 °C. Surface roughness parameters before and after immersion were measured using atomic force microscopy (AFM) and data was statistically analyzed using one-way ANOVA and post-hoc testing at a confidence level of $p < 0.05$. There were significant differences in the changes of Ra, Rq and Rz of SS, NiTi and TMA wires among soft drink groups ($p < 0.05$). ΔRa and ΔRq of the SS wire immersed in Coca Cola were significantly higher than that of the SS wires immersed in other soft drinks and the artificial saliva ($p < 0.001$). ΔRa of the NiTi wires immersed in Coca Cola were significantly higher than that of the NiTi wires immersed in other soft drinks and the artificial saliva ($p < 0.001$). ΔRa of the TMA wires immersed in Coca Cola were significantly higher than that of the TMA wires immersed in other soft drinks and the artificial saliva ($p < 0.01$). Surface roughness changes of SS wires were significantly smaller than that of NiTi and TMA wires in all soft drinks ($p < 0.05$). More acidic soft drinks caused more surface roughness changes on the archwires. In general, NiTi and TMA wires exhibited more increase in surface roughness compared to SS wires when immersed in soft drinks with different pH levels.

Keywords: archwires; SS; NiTi, TMA; surface roughness; soft drinks

ÖZET

Algadhy, Ranya Rafa Saleh, 2021. Farklı pH Seviyelerinin Ortodontik Tellerin Yüzey Topografyası Üzerine Etkisi. Yeditepe Üniversitesi Sağlık Bilimleri Enstitüsü, Ortodonti Anabilim Dalı, Doktora Tezi, İSTANBUL.

Bu çalışmanın amacı, üç farklı ortodontik tel tipinin birbirinden farklı pH seviyelerine sahip farklı alkolsüz içeceklere daldırıldıktan sonra yüzey pürüzlülüklerindeki değişiklikleri değerlendirmek ve karşılaştırmaktır. 30 paslanmaz çelik (SS), 30 nikel titanyum (NiTi) ve 30 titanyum molibdenyum alaşımı (TMA) olmak üzere toplam 90 adet tel parçası Coca Cola (pH:2.2), buzlu çay (pH:3.1), kefir (pH:4.3), kahve (pH:6.8) sıvılarına daldırılmıştır. Kontrol grubu olarak da yapay tükürük (pH:7.1) kullanılmıştır. Daldırma süresi, her bir sıvı içinde 60 dakika olarak belirlenmiştir. Sonraki aşama olarak örnekler deiyonize su ile yıkanmıştır ve yapay tükürükte 37 °C'de 28 gün süreyle saklanmıştır. Daldırma öncesi ve sonrası yüzey pürüzlülük parametreleri atomik kuvvet mikroskopu (AFM) kullanılarak ölçülmüştür ve veriler tek yönlü ANOVA ve post-hoc testi kullanılarak $p<0.05$ güven seviyesinde istatistiksel olarak analiz edilmiştir. İçecek grupları arasında SS, NiTi ve TMA tellerinin Ra, Rq ve Rz değişimlerinde önemli farklılıklar görülmüştür ($p<0.05$). Coca Cola'ya daldırılan SS telinin ΔRa ve ΔRq değerleri, diğer içecekler ve yapay tükürük içine daldırılan SS tellerinden önemli ölçüde daha yüksek bulunmuş olup ($p<0,001$); Coca Cola'ya daldırılmış NiTi tellerinin ΔRa değeri, diğer içecekler ve yapay tükürük içine daldırılmış NiTi tellerin ΔRa değerlerinden önemli ölçüde daha yüksek bulunmuştur ($p<0,001$). Coca Cola'ya daldırılan TMA tellerinin ΔRa değeri de diğer içecekler ve yapay tükürük içine daldırılan TMA tellerinden önemli ölçüde daha yüksek bulunmuştur ($p<0.01$). Tüm içeceklerde SS tellerinin yüzey pürüzlülük değişiklikleri; NiTi ve TMA tellerinden önemli ölçüde daha düşük bulunmuştur ($p<0.05$). Daha asidik içecekler, ark tellerinde daha fazla yüzey pürüzlülüğü değişikliğine neden olmuştur. Genel olarak, NiTi ve TMA telleri, farklı pH seviyelerine sahip içeceklere daldırıldığında, SS tellere kıyasla yüzey pürüzlülüğünde daha fazla artış sergilemişlerdir.

Anahtar Kelimeler: ark telleri; SS; NiTi, TMA; yüzey pürüzlülüğü; alkolsüz içecekler

1. INTRODUCTION AND PURPOSE

One of the most common methods to treat and correct malocclusion is fixed orthodontic appliances, which either simulate the movement of dentition, the modification of the whole of dentofacial complex, or both (1). The fundamental principle of orthodontic treatment is based on application of a light force for a long time on the tooth through the bracket and the wire assembly. Consequently, structures surrounding the tooth are affected by the applied force, tend to reshape the bone and promote the tooth movement to start. To create this kind of force, an ideal wire must be selected and engaged to the bracket to activate it and start the tooth movement (2).

In recent research and practice, a range of alloys has been utilized to fabricate wires that can generate the proper biomechanical action through the different treatment stages (3). The optimal arch wire affords a light and continuous force on the tooth to move it to the correct position (4). Mainly, four types of wire alloys were developed in the orthodontic field as a result of advances in orthodontic material sciences for this purpose: Stainless steel (SS), cobalt-chrome alloys (CoCr), Nickel-Titanium (NiTi) and Beta-titanium (TMA). Each of these has unique properties and characteristics (5).

In the dental field, the major factors influencing the selection of materials are biocompatibility, mechanical properties, workability and resistance to tarnish and corrosion (5). As technology develops and research advances in offering new orthodontic wires, it is important to understand the properties and characteristics of these wires to achieve the desired results. The evaluation, choice, and use of archwire is made based on specific properties, including springback, resilience, weldability, formability, friction, biostability, and aesthetics (6). Through experimental evidence these properties were found to change, where surface roughness is a key characteristic in that aspect. The characteristics of wire surface were found to impact its biocompatibility and performance, as well as efficiency and corrosion (7) (8). To provide easy sliding movement during space closing at the time of orthodontic treatment, friction and corrosion should be at the minimum degree, which help decreasing force and treatment time needed to reach the ideal occlusion (5).

The oral cavity is a complex environment, where an orthodontic appliance is subjected to chemical, thermal, and mechanical challenges. Accordingly, wires that are used intraorally should tolerate the changing in temperature (0-70 °C), moisture, enzymes, and variations in pH levels from 2 to 11 during food consumption (9). Studies experimented with drinks containing several acids, such as phosphoric, citric, tartaric, lactic and maleic acids (10), as well as commercial nonalcoholic drinks with pH levels ranging from 2.1 to 7.4 (11). Unfortunately, food has a variety of pH levels and mostly in a lower degree than neutral level. Commercially available beverages with a pH less than 4 are potentially damaging of the dentition (12) (13) and today the consuming of drinks increased as the life style changes, especially among the children and young adults, whom are undergoing orthodontic treatment (14). Orthodontic appliances become unstable as a result of variety in food temperature and acidity. Subsequently, the surface topography and surface roughness of the orthodontic wire change over time. The alteration of wire properties, including surface characteristics, has various effects on surface roughness and leads to corrosion. Surface roughness has considerable influence on friction coefficients (15), in addition to plaque accumulation (7). The corrosion properties of metals and alloys depend upon their compositions, their electrode potentials, stress over the metals and surface roughness, which leads to the increase of friction between wire and brackets during sliding. Previous studies have shown a positive correlation between corrosion and pH level, indicating the wire manufacture and solution pH had a significant effect on the corrosion resistance of NiTi wire (16). Stainless steel and stressed NiTi wires showed a statically significant tendency to corrode by changing of pH level during the cyclic potentiodynamic test, thus the corrosion behavior of these wires had a correlation with their surface characterization. Further, immersion of orthodontic brackets in acidic artificial saliva showed strong association with corrosion (17).

Understanding the corrosion promoting factors and variation in surface topography of available orthodontic wires grew in recent research as a necessity and prerequisite to orthodontic treatments, especially for patients who drink low-pH-level beverages on a regular or daily basis (18). Beverages can be classified as carbonated or

noncarbonated. Furthermore, the carbonated soft drinks can be subdivided into colorless and flavorless drinks like soda and water, and flavor and sweetness contain drinks with added acids like phosphoric acid to cola drinks. Additionally, the noncarbonated beverages are citrus drinks naturally or acid is added to the drinks such as iced teas, fruit drinks and sport drinks. These acidic substances and sweeteners donate the beverages sugary and acidic taste and reduce the pH level (11). As the pH level decreases from neutral saliva level to the lowest level, surface roughness of the wire increases. In contempt of wires nature of the material, beverages have an effect on the surface roughness of the wires (19). However, based on the results of previous research, there are conflicting results and a gap identified in the data available for soft drinks and their impact on the most commonly used orthodontic wire alloys. Although few studies tried to establish a similar hypothesis, there was no clear affirmation on the behavior of orthodontic wires in response to regular commercial beverage usage (20) (12) (19) (21). Therefore, the results of the current research will contribute to the literature with additional and comprehensive data that would assist orthodontic specialists in material selection and development based on the patient's dietary behavior. Moreover, the development of clear profiles for roughness values against different pH levels allows orthodontists to provide the necessary and suitable recommendations to their patients in order to increase the efficiency of the treatment period.

Thus, the aim of this study was to evaluate and compare the change in surface roughness of three different orthodontic wire types after their immersion in four different drinks (coca cola, iced tea, kefir, and coffee). The hypothesis tested in the study is that beverages with different pH levels cause an increase in surface roughness of different orthodontic wires.

2. LITERATURE REVIEW

2.1 Orthodontic malocclusion, forces, and the use of wires

A normal occlusion is defined by having acceptable deviation from an ideal occlusion without imposing functional or aesthetic issues (22). An anomaly causing disfigurement or impediment to the functionality of the patient and therefore requiring treatment to correct the occlusion is defined as malocclusion. Nonetheless, malocclusion is considered as one or several deviations from normal occlusion according to its known standards (2) (23). The types of malocclusions result from several deviations, including (2):

- Dental arches with abnormalities.
- The presence of displaced, tipped, rotated, transposed teeth, as well as in supra-occlusion and in infra-occlusion, when jaws are closed, which are all related to imperfections in positioning.
- Dental arches with malrelation in transverse, vertical and sagittal dimension.
- Skeletal discrepancies.

Orthodontic interventions are provided for treatment depending on the patient through different orthodontic appliances. Orthodontic forces are applied to correct the positioning of a tooth or a group of teeth by the means of fixed appliances composed of brackets and archwires. The orthodontic wires are considered the most crucial part of the fixed system, as they control the movement and alignment of teeth at the conjunctions with the brackets. The use of wires allows for creating anchorage between teeth or applying forces through the engagement with the brackets (24). The main objective behind using orthodontic appliances is exerting extrinsic forces on the teeth to achieve the desired movement over a period of time. Since their inception in the 1920s, archwires became the most preferred orthodontic treatment, as they are prefabricated to the ideal dental arch in order to deliver the required forces to align and level the teeth, which causes the tooth movement (25). In the treatment of spacing issues, wires can be shaped into different types of closing loops. Nonetheless, the engagement between the wire and the

brackets is where the mechanical properties are transmitted to the dentition through activating the necessary forces.

The main objective of using orthodontic wires during the treatment is to move the teeth towards the desired correct position through applying a specific force on them. The force applied to a tooth, or a group of teeth is one of the most important components of the treatment, as it should enable tooth movement without causing any damages to the periodontal tissues or the teeth. Nevertheless, it is challenging to ascertain a precise ideal force value of the applied force, as there are several biological factors to be considered, in addition to the tooth size and movement type (22). The value of the orthodontic force range between 150 to 510 grams-force in most case (26). The use of an excessive force that exceeds vascular blood pressure results into stopping the movement of the tooth through reducing cellular activities in the periodontal tissues, while using lower forces is recommended to achieve optimal results (27).

The application of lower forces contributes into improving the performance and quality of the treatment and enhances tooth maneuvering throughout the sessions. The force used for orthodontic treatment is applied using orthodontic wires, which are used as fixed appliances with stored energy to stimulate force and torque on the teeth by the brackets fixed to each one of them (28).

Orthodontic wires, which are the source of force exertion during the treatment, are used to achieve different tooth movements. Therefore, the properties, characteristics, and performance of orthodontic wires are highly significant (29). A specific force is applied at the targeted tooth in order to correct its position. The friction force is equal to the applied force and multiplied by the friction coefficient of the surface between the orthodontic wire and the bracket. The surface roughness of orthodontic appliances plays the main role in determining the friction force. Due to the irregularities of the material at the molecular level, the friction coefficient does not have full impact on the smoothness of the surface and the contact area, i.e. asperities, are not considered the apparent surface of contact between the two materials (2), as shown in Figure 2.1.

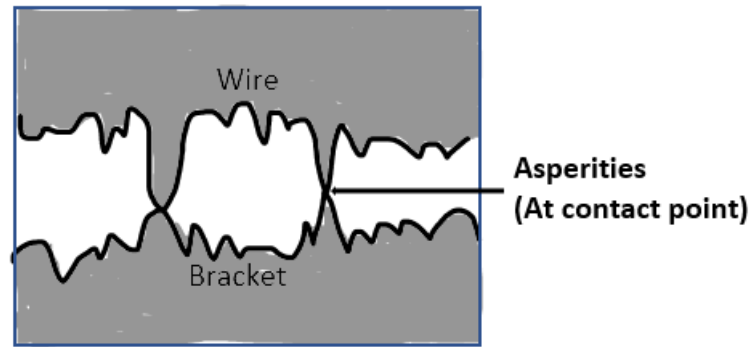


Figure 2.1. Illustration of the contact points between the wire and the bracket (30)

A shear force at the contact points is created by the application of a tangential force from one material to the other. Plastic deformations occur at the asperities due to the applied force, which depend on the yield strength of the used material. Moreover, the yield strength of the material at the asperities determines the value of the friction coefficient proportionally, while the yield strength of the materials have an inversely proportional relationship to it. A jump takes place at the contact points when sufficient force builds up at the asperities under the influence of the resistance of the material, which is also called the stick-slip phenomenon (2).

The resistance to the sliding motion is affected by the hardness of the used material, as harder material infuse into a softer one creating a stronger junction. Furthermore, it is affected by the interlock between the surface irregularities, especially if the later has pointed and large shapes. The shear force is dominant in the case of smooth surfaces between materials that are similar in hardness. Thus, three factors determine the friction of orthodontic appliances' materials (2):

1. The sufficient shear force at all asperities.
2. Surface roughness interlocking and the created resistance.
3. The infusion of material depending on their hardness.

After the advancements in preadjusted edgewise systems, the sliding mechanics were effectively utilized, and attention grew towards the contribution of the friction between the wire and the bracket to the resistance to tooth movement (31). Research on

the friction generally concluded that the greatest friction values were found between ceramic brackets and NiTi or TMA wires, while the lowest values between metallic brackets with stainless steel wires (32). The use of material that has the same or close hardness values, such as stainless-steel brackets and wires, became popular to avoid the infusion effect mentioned earlier. TMA demonstrated higher friction resistance in comparison with NiTi that has a higher surface roughness value, which is mainly attributed to the titanium composition in these two types that increases the value of the friction coefficient and the possibility of a cold weld between the metallic materials (33).

In orthodontic treatment, several archwires are fabricated consecutively from different material as the therapy progresses. In the levelling and aligning phase, flexible wires are used, such as NiTi, to utilize their low modulus of elasticity and high-spring back properties (24). In the detailing and finishing phase, stiff wires, such as stainless steel, are used for their high modulus of elasticity, good formability, and low friction (5).

The tooth movement in the orthodontic treatment is achieved through applying specific forces to the teeth to move through alveolar bone. While the brackets are connected with certain orientations and positions to the teeth, the wires are deflected with specific forces into the brackets' slots and ligated (34). The teeth then move to return to the ideal arch through the applied force from the wire, known as the unloading forces, moving the ligated brackets connected to the teeth (35). Thus, the ability to move the teeth is comprehended through understanding the unloading forces exerted by the archwire, while their light and continuous nature allow to predict the movements without damage to the supporting tissue (34). The NiTi wires are considered the best option to achieve their goals due to their high formability, high strength, high range of activation and low stiffness (36).

2.2 Orthodontic wires and their properties

Archwires were first used in orthodontic treatments in the 1800s; however, several developments have occurred since then in order to utilize the best aspects and systems for the desired tooth movement. The first significant development was made by Edward Angle through an E-arch in 1887 through using a 0.032-inch rigid labial platinum-gold

or nickel-silver wire attached only to the molars and extended around the arch (25). The wire was ligated to the teeth individually and expanding the wire through placing nuts on its threaded ends. The orthodontic treatment using this wire was limited to tipping the teeth into position. Bands with vertical rectangular slots were after placed on the teeth and holding them with the wire through pins. Nonetheless, this system did not allow Angle to control torque and root positioning (24). In 1928, a breakthrough was achieved by Angle through the development of the edgewise appliance. The slots were oriented by 90 degrees and wires made of noble metals were used, which allowed for controlling each tooth in all three planes (25).

Due to the focus on the wire properties, the use of several wires to suite each phase of the orthodontic treatment and solve the cost issue associated with the use of noble metals, modern wires were developed in the 1930s: NiTi, TMA and SS (5). There are specific clinical properties that are desired in orthodontic archwires, which cannot be achieved through using a single wire. Archwires are required to have biocompatibility, large spring back, high formability, environmental stability, low stiffness, high stored energy, capability for soldering or welding to the bands and low surface friction (36). A higher spring back increases the appliance's working time by applying large activation, which results into less adjustments or changes in the system. The ability to apply lower, continuous, and accurate forces is achieved through low stiffness. The ability to bend the wire into the desired shape is determined by its high formability, while its stored energy determines the working range. The properties of the wire are ensured to be maintained for a longer period through a good environmental stability and biocompatibility. The friction between the wire and the bracket through their connection determines achieving an adequate anchorage to simulate the needed tooth movement (36).

During treatment planning, it is necessary for the orthodontist to acquire sufficient knowledge on the clinical applications and biomechanical performance of orthodontic wires. Wide range of orthodontic wires were developed in order to achieve the desired treatment results, which mainly depends on their bending, tension and torsional performances (36). Other properties are also vital for the choice of the orthodontic wire, as shown in Figure 2.2.

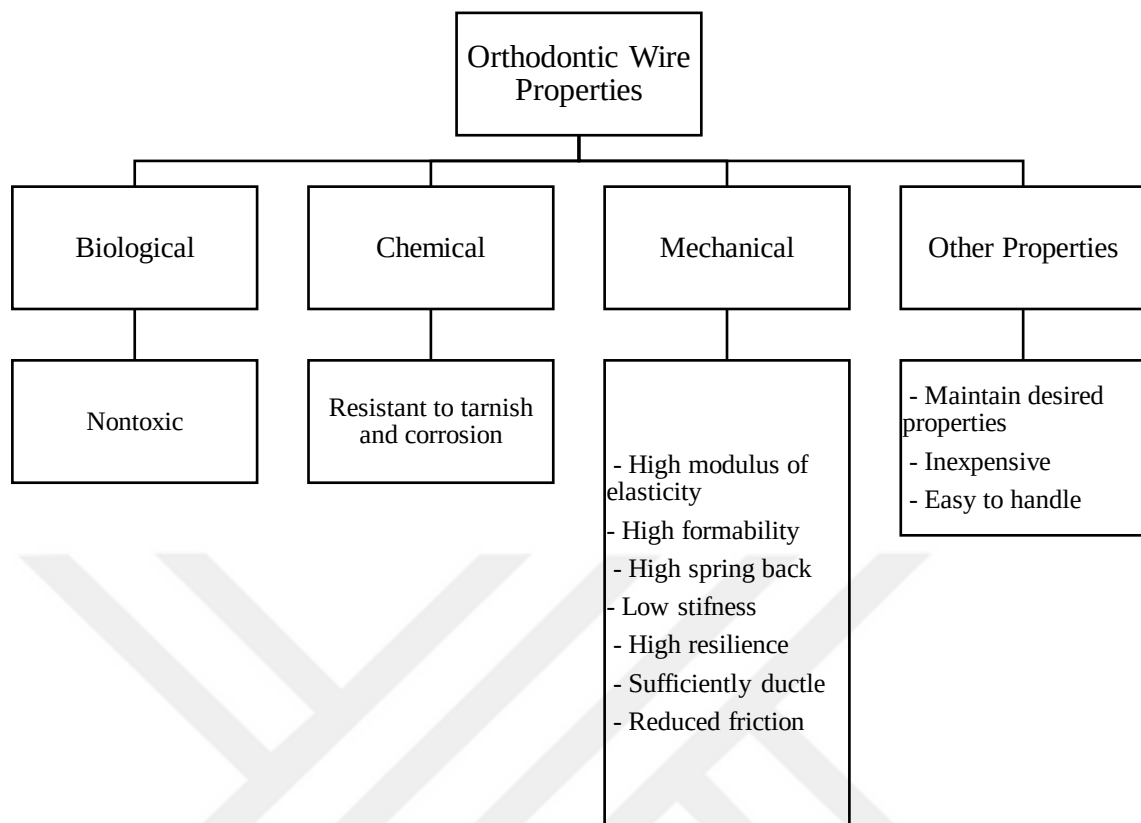


Figure 2.2. Hierarchy of the ideal performance requirements of orthodontic wires (5)

2.2.1 Stainless steel wires (SS)

The most common type used in stainless steel orthodontic wires is the austenitic 18-8 SS, which contains 18% chromium and 8% nickel. The 18-8 SS wire is highly resistant to corrosion through forming a passive oxide layer that prevents the underlying wire material from oxygen diffusion (37). The different types of SS orthodontic wires that are available in the market have various ranges of yield strength and elasticity resulting from the different production techniques and the parameters that are used at each stage, especially during cold working. Due to their lower energy compared to other orthodontic wire types and lower ability at spring back, SS orthodontic wires have the ability to apply higher forces over shorter periods (38).

