Microstructure and Mechanical Properties of Nickel-Free and Nickel-Containing Stainless Steel Orthodontic Wires

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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF NICKEL-FREE AND NICKEL-CONTAINING STAINLESS STEEL ORTHODONTIC WIRES

by

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Marquette University,
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the Degree of Master of Science

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ABSTRACT
MICROSTRUCTURE AND MECHANICAL PROPERTIES OF NICKEL-FREE AND NICKEL-CONTAINING STAINLESS STEEL ORTHODONTIC WIRES

Amanda Olejniczak, D.D.S.

Marquette University, 2014

Introduction: In orthodontics, contact dermatitis caused by nickel allergy should be of concern with the number of nickel-containing appliances and wires used. Stainless steel archwires are commonly used throughout orthodontic treatment. With the release of nickel from these wires, some manufacturers have turned to nickel-free stainless steel alternatives. The goal of this research was to compare nickel-free stainless steel with traditional stainless steel archwires with regard to mechanical properties and microstructure.

Materials and Methods: Nickel-free stainless steel and regular stainless steel archwires from four companies were included. Five random samples of each wire, vertically mounted in fast-set acrylic, were indented three times to determine their Vickers microhardness. Force deflection properties were investigated with the three point bending test in which fifteen random samples of each wire were tested. Wire samples were horizontally mounted in fast-set acrylic, acid-etched for variable amounts of time, and then analyzed with a metallurgical microscope to assess microstructure. All quantitative data were compared using one-way analysis of variance (ANOVA) at a 0.05 significance level with a Tukey's HSD (honest significant difference) test post hoc analysis, when necessary.

Results: Vickers microhardness number, activation stiffness, elastic recovery, and activation bending force values were calculated for each sample. Activation modulus showed no significant differences between Dentaurum wires. All wires were statistically different when considering percent recovery. Scheu and Dentaurum stainless steel wires were statistically similar to the respective nickel-free alternatives when investigating activation stiffness. Scheu Chromium bending force values were always greater than Scheu Menzanium. Acme Monaco’s nickel-free alternative had force values greater than Acme stainless steel. Force values for Dentaurum wires through 1.0 mm of deflection showed no significant differences. Nickel-free alternatives and stainless steel wires manufactured by Scheu, Acme-Monaco, and Pozzi/Leone showed no statistical significant difference with regards to microhardness values. Microstructure analysis revealed differences between grain structure and sizes between all wires.

Conclusions: Dentaurum Remanium and Noninium archwires appear to have the most similarities with regards to the mechanical and microstructure properties investigated in this study. With regards to the mechanical properties tested, nickel-free stainless steel may be a viable alternative to traditional stainless steel archwires.

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TABLE OF CONTENTS

ACKNOWLEDGMENTS i

LIST OF TABLES iii

LIST OF FIGURES iv

CHAPTER 1: INTRODUCTION 1

CHAPTER 2: LITERATURE REVIEW 4

CHAPTER 3: MATERIALS AND METHODS 14

CHAPTER 4: RESULTS 22

CHAPTER 5: DISCUSSION 40

CHAPTER 6: CONCLUSION 47

REFERENCES 48

LIST OF TABLES

Table 1. Manufacturers and characteristics of the orthodontic wires tested......................15

Table 2. Activation stiffness and elastic recovery during bending for the stainless steel wires..24

Table 3. Activation bending force values at various deflections for the stainless steel wires..25

Table 4. Vickers microhardness values for the stainless steel wires 30

LIST OF FIGURES

Figure 1. Instron 5500R utilized for data collection during the three-point bending test 16

Figure 2. Testing set-up for three-point bending 17

Figure 3. Three-point bending test in progress 17

Figure 4. Sample segment of wire placed vertically in quick-set acrylic for Vickers microhardness test 19

Figure 5. Kentron Vickers microhardness tester with acrylic block mounted 19

Figure 6. Polished acrylic block with wire vertically positioned for Vickers microhardness test 20

Figure 7. Acrylic block curing 21

Figure 8. Comparison of typical force-deflection curves of Acme Monaco Nickel-free archwire and Acme Monaco Stainless Steel archwire 27

Figure 9. Comparison of typical force-deflection curves of nickel-free (Menzanium) and nickel-containing (Chromium) wires manufactured by Scheu 27

Figure 10. Comparison of typical force-deflection curves of nickel-free (Leowire) and nickel-containing (Biosteel) wires manufactured by Pozzi/Leone 28

Figure 11. Comparison of typical force-deflection curves of nickel-free (Noninium) and nickel-containing (Remanium) wires manufactured by Dentaurum 28

Figure 12. Comparison of typical force-deflection curves for all wires 29

Figure 13. Optical micrograph of Acme Monaco Nickel-free archwire surface at 20x magnification 32

Figure 14. Optical micrograph of Acme Monaco Nickel-free archwire surface at 50x magnification 32

Figure 15. Optical micrograph of Acme Monaco Stainless Steel archwire surface at 20x magnification 33

Figure 16. Optical micrograph of Acme Monaco Stainless Steel archwire surface at 50x magnification 33

Figure 17. Optical micrograph of Scheu Menzanium wire surface at 20x magnification 34

Figure 18. Optical micrgraph of Scheu Menzanium wire surface at 50x magnification 34

Figure 19. Optical micrograph of Scheu Chromium wire surface at 20x magnification 35

Figure 20. Optical micrograph of Scheu Chromium wire surface at 50x magnification 35

Figure 21. Optical micrograph of Pozzi/Leone Biosteel wire surface at 20x magnification 36