SS wires are solderable and weldable. A fastening agent is used to solder SS wires with biomechanical attachments, while alternative methods using tungsten inert gas

(TIG), or LASER can also be used for soldering as a substitution. The surface roughness of SS wires is considered the lowest, when compared to wires made from other alloys. D'Anto et al. (39) measured surface roughness values for stainless steel archwires as $Ra = 36.6 \pm 5.8$, $Rms = 48 \pm 7.7$, and $Mh = 328.1 \pm 64$ using AFM. Bourauel et al. (40) confirmed that SS wires are the least rough of wires with measured optical roughness of $0.10 \mu m$. Marques et al. (41) reported much lower values of as-received SS wires, where Ra is 0.02 ± 0.02 , which was increased to 1.09 ± 0.89 after eight weeks in the oral environment.

SS wires are corrosion resistant. Despite the high corrosion resistance properties of SS wires, hypersensitivity reactions can be induced due to the release of chromium and nickel during usage (42). Nonetheless, hypersensitivity claims was objected to by another study that stated that the probability of such a reaction is only increased if the patient history contains usage of skin piercing (43).

The bracket-wire friction is lower with the use of SS orthodontic wires in comparison with other wire types (44), while further reduction of the friction value was simulated through nanotechnology in dental material enhancement study (45). Another type of SS orthodontic wire is the Australian type, which its increased carbon content up to ten times than standard SS wires that contain a maximum of 0.20% C, increase their resiliency, hardness, susceptibility, porosity and surface roughness. Thus, Australian SS orthodontic wires are used at biomechanical attachments to control friction (46). A SS wire type, also known as super stainless steel, was developed with enhanced mechanical properties, higher corrosion resistance and reduced nickel content formed a decent substitution to expensive titanium orthodontic wires (47). Choi et al. (48) correlated surface roughness and friction forces, where higher values of surface roughness were found for SS wires than NiTi counterparts.

Stannard et al. (49) compared friction values of SS wires with NiTi, CoCr, Teflon, and TMA wires under dry and wet conditions. Normal forces ranging between 4.40 kg and 8.76 kg were used. SS wires had lower frictional force than CoCr, NiTi, and TMA wires under dry conditions, while they had higher values than Teflon. Under wet conditions, SS wires had yielded a similar order with different values. The coefficient of

friction of SS wires at dry conditions was in the middle between the other wire types for normal forces below 7.31 kg, while it decreased when normal force reached 8.76 kg. However, wet conditions caused the values of friction coefficients to drop towards the lower range under a normal force of 5.86 kg and maintain its respective order under other values of normal forces. Angolkar (50) included SS wires in comparison with CoCr, TMA, and NiTi wires for their friction forces with two types of brackets: SS and ceramic. Mean friction forces of SS wires were lower than TMA and NiTi wires but higher than CoCr wires. The use of ceramic brackets increased friction forces with all wires including SS.

2.2.2 Cobalt-chromium wires (CoCr)

ELGIU developed the elgiloy, which is a cobalt-chromium-nickel alloy, that is used to manufacture the CoCr orthodontic bands, wires and other dental appliances. Variety of tempering properties are available from the CoCr orthodontic wires based on the extent of cold work during manufacturing (5). Color-coding is used to distinguish the different types of CoCr wires, which come in four main varieties:

- Red: high spring tempers (flexible)
- Green: semispring tempers (half elastic)
- Yellow: ductile or soft tempers (elastic)
- Blue: soft tempers (ultra-elastic)

The non-heated CoCr wires are easy to bend and has lower spring back than SS wires, while their strength or hardness can be manipulated to reach the level of SS wires through heat hardening them for 7 minutes at 482 °C (51). Furthermore, CoCr wires are not expensive and are decently resistant to corrosion and tarnish. They can be welded and soldered using fluoride fluxes. Blue Elgiloy CoCr wires are produced by heat treating to increase formability by 10% and yield strength and elasticity by 20% to 30% (52).

2.2.3 Beta-titanium wires (TMA)

In 1979, the titanium-molybdenum alloy, also known as Titanium-Niobium developed by ORMCO, were first used as orthodontic wires and carried the name beta-titanium (53). Although experiments have shown that beta-titanium wires has lower than half the modulus of elasticity of SS wires (54), others also showed that it has approximately twice the modulus of elasticity of NiTi wires (55). The beta-titanium wires can break if bent strongly but they have good formability generally. Attachment to biomechanical components is performed through electrical welding taking into consideration that the wire may become brittle, if overheated. Due to their superior structural characteristics, surface properties and higher resilience, beta-titanium wires are considered better than SS wires in joinability, even after welding (56).

Due to the absence of nickel in its composition, beta-titanium has good biocompatibility, in addition to its similar corrosion resistance properties and mechanism to the CoCr and SS wires (57). However, the risk of alteration of surface properties and corrosion of the beta-titanium wires increases, if exposed to fluoride agents (58), while the degradation severity increases with the exposure time (59). When compared to other orthodontic wires, the beta-titanium wires have the highest bracket-wire friction, and they are more expensive (60). Moreover, the TiMolium alloy, also known as alpha-beta titanium, was developed afterwards, which is more ductile than the beta-titanium wires and has middle values between the latter and SS wires in terms of yield strength and elasticity (56).

2.2.4 Nickel-titanium wires (NiTi)

Nickel-titanium alloy (also known as Nitinol) was developed in 1972 with superplastic and high resilience characteristics, in addition to its shape or thermal memory (61). The change in the crystal structure of the alloy, thermo-elasticity, is the property that defines its shape memory, which allows it to return to its original shape following a plastic deformation. NiTi wires can withstand reversible and large strains, allowing them to achieve super-elasticity or pseudo-elasticity. The ability of the NiTi wires to perform

transition through martensite-austenite phases in room temperatures is attributed to this property, which allows it to apply the same force regardless of its deflection distance (62).

Depending on the temperature, the NiTi alloy exists in three phases: two major and one intermediate. The high major phase is austenitic in centred cubic structure (BCC) at high temperature, while the low major phase is martensitic in hexagonal close packed structure (HCP) at low temperature. A delay in the transition from the austenitic phase to the martensitic phase is carried out by the intermediate phase until cooling to the lower temperature is reached (61). The induction of phase transition by volumetric change and applied stress results into the unique features of NiTi alloy of super-elasticity and shape memory, which can be observed during the reduction of the temperature (63). If the NiTi wire is initially heated up to 482 °C, then cooled and then shaped differently, the wire returns to the original shape when heated using a lower transition temperature range. The temperature range of the transition is controlled through the wire's cobalt content, while super-elasticity is produced through phase transition using stress application (64).

Different variations of the NiTi wire were developed. If a constant force is applied to the middle of the deactivation range, the Chinese NiTi wire produced by ORMCO has 1.6 the spring-back of the conventional Nitinol and 4.4 of SS wire (65). A similar wire to the Chinese NiTi was developed afterwards and it was known as the Japanese NiTi (66). In the 1990s, the Copper-Nickel-Titanium (Cu-NiTi) alloy wire and NeoSent alloy wire were developed. While in oral cavity, the NeoSent wire has a pure shape memory (61). While the oral temperature is not sufficient for the Nitinol to reach austenitic structure, the NeoSent can achieve it, while CuNiTi wires can achieve austenitic structure at temperatures between 27 °C and 40 °C. Additionally, in vitro studies show that the mechanical properties of super elastic Nitinol wires are altered at high temperatures and the wires are sensitive to high temperatures, leading them to achieve pure shape memory (67). Nevertheless, in vivo studies showed that these wires do not have thermoelastic shape memory (37).

Using the same magnitude of bending, NiTi wires can store higher energy than SS wires and beta-titanium wires (68), which is caused by the increased elasticity and allowing NiTi wires to deliver lower forces than its counterparts (16). NiTi wire can also

develop high friction at the bracket-wire connection, when compared to SS and CoCr wires (44). The corrosion resistance properties and mechanism are similar to the SS, CoCr and TMA wires (16). However, NiTi wires cannot be fused or welded, in addition to their limited formability, which can be disadvantageous characteristics (37). Moreover, failure caused by normal wear is common for NiTi wires if worn for several days, which is a phenomenon that increases with the increase with the wire cross-sectional area (69).

2.3 Surface roughness of the orthodontic wires

As orthodontic wires are considered the most vital component in the orthodontic assembly, its quality and performance determine the success of the treatment (70). There are several mechanical and chemical properties that determine the quality and performance of an orthodontic wire; however, surface roughness is considered the most important of them because it affects tooth movement efficiency, surface friction, aesthetics, color stability, corrosion behavior, hygiene, and biocompatibility of the wire (40). There is a direct positive correlation between the increase in surface roughness of the orthodontic wire and corrosion (70). Nonetheless, surface roughness is a functional property of the wire as it determines the frictional force with the brackets in contact and it can affect the value of the orthodontic force by at least 50%, resulting in a less effective orthodontic treatment (71). Similarly, the eradication of friction becomes necessary for a quality treatment if a misaligned tooth need to be corrected for more than 3 mm (72).

The impact of corrosion on the patient's health and treatment efficiency was discussed earlier. Additional risks are imposed on the patient through metal ion release, including allergies and negative impact on biological function, immune system, and oral mucosa (73). Most of the alloys used to manufacture orthodontic wires have high content of metals that can cause cytotoxicity, carcinogenicity and allergies, such as nickel (74). Therefore, it is crucial to understand the changes in surface roughness of the orthodontic wires in order to avoid the adverse effects and the negative impact on the quality of orthodontic treatment. In the orthodontic literature, the increase of the number of studies concerned with the evaluation of the surface roughness of the orthodontic wires can be

an indication of its importance. As shown in Figure 2.3, 63.3% of wire's surface roughness studies were published in the last 10 years.

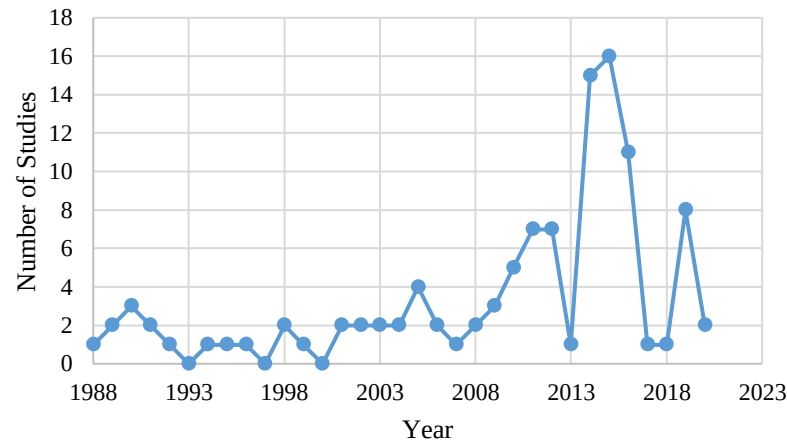


Figure 2. 1. Publication of the orthodontic wire's surface roughness studies as per PubMed

Choi et al. (48) established the statistical relationship between surface roughness and the orthodontic frictional force through measuring the values through atomic force microscopy (AFM) and lateral force microscopy (LFM). The authors created four combinations of wires and brackets of different alloys to study the correlation between the two factors. Two wires were used in the experiment: a 0.016-inch NiTi circular wire and 0.019 x 0.025 SS rectangular wire, while two bracket types were used: ceramic and stainless steel. The four combinations were created from these four components. The quantitative analysis of the roughness values and frictional forces evaluated through AFM and LFM showed a strong correlation between the two parameters in all samples and test types.

Kusy and Whitley (75) studied the impact of surface roughness in orthodontic appliances on their friction coefficient, as the latter is identified as the main factor influencing tooth movements during treatment. The authors tested the four standard orthodontic wire types: SS, CoCr, NiTi, TMA, with standard SS and Alumina brackets using a SEM analysis. Through studying the regression models between surface

roughness and frictional forces, the authors concluded that the relationship between the two parameters can not always be determined, especially in the use of abrasive or adhesive mechanisms. Therefore, the values measured for surface roughness and friction coefficients of orthodontic appliances can underestimate the actual values.

For the application of a continuous light force for tooth movement during the orthodontic treatment, it is essential to identify and control the frictional resistance between the wire and the bracket, as a key counterforce. Thus, research developed in recent years to identify the best wire-bracket combinations that can provide a solution to the friction issue. Dosh and Bhad-Patil (76) used a SEM analysis to study surface roughness and frictional forces for combinations between three bracket types: stainless steel, ceramic and ceramic with gold-palladium slot (CGP), and four wire types: rectangular 0.019 x 0.025-inch SS, TMA, low-friction colored TMA, and NiTi. The lowest surface roughness and frictional forces were achieved by the SS wire-CGP bracket combination, followed by SS wire-SS bracket combination and colored TMA wire-CGP bracket combination. The highest surface roughness and frictional forces were observed for TMA wire-Ceramic bracket combination.

Amini et al. (77) performed an in vitro experiment on seven orthodontic wires in order to determine their surface roughness values using a SEM analysis. The samples were four NiTi wires and three SS wires from four different manufacturers. After obtaining the data, the values were analyzed statistically. In the NiTi wire group the most significant differences in roughness values were between American Orthodontics and All-Star Orthodontics, OrthoTechnology and All-Star Orthodontics, and All-Star Orthodontics and Smart Technology, respectively. In the SS wire group, the most significant differences in roughness values were between American Orthodontics and All-Star Orthodontics. Cracks and defects were found through SEM in SS wire of American Orthodontics and the NiTi wire of All-Star Orthodontics, which had the highest surface roughness values, while the SS wire of All-Star Orthodontics have recorded the lowest values.

Alsanea and Al Shehri (78) performed a similar study, where the surface roughness was assessed beside color stability and mechanical properties for Nitinol wires

with three coats: Teflon, epoxy, and rhodium. The samples were divided into four groups for each type and immersed in a staining solution for 2, 14, 21 and 28 days, in addition to a control group. The surface roughness was evaluated using a spectrophotometer. The highest surface roughness was recorded for the epoxy coated wire, while the lowest surface roughness was recorded for the rhodium coated wire. Statistical testing showed significant differences between all groups, except between the control group and the rhodium coated wires. All experimental groups showed significant differences with the control group in terms of color change after four weeks and hardness.

Mousavi et al. (79) investigated the differences in surface roughness values and the effect of coating on them using Nitinol 0.016 x 0.022-inch rectangular wires from four brands. Uncoated wires were also used as a control group for the experiment. The results showed that the uncoated control group was observed with the highest surface roughness value. Results were statistically significant between the control group and the coated groups for the Sa and Sy parameters, while they were insignificant for the Sdq and Sv parameters.

Facchin et al. (80) assessed the surface roughness of a rectangular 0.016 x 0.022-inch SS wire produced by four orthodontic supply companies using AFM. Three-dimensional images of each wire were produced through obtaining more than 500 readouts for each sample. After comparing the roughness values for the four brands, where the SS wire of Incognito showed the lowest value. The result showed that the differences between the roughness value of the four wires using AFM were statistically significant.

D'Anto et al. (39) carried out a similar study for the evaluation of surface roughness with four NiTi wires, three TMA wires and one SS wire using AFM. Topography images were obtained, and three parameters were recorded for the samples: roughness average (Ra), root mean square (Rms), and maximum height (Mh). Values were averaged and the standard deviation was expressed as the error margin, which showed that the SS wire had the least surface roughness and friction resistance values, and the TMA wires had the highest values. An ANOVA statistical testing was performed to highlight significant differences between the tested specimens. Titanium Memory

Esthetic was the least rough among the NiTi wires, while Colored TMA was the least rough in its group.

Lee et al. (81) used AFM to investigate the changes in surface roughness of orthodontic bracket slots *in vivo* and *in vitro* before and after the wire sliding movement. Four bracket types were used standard ceramic, standard stainless steel, self-ligating ceramic, and self-ligating stainless steel. The least rough surfaces before usage were observed in standard SS and self-ligating SS, while the roughest surface was observed in standard ceramic. Following the sliding test *in vitro* with a TMA wire on the standard SS and ceramic, the only significant increase in roughness was observed for the standard SS bracket. The *in vivo* study was performed on specimens that were retrieved after two years of orthodontic treatment. AFM results showed that surface roughness increased significantly for the self-ligating SS brackets, while the self-ligating ceramic showed the least increase.

2.4 Impact of dietary factors on orthodontic wires

The effect of the dietary behavior of the orthodontic patient emerges from different factors associated with the type of diet in terms of acidity, oxygenation, temperature, and chemical composition. The impact on the orthodontic treatment system extend to increasing the friction between the bracket and the wire, discoloration, and deterioration of the mechanical properties of the wire and the brackets, which can hinder tooth movement and alter forces of the wire (82). Moreover, there are biologic and cytotoxic risks associated as the liquids in the oral environment act as electrolytes, which can result into the release of heavy metals from the wire and brackets' material (83). The hypersensitivity of the patient after orthodontic treatment is one of the significant concerns (84). For instance, the presence of nickel in the composition of orthodontic wires triggers hypersensitivities towards it, which is present in at least 15% of the population and reaches in some statistics to 30% (85). The main factor that is resulting into several risks with the use of orthodontic appliances is the extent of their material tendency for mechanical changes caused by the changes in the oral environment (86). Experimental research showed that orthodontic appliances of different material have different

sensitivity to surface changes and corrosive effects (87). Another study also suggested that the exposure of dental appliances to alcohol showed significant delays in tooth movement, which suggests an impact on the integrity of the assembly and reduction of the applied force (88).

Shahabi et al. (20) experimented with sixty stainless steel central incisor brackets on three types of dietary liquids: cola, vinegar, and lemon juice. The SS brackets were divided into three equal groups of twenties, in addition to another twenty brackets that were kept in artificial saliva as a control group. The experiment extended over six weeks, where the brackets in each group were submerged in the three liquids for a week's time, removed at the end of each week, cleansed, dried, and weighted on a scale. The means of the twenty brackets in each group were calculated and compared with the other experimental groups. The highest weight loss was caused by the cola, followed by vinegar and lemon juice, respectively, at the end of the six weeks. Cola caused a higher rate of weight loss after the first week, while the rate increased after the third week for the vinegar and lemon juice by a similar base. A statistical analysis was performed through comparing mean differences for the three study groups, where all the three groups showed significant differences.

Nanjundan and Vimala (19) applied the same methodology on SS brackets, PCA brackets and SS wires, where each of the tested specimens was distributed into four liquid groups: vinegar, cola, mouth rinse solution and artificial saliva. The immersion time extended only for twenty-four hours and then the surface morphology was tested using a SEM analysis, in addition to surface roughness and frictional resistance. The results of this *in vitro* study showed that the frictional force of the brackets increased with the level of acidity of the tested liquid, which was positively correlated with the surface roughness value. Moreover, PCA brackets showed higher deterioration level than the SS brackets and wires; therefore, higher surface roughness and frictional force.

Pop et al. (89) conducted a study on 270 new and used orthodontic Nitinol, stainless steel, physiognomic covered Nitinol, beta-titanium wires through immersing them in soft drinks and fluoride solution. The results of the study showed changes in the deactivation and activation forces in all the cases, while the used orthodontic wire had the

most deteriorated and weakened condition. Nevertheless, the differences in changes of mechanical properties could not be found through statistical evidence.

Parenti et al. (12) tested three of the most consumed soft drink in Italy on thirty-two Nitinol heat-activated orthodontic wires, where they were divided into four groups: cola, orange juice, sport energy drink, and distilled and deionized water. The authors aimed at measuring the changes in chemical composition, surface topography, hardness, and Young's modulus. The wires were then immersed at 37 °C in each of the soft drink types and water for sixty minutes. Using a nano indenter and a SEM analysis, the authors concluded that they did not observe any statistically significant differences between the samples. They also argued that patients undergoing fixed orthodontic treatment do not consume soft drinks for long periods of time. Therefore, the study suggested that soft drinks do not impose a significant risk on the mechanical and chemical properties of nitinol orthodontic wires.

Chewing gum is another dietary factor that was tested in few studies. Nonetheless, the studies that evaluated this factor focused on the impact of chewing gum, i.e. mastication and ligation forces, on altering the forces in the wires and frictional forces between the wires and the brackets. None of research has studied the effect of the chemical composition of the consumed gum on the mechanical and chemical properties of the orthodontic appliances. Benson et al. (90) have found that chewing gum relieved the pain resulting from fixed appliances with no risk for breakage, while Iwasaki et al. (91) stated that the vibration caused by mastication did not cause changes in the SS wire applied forces or the frictional forces with the SS brackets.

Sherief and Abbas (92) tested NiTi, TMA and SS wires for changes in their corrosion and static frictional forces through immersing them for two and four weeks into ethanol, citric acid, and heptane. SS brackets were used in the experiment. The highest significant difference in the static frictional forces were recorded for the four-week SS wires that were immersed in ethanol and citric acid, followed by the NiTi and TMA wires that were immersed in the same liquids for four weeks. The highest corrosion activity was recorded for the citric acid for all wire types, while SS had the highest values in ethanol as well.

Hobbelink et al. (93) tested the changes in surface roughness on 0.43 x 0.64-inch rectangular wires, in addition to other mechanical properties, after immersing in artificial saliva solutions with different pH levels. One-hundred and twenty wires were used and divided into four equal groups: pH 5.6, pH 6.6, pH 7.6 and control group. Half of the specimens in each group were bent, while the other half was left straight. The results show that bending the SS wire increases its surface roughness, while samples with acidic pH had greater values than samples in other groups, which caused a synergistic effect. In mechanical performance testing, a four-point flexural testing was performed on two control group specimens (straight and bent), where the straight specimen showed a higher Young's modulus of elasticity and lower maximum force in comparison with the bent specimen.

Jaber et al. (94) recorded the differences in surface roughness and friction forces of CuNiTi wires immersed in an erosive solution, cariogenic solution, and artificial saliva. Erosive acidic solution had the highest impact in increasing surface roughness from $0.076 \pm 0.011 \mu\text{m}$ to $0.112 \pm 0.029 \mu\text{m}$ (Ra value), while the same occurred to the friction force by increasing from $1.51 \pm 1.3 \text{ N}$ to $1.63 \pm 1.11 \text{ N}$.

Holla et al. (17) showed that all wire types had significant increases of surface roughness value between low acidic (citric) and high acidic solutions (phosphoric), while higher differences were recorded when compared to artificial saliva.

Abalos et al. (21) tested NiTi wires for surface roughness when immersed in low pH solutions, where soft drinks were used. Statistically significant increases were found in surface roughness for different wire types. The defects worsened with the increased immersion time. Several defects were recorded including cracks and scratch patterns that led to the decrease of the corrosion resistance properties of the wire.

2.5 Methods of measuring surface roughness

For studying material surface on the microscopic level, several techniques were developed and used in different scientific domains. Scanning electron microscopy (SEM) is one of the early implemented methods that was pursued for its high-resolution yield.

The method provides two-dimensional scans of the surface and may require the addition of other technologies to increase its output. Surface profilometry is another method that can provide three-dimensional images. However, it is a surface contact method which has its measurement limitations and causes wear on the surface of the sample (77). Transmission electron microscopy (TEM) can provide very high-resolution images of the surface, but it is not preferred due to its difficult handling techniques and severe risks of radiation damage (95). Atomic force microscopy (AFM) is one of the most preferred methods that allows for capturing three-dimensional high-resolution images of the surface with contacting it (39).

In measuring surface roughness, the most common parameter is Ra, which represents an average value of the measured highest of the surface and typically measured in micrometer (μm). Rq (also represented as Rms) is another surface roughness measurement that is calculated through measuring the different heights of the surface and then representing through their root mean square values. Rz (also represented as Mh) is another measure that provides the difference between the highest and lowest heights at the surface (96).

Out of more than 500 studies that were published on the surface roughness of orthodontic appliances since 1975, 231 studies used microscopic techniques to evaluate the different parameters. As shown in Figure 2.4, 45.9% of the studies used SEM, followed by 29.9% AFM, 23.8% for profilometry and 0.43% for TEM. Moreover, Table 2.1 shows a comparison between SEM, TEM and AFM based on key features. It is evident that atomic force microscopy is one of the best methods for surface roughness evaluation due to its high magnification ability, high resolution, easiness of sample preparation and lack of radiation hazard (97).

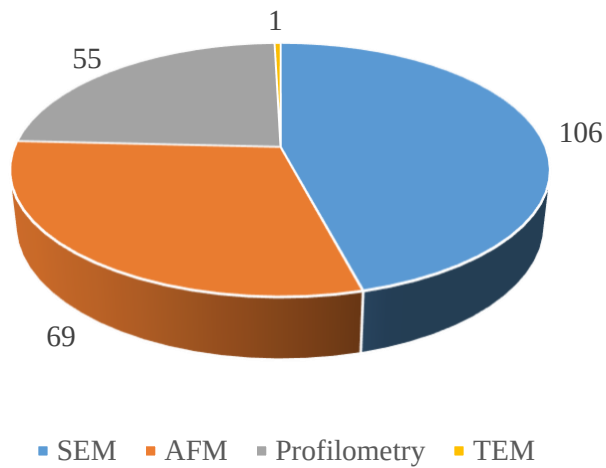


Figure 2. 2. Number of orthodontic surface roughness studies that used microscopic techniques since 1975 as per PubMed

Table 2. 1. Comparison between SEM, TEM and AFM microscopy techniques (97)

Parameter	SEM	TEM	AFM
Features	Surface topography	Crystalline structures, lamellar and internal morphology	Surface topography
Size range of polymer structure	10 μm to 0.2 nm	100 μm to 10 nm	10 μm to 0.2 nm
Useful magnification	20 to 60000 x	3000 to 250000 x	3000 to 250000 x
Best resolution	4 nm	0.2 nm	0.3 nm
Radiation damage	Rarely serious	Severe	None
Sample preparation	Easy	Difficult and time consuming	Easy

Atomic force microscopy is a technique used to investigate the surface features of polymers. As shown in Figure 2.5, the AFM comprises of a cantilever with a silicon nitride or silicon tip and has nanometer measured radius of curvature. Van der Waals forces determine the repulsion and attraction forces between the sample and the cantilever tip. Based on the latter forces, the cantilever deflects based on Hooke's law. The reflection of the laser light on the back of the cantilever, which measures the magnitude of the deflection in the cantilever, gets detected by a photodiode with four-quadrants. Adjustment of the distance between the sample and the tip is fed back to the scanning components to maintain the acting force in a constant pattern, which enables surface asperities to be scanned perfectly. The force pattern is acted by the piezo electric tube that moves horizontally in the x and y direction and perpendicularly in the z direction. The topography of the surface of the sample is presented by the map drawn on the x and y planes (39).

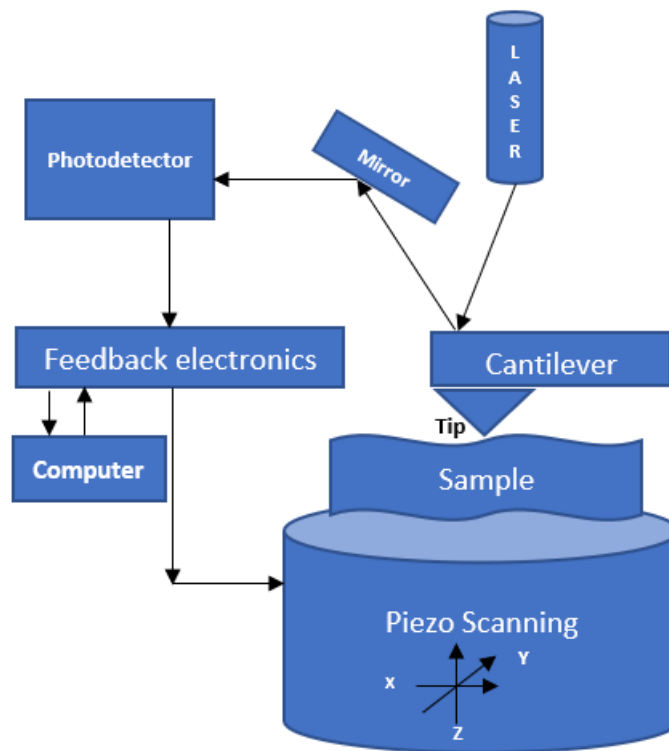


Figure 2. 3. Schematic diagram of atomic force microscopy (39)

Surface topography is imaged through the change in the repulsive and attractive forces between the two components. AFM has three imaging modes depending on the force of interaction between the tip and the sample (98):

- Contact mode is demonstrated through a separation between the surface and the probe that is less than 0.5 nm (Figure 2.6). This mode is also called the repulsive regime, where the cantilever bends if its spring constant is less than the surface. The repulsive force between the tip and the sample is maintained to measure surface deflections and obtain its image. The contact mode is featured for its efficient use for rough samples, fast scanning, and the ability to use the obtained data in friction analysis. However, the use of this mode on soft samples can cause deformations to their surfaces.

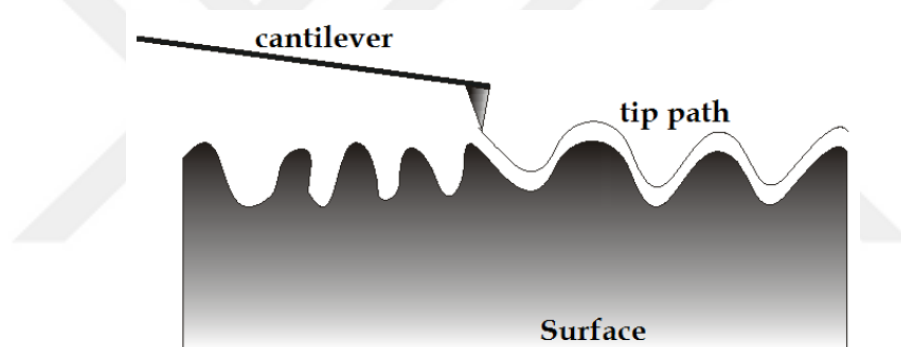


Figure 2. 4. AFM contact mode (98)

- Intermittent contact mode is demonstrated through a separation between the surface and the probe that is ranging between 0.5 and 2 nm (Figure 2.7). A resonant frequency of hundreds of kHz is created to create the contact between the tip and the surface. Through its swinging in a constant frequency, the tip contacts the surface of the sample at the bottom of the wave, which causes the lateral forces to be reduced with the small oscillation period. The intermittent mode is best utilized for soft surfaces or materials with weak surface structure.

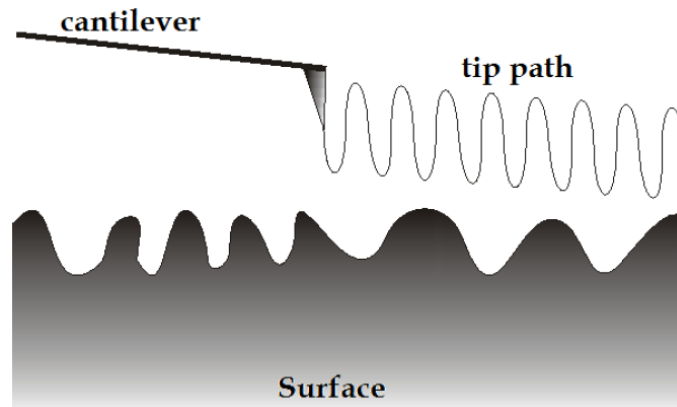


Figure 2. 5. AFM intermittent mode (98)

- Non-contact mode is demonstrated through a separation between the surface and the probe that is ranging between 0.1 and 10 nm (Figure 2.8). This mode is also called the attractive regime, where no contact is made between the tip and sample and the tip oscillates above it. Due to the attractive forces between the sample and the tip, the amplitude of the feedback loop is measured. The most is best used for material with liquid absorption at the surface. The probe lifetime is extended because of this mode because the applied forces on the surface of the sample are very low (10^{-12} N). Nevertheless, UHV needs to be used with mode to require better images. Otherwise, lower imaging resolution is achieved, especially if the surface is contaminated.

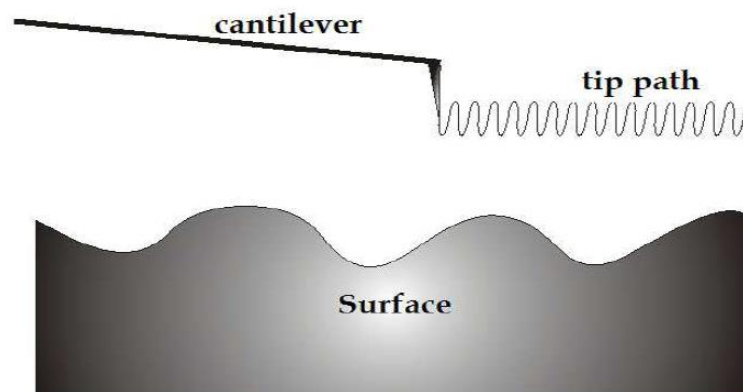


Figure 2. 6. AFM non-contact mode (98)

3. MATERIALS AND METHODS

3.1 Experimental design and samples

An *in vitro* experimental study design was adopted with a control group. Three different alloys as preformed orthodontic archwire were included in the study: Stainless steel wire (SS), Nickel Titanium (NiTi) and Beta Titanium (TMA). All the wires were obtained from American Orthodontic (AO, Sheboygan, WI US).

To determine the sample size, power analysis was performed using the G * Power program. The sample size was calculated based on the ability to detect a change in the Average Roughness (Ra) of 0.807 ± 0.35 (12) (20) (21) (99). The calculation indicated that for a study with a power of 0.80 and an alpha of 0.05, we required a total of 90 specimens (n=6 for each subgroup). The total number of wires were 90 wires (n=90), divided into three major groups according to the wire's alloy (SS, NiTi and TMA), each main group was further subdivided into five subgroups according to the immersion solution (cola, ice tea, kefir, coffee latte and artificial saliva as control group). The distribution of the sample wires based on immersion media is shown in Figure 3.1.

The examination of the effect of soft drinks on the surface roughness of the orthodontic wire was conducted by using AFM. A random point at the middle of each wire was selected for the before and after measurements. The samples were investigated before and after immersion in the selected beverages solution for a specific time.

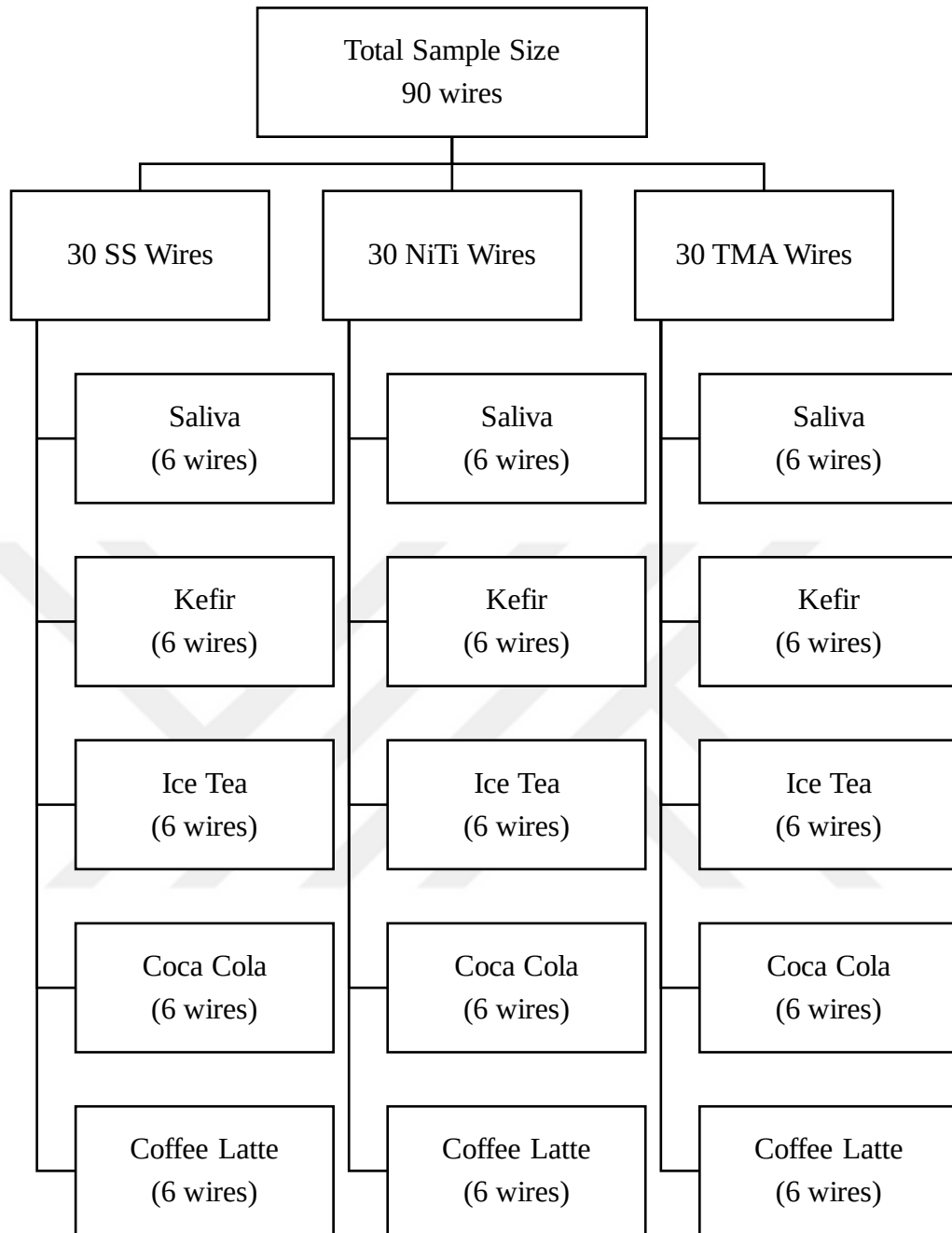


Figure 3. 1. Descriptive diagram showing sample size and groups

3.2 Materials

3.2.1 Wires

In the current study, the investigated wires were obtained from American Orthodontics (AO). Regarding the sample size, six basal archwires were used for each group of drinks. The archwire used in this study was rectangular (16 x 22 inches), which is the common size used in different orthodontic treatment stages. In order to investigate a relatively straight wire segment from each preformed archwire, four samples with 20 mm length were delivered by cutting each wire into two pieces from each end. Surface roughness values for all wire types were examined before and after immersion in the test solution. The following sections provide the specifications of the used wires.

3.2.1.1 Stainless steel (SS) wire

The first wire material tested was stainless steel wire (SS, American Orthodontics, Sheboygan, WI USA). According to the manufacturer's information, the composition of the stainless-steel wire is as shown in Table 3.1.

Table 3. 1. Material composition of SS wire

Element	Wt. % (percentage by weight)
Iron	Balance
Nickel	0 – 15
Chromium	11.5 – 20
Silicon	0 – 2
Manganese	0 – 2
Molybdenum	0 – 6.5
Titanium	0 – 0.7
Copper	0 – 5
Aluminum	0 – 4

Niobium	0 – 0.6
Carbon	0 – 1.2
Tantalum	0 – 0.5 and < 0.1% of other trace elements

3.2.1.2 Nickel-Titanium wire

The second wire material tested was Nickel-Titanium wire (NT3, American Orthodontics, Sheboygan, WI USA). According to the manufacturers information, the composition of the Nickel-Titanium wire (NiTi) is as shown in Table 3.2.

Table 3. 2. Material composition of NiTi wire

Element	Wt. % (percentage by weight)
Nickel	45 – 60
Titanium	40 – 50

3.2.1.3 TMA wire

The third wire material tested was titanium molybdenum alloy (bt, American Orthodontics, Sheboygan, WI USA). According to the manufacturers information, the composition of the titanium molybdenum alloy (TMA) wire is as shown in Table 3.3.

Table 3. 3. Material composition of TMA wire

Element	Wt. % (percentage by weight)
Titanium	60 – 80
Molybdenum	10 – 20
Zirconium	5 – 10
Tin	1 – 5

3.2.2 Immersion media

The beverages were selected in agreement to their popularity and wide consumption among the category of young adults, who are more exposed to orthodontic treatment. The beverages that were selected as immersion media for wires were: Coca-Cola®, Kefir, Iced Tea and Coffee latte. It was confirmed that the beverages' expiry date was beyond the time of the experiment. Artificial saliva was used for the control group.

3.2.2.1 Artificial saliva

To assess the surface roughness of various orthodontic wires in conditions similar to that of the oral cavity environment, the samples were stored in artificial saliva for the test period time at $37\pm1^{\circ}\text{C}$ (Figure 3.2). Artificial saliva was prepared according to Amaechi et al. (100).



Figure 3. 2. Artificial saliva

To imitate the saliva, the inorganic components and rheological characteristics of natural human saliva was used as described by Amaechi et al. (100). The artificial saliva contained 1.2856 g/l Sodium Chloride (NaCl), 0.0320 g/l Magnesium Chloride Hexahydrate ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$), 0.0794 g/l Calcium Chloride ($\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$), 0.2985g/l Potassium Chloride (KCl), 0.897 g/l Potassium Hydroxide (KOH), 472 ml Phosphoric Acid (H_3PO_4) and water with pH level of 7 ± 0.10 . The pH level was measured using a pH meter, as shown in Figure 3.3.



Figure 3. 3. pH level measurement of the artificial saliva by Thermo Scientific Orion 720A+ and 920A+ pH meter (Hard Tissue Laboratory; Faculty of Dentistry - University of Yeditepe)

Wire segments of both control groups and those exposed to test solutions groups were immersed in 10 mL of artificial saliva for 28 days at $37 \pm 1^\circ\text{C}$ (Figure 3.4). After immersion to soft drinks and before immersion to artificial saliva, the wires were rinsed with deionized water. The saliva was renewed every 7 days with fresh solution to avoid any saturation with degradation products.

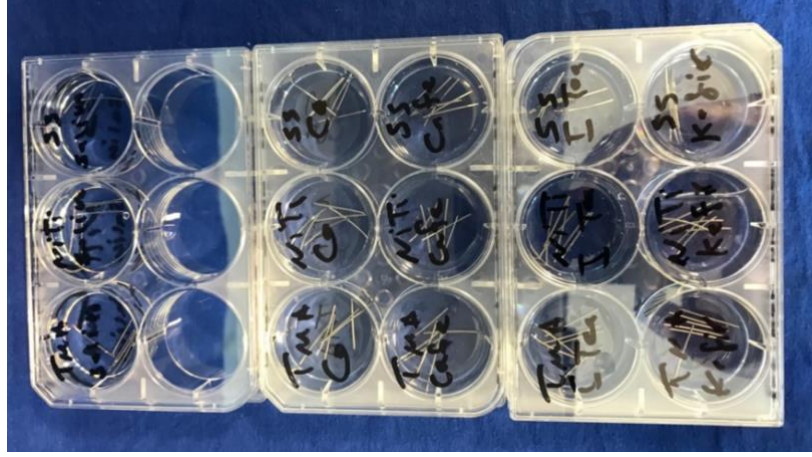


Figure 3. 4. Immersion of wire samples in the artificial saliva (Hard Tissue Laboratory; Faculty of Dentistry- University of Yeditepe)

3.2.2.2 Cola

Coca Cola is an acidic drink commonly consumed by the young population. As mentioned on the can (Figure 3.5), the contents of Coca-Cola (Coca-Cola® original, Coca-Cola Company, Atlanta, USA) are water, sugar (S) or fructose-glucose syrup (F) (the sugar or fructose-glucose syrup used was coded on the package), carbon dioxide, colorant (caramel), acidity regulator (phosphoric acid), natural flavors, caffeine (max. 0.150 g / l). Table 3.4 shows the nutritional values per 100 ml, while the percentages of the contents are not explained for patent reasons.



Figure 3. 5. Coca Cola used in the experiment

Table 3. 4. Average nutritional values per 100 ml for cola

Criteria	Value
Energy (Kcal)	45
Energy (KJ)	188
Protein (g)	0
Carbohydrates (g)	11.2
Sugar (g)	11.2
Fat (g)	0
Salt (g)	0

3.2.2.3 Kefir

Kefir is a fermented milk drink valuable with probiotics containing mixed of bacteria and yeasts persisting in milk's polysaccharide. In the current study, plain kefir (Kefir sade, ALTINKILIÇ®, İstanbul, Türkiye) was used (Figure 3.6). Table 3.5 shows the nutritional values per 100 ml.



Figure 3. 6. Kefir used in the experiment

Table 3. 5. Average nutritional values per 100 ml for kefir

Criteria	Value
Energy (Kcal)	78
Energy (KJ)	313
Protein (g)	2.7
Carbohydrates (g)	10
Sugar (g)	3.9
Fat (g)	3
Salt (g)	0.1
Calcium (mg)	102

3.2.2.4 Coffee latte

According to the producer, Coffee latte (Starbucks Corporation, Washington, USA) is a ready-to-drink coffee that contains the following ingredients: 3.1% Fat Milk (75%), Starbucks Arabica Coffee (Water and Coffee Extract) (20%), Sugar (5%), Natural Coffee Flavoring, Acidity Regulator (Potassium Carbonate), Stabilizers (Carrageenan, Guar Gum), Emulsifiers (Mono- and Diglycerides of Fatty Acids from Rapeseed Oil and Palm Oil (E471)) (Figure 3.7). Table 3.6 shows the nutritional values per 100 ml.

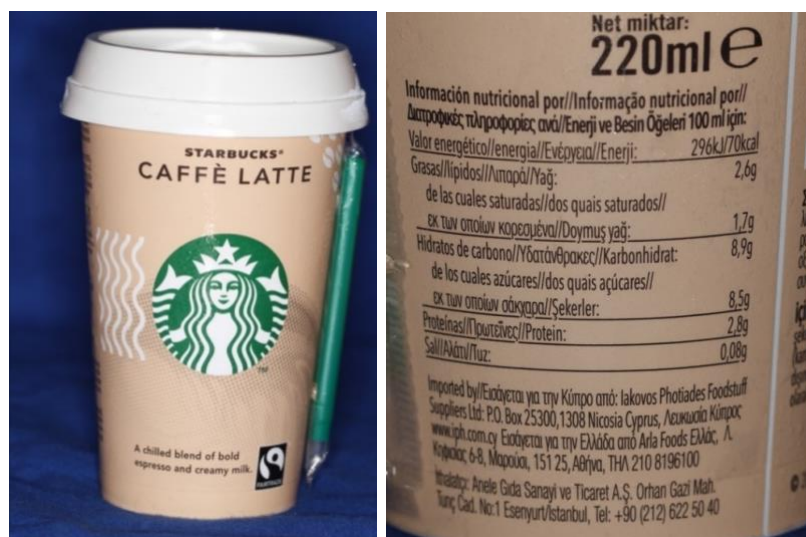


Figure 3. 7. Coffee latte used in the experiment

Table 3. 6. Average nutritional values per 100 ml for coffee latte

Criteria	Value
Energy (Kcal)	70
Energy (KJ)	296
Protein (g)	2.8
Carbohydrates (g)	8.9
Sugar (g)	8.5
Fat (g)	2.6
Salt (g)	0.08

3.2.2.5 Ice tea

The ice tea (Lipton Ice Tea peach flavored, Unilever and Pepsi Co, UK) is made from tea leaves with aromatic peach (Figure 3.8). Table 3.7 shows the nutritional values per 100 ml.



The figure shows a can of Lipton Ice Tea peach flavored on the left and its nutritional label on the right. The label is in Turkish and provides nutritional information per 100 ml and per 330 ml (1 cup).

Enerji ve Besin Öğeleri	100 ml için	1 Kupa (330ml) için (RA*)
Enerji	82 kJ/19 kcal	271 kJ / 63 kcal (% 3*)
Yağ	0 g	0 g (% 0*)
Doymuş yağ	0 g	0 g (% 0*)
Karbonhidrat	4,6 g	15 g (% 6*)
Şekerler	4,5 g	15 g (% 17*)
Lif	0 g	0 g (% 0*)
Protein	0 g	0 g (% 0*)
Tuz	0,03 g	0,1 g (% 2*)

*Değerler ortalama bir yetişkinin Referans Alım düzeyini belirtir (8400kJ/2000 kcal)

Figure 3. 8. Iced tea used in the experiment

Table 3. 7. Average nutritional values per 100 ml for iced tea

Criteria	Value
Energy (Kcal)	19
Energy (KJ)	82
Protein (g)	0
Carbohydrates (g)	4.6
Sugar (g)	4.5
Fat (g)	0
Salt (g)	0.03

3.3 pH measurement of immersion media

The test solutions were kept at the room temperature to become ready for the measurements of pH levels. The pH level of all experimental beverages was measured six times by a pH meter (Thermo Scientific orion 720A+ and 920A+ pH meter) under equal condition (temperature= $20\pm 2^{\circ}\text{C}$) (Figures 3.9, 3.10, 3.11, 3.12, 3.13). Table 3.8 shows the six pH measurements for each of the immersion media used in the study.



Figure 3. 9. Thermo Scientific orion 720A+ and 920A+ pH meter (Hard Tissue Laboratory; Faculty of Dentistry- University of Yeditepe)



Figure 3. 10. pH measurement for Kefir ($\text{pH} = 4.254 \pm 0.05$)



Figure 3. 11. pH measurement for Cola ($\text{pH} = 2.225 \pm 0.05$)



Figure 3. 12. pH measurement for iced tea ($\text{pH} = 3.059 \pm 0.05$)



Figure 3. 13. pH measurement for coffee latte (pH= 6.655± 0.060)

Table 3. 8. Measurements of the pH level of the immersion media used in the study

Immersion Media	pH Reading					
	1	2	3	4	5	6
Coffee latte	6.766	6.770	6.788	6.655	6.653	6.768
Coca Cola	2.225	2.239	2.227	2.222	2.220	2.226
Iced Tea	3.116	3.047	3.087	3.035	3.098	3.114
Kefir	4.254	4.284	4.292	4.278	4.243	4.288
Artificial Saliva	7.106	7.004	7.041	7.039	7.117	7.000

Then, the average value was calculated using these 6 measurements to determine the mean pH for different test solutions, which were as the follows:

- Coca Cola (pH= 2.225 ± 0.05)
- Iced Tea (pH= 3.100 ± 0.015)
- Kefir (pH= 4.270 ± 0.015)

- Coffee Latte (pH= 6.770 ± 0.01)
- Artificial saliva (pH= 7.1 ± 0.3)

3.4 Immersion test procedure

In each subgroup, the wire specimen was completely immersed in plastic container containing 10 ml of one of the test solutions for 60 minutes and incubated at 37°C, as shown in Figure 3.14. After submerging the wires in the test solution, the specimens were removed from the containers and rinsed with deionized water, and dried. Thereafter, each wire specimen's subgroup was immersed in 10 ml of artificial saliva separately and stored at 37°C for 28 days with renewal of the artificial saliva every 7 days (Figure 3.15). Subsequently, the wires were removed from artificial saliva and rinsed with deionized water, dried and maintained in clean individual numerical coded plastic vials (Figure 3.16). The soaking time was selected according to the study of Parenti et al. (12), which specified the soaking time based on an *in vivo* procedure recommendation.



Figure 3. 14. Immersion of wires in tested beverages



Figure 3. 15. Incubator used to control environmental conditions of immersed samples

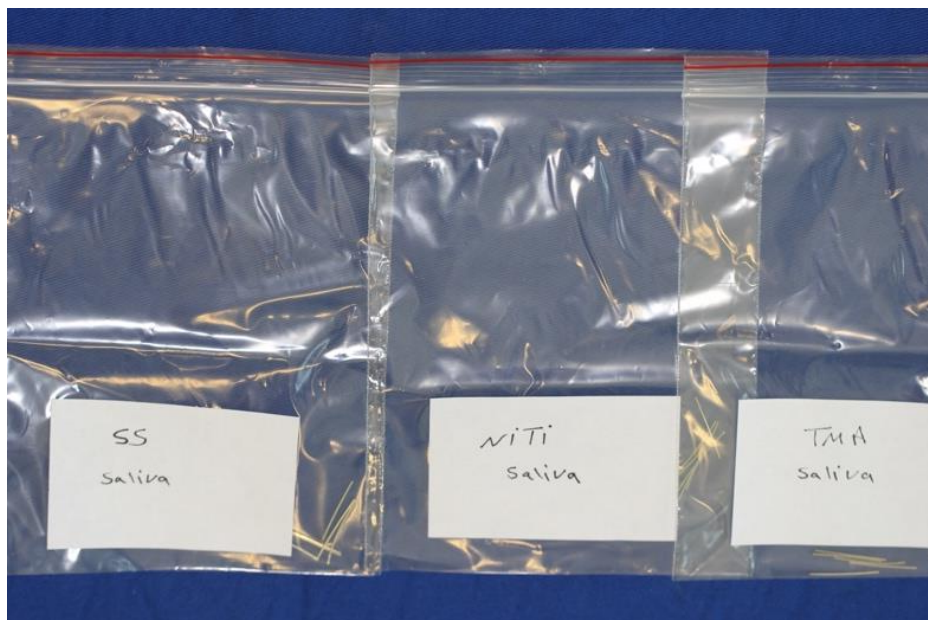


Figure 3. 16. Separated samples cleaned and maintained in plastic vials after immersion period and before AFM measurements

3.5. Surface roughness measurement by Atomic Force Microscopy

To analysis of the topography of the wire surface, Atomic Force Microscope (AFM, XE-100, PSIA Corp. Sunganam, Korea) was used at the Department of Genetics and Bioengineering of Yeditepe University before and after immersion in the soft drinks (Figure 3.17). A satisfactory cantilever tip type (10M-NSC36, Si 3N4 10 m) was used to measure surface roughness values. The tested wire segment was fixed on glass slide with carbon disc during AFM examination, as shown in Figure 3.18. In order to use AFM for analysis, contact mode was used but without any damaging to both the wire and the cantilever tip. To represent each subgroup, two wire specimens were selected randomly for AFM testing, and marked it with an insoluble marker, to confirm that we used the same wires. Selection of scanning area was as 10 μm x 10 μm with speed 0.5 Hz at two areas on each wire, one at the middle and the other at the end of the wire. The analysis was carried out on two lines at each point with two readings at each line. And Emphasizing that the measurement is at the same point before and after the test.

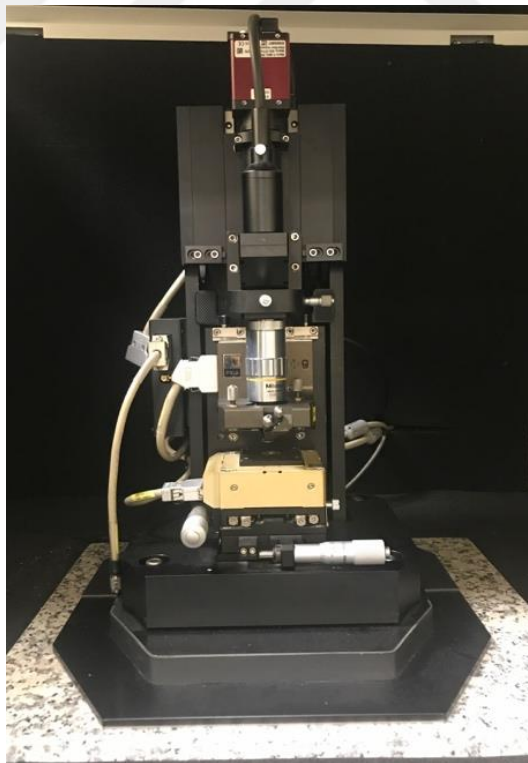


Figure 3. 17. Atomic Force Microscope (AFM, XE-100, PSIA Corp. Sunganam, Korea)

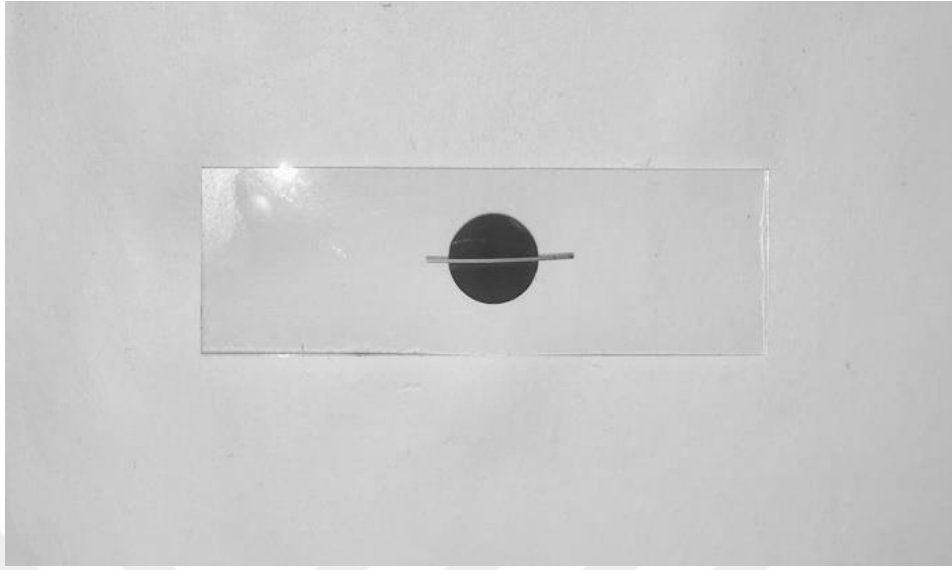


Figure 3. 18. Tested wire segment fixed on glass slide with carbon disc for AFM examination

The surface roughness data recorded for the wires were based on readings before and after immersion in different liquids. The values that were recorded are as the following:

- Ra: arithmetic average of absolute values of the roughness profile ordinates.
- Rq: root mean square average of the profile heights over the evaluation length.
- Rz: mean roughness depth

The difference in roughness value was calculated according to the following equation:

$$\Delta Rn (Rn) = Rn \text{ after} - Rn \text{ before}$$

Where, n : the surface roughness value type, i.e. Ra, Rq or Rz.

3.6. Statistical Analysis

Statistical testing was performed on the data in order to investigate statistically significant differences between the different sample groups based on the wire type and immersion liquid. All statistical analyses were performed with the SPSS software package (IBM SPSS statistics, version 23.0, IBM, Chicago, USA). For each variable, the arithmetic mean, and standard deviation were calculated. Analysis of variance (ANOVA) was used for that purpose, while further investigation of the differences was performed using post-hoc testing (Tukey HSD). Homogeneity of variance between groups is tested and all p values were higher than 0.05. Minimum significance level of the results was set at the $p < 0.05$.



4. RESULTS

4.1 Surface roughness changes of wires immersed in different soft drinks

4.1.1. Surface roughness changes of SS wires immersed in different soft drinks

Table 4.1 shows the surface roughness values for the SS wire immersed in the different soft drinks used in the experiment, including values before and after immersion and the difference between them. The findings showed that the highest increase in surface roughness values were indicated for Coca cola, followed by kefir, and iced tea at a close level. The least increase was observed for coffee and artificial saliva. The lowest T_1 values were recorded for artificial saliva and coffee, respectively, whereas the highest values were recorded for Coca cola, followed by iced tea and kefir.

Table 4.2 shows the comparison of changes in surface roughness measurements of SS wires immersed in different soft drinks. There were significant differences in the changes of all three surface roughness parameters: R_a , R_q and R_z ($p < 0.001$, $p < 0.001$ and $p < 0.05$, respectively.). Changes in R_a and R_q of the SS wires immersed in Coca Cola were significantly higher than that of the SS wires immersed in other soft drinks and the artificial saliva ($p < 0.001$) (Table 4.3). The changes in R_q of the SS wires immersed in Coca Cola were significantly greater than that of the control group ($p < 0.05$). Figure 4.1 shows three-dimensional images of the SS wires before and after immersion in different liquids. Visually different surface morphologies were observed depending on the immersion media, with a significant difference in Coca Cola group.

Table 4. 1. Descriptive statistics of surface roughness values for SS wires immersed in different soft drinks

Immersion Media	Surface Roughness Parameter	Before (T ₀) Mean $\pm$ SD	After (T ₁) Mean $\pm$ SD	Δ (T ₁ -T ₀) Mean $\pm$ SD
Coffee Latte	Ra	4.519 $\pm$ 1.828	5.151 $\pm$ 2.149	0.632 $\pm$ 0.496
	Rq	5.384 $\pm$ 1.839	6.237 $\pm$ 2.149	0.853 $\pm$ 0.575
	Rz	17.486 $\pm$ 4.196	20.592 $\pm$ 5.588	3.106 $\pm$ 1.421
Coca Cola	Ra	4.888 $\pm$ 1.537	9.923 $\pm$ 3.743	5.035 $\pm$ 2.214
	Rq	6.185 $\pm$ 1.886	11.398 $\pm$ 3.992	5.213 $\pm$ 2.201
	Rz	27.198 $\pm$ 7.985	35.999 $\pm$ 11.205	8.801 $\pm$ 6.588
Iced Tea	Ra	5.266 $\pm$ 1.694	6.355 $\pm$ 1.570	1.089 $\pm$ 0.355
	Rq	6.432 $\pm$ 2.016	7.808 $\pm$ 2.085	1.376 $\pm$ 0.442
	Rz	22.575 $\pm$ 6.113	25.509 $\pm$ 6.253	2.934 $\pm$ 2.243
Kefir	Ra	4.936 $\pm$ 1.456	5.785 $\pm$ 1.585	0.849 $\pm$ 0.559
	Rq	6.007 $\pm$ 1.795	7.686 $\pm$ 2.881	1.680 $\pm$ 1.153
	Rz	21.037 $\pm$ 6.925	25.149 $\pm$ 7.974	4.112 $\pm$ 3.721
Artificial Saliva	Ra	3.965 $\pm$ 1.042	4.351 $\pm$ 1.060	0.386 $\pm$ 0.251
	Rq	4.831 $\pm$ 1.262	5.529 $\pm$ 1.565	0.698 $\pm$ 0.666
	Rz	17.045 $\pm$ 3.090	19.171 $\pm$ 3.594	2.126 $\pm$ 1.171

Table 4. 2. Comparison of the changes in surface roughness values of SS wires immersed in different soft drinks by ANOVA test

SS wire	Coffee Latte Mean $\pm$ SD	Coca Cola Mean $\pm$ SD	Iced tea Mean $\pm$ SD	Kefir Mean $\pm$ SD	Artificial saliva Mean $\pm$ SD	p value
Δ Ra	0.632 $\pm$ 0.496	5.035 $\pm$ 2.214	1.089 $\pm$ 0.355	0.849 $\pm$ 0.559	0.386 $\pm$ 0.251	.000***
Δ Rq	0.853 $\pm$ 0.575	5.213 $\pm$ 2.201	1.376 $\pm$ 0.442	1.680 $\pm$ 1.153	0.698 $\pm$ 0.666	.000***
Δ Rz	3.106 $\pm$ 1.421	8.801 $\pm$ 6.588	2.934 $\pm$ 2.243	4.112 $\pm$ 3.721	2.126 $\pm$ 1.171	.029*

* p<0.05, *** p<0.001

Table 4. 3. Results of Post-hoc (Tukey HSD) comparison test for SS wires

Surface Roughness Parameter	Liquid A	Liquid B	p value
ΔR_a	Coca Cola	Coffee latte	.000***
	Coca Cola	Iced Tea	.000***
	Coca Cola	Kefir	.000***
	Coca Cola	Artificial Saliva	.000***
ΔR_q	Coca Cola	Coffee latte	.000***
	Coca Cola	Iced Tea	.000***
	Coca Cola	Kefir	.000***
	Coca Cola	Artificial Saliva	.000***
ΔR_z	Coca Cola	Artificial Saliva	.028*

* $p < 0.05$, *** $p < 0.001$

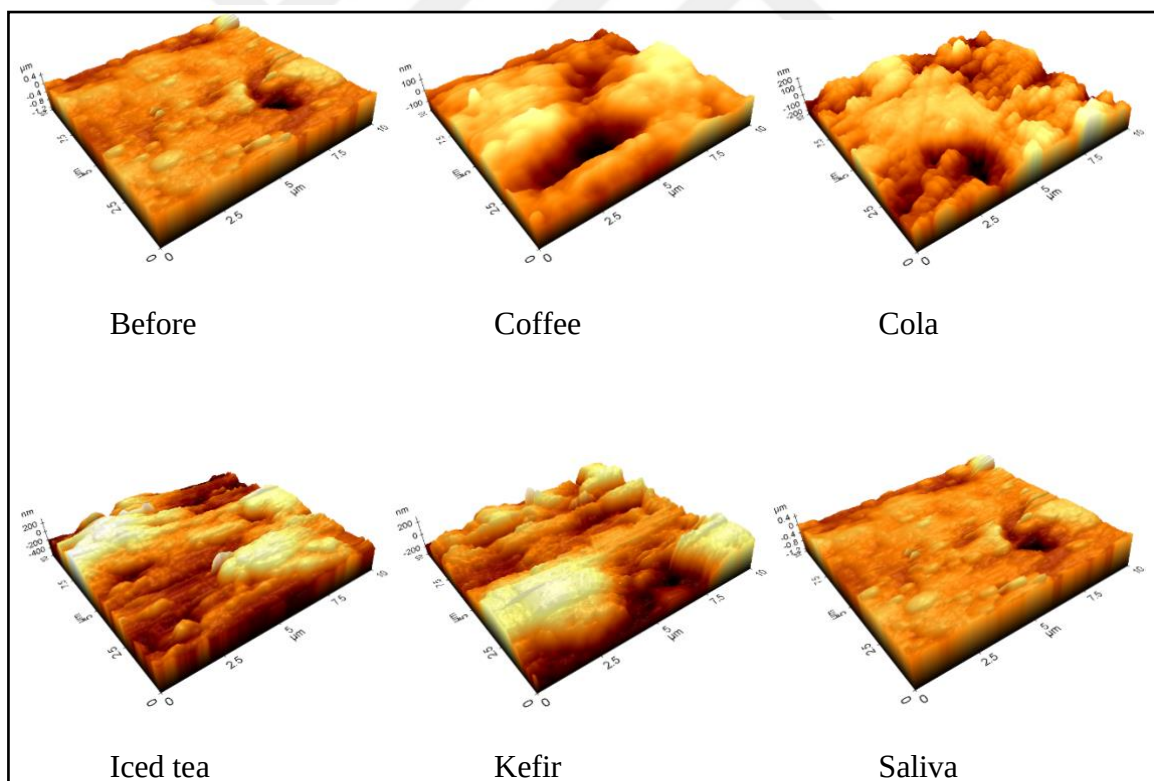


Figure 4. 1. Three-dimensional images of the SS wires before and after immersion in different soft drinks and artificial saliva

4.1.2. Surface roughness changes of NiTi wires immersed in different soft drinks

Table 4.4 shows the surface roughness values for the NiTi wire immersed in the different immersion media used in the experiment, including values before and after immersion and the difference between them. The results show that the highest increase in surface roughness values were indicated for Coca cola, followed by kefir, and iced tea at a close level. The least increase was observed for artificial saliva and coffee, respectively. T_1 values were the highest for Coca cola, followed by iced tea and artificial saliva, respectively whereas lowest T_1 values were recorded for coffee and kefir, respectively.

Table 4.5 shows the comparison of changes in surface roughness measurements of NiTi wires immersed in different soft drinks. Statistically significant differences were revealed in the changes of all three surface roughness parameters: R_a , R_q and R_z ($p < 0.001$). Table 4.6 gives subgroup comparisons by Tukey's test. Changes in R_a of the NiTi wires immersed in Coca Cola were significantly higher than that of the NiTi wires immersed in other soft drinks and the artificial saliva ($p < 0.001$). Changes in R_q of the NiTi wires immersed in Coca Cola were significantly higher than that of the NiTi wires immersed in Coffee Latte and Ice Tea ($p < 0.01$), and Kefir and artificial saliva ($p < 0.001$). Changes in R_z of the NiTi wires immersed in Coca Cola were significantly higher than that of the NiTi wires immersed in Coffee Latte and Ice Tea ($p < 0.001$), Kefir (0.05) and artificial saliva ($p < 0.01$). Figure 4.2 shows three-dimensional images of the NiTi wires before and after immersion in different liquids. Visually different surface morphologies were observed depending on the immersion media, with a significant difference in Coca Cola group.

Table 4. 4. Descriptive statistics of surface roughness values for NiTi wires immersed in different soft drinks

Immersion Media	Surface Roughness Parameter	Before (T ₀) Mean $\pm$ SD	After (T ₁) Mean $\pm$ SD	Δ (T ₁ -T ₀) Mean $\pm$ SD
Coffee Latte	Ra	29.031 $\pm$ 10.099	38.394 $\pm$ 10.830	9.363 $\pm$ 7.289
	Rq	34.900 $\pm$ 12.560	45.623 $\pm$ 11.637	10.722 $\pm$ 9.589
	Rz	111.376 $\pm$ 40.779	121.215 $\pm$ 46.684	9.840 $\pm$ 11.792
Coca Cola	Ra	24.066 $\pm$ 11.855	60.572 $\pm$ 26.662	36.506 $\pm$ 15.189
	Rq	29.846 $\pm$ 15.689	76.628 $\pm$ 37.124	46.782 $\pm$ 25.088
	Rz	96.112 $\pm$ 53.175	153.958 $\pm$ 63.594	57.846 $\pm$ 21.767
Iced Tea	Ra	32.105 $\pm$ 13.276	42.783 $\pm$ 15.415	10.678 $\pm$ 6.353
	Rq	38.550 $\pm$ 15.030	52.071 $\pm$ 21.501	13.521 $\pm$ 7.630
	Rz	118.176 $\pm$ 42.199	124.207 $\pm$ 40.531	6.031 $\pm$ 8.165
Kefir	Ra	29.780 $\pm$ 12.103	39.581 $\pm$ 16.535	9.801 $\pm$ 5.705
	Rq	37.354 $\pm$ 14.848	45.617 $\pm$ 16.572	8.263 $\pm$ 3.782
	Rz	92.151 $\pm$ 43.618	121.467 $\pm$ 40.602	29.316 $\pm$ 23.270
Artificial Saliva	Ra	32.765 $\pm$ 11.011	41.384 $\pm$ 13.779	8.619 $\pm$ 5.163
	Rq	38.758 $\pm$ 11.929	48.796 $\pm$ 16.349	10.038 $\pm$ 7.401
	Rz	112.525 $\pm$ 32.789	125.539 $\pm$ 25.353	13.015 $\pm$ 8.887

Table 4. 5. Comparison of the changes in surface roughness values of NiTi wires immersed in different soft drinks by ANOVA test

NiTi wire	Coffee Latte Mean $\pm$ SD	Coca Cola Mean $\pm$ SD	Iced tea Mean $\pm$ SD	Kefir Mean $\pm$ SD	Artificial saliva Mean $\pm$ SD	p value
Δ Ra	9.363 $\pm$ 7.289	36.506 $\pm$ 15.189	10.678 $\pm$ 6.353	9.801 $\pm$ 5.705	8.619 $\pm$ 5.163	.000***
Δ Rq	10.722 $\pm$ 9.589	46.782 $\pm$ 25.088	13.521 $\pm$ 7.630	8.263 $\pm$ 3.782	10.038 $\pm$ 7.401	.000***
Δ Rz	9.840 $\pm$ 11.792	57.846 $\pm$ 21.767	6.031 $\pm$ 8.165	29.316 $\pm$ 23.270	13.015 $\pm$ 8.887	.000***

***p<0.001

Table 4. 6. Results of Post-hoc (Tukey HSD) comparison test for NiTi wires

Surface Roughness Parameter	Liquid A	Liquid B	p value
ΔRa	Coca Cola	Coffee latte	.000***
	Coca Cola	Iced Tea	.000***
	Coca Cola	Kefir	.000***
	Coca Cola	Artificial Saliva	.000***
ΔRq	Coca Cola	Coffee latte	.001**
	Coca Cola	Iced Tea	.001**
	Coca Cola	Kefir	.000***
	Coca Cola	Artificial Saliva	.000***
ΔRz	Coca Cola	Coffee latte	.000***
	Coca Cola	Iced Tea	.000***
	Coca Cola	Kefir	.040*
	Coca Cola	Artificial Saliva	.001**

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

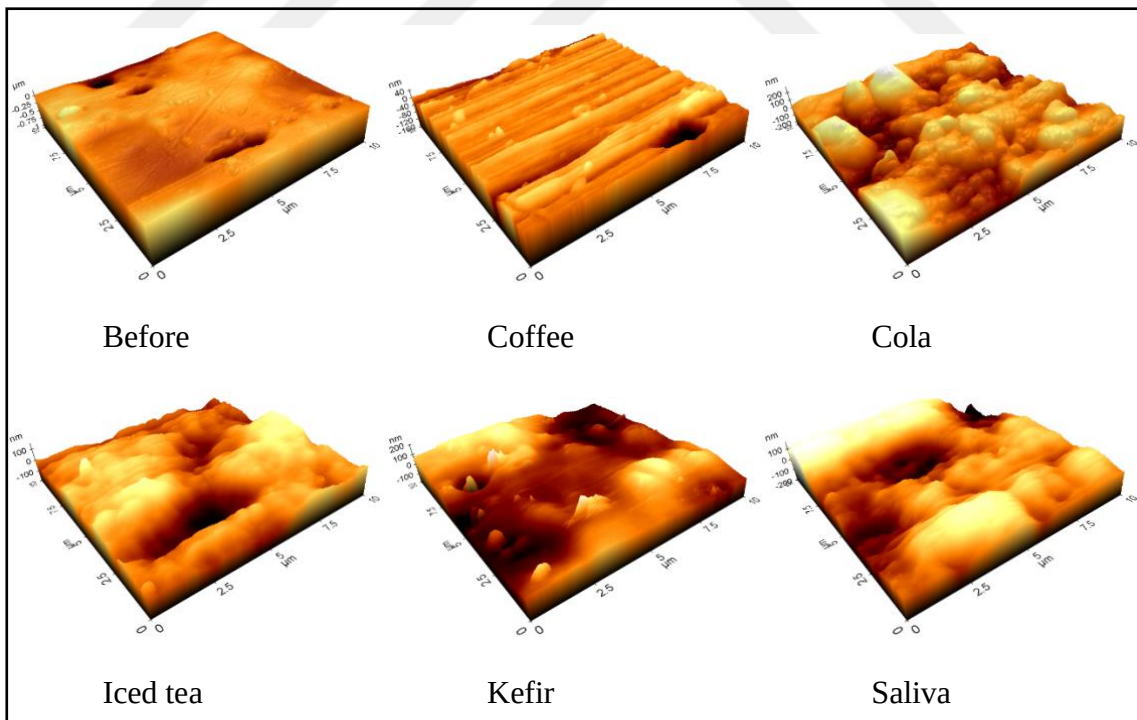


Figure 4. 2. Three-dimensional images of the NiTi wires before and after immersion in different liquids

4.1.3. Surface roughness changes of TMA wires immersed in different soft drinks

Table 4.7 shows the surface roughness values for the TMA wire immersed in the different immersion media used in the experiment, including values before and after immersion and the difference between them. The results show that the highest increase in surface roughness values were indicated for Coca cola, followed by kefir, and coffee, respectively. The least increase was observed for artificial saliva and ice tea, respectively. T_1 values were the highest for Coca cola, followed by kefir and coffee, respectively. The lowest T_1 values were recorded for ice tea and artificial saliva, respectively.

Table 4.8 shows the comparison of changes in surface roughness measurements of TMA wires immersed in different soft drinks. There were significant differences in the changes of all three surface roughness parameters: R_a , R_q and R_z ($p < 0.001$, $p < 0.05$ and $p < 0.05$, respectively.). Table 4.9 gives subgroup comparisons by Tukey's test. Changes in R_a of the TMA wires immersed in Coca Cola were significantly higher than that of the TMA wires immersed in other soft drinks and the artificial saliva ($p < 0.01$). Changes in R_q of the TMA wires immersed in Coca Cola were significantly higher than that of the TMA wires immersed in Coffee Latte and Ice Tea ($p < 0.05$). Changes in R_z of the TMA wires immersed in Coca Cola were significantly higher than that of the TMA wires immersed in artificial saliva ($p < 0.05$). Figure 4.3 shows three-dimensional images of the TMA wires before and after immersion in different liquids. Visually different surface morphologies were observed depending on the immersion media, with a significant difference in Coca Cola group.

Table 4. 7. Descriptive statistics of surface roughness values for TMA wires immersed in different soft drinks

Immersion Media	Surface Roughness Parameter	Before (T ₀) Mean ± SD	After (T ₁) Mean ± SD	Δ (T ₁ -T ₀) Mean ± SD
Coffee Latte	Ra,	45.719 ± 12.649	49.718 ± 12.651	3.999 ± 2.177
	Rq	54.625 ± 15.005	59.526 ± 16.605	4.901 ± 3.045
	Rz	155.256 ± 42.301	194.637 ± 55.229	39.382 ± 23.261
Coca Cola	Ra	50.433 ± 12.158	65.058 ± 11.994	14.625 ± 5.946
	Rq	61.820 ± 13.021	76.477 ± 16.559	14.657 ± 8.664
	Rz	159.520 ± 33.461	209.849 ± 34.545	50.329 ± 22.911
Iced Tea	Ra	48.211 ± 11.424	52.248 ± 11.500	4.036 ± 2.865
	Rq	57.080 ± 10.401	62.212 ± 12.448	5.132 ± 3.295
	Rz	150.858 ± 33.127	173.836 ± 30.074	22.978 ± 11.239
Kefir	Ra	50.808 ± 10.099	56.667 ± 12.356	5.858 ± 4.072
	Rq	60.087 ± 11.381	71.000 ± 14.846	10.914 ± 5.905
	Rz	166.018 ± 27.743	207.333 ± 44.925	41.316 ± 22.697
Artificial Saliva	Ra	55.796 ± 10.502	58.418 ± 9.099	2.622 ± 2.196
	Rq	66.662 ± 11.964	73.035 ± 13.551	6.373 ± 2.645
	Rz	175.486 ± 15.579	192.150 ± 18.747	16.664 ± 13.083

Table 4. 8. Comparison of the changes in surface roughness values of TMA wires immersed in different soft drinks by ANOVA test

TMA wire	Coffee Latte Mean ± SD	Coca Cola Mean ± SD	Iced tea Mean ± SD	Kefir Mean ± SD	Artificial saliva Mean ± SD	p value
ΔRa	3.999 ± 2.177	14.625 ± 5.946	4.036 ± 2.865	5.858 ± 4.072	2.622 ± 2.196	.000***
ΔRq	4.901 ± 3.045	14.657 ± 8.664	5.132 ± 3.295	10.914 ± 5.905	6.373 ± 2.645	.013*
ΔRz	39.382 ± 23.261	50.329 ± 22.911	22.978 ± 11.239	41.316 ± 22.697	16.664 ± 13.083	.034*

*p<0.05, ***p<0.001

Table 4. 9. Results of Post-hoc (Tukey HSD) comparison test for TMA wires

Surface Roughness Parameter	Liquid A	Liquid B	p value
ΔRa	Coca Cola	Coffee latte	.000***
	Coca Cola	Iced Tea	.000***
	Coca Cola	Kefir	.003**
	Coca Cola	Artificial Saliva	.000***
ΔRq	Coca Cola	Coffee latte	.026*
	Coca Cola	Iced Tea	.031*
ΔRz	Coca Cola	Artificial Saliva	.043*

*p<0.05, **p<0.01, ***p<0.001

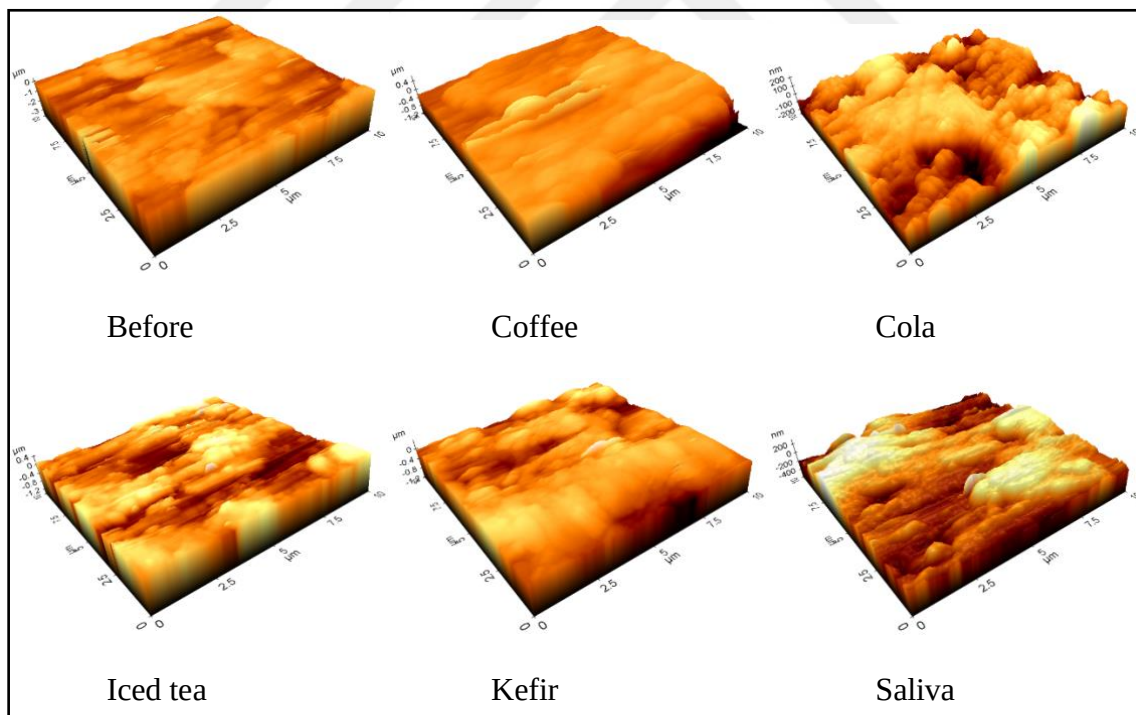


Figure 4. 3. Three-dimensional images of the TMA wires before and after immersion in different liquids

4.2 Surface Roughness Changes of Different Wires immersed in the same soft drink

4.2.1 Surface roughness changes of SS, NiTi and TMA wires immersed in Coffee Latte

Table 4.10 shows the comparison of surface roughness changes of SS, NiTi and TMA wires immersed in coffee latte. Statistically significant differences were found among changes in Ra, Rq and Rz of different wires ($p < 0.05$, $p < 0.05$ and $p < 0.01$, respectively). ΔRa and ΔRq of NiTi wires were significantly higher than that of the SS wires ($p < 0.05$) whereas ΔRz of TMA wires were significantly higher than that of SS and NiTi wires ($p < 0.01$ and $p < 0.05$, respectively) (Table 4.11).

Table 4. 10. Comparison of changes in surface roughness values of various wire types immersed in coffee latte by one way ANOVA test

Coffee Latte	SS Mean $\pm$ SD	NiTi Mean $\pm$ SD	TMA Mean $\pm$ SD	p value
ΔRa	0.632 ± 0.497	9.363 ± 7.289	3.999 ± 2.177	.012*
ΔRq	0.853 ± 0.575	10.722 ± 9.589	4.901 ± 3.045	.032*
ΔRz	3.106 ± 1.421	9.840 ± 11.792	39.382 ± 23.261	.002**

* $p < 0.05$, ** $p < 0.01$

Table 4. 11. Results of Post-hoc (Tukey HSD) comparison test for different wires immersed in Coffee Latte

Surface Roughness Parameter	Wire A	Wire B	p value
ΔRa	SS	NiTi	.010*
ΔRq	SS	NiTi	.026*
ΔRz	TMA	SS	.002**
	TMA	NiTi	.011*

* $p < 0.05$, ** $p < 0.01$

4.2.2 Coca Cola

Table 4.12 shows the comparison of surface roughness changes of SS, NiTi and TMA wires immersed in Coca Cola. Statistically significant differences were found among changes in Ra, Rq and Rz of different wires ($p < 0.001$, $p < 0.01$ and $p < 0.01$, respectively). ΔRa of NiTi wires were significantly higher than ΔRa of the SS and TMA wires ($p < 0.001$ and $p < 0.01$, respectively). Similarly, ΔRq of NiTi wires were significantly higher than ΔRq of the SS and TMA wires ($p < 0.01$). ΔRz of NiTi and TMA wires were significantly higher than ΔRz of SS wires ($p < 0.01$) (Table 4.13).

Table 4. 12. Comparison of changes in surface roughness values of various wire types immersed in Coca Cola by one way ANOVA test

Cola	SS Mean $\pm$ SD	NiTi Mean $\pm$ SD	TMA Mean $\pm$ SD	p value
ΔRa	5.035 $\pm$ 2.214	36.506 $\pm$ 15.189	14.625 $\pm$ 5.946	.000***
ΔRq	5.213 $\pm$ 2.201	46.782 $\pm$ 25.088	14.657 $\pm$ 8.664	.001**
ΔRz	8.801 $\pm$ 6.588	57.846 $\pm$ 21.767	50.329 $\pm$ 22.911	.001**

** $p < 0.01$, *** $p < 0.001$

Table 4. 13. Results of Post-hoc (Tukey HSD) comparison test for different wires immersed in Coca Cola

Surface Roughness Parameter	Wire A	Wire B	p value
Ra	NiTi	SS	.000***
	NiTi	TMA	.003**
Rq	NiTi	SS	.001**
	NiTi	TMA	.007**
Rz	NiTi	SS	.001**
	TMA	SS	.004**

** $p < 0.01$, *** $p < 0.001$

4.2.3 Iced tea

Table 4.14 shows the comparison of surface roughness changes of SS, NiTi and TMA wires immersed in Iced tea. Statistically significant differences were found among changes in Ra, Rq and Rz of different wires ($p < 0.01$, $p < 0.01$ and $p < 0.01$, respectively). ΔRa and ΔRq of NiTi wires were significantly higher than that of the SS and TMA wires ($p < 0.05$, $p < 0.01$) whereas ΔRz of TMA wires were significantly higher than that of SS and NiTi wires ($p < 0.01$ and $p < 0.05$, respectively) (Table 4.15)

Table 4. 14. Comparison of changes in surface roughness values of various wire types immersed in iced tea by one-way ANOVA test

Iced tea	SS Mean $\pm$ SD	NiTi Mean $\pm$ SD	TMA Mean $\pm$ SD	p value
ΔRa	1.089 ± 0.355	10.678 ± 6.353	4.036 ± 3.865	.003**
ΔRq	1.376 ± 0.442	13.521 ± 7.630	5.132 ± 3.295	.002**
ΔRz	2.934 ± 2.243	6.031 ± 8.165	22.978 ± 11.239	.001**

** $p < 0.01$

Table 4. 15. Results of Post-hoc (Tukey HSD) comparison test for different wires immersed in Iced tea

Surface Roughness Parameter	Wire A	Wire B	P value
ΔRa	NiTi	SS	.002**
	NiTi	TMA	.030*
ΔRq	NiTi	SS	.001**
	NiTi	TMA	.022*
ΔRz	TMA	SS	.002**
	TMA	NiTi	.007**

* $p < 0.05$, ** $p < 0.01$

4.2.4 Kefir

Table 4.16 shows the comparison of surface roughness changes of SS, NiTi and TMA wires immersed in Kefir. Statistically significant differences were found among changes in Ra, Rq and Rz of different wires ($p < 0.01$, $p < 0.01$ and $p < 0.05$, respectively). ΔRa of SS wires were significantly higher than ΔRa of the NiTi wires ($p < 0.01$). Similarly, ΔRq of SS wires were significantly higher than ΔRq of the NiTi and TMA wires ($p < 0.05$ and $p < 0.01$, respectively). ΔRz of SS wires were significantly higher than ΔRz of TMA wires ($p < 0.05$) (Table 4.17).

Table 4. 16. Comparison of changes in surface roughness values of various wire types immersed in Kefir by one way ANOVA test

Kefir	SS Mean $\pm$ SD	NiTi Mean $\pm$ SD	TMA Mean $\pm$ SD	p value
ΔRa	0.849 ± 0.559	9.801 ± 5.705	5.858 ± 4.072	.006**
ΔRq	1.680 ± 1.153	8.263 ± 3.782	10.914 ± 5.905	.004**
ΔRz	4.112 ± 3.721	29.316 ± 23.670	41.316 ± 22.697	.012*

* $p < 0.05$, ** $p < 0.01$

Table 4. 17. Results of Post-hoc (Tukey HSD) comparison test for different wires immersed in Kefir

Surface Roughness Parameter	Wire A	Wire B	P value
ΔRa	SS	NiTi	.004**
ΔRq	SS	NiTi	.035*
	SS	TMA	.004**
ΔRz	SS	TMA	.011*

* $p < 0.05$, ** $p < 0.01$

4.2.5 Artificial saliva

Table 4.18 shows the comparison of surface roughness changes of SS, NiTi and TMA wires immersed in Artificial Saliva. Statistically significant differences were found among changes in Ra, Rq and Rz of different wires ($p < 0.01$, $p < 0.05$ and $p < 0.05$, respectively). ΔRa and ΔRq of NiTi wires were significantly higher than that of the SS and TMA wires ($p < 0.01$ and $p < 0.05$, respectively) whereas ΔRz of TMA wires were significantly higher than that of SS wires ($p < 0.05$) (Table 4.19)

Table 4. 18. Comparison of changes in surface roughness values of various wire types immersed in Artificial Saliva by one way ANOVA test

Artificial Saliva	SS Mean $\pm$ SD	NiTi Mean $\pm$ SD	TMA Mean $\pm$ SD	p value
ΔRa	0.386 ± 0.251	8.619 ± 5.163	2.622 ± 2.196	.002**
ΔRq	0.698 ± 0.666	10.038 ± 7.401	6.373 ± 2.645	.010*
ΔRz	2.126 ± 1.171	13.015 ± 8.887	16.664 ± 13.083	.038*

* $p < 0.05$, ** $p < 0.01$

Table 4. 19. Results of Post-hoc (Tukey HSD) comparison test for different wires immersed in Artificial Saliva

Surface Roughness Parameter	Wire A	Wire B	P value
ΔRa	NiTi	SS	.001**
	NiTi	TMA	.015*
ΔRq	NiTi	SS	.008**
ΔRz	TMA	SS	.037*

* $p < 0.05$, ** $p < 0.01$

5. DISCUSSION

5.1 Discussion of Purpose and Methods

Orthodontic wires are vital components of fixed appliances that are necessary to apply and control the light and continuous forces on teeth throughout treatment. The properties of the wire material are significant in determining the efficiency of the treatment. Therefore, archwires of different materials were developed in order to utilize their properties in orthodontics: SS, CoCr, NiTi and TMA. The easiness of the sliding movement between the wire and brackets is determined by the friction between them, which is correlated to the corrosion activity and surface roughness increase in their material. There are several factors that can affect the physical and chemical properties of the orthodontic wire, particularly for the reason that the oral cavity is exposed to different environmental changes. During eating, drinking, and speaking, orthodontic appliances are subject to mechanical impacts, temperature changes, moisture, enzymes, chemical elements, and changes in pH levels, which in turn may cause surface changes of the material and leading to corrosion, increased surface roughness and friction.

The motivation behind this research lies within the different and contradictory results found in the literature. Although there seems to be a relationship between consumed soft drinks and change in the surface topography of orthodontic wires, there are few studies in the literature evaluating the effects of different soft drinks on different orthodontic wires alloys. Furthermore, there are contradictory results between studies that tested similar drinks and wire types (99). Shahabi et al (20) tested soft drinks, along with other acidic liquids, on SS orthodontic appliances and found that the soft drink had higher impact on surface roughness than acidic liquids like vinegar and lemon juice. However, Parenti et al. (12) evaluated several soft drinks and found no impact on surface roughness by any of the tested liquids. The argument of the authors was that since a real-life exposure to soft drinks is time limited, the experiment did not expose orthodontic wires to those drinks for long periods. The same study recognizes that drinking habits vary from one person to another and concluded that the one-hour exposure is an extreme condition

(12). Other studies used a similar technique but found different results. Abalos et al. (21) followed the same one-hour immersion procedure with NiTi wires and soft drink. Nonetheless, the results indicated significant increase in surface roughness. The authors justified the 50 minutes immersion time through an average and constant use of soft drinks with the rate of one can per day for twenty-eight days. The artificial saliva immersion time of twenty-eight day is simulating the washing of the wire with saliva after drinking the soft drink (21). Moreover, the typical orthodontic treatment allows the replacement of the wire after one month of usage. Thus, the twenty-eight days cycle simulates the closet scenario to the actual wire exposure to substances that can alter its properties (101).

Other studies preferred to increase exposure time to measure the effect on surface roughness. Nanjundan and Vimala (19) used an immersion time of 24-hours, which had a significant impact on the increase of surface roughness. In our study, we aimed to investigate the effects of drinks with different pH levels on different orthodontic wire types while simulating a real-life exposure. Therefore, it was chosen to follow the one-hour drink immersion and twenty-eight days artificial saliva immersion as recommended by several studies (12) (20) (21) (101). There was no reason to increase the immersion time as performed by Nanjundan and Vimala (19), unless the effect was meant to be exaggerated, which is not one of the study objectives.

It is evident that surface roughness values are correlated the immersion time of the wires in different fluids. Stefanski, et al. (102) tested immersion SS, NiTi and TMA wires in 1% citric acid with 3.2 pH level for ten minutes, followed by immersing them in artificial saliva with 6.8 pH level for one hour. The experiment procedure had a repetitive nature, where it was repeated six times daily over five consecutive days. The surface roughness was determined through the increase in friction between the three wire types and different brackets with a friction apparatus. The authors could not obtain any significant values for the change in frictional forces of any of the wires or their combinations with bracket types. Since the relationship between surface roughness and friction forces are confirmed through several studies for different wire types (75) (76) (79), it can be suggested that the results of Stefanski et al. (102) are reflections of

procedural issues, where the immersion time was not sufficient to create enough change in the surfaces of the wires. A similar case was observed through the results of Parenti et al. (12). It needs to be pointed out that while the oral environment may experience short and repetitive exposure to dietary or chemical fluids, it will still be subjected to a long and continuous exposure to saliva. Therefore, the procedure adopted in the current research is believed to reflect a better simulation to the real oral condition.

One of the most important parameters that are used to assess performance and changes in the different types of archwires is surface roughness. Profilometry was the main method used for that purpose through scanning a selected area with a single line (40). However, the method was found inefficient as no data can be acquired from adjacent areas to the scanned one, which is attributed to the invasive nature of profilometry. The invasiveness of the profilometry method prevented researchers from acquiring additional data from the same sample, which made the results hard to be verified or confirmed. Therefore, non-invasive techniques have become more preferable in studying surface roughness, especially scanning tunnelling microscopes (103) and optical methods (104). The development of non-invasive techniques led to the abandonment of invasive techniques, such as profilometry, for surface roughness applications. However, other techniques, such as SEM, had their many drawbacks such as the lack of parameters, low accuracy and resolution, or providing a two-dimensional image only (97). On the other hand, the ease of use, lack of need for special sample treatment, accuracy of results, radiation safety, and possibility for three-dimensional imaging made AFM one of the most preferred method for surface roughness assessments (39). It is non-invasive and does not alter the nature of the sample surface (105). Furthermore, studies revealed superior results for AFM compared to other techniques. Choi, et al. (48) has confirmed through their AFM study on NiTi and SS wires that the friction force is highly affected by the surface roughness values of the wires and the brackets with strong significant correlations. SEM analysis results confirm such results but were not as reliable as AFM results. Kusy and Whitley (75) tested SS, NiTi, and TMA wires through SEM where the relationship could not be determined in several cases. The use of AFM in measuring surface roughness was proven through several studies to yield more accurate and reliable results. Facchini et al. (80) showed differences between surface roughness values of four

orthodontic wire types. In comparison studies between the surface roughness values of orthodontic wire, AFM showed high competitiveness in acquiring the necessary data and showed high reliability as shown from the findings of D'Anto et al. (39) that compared eight wires between SS, NiTi and TMA types. The reliability of AFM technique is proven for the in-vivo and in-vitro studies on orthodontic appliances (81). Thus, AFM was chosen as the method to quantitatively evaluate the surface roughness of the wires in our study.

The current study evaluated the effect of the pH level of drinks on three types of orthodontic wires manufactured by American Orthodontics (AO): stainless steel (SS), Nickel-Titanium (NiTi), and beta Titanium (TMA). The reason for selecting these wire materials is that SS, NiTi and TMA wires are generally used in different phases of any fixed orthodontic treatment.

In our study, we preferred to use four different most consumed drinks: coffee latte (Starbucks Café Latte, STARBUCKS®, Seattle, Washington, USA), Coca Cola (Coca-Cola® original, Coca-Cola Company, Atlanta, USA), Kefir (Kefir sade, ALTINKILIÇ®, İstanbul, Türkiye), and iced tea (Lipton ice tea, LIPTON®, Unilever®, London, England, UK). A fifth group is added to the experiment as a requirement for the *in vitro* study as control group, where artificial saliva is used. Most of the studies evaluating the effects of soft drinks on surface topography of the wires assessed coca cola as a low pH soft drink (ref). However, in the literature, no study has evaluated another acidic beverage, kefir, as a medium. Therefore, our study is to first to evaluate the effects of kefir with a pH of 4.3, which is a highly consumed drink in Turkey, due to its beneficial effects as a probiotic.

5.2. Discussion of Results

In our study, the analysis was carried out based on the immersion liquid and the type of wire. When the effects of the different soft drinks on SS wires were evaluated, significant differences were found in terms of surface roughness changes. It was revealed that the main difference was between Coca Cola and the rest of the immersion liquids. Coca Cola showed the highest surface roughness increases compared to kefir, iced tea, coffee, and the artificial saliva. However, the analysis showed no significant differences between the other immersion liquids. Similar to SS wires, NiTi wires immersed in

different soft drinks showed significant differences in changes of the surface topography. Again, significant differences were found between Coca Cola and the rest of the immersion liquids. Coca Cola caused a significant increase in surface roughness of NiTi wires compared to other soft drinks. For TMA wires as well, the changes in surface topography after immersion into different soft drinks significantly differed between groups. When Ra, the most common parameter for measuring surface roughness and representative of an average value of the measured highest of the surface, was evaluated, Coca Cola resulted in greater surface roughness increases for TMA wires compared to other soft drinks and artificial saliva. Meanwhile, the changes in Rq (the root mean square values calculated through measuring the different heights of the surface) of TMA wires were significant greater when immersed in Coca Cola compared to coffee and iced tea, while the changes in Rz (the difference between the highest and lowest heights at the surface) were only different between Coca Cola and artificial saliva.

It is apparent that the surface roughness increase caused by Coca Cola was significantly higher compared to the other soft drinks for all type of wires. When reading our results in conjunction with the acidity level of the immersion liquids, it is evident that the acidity of the liquids plays a vital role in increasing the surface roughness of the three wires, similar to the results of previous studies showing the relationship between increased surface roughness and lower acidity levels regardless of wire type (19) (106). Coca Cola had the lowest pH level (2.225) compared to the other drinks (pH of Iced Tea:3.059, pH of Kefir:4.254, pH of Coffee Latte: 6.655, pH of artificial saliva:7.106), which helps to explain the findings of the present study. Similar to our findings, Nanjundan and Vimla (19) also found that SS wires and brackets immersed in highly acidic beverages (pH:2.46) showed more surface irregularities and roughness followed by vinegar with a pH of 3-4 and Phos-Flur with a pH of 5-6. Despite the high corrosion resistance property of stainless-steel wires, as indicated by Oh et al. (47), the literature shows that acidic beverages and environment have significant effects on these wires. Marques et al. (41) found an increase in surface roughness values after the use of SS wires for eight weeks in the oral environment, which confirm the effect of dietary factors on this type of wires. The increase in acidity was noted as the main factor affecting the corrosive reaction in SS wires, when compared with other acidic liquids such as vinegar

and lemon juice, by Shahabi et al. (20). The change in the surface roughness simulated by the immersion liquids used in the current study might have a high potential in increasing the corrosive reaction of the wires and the frictional forces, as stated by Sherief and Abbas (92). In addition to SS wires, the effect of acidity on increasing corrosive reaction for NiTi wires was confirmed by Huang (99) and Jaber et al. (94), who showed an increase in surface roughness as acidity increased in immersion solutions. Abalos et al. (21) confirmed the increase in corrosive reaction with the increase of the acidity of immersion liquid and also recommended taking surface patterns into consideration.

On the other hand, we couldn't find any difference in the surface topography changes caused by other soft drinks with still lower pH levels (i.e., Iced Tea and Coffee Latte) when the control group was taken into consideration. Nevertheless, there could be other factors influencing the surface roughness increase of the wires, including the enzymes and chemical contents of the liquids (20). Shahabi et al. (20) found that the corrosion caused by vinegar on SS brackets was not equal to that of Coca cola although the acidity of Coca cola and vinegar were the same and equal to 2.5. Therefore, they concluded that the high intensity of corrosion seen in Coca cola could not solely be attributed to its lower pH, but also to the chemical composition of the drink. The presence of small and ample bubbles of carbon dioxide gas solved in cola, and their adhesion to different surfaces of brackets might have led to very small and abundant pointed corrosion. The gradual development and unification of these corrosion sites might cause greater surface roughness and destruction. The authors also recommended evaluating factors other than acidity of the environment, which may contribute to the corrosion and surface changes of the orthodontic materials.

Nonetheless, the results of our study contradict with the findings of a study by Shin et al. (87), where artificial saliva had the highest corrosive effect on SS wires. The high surface roughness increase in the SS wires can be originated by the corrosive chemical reaction, rather than an impact of acidity for that specific study. The contradiction extends as well to the research of Holla et al. (17), who found out that increase in surface roughness of SS, NiTi, and TMA wires were greater when exposed to artificial saliva compared to soft drinks. Apart from the acidity, it was shown that when

orthodontic appliances are exposed to the aggressive action of Cl^- or F^- ions in saliva in the oral cavity, they undergo rapid dissolution of surface oxide layer of the metal because of thermodynamical instability and releases of iron, zinc, silver, nickel, and chromium ions until equilibrium was reached or impedance occurs (57) (107). Although not as significant as the surface roughness increase in Coca Cola, the artificial saliva also caused an increase in surface roughness of the orthodontic wires evaluated in our study. In accordance with the findings in the literature, even though the acidity of the environment is neutral, the artificial saliva may lead changes in the surface topography due to the interaction between the ions of the solution and wire.

In contrast to our findings, Parenti et al. (12) did not show changes in the hardness, surface topography and chemical composition of NiTi wires immersed in five types of drinks, including Coca cola. The contradictory findings may be related to the methodological differences between the studies. In Parenti et al.'s study, the surface topography was evaluated qualitatively using SEM observations whereas we did quantitative measurements using AFM. Furthermore, although the authors couldn't reveal any difference in the chemical composition of the wire by the EDS analysis, they noted the appearance of some dark areas on the wire surfaces after immersion in Coca Cola and claimed that although this may be of little clinical significance since the Young's modulus and hardness were unaffected, this requires further investigation.

In the second part of our study, the findings were evaluated according to the wire type immersed in the same drink. In general, regardless of the immersion media, stainless steel wires appeared to show the lowest rate of change in surface roughness compared to NiTi and TMA wires. In Coca Cola, the change in surface roughness parameters of NiTi wires were significantly greater than that of TMA and SS wires except for ΔR_z . The change in R_z of NiTi and TMA wires were significantly higher than that of SS wires. In Coffee Latte and Iced Tea, the change in surface roughness of NiTi wires (ΔR_a and ΔR_q) was greater compared to SS wires and ΔR_z of TMA wires were greater than that of SS and NiTi wires. The change in surface roughness of NiTi wires (ΔR_a and ΔR_q) was greater compared to SS wires and ΔR_z of TMA wires were greater than that of SS wires when exposed to Kefir and artificial saliva.

It can be summarized as most of the tested immersion liquids have the main effect in increasing the surface roughness of TMA and NiTi wires. Coca Cola caused the highest increase in surface roughness for NiTi wires, compared to TMA and SS wires. The low impact of artificial saliva in increasing the surface roughness of SS wires contradicts the findings of Hobbelink et al. (93). Nonetheless, the authors tested several pH levels artificial saliva solutions: pH 5.6, pH 6.6, pH 7.6, which showed the increase in surface roughness with the decrease in pH level. It is worth mentioning that the acidity and alkaline levels of the tested solution ranged between low acidic to low alkaline, which also contradicts some of the findings of the current experiment, especially in the artificial saliva and coffee latte cases. Furthermore, the results of our study contradict the findings of Shin et al. (87), where artificial saliva had the highest corrosive effect on SS wires, while it had no effect on the NiTi wires.

Based on the wire type, our findings may be explained by the difference of the initial surface roughness, surface characteristics and corrosion resistance of different wires. It is known that the SS wires have smoother surfaces compared to NiTi and TMA wires (39). Higher surface roughness values were reported for TMA and NiTi wires, with contradictory findings in terms of the roughest wire (8) (76). The wire surface may play an important role in corrosion, where archwire roughness is considered to be an indicator of the tendency toward corrosion (108). Previous studies have shown that surface defects produced during the wire manufacturing process are preferential corrosion areas (16) (109) (110). Abalos et al. (21) found that there was an increase in surface defects and roughness of the NiTi wires when exposed to soft drinks with low pH. They found a relationship between the surface pattern and the extent of the corrosion. If the surface of the wire contains cracks and scratches, these defects are responsible for the increase in total surface defects, producing an increase in the discontinuities in the archwire surface. On the other hand, if the surface is smooth there is no sign of corrosion. Therefore, they concluded that surface defects could play an important role in archwires corrosion by carbonated drinks. In the light of these studies, we may relate our findings to the likelihood of more corrosion of the roughest surfaces of NiTi and TMA wires when exposed to soft drinks, leading to significantly pronounced changes of the surface roughness of these wires compared to SS wires.

Coated wires and those of different manufacturers have different initial roughness values prior the exposure to immersion liquids. In this study, American Orthodontic wires without coating were used. Thus, the results found in this research should not be generalized to these cases. Studies on the NiTi wires for surface roughness by Alsanea and Al Shehri (78) and Mousavi et al. (79) were mainly focused on the effect of coating on the wire's surface roughness values, which contradicts with the uncoated NiTi wire types used in the current study. NiTi wires experienced moderate increase in surface roughness in most of the soft drinks and low increase in artificial saliva. The stand-alone wire without any protective coating performed relatively well under acidic and dietary changes in the oral cavity, which is the main contradiction with the aforementioned studies. Therefore, the manufacturing process and protective measures against corrosion may change the behavior of the orthodontic wires when exposed to beverages.

TMA wires have been shown to have the roughest surface among the wires (39) (76). In our study, TMA wires showed low resistance to surface roughness changes compared to SS wire. This contradicts with the findings of Pulikkottil et al. (111), who found that TMA wires had the highest resistance to moderate acidity levels simulated by mixing artificial saliva with 0.5% acidic fluoride although they showed that TMA wires had the highest surface roughness at the beginning and underwent pitting corrosion during the experiment. They concluded that the chemical composition of the wire is the primary factor influencing the corrosion resistance and surface roughness is only secondary. TMA wires form a passive film of TiO_2 and their increased Ti content may lead to better corrosion resistance. However, in our study, TMA wires exhibited more surface roughness changes compared to SS wires. It is well known that chromium element in SS alloy can form a thin and adherent Cr_2O_3 -based protective film which provides the corrosion resistance (86).

Based on our findings, the clinical implication of our study is to avoid or at least restrict consuming highly acidic and effervescent beverages (particularly Coca Cola), due to their hazardous effects on the wires, when undergoing fixed orthodontic treatment using NiTi and TMA wires.

The main limitation of our study was its in vitro nature. As with any in vitro investigation, it was virtually impossible to design a model that mimicked the real-life situation. Although we tried to mimic the oral environment by following the specific test conditions (incubation in the artificial saliva for 28 days at 37 °C, immersion in the beverages for 60 minutes per day), it is evident that in the oral cavity other conditions including galvanic corrosion because of the contact of non-homogenous archwires and brackets, or crevice corrosion because of the alteration in oxygen concentration in different areas (because of debris accumulation), or contacts created by occlusal forces or foods and other uncontrollable conditions might be the dominant factors which may further affect the surface topography of the orthodontic wires. Furthermore, in real life, the soft drinks probably contact only shortly with the wire surface before it is swallowed and washed away and diluted by saliva. In addition, the characteristics of the saliva (composition, pH, secretion flow, rate and volume), as well as the drinking habits (frequency of consumption or drinking techniques) vary from one individual to another (112). Therefore, we recommend conducting in vivo studies in this field containing controversies. Lastly, as found by Bourauel et al. (69) the manufacturing plays an important role in the surface topography of the NiTi wires, showing an extreme variability of the surface roughness of NiTi wires of different brands. Therefore, one should not generalize the findings of our study in terms of wires fabricated by different manufacturers .

6. CONCLUSION

Within the limitations of this in vitro study, following conclusions were drawn:

- 1- More acidic soft drinks (Coca Cola) caused more surface roughness changes on the archwires than other soft drinks (Kefir, Coffee Latte and Ice tea) and artificial saliva.
- 2- In general, NiTi and TMA wires exhibited more increase in surface roughness compared to SS wires when immersed in soft drinks with different pH levels.



7. REFERENCES

1. Huang ZM, Gopal R, Fujihara K, Ramakrishna S, Loh P, Foong W, et al. Fabrication of a new composite orthodontic archwire and validation by a bridging micromechanics model. *Biomaterials*. 2003; 24: p. 2941-2953.
2. Proffit WR, Fields HW, Sarver DM. *Contemporary Orthodontics*. 6th ed. St. Louis, Mo: Mosby Elsevier; 2007.
3. O'Brien WJ. *Dental Materials and Their Selection*. 3rd ed. Chicago: Quintessence Pub. Co.; 2002.
4. Van Leeuwen EJ, Maltha JC, Kuijpers-Jagtman AM. Tooth movement with light continuous and discontinuous force in beagle dogs. *European Journal of Oral Sciences*. 1999; 107: p. 468-474.
5. Kusy RP. A review of contemporary archwires: their properties and characteristics. *The Angle Orthodontist*. 1997; 67: p. 197-207.
6. Kusy RP, Whitley JQ. Friction between different wire-bracket configurations and materials. *Seminars in Orthodontics*. 1997 September; 3(3): p. 166-177.
7. Wichelhaus A, Geserick M, Hibst R, Sander FG. The effect of surface treatment and clinical use on friction in NiTi orthodontic wires. *Dental Materials*. 2005 October; 21(10): p. 938-945.
8. Kusy RP, Whitley JQ, Mayhew MJ, Buckthal JE. Surface roughness of orthodontic archwires via laser spectroscopy. *Angle Orthodontist*. 1988 January; 58(1): p. 33-45.
9. Kedici SP, Akşüt AA, Arslan MAK, Bayramoğlu G, Gökdemir K. Corrosion behaviour of dental metals and alloys in different media. *Journal of Oral Rehabilitation*. 1998; 25: p. 800-808.
10. Eygen IV, Vannet BV, Wehrbein H. Influence of a soft drink with low pH on enamel surfaces: an in vitro study. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2005 September; 128(3): p. 372-377.
11. Reddy A, Norris DF, Momeni SS, Waldo B, Ruby JD. The pH of beverages in the United States. *The Journal of the American Dental Association*. 2016 April; 147(4): p. 255-263.
12. Parenti SI, Guicciardi S, Melandri C, Sprio S, Lafratta E, Tampieri A, et al. Effect of soft drinks on the physical and chemical features of nickel-titanium-based orthodontic wires. *Acta Odontologica Scandinavica*. 2012 January; 70(1): p. 49-55.

13. Yip HHY, Wong RWK, Hang U. Complications of orthodontic treatment: are soft drinks a risk factor? *World Journal of Orthodontics*. 2009; 10: p. 33-40.
14. McCabe JF. *Applied Dental Materials*. 7th ed. London: Butler & Tanner Ltd; 1990.
15. Tselepis M, Brockhurst P, West VC. The dynamic frictional resistance between orthodontic brackets and arch wires. *American Journal of Orthodontics and Dentofacial Orthopedics*. 1994 August; 106(2): p. 131-138.
16. Huang HH, Chiu YH, Lee TH, Wu SC, Yang HW, Su KH, et al. Ion release from NiTi orthodontic wires in artificial saliva with various acidities. *Biomaterials*. 2003 September; 24(20): p. 3585-3592.
17. Holla AK, Kumar S, Mogra S, Shetty SV, Urala A, Prasad MB. Evaluation of the Breakdown Potential of Orthodontic Archwires in Acidic Soft Drinks. *The Journal of Indian Orthodontic Society*. 2012 October-December; 46(4): p. 238-244.
18. Sajadi SS, Eslami Amirabadi G, Sajadi S. Effects of two soft drinks on shear bond strength and adhesive remnant index of orthodontic metal brackets. *Journal of Dentistry (Tehran, Iran)*. 2014 July; 11(4): p. 389-397.
19. Nanjundan K, Vimala G. Evaluation of frictional resistance and surface characteristics after immersion of orthodontic brackets and wire in different chemical solutions: A comparative in-vitro study. *Indian Journal of Dental Research*. 2016 September-October; 27(5): p. 513-520.
20. Shahabi M, Jahanbin A, Esmaily H, Sharifi H, Salari S. Comparison of Some Dietary Habits on Corrosion Behavior of Stainless Steel Brackets: An invitro Study. *The Journal of Clinical Pediatric Dentistry*. 2011; 35(4): p. 429-432.
21. Abalos C, Paul A, Mendoza A, Solano E, Palazon C, Gil FJ. Influence of Soft Drinks with Low pH on Different Ni-Ti Orthodontic Archwire Surface Patterns. *Journal of Materials Engineering and Performance*. 2013 March; 22(3): p. 759-766.
22. Houston WJB, Stephens CD, Tulley WJ. *A textbook of orthodontics* Boston: Butterworth-Heinemann; 1992.
23. O'Brien C, Benson PE, Marshman Z. Evaluation of a quality of life measure for children with malocclusion. *Journal of Orthodontics*. 2007 September; 34(3): p. 185-193.
24. Nikolai RJ. Orthodontic wire: a continuing evolution. *Seminars in Orthodontics*. 1997 September; 3(3): p. 157-165.

25. Proffit W, Fields H, Sarver D. Contemporary orthodontics St. Louis: Elsevier,/ Mosby; 2013.
26. Holberg C, Holberg N, Rudzki-Janson I. Sutural strain in orthopaedic headgear therapy: A finite element analysis. American Journal of Orthodontics and Dentofacial Orthopedics. 2008 July; 134(1): p. 53-59.
27. Leach HA, Ireland AJ, Whaites EJ. Radiographic diagnosis of root resorption in relation to orthodontics. British Dental Journal. 2001 January; 190: p. 16-22.
28. Rudolph DJ, Willes PMG, Sameshima GT. A finite element model of apical force distribution from orthodontic tooth movement. The Angle Orthodontist. 2001 April; 71(2): p. 127-131.
29. Graber L, vanarsdall R, Vig K, Huang G. Orthodontics: Current Principles and Techniques. 6th ed. St. Louis: Mosby Publishing; 2016.
30. Surani SS, Powar SN, Ramugade MM. Friction: An Indispensable Aspect of Biomechanics in Orthodontics - A Review. Saudi Journal of Oral and Dental Research. 2018 October;; p. 323-330.
31. Reicheneder CA, Baumert U, Gedrange T, Proff P, Faltermeier A, Muessig D. Frictional properties of aesthetic brackets. European Journal of Orthodontics. 2007 August; 29(4): p. 359-365.
32. Eliades T, Brantley WA. Orthodontic Materials: Scientific and Clinical Aspects: Thieme; 2001.
33. Khalid SA, Kumar V, Jayaram P. The comparison of frictional resistance in titanium, self-ligating stainless steel, and stainless steel brackets using stainless steel and TMA archwires: An in vitro study. Journal of Pharmacy & BioAllied Sciences. 2012 August; 4(Suppl 2): p. S203-S211.
34. Jian F, Lai W, Furness S, McIntyre GT, Millett DT, Hickman J, et al. Initial arch wires for tooth alignment during orthodontic treatment with fixed appliances. The Cochrane Database of Systematic Reviews. 2013 April;(4).
35. Nucera R, Gatto E, Borsellino C, Aceto P, Fabiano F, Matarese G, et al. Influence of Bracket-Slot Design on the Forces Released by Superelastic Nickel-Titanium Alignment Wires in Different Deflection Configurations. The Angle Orthodontist. 2014 May; 84(3): p. 541-547.
36. Kapila S, Sachdeva R. Mechanical properties and clinical applications of orthodontic wires. American Journal of Orthodontics and Dentofacial Orthopedics. 1989 August; 96(2): p. 100-109.

37. Brantly WA. Orthodontic wires. In Brantly WA, Eliades T, editors. Orthodontic materials: scientific and clinical aspects. Stuttgart: Thieme; 2001. p. 91-99.
38. Drake SR, Wayne DM, Powers JMAK. Mechanical properties of orthodontic wires in tension, bending and torsion. American Journal of Orthodontics. 1982 September; 82(3): p. 206-210.
39. D'Anto V, Rongo R, Ametrano G, Spagnuolo G, Manzo P, Martina R, et al. Evaluation of Surface Roughness of Orthodontic Wires by Means of Atomic Force Microscopy. The Angle Orthodontist. 2012 September; 82(5): p. 922-928.
40. Bourauel C, Fries T, Drescher D, Plietsch R. Surface roughness of orthodontic wires via atomic force microscopy, laser specular reflectance, and profilometry. European Journal of Orthodontics. 1998 February; 20(1): p. 79-92.
41. Marques ISV, Araujo AM, Gurgel JA, Normando D. Debris, Roughness and Friction of Stainless Steel Archwires Following Clinical Use. Angle Orthodontist. 2010; 80(3): p. 521-527.
42. House K, Sernetz F, Dymock D, Sandy JR, Ireland AJ. Corrosion of orthodontic appliances—should we care? The American Journal of Orthodontics and Dentofacial Orthopedics. 2008 April; 133(4): p. 584-592.
43. Kolokitha OEK, Papadopoulos MA. Prevalence of nickel hypersensitivity in orthodontic patients: a meta-analysis. The American Journal of Orthodontics and Dentofacial Orthopedics. 2008 December; 134(6): p. 722.e1-722.e12; discussion 722-723.
44. Kapila S, Angolkar PV, Duncanson MG, Nanda RS. Evaluation of friction between edgewise stainless steel brackets and orthodontic wires of four alloys. American Journal of Orthodontics and Dentofacial Orthopedics. 1990 August; 98(2): p. 117-126.
45. Redlich M, Katz A, Rapoport L, Wagner HD, Feldman Y, Tenne R. Improved orthodontic stainless steel wires coated with inorganicfullerene-like nanoparticles of WS(2) impregnated in electroless nickel-phosphorous film. Dental Materials. 2008 December; 24(12): p. 1640-1646.
46. Pelsue BM, Zinelis S, Bradley TG, Berzins DW, Eliades T, Eliades G. Structure, composition, and mechanical properties of Australianorthodontic wires. The Angle orthodontist. 2009 january; 79(1): p. 97-101.
47. Oh K, Kim Y, Park Y, Kim K. Properties of super stainless steels for orthodontic applications. Journa of Biomedical Materials Research - Part B: Applied Biomaterials. 2004 May; 69(2): p. 183-194.

48. Choi S, Hwang EY, Park HK, park YG. Correlation Between Frictional Force and Surface Roughness of Orthodontic Archwires. *Scanning*. 2015 November-December; 37(6): p. 399-405.
49. Stannard JG, Gau JM, Hanna MA. Comparative friction of orthodontic wires under dry and wet conditions. *American Journal of Orthodontics*. 1986 June; 89(6): p. 485-491.
50. Angolkar PV, Kapila S, Duncanson MG, Nanda RS. Evaluation of friction between ceramic brackets and orthodontic wires for four alloys. *the American Journal of Orthodontics and Dentofacial Orthopedics*. 1990 December; 98(6): p. 499-506.
51. Ingram SB, Gipe DP, Smith RJ. Comparative range of orthodontic wires. *American Journal of Orthodontics*. 1986 October; 90(4): p. 296-307.
52. Alobeid A, Hasan M, Al-Suleiman M, El-Bialy T. Mechanical properties of cobalt-chromium wires compared to stainless steel and β -titanium wires. *Journal of Orthodontic Science*. 2014 October-December; 3(4): p. 137-141.
53. Burstone CJ, Goldberg AJ. Beta titanium: a new orthodontic alloy. *American Journal of Orthodontics*. 1980 February; 77(2): p. 121-132.
54. Verstrynge A, Van Humbeeck J, Willemsc J. In-vitro evaluation of the material characteristics of stainless steel and beta-titaniumorthodontic wires. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2006 October; 130(4): p. 460-470.
55. Juvvadi SR, Kailasam VpS, Chitharanjan AB. Physical, mechanical, and flexural properties of 3 orthodontic wires: aninvitro study. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2010 November; 138(5): p. 623-630.
56. Krishnan V, Kumar KJ. Weld characteristics of orthodontic arch wire materials. *The Angle Orthodontist*. 2004 August; 74(4): p. 533-538.
57. Kim H, Johnson JW. Corrosion of stainless steel, nickel-titanium, coated nickel-titanium, and titanium orthodontic wires. *The Angle Orthodontist*. 1999 February; 69(1): p. 39-44.
58. Walker MP, Ries D, Kula K, Ellis M, Fricke B. Mechanical properties and surface characterization of beta titanium and stainless steelorthodontic wire following topical fluoride treatment. *The Angle Orthodontist*. 2007 March; 77(2): p. 342-348.
59. Ogawa T, Yokoyama K, Asaoka K, Sakai J. Hydrogen absorption behavior of beta titanium alloy in acid fluoride solutions. *Biomaterials*. 2004 May; 25(12): p. 2419-2425.

60. Cash A, Curtis R, Garrigia-Majo D, McDonald F. A comparative study of the static and kinetic frictional resistance of titanium molybdenum alloy archwires in stainless steel brackets. *European Journal of Orthodontics*. 2004 February; 26(1): p. 105-111.
61. Gioka C, Eliades T. Superelasticity of nickel-titanium orthodontic archwires: metallurgical structure and clinical importance. *Hellenic Orthodontic Review*. 2002; 5: p. 111-127.
62. Fernandes DJ, Peres RV, Mendes AM, Elias CN. Understanding the Shape-Memory Alloys Used in Orthodontics. *ISRN Dentistry*. 2011 October; 132408.
63. Andreasen G, Hileman H, Krell D. Stiffness changes in thermodynamic nitinol with increasing temperature. *The Angle Orthodontist*. 1985 April; 55(2): p. 120-126.
64. Meling TR, Odegaard J. The effect of short-term temperature changes on superelastic nickel-titanium archwires activated in orthodontic bending. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2001 March; 119(3): p. 263-273.
65. Bradley TG, Brantly WA, Culberston B. Differential scanning calorimetry (DSC) analyses of superelastic and nonsuperelasticity nickel-titanium orthodontic wires. *The American Journal of Orthodontics and Dentofacial Orthopedics*. 1996 June; 109(6): p. 589-597.
66. Miura F, Mogi M, Ohura Y, Hamanaka H. The super-elastic property of the Japanese NiTi alloy wire for use in orthodontics. *American Journal of Orthodontics and Dentofacial Orthopedics*. 1986 July; 90(1): p. 1-10.
67. Wilkinson PD, Dysart PS, Hood JA, Herbison GP. Load-deflection characteristics of superelastic nickel-titanium orthodontic wires. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2007 November; 77(6): p. 991-998.
68. Burstone CJ, Qin B, Morton JY. Chinese NiTi wire: A new orthodontic alloy. *American Journal of Orthodontics*. 1985 June; 87(6): p. 445-452.
69. Bourauel C, Scharold W, Jager A, Eliades T. Fatigue failure of as received and retrieved NiTi orthodontic archwires. *Dental Materials*. 2008 August; 24(8): p. 1095-1101.
70. Faccioni F, Franceschetti P, Cerpelloni M, Fracasso ME. In vivo study on metal release from fixed orthodontic appliances and DNA damage in oral mucosa cells. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2003 December; 124(6): p. 687-693.

71. Rapiejko C, Fouvry S, Grosgeat B, Wendler B. A representative ex-situ fretting wear investigation of orthodontic arch-wire/bracket contacts. *Wear*. 2009 March; 266(7-8): p. 850-858.
72. Baccetti T, Franchi L, Camporesi M, Defraia E, Barbato E. Forces produced by different nonconventional bracket or ligature systems during alignment of apically displaced teeth. *The Angle Orthodontist*. 2009 May; 79(3): p. 533-539.
73. Staffolani N, Damiani F, Lilli C, Guerra M, Staffolani NJ, Belcastro S, et al. Ion release from orthodontic appliances. *Journal of Dentistry*. 1999 August; 27(6): p. 449-454.
74. Amini F, Jafari A, Amini P, Sepasi S. Metal ion release from fixed orthodontic appliances--an in vivo study. *European Journal of Orthodontics*. 2012 February; 34(1): p. 126-130.
75. Kusy RP, Whitley JQ. Effects of Surface Roughness on the Coefficients of Friction in Model Orthodontic Systems. *Journal of Biomechanics*. 1990; 23(9): p. 913-925.
76. Doshi UH, Bhad-Patil WA. Static frictional force and surface roughness of various bracket and wire combinations. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2011 January; 139(1): p. 74-79.
77. Amini F, Rakhshan V, Pousti M, Rahimi H, Shariati M, Aghamohamadi B. Variations in Surface Roughness of Seven Orthodontic Archwires: An SEM-profilometry Study. *Korean Journal of Orthodontics*. 2012 June; 42(3): p. 129-137.
78. Alsanea JA, Al Shehri H. Evaluation of Nanomechanical Properties, Surface Roughness, and Color Stability of Esthetic Nickel-Titanium Orthodontic Archwires. *Journal of International Society of Prevention & Community Dentistry*. 2019 January-February; 9(1): p. 33-39.
79. Mousavi SM, Shamohammadi M, Rastegar Z, Skini M, Rakhshan V. Effect of Esthetic Coating on Surface Roughness of Orthodontic Archwires. *International Orthodontics*. 2017 September; 15(3): p. 312-321.
80. Facchini FM, Filho MV, Vedovello SA, Cotrim FA, Cotrim-Ferreira A, Tubel CA. Wire Roughness Assessment of 0.016" × 0.022" the Technique Lingual Orthodontics. *The Journal of Contemporary Dental Practice*. 2017 April; 18(4): p. 295-299.
81. Lee GJ, Park KH, Park YG, Park HK. A Quantitative AFM Analysis of Nano-Scale Surface Roughness in Various Orthodontic Brackets. *Micron*. 2010 October; 41(7): p. 775-782.

82. Hensten-Pattersen A, Jacobsen N, Grimsdottir MR. Allergic reactions and safety concerns. In Brantly WA, Eliades T, editors. *Orthodontic Materials: Scientific and Clinical Aspects*. 1st ed. New York: Thieme; 2001. p. 287-289.
83. Eliades T. Orthodontic Materials Research and Applications: Part 2. Current Status and Projected Future Developments in Materials and Biocompatibility. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2007 February; 131(2): p. 253-262.
84. Messer RL, Bishop S, Lucas LC. Effects of Metallic Ion Toxicity on Human Gingival Fibroblasts Morphology. *Biomaterials*. 1999 September; 20(18): p. 1647-1657.
85. Lindsten R, Kurol J. Orthodontic Appliances in Relation to Nickel Hypersensitivity. A Review. *Journal of Orofacial Orthopedics*. 1997; 58(2): p. 100-108.
86. Lin MC, Lin SC, H LT, Huang HH. Surface analysis and corrosion resistance of different stainless steel orthodontic brackets in artificial saliva. *The Angle Orthodontist*. 2006 March; 76(2): p. 322-329.
87. Shin JS, Oh KT, Hwang CJ. In vitro surface corrosion of stainless steel and NiTi orthodontic appliances. *Australasian Orthodontic Journal*. 2003 April; 19(1): p. 13-18.
88. de Araujo CM, Johann ACBR, Camargo ES, Tanaka OM. The effects of binge-pattern alcohol consumption on orthodontic tooth movement. *Dental Press Journal of Orthodontics*. 2014 November-December; 19(6): p. 93-98.
89. Pop SI, Dudescu M, Merie VV, Pacurar M, Bratu CD. Evaluation of the Mechanical Properties and Surface Topography of As-Received, Immersed and As-Retrieved Orthodontic Archwires. *Clujul Medical*. 2017 July; 90(3): p. 313-326.
90. Benson PE, Razi RM, Al-Bloushi RJ. The Effect of Chewing Gum on the Impact, Pain and Breakages Associated With Fixed Orthodontic Appliances: A Randomized Clinical Trial. *Orthodontics & Craniofacial Research*. 2012 August; 15(3): p. 178-187.
91. Iwasaki LR, Beatty MW, Randall CJ, Nickel JC. Clinical Ligation Forces and Intraoral Friction During Sliding on a Stainless Steel Archwire. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2003 April; 123(4): p. 408-415.
92. Sherief DI, Abbas NH. The effect of food simulating liquids on the static frictional forces and corrosion activity of different types of orthodontic wires. *Journal of the World Federation of Orthodontists*. 2017 November; 6: p. 165-170.

93. Hobbelink MG, He Y, Xu J, Xie H, Stoll R, Ye Q. Synergistic Effect of Wire Bending and Salivary pH on Surface Properties and Mechanical Properties of Orthodontic Stainless Steel Archwires. *Progress in Orthodontics*. 2015 October; 16:37.
94. Jaber LCL, Rodrigues JA, Amaral FLB, Franca FMG, Basting RT, Turssi CP. Degradation of orthodontic wires under simulated cariogenic and erosive conditions. *Brazilian Oral Research*. 2014; 28(1): p. 1-6.
95. Choudhary P, Choudhary OP. Uses of transmission electron microscope in microscopy and its advantages and disadvantages. *International Journal of Microbiological Applied Sciences*. 2018; 7(5): p. 743-747.
96. Gadelmawla ES, Koura MM, Maksoud TMA, Elewa IM, Soliman HH. Roughness parameters. *Journal of Materials Processing Technology*. 2002; 123: p. 133-145.
97. Jagtap RN, Ambre AH. Overview literature on atomic force microscopy (AFM): Basics and its important applications for polymer characterization. *Indian Journal of Engineering & Materials Sciences*. 2006 August; 13: p. 368-384.
98. De Oliveira RRL, Albuquerque DAC, Cruz TGS, Yamaji FM, Leite FL. Measurement of the nanoscale roughness by atomic force microscopy: Basic principles and applications. In Bellitto V, editor. *Atomic Force Microscopy - Imaging, Measuring and Manipulating Surfaces at the Atomic Scale.*: IntechOpen; 2012.
99. Huang HH. Surface characterizations and corrosion resistance of nickel–titanium orthodontic archwires in artificial saliva of various degrees of acidity. *Journal of Biomedical Materials Research Part A*. 2005 September; 74(4): p. 629-639.
100. Amaechi BT, Higham SM, Edgar WM, Milosevic A. Thickness of Acquired Salivary Pellicle as a Determinant of the Sites of Dental Erosion. *Journal of Dental Research*. 1999 December; 78(12): p. 1821-1828.
101. Huang HH. Variation in surface topography of different NiTi orthodontic archwires in various commercial fluoride-containing environments. *Dental Materials*. 2007 January; 23(1): p. 24-33.
102. Stefanski T, Kloc-Ptaszna A, Postek-Stefanska L. The Effect of Simulated Erosive Conditions on the Frictional Behavior of Different Orthodontic Bracket-Wire Combinations. *Dental and Medical Problems*. 2019 April-June; 56(2).
103. Binning G, Rohrer H, Gerber C, Weibel E. Tunneling through a controllable vacuum gap. *Applied Physics Letters*. 1982; 40: p. 178-186.

104. Vorburger TV, Teague EC. Optical techniques for on-line measurement of surface topography. *Precision Engineering*. 1981; 3(2): p. 61–83.
105. Wennerberg A, Ohlsson R, Rosén BG, Andersson B. Characterizing three-dimensional topography of engineering and biomaterial surfaces by confocal laser scanning and stylus techniques. *Medical Engineering & Physics*. 1996 October; 18(7): p. 548-556.
106. Alavi S, Barooti S, Borzabadi-Farahani A. An in vitro assessment of the mechanical characteristics of nickel-titanium orthodontic wires in Fluoride solutions with different acidities. *Journal of Orthodontic Science*. 2015 April-June; 4(2): p. 52-56.
107. Amini F, Borzabadi Farahani A, Jafari A, Rabbani M. In vivo study of metal content of oral mucosa cells in patients with and without fixed orthodontic appliances. *Orthodontics & Craniofacial Research*. 2008 February; 11(1): p. 51-56.
108. Widu F, Drescher D, Junker R, Bourauel C. Corrosion and biocompatibility of orthodontic wires. *Journal of Materials Science: Materials in Medicine*. 1999 May; 10(5): p. 275-281.
109. Es-Souni M, Es-Souni M, Fischer-Brandies H. On the properties of two binary NiTi shape memory alloys. Effects of surface finish on the corrosion behaviour and in vitro biocompatibility. *Biomaterials*. 2002 July; 23(14): p. 2887-2894.
110. Oshida Y, Sachdeva RC, Miyazaki S. Microanalytical characterization and surface modification of TiNi orthodontic archwires. *Bio-Medical Materials and Engineering*. 1992; 2(2): p. 51-69.
111. Pulikkottil VJ, Chidambaram S, Bejoy P, Femin PK, Paul P, Rishad M. Corrosion Resistance of Stainless Steel, Nickel-Titanium, Titanium Molybdenum Alloy, and Ion-Implanted Titanium Molybdenum Alloy Archwires in Acidic Fluoride-Containing Artificial Saliva: An in vitro Study. *Journal of Pharmacy And Bioallied Sciences*. 2016 October; 8(Suppl 1).
112. Johansson AK, Lingstrom P, Birkhed D. Effect of soft drinks on proximal plaque pH at normal and low salivary secretion rates. *Acta Odontologica Scandinavica*. 2007 November; 65(6): p. 352-356.

APPENDIX A: RAW DATA



Sample no	Wire Type	Immersion Liquid	Ra Before	Rq Before	Rz Before	Ra After	Rq After	Rz After	Ra Difference	Rq Difference	Rz Difference
SSCL1	SS	CL	7,725	8,325	23,435	9,203	10,210	28,645	1,478	1,885	5,210
SSCL2	SS	CL	5,483	6,464	19,365	5,606	6,605	23,331	,123	,141	3,966
SSCL3	SS	CL	4,299	5,729	20,298	4,654	6,388	23,798	,355	,659	3,500
SSCL4	SS	CL	3,618	4,570	15,373	4,558	5,266	18,095	,940	,696	2,722
SSCL5	SS	CL	3,005	3,545	12,806	3,538	4,515	14,102	,533	,970	1,296
SSCL6	SS	CL	2,984	3,672	13,636	3,346	4,436	15,580	,362	,764	1,944
SSCC1	SS	CC	7,068	9,310	41,944	14,916	16,988	51,251	7,848	7,678	9,307
SSCC2	SS	CC	6,189	7,169	26,260	13,313	15,104	47,362	7,124	7,935	21,102
SSCC3	SS	CC	4,926	6,130	28,878	10,174	11,526	35,411	5,248	5,396	6,533
SSCC4	SS	CC	4,617	5,782	23,279	9,449	10,060	32,197	4,832	4,278	8,918
SSCC5	SS	CC	3,344	4,692	24,187	5,722	7,670	26,338	2,378	2,978	2,151
SSCC6	SS	CC	3,184	4,026	18,639	5,962	7,040	23,435	2,778	3,014	4,796
SSIT1	SS	IT	7,656	8,993	29,293	8,181	9,744	30,771	,525	,751	1,478
SSIT2	SS	IT	6,831	8,641	30,253	7,991	10,775	33,856	1,160	2,134	3,603
SSIT3	SS	IT	5,001	6,193	22,009	6,035	7,564	28,231	1,034	1,371	6,222
SSIT4	SS	IT	4,621	5,422	20,117	6,088	6,800	20,998	1,467	1,378	,881
SSIT5	SS	IT	4,468	5,572	19,313	5,914	6,832	20,091	1,446	1,260	,778
SSIT6	SS	IT	3,017	3,773	14,465	3,918	5,132	19,106	,901	1,359	4,641
SSKF1	SS	KF	6,507	8,574	33,700	8,025	11,593	34,919	1,518	3,019	1,219
SSKF2	SS	KF	6,923	7,722	22,916	7,312	10,514	30,480	,389	2,792	7,564
SSKF3	SS	KF	4,648	5,982	21,231	5,874	8,123	30,771	1,226	2,141	9,540
SSKF4	SS	KF	4,312	5,067	17,602	4,798	6,053	21,802	,486	,986	4,200
SSKF5	SS	KF	3,936	4,651	15,710	4,124	4,745	16,073	,188	,094	,363
SSKF6	SS	KF	3,289	4,044	15,062	4,575	5,089	16,850	1,286	1,045	1,788
SSCNT1	SS	CNT	5,783	6,937	22,320	6,157	8,418	24,835	,374	1,481	2,515
SSCNT2	SS	CNT	4,055	5,081	17,835	4,780	5,687	21,413	,725	,606	3,578
SSCNT3	SS	CNT	4,051	4,861	17,680	4,461	5,632	19,572	,410	,771	1,892
SSCNT4	SS	CNT	3,996	5,013	15,865	3,950	4,541	15,943	-,046	-,472	,078
SSCNT5	SS	CNT	3,111	3,803	15,347	3,606	4,966	18,043	,495	1,163	2,696
SSCNT6	SS	CNT	2,793	3,291	13,221	3,151	3,927	15,217	,358	,636	1,996
NTCL1	NiTi	CL	40,066	47,253	155,385	57,780	67,249	188,386	17,714	19,996	33,001
NTCL2	NiTi	CL	37,410	45,316	139,001	43,075	49,346	145,249	5,665	4,030	6,248
NTCL3	NiTi	CL	30,019	36,060	116,837	36,000	44,000	124,000	5,981	7,940	7,163
NTCL4	NiTi	CL	29,203	37,347	114,141	34,963	39,327	115,411	5,760	1,980	1,270
NTCL5	NiTi	CL	26,000	31,000	106,000	27,722	36,074	107,764	1,722	5,074	1,764
NTCL6	NiTi	CL	11,487	12,426	36,889	30,822	37,740	46,481	19,335	25,314	9,592
NTCC1	NiTi	CC	42,000	54,000	176,000	94,844	109,161	263,382	52,844	55,161	87,382
NTCC2	NiTi	CC	32,627	41,147	136,953	85,074	100,537	196,914	52,447	59,390	59,961
NTCC3	NiTi	CC	26,895	32,774	106,364	72,000	120,000	135,000	45,105	87,226	28,636
NTCC4	NiTi	CC	16,669	19,669	62,838	38,826	49,569	100,972	22,157	29,900	38,134
NTCC5	NiTi	CC	14,635	17,921	54,413	37,310	40,860	113,778	22,675	22,939	59,365
NTCC6	NiTi	CC	11,570	13,562	40,104	35,376	39,639	113,700	23,806	26,077	73,596
NTIT1	NiTi	IT	54,929	64,076	191,756	60,384	82,508	192,067	5,455	18,432	,311

Sample no	Wire Type	Immersion Liquid	Ra Before	Rq Before	Rz Before	Ra After	Rq After	Rz After	Ra Difference	Rq Difference	Rz Difference
NTIT2	NiTi	IT	36,983	42,840	126,973	53,000	64,000	127,000	16,017	21,160	,027
NTIT3	NiTi	IT	33,608	41,380	117,511	52,193	61,661	118,496	18,585	20,281	,985
NTIT4	NiTi	IT	26,000	32,000	106,000	38,000	43,000	123,000	12,000	11,000	17,000
NTIT5	NiTi	IT	24,438	31,335	103,979	34,808	39,259	120,051	10,370	7,924	16,072
NTIT6	NiTi	IT	16,669	19,669	62,838	18,312	21,999	64,627	1,643	2,330	1,789
NTKF1	NiTi	KF	49,155	60,375	129,695	63,706	69,931	188,723	14,551	9,556	59,028
NTKF2	NiTi	KF	36,000	44,000	124,000	53,000	58,000	126,000	17,000	14,000	2,000
NTKF3	NiTi	KF	31,707	42,843	134,828	43,480	49,662	145,690	11,773	6,819	10,862
NTKF4	NiTi	KF	25,719	30,086	80,363	29,071	37,854	94,517	3,352	7,768	14,154
NTKF5	NiTi	KF	21,435	28,719	34,945	24,764	31,147	87,440	3,329	2,428	52,495
NTKF6	NiTi	KF	14,664	18,102	49,073	23,466	27,107	86,429	8,802	9,005	37,356
NTCNT1	NiTi	CNT	48,560	55,613	142,527	66,000	79,000	149,000	17,440	23,387	6,473
NTCNT2	NiTi	CNT	40,626	47,664	146,364	47,000	54,000	150,000	6,374	6,336	3,636
NTCNT3	NiTi	CNT	31,360	37,398	112,326	37,906	42,251	121,892	6,546	4,853	9,566
NTCNT4	NiTi	CNT	32,000	39,000	125,000	34,000	42,000	136,000	2,000	3,000	11,000
NTCNT5	NiTi	CNT	27,567	31,051	86,247	37,063	43,441	113,078	9,496	12,390	26,831
NTCNT6	NiTi	CNT	16,474	21,823	62,683	26,334	32,083	83,266	9,860	10,260	20,583
TMACL1	TMA	CL	62,312	74,614	213,635	66,376	80,456	261,386	4,064	5,842	47,751
TMACL2	TMA	CL	55,103	65,297	162,410	59,653	74,337	244,873	4,550	9,040	82,463
TMACL3	TMA	CL	52,456	61,964	187,997	53,775	64,825	220,220	1,319	2,861	32,223
TMACL4	TMA	CL	39,397	49,042	150,693	47,000	55,000	170,000	7,603	5,958	19,307
TMACL5	TMA	CL	33,763	37,440	109,734	38,000	43,000	141,000	4,237	5,560	31,266
TMACL6	TMA	CL	31,285	39,393	107,064	33,504	39,536	130,343	2,219	,143	23,279
TMACC1	TMA	CC	64,483	76,978	203,032	81,000	106,000	255,000	16,517	29,022	51,968
TMACC2	TMA	CC	60,279	71,161	194,322	78,686	84,559	232,015	18,407	13,398	37,693
TMACC3	TMA	CC	58,667	69,941	153,933	61,422	72,696	228,697	2,755	2,755	74,764
TMACC4	TMA	CC	43,931	59,128	140,661	61,681	70,262	197,200	17,750	11,134	56,539
TMACC5	TMA	CC	39,397	49,042	150,693	54,232	62,549	162,618	14,835	13,507	11,925
TMACC6	TMA	CC	35,843	44,668	114,478	53,326	62,794	183,564	17,483	18,126	69,086
TMAIT1	TMA	IT	66,375	73,279	196,085	67,000	81,000	211,000	,625	7,721	14,915
TMAIT2	TMA	IT	53,102	61,641	161,762	60,000	68,000	202,000	6,898	6,359	40,238
TMAIT3	TMA	IT	52,529	61,019	169,309	58,581	68,624	178,275	6,052	7,605	8,966
TMAIT4	TMA	IT	42,899	53,925	143,771	46,085	54,656	162,358	3,186	,731	18,587
TMAIT5	TMA	IT	39,251	46,021	135,191	45,829	53,275	160,466	6,578	7,254	25,275
TMAIT6	TMA	IT	35,112	46,596	99,028	35,991	47,715	128,917	,879	1,119	29,889
TMAKF1	TMA	KF	64,038	74,662	212,028	76,000	92,000	285,000	11,962	17,338	72,972
TMAKF2	TMA	KF	60,568	71,863	181,542	66,000	85,000	204,000	5,432	13,137	22,458
TMAKF3	TMA	KF	52,653	61,323	148,126	53,000	63,000	200,000	,347	1,677	51,874
TMAKF4	TMA	KF	45,709	53,421	166,817	52,000	69,000	225,000	6,291	15,579	58,183
TMAKF5	TMA	KF	43,726	53,602	153,337	52,000	65,000	172,000	8,274	11,398	18,663
TMAKF6	TMA	KF	38,156	45,648	134,257	41,000	52,000	158,000	2,844	6,352	23,743
TMACNT1	TMA	CNT	72,000	85,000	198,000	72,000	95,000	209,000	,000	10,000	11,000
TMACNT2	TMA	CNT	58,667	69,941	153,000	63,000	78,000	177,000	4,333	8,059	24,000

Sample no	Wire Type	Immersion Liquid	Ra Before	Rq Before	Rz Before	Ra After	Rq After	Rz After	Ra Difference	Rq Difference	Rz Difference
TMACNT3	TMA	CNT	57,719	65,157	173,687	59,000	69,000	211,000	1,281	3,843	37,313
TMACNT4	TMA	CNT	55,529	71,162	187,167	59,000	75,000	207,000	3,471	3,838	19,833
TMACNT5	TMA	CNT	51,000	59,000	173,000	52,000	67,000	179,000	1,000	8,000	6,000
TMACNT6	TMA	CNT	39,861	49,709	168,062	45,509	54,207	169,902	5,648	4,498	1,840