Figure 22. Optical micrograph of Pozzi/Leone Biosteel wire surface at 50x magnification 36

Figure 23. Optical micrograph of Pozzi/Leone Leowire wire surface at 20x magnification 37

Figure 24. Optical micrograph of Pozzi/Leone Leowire wire surface at 50x magnification 37

Figure 25. Optical micrograph of Dentaurum Noninium wire surface at 20x magnification 38

Figure 26. Optical micrograph of Dentaurum Noninium wire surface at 50x magnification 38

Figure 27. Optical micrograph of Dentaurum Remanium wire surface at 20x magnification 39

Figure 28. Optical micrograph of Dentaurum Remanium wire surface at 50x magnification 39

CHAPTER 1
INTRODUCTION

Orthodontics is the dental specialty focusing on movement of the dentition and alteration of the dentofacial complex as a whole (Huang et al., 2003). Treatment goals for orthodontists include achieving a stable, esthetic, and functional occlusion while still maintaining, or possibly improving, the facial balance. Archwires play a critical role throughout treatment, delivering force to move and align the dentition, transmit forces within the dentofacial complex, and even prevent unwanted movements. The first step often involves aligning the dentition (Nikolai, 1997). In order to achieve this tooth movement, a series of archwires can be utilized, as no one archwire is ideal to progress solely through treatment in its entirety (Kusy, 1997). Initial stages of orthodontics rely mainly on flexible wires composed of nickel-titanium (NiTi) or multistranded stainless steel (Kusy, 1997; Nikolai, 1997). Once teeth are aligned, a stiffer wire can be used, very commonly composed of stainless steel (Kusy, 1997; Proffit, 2013). For those patients with nickel hypersensitivity issues, using materials such as NiTi or stainless steel may be a potential cause for concern with regards to one's health.

Nickel sensitivity continues to be a health concern throughout the population with the increased awareness of allergic reactions (Kusy, 2004). It has been reported that the prevalence of nickel sensitivity among the general population has increased from about 10% to 20% (Bass et al., 1993; Menezes et al., 2004). Contact dermatitis, an adverse allergic reaction, is most frequently caused by nickel (Rahilly & Price, 2003). In orthodontics, nickel is readily found in NiTi and stainless steel wires, stainless steel brackets, as well as other fixed and removable appliances. Few studies have investigated the prevalence of nickel sensitivity in orthodontic patients specifically; however, reports have ranged from 17.2% to 21.2% (Bass et al., 1993; Menezes et al., 2004). For those with severe nickel allergies, orthodontists may be required to find alternative materials for providing the patient with treatment of the same standards (Kolokitha et al., 2008). As long as the allergy to nickel remains a worldwide concern, nickel-free alternatives will be a necessity, especially in the area of orthodontics.

As mentioned above, metal orthodontic brackets and wires are commonly made of stainless steel or nickel-titanium, materials that contain nickel. For example, the austenitic stainless steel used to make orthodontic brackets and archwires contains approximately eight percent nickel (Barrett et al., 1993; Daems et al., 2009). It is possible for stainless steel archwires to contain up to 12% nickel (Kerosuo & Dahl, 2007). Alternatives to nickel-containing materials in orthodontics include ceramic or polymer-based brackets and wires, beta-titanium wires, and “nickel-free” stainless steel brackets and wires (Kolokitha et al., 2008). As different materials are being introduced for the fabrication of wires and brackets in orthodontics, one can expect significant variability in physical and mechanical properties as compared with the traditional stainless steel. In orthodontics, it is important that materials have the proper composition and properties to withstand the physical, mechanical, and biological forces within the oral cavity (Kusy, 2004; Daems et al., 2009). Early in orthodontic treatment, nickel-titanium archwires are frequently used. With such qualities as high resiliency, high yield strength and springback, and low elastic modulus these wires are ideal for beginning the leveling and aligning phase of treatment (Ballard et al., 2012). Stainless steel is more traditionally an archwire utilized later in treatment when low friction, good formability, but greater stiffness and lower springback compared to nickel-titanium are typically desired (Verstrynge et al., 2006). Studying the properties of nickel-free orthodontic wires will provide orthodontists with the information to determine if these are acceptable for clinical use during treatment.

A study comparing one nickel-free stainless steel wire to conventional stainless steel wires found no difference between them with regard to elastic modulus, hardness, ductility, and yield strength (Verstrynge et al., 2006). In addition, stainless steel is frequently used for medical applications. Incorporation of nickel-free stainless steel implants within the medical field has been done so successfully (Zardiackas et al., 2003; Zardiackas et al., 2003). However, with limited research on the properties and structure of nickel-free stainless steel alternatives, little is known about how these materials would behave as archwires in orthodontics. The goal of this study was to determine if the nickel-free stainless steels exhibit these properties and could, therefore, be viable alternatives for orthodontists treating patients with nickel hypersensitivity concerns.

CHAPTER 2
LITERATURE REVIEW

Introduction to Orthodontics

Orthodontics relies on light, continuous forces in order to produce the most efficient biologic response and, therefore, the anticipated tooth movement (Kusy, 1997; Proffit et al. 2013). A critical component in fixed appliance orthodontic tooth movement is the wire. Wires can be used in a number of fixed and removable appliances utilized by the orthodontist. In addition, ligature wires can be used to engage the archwire into brackets or join individual teeth together as “anchorage” (Nikolai, 1997). Wire can also be shaped into open and closed coil helices to manage space concerns while moving the surrounding dentition (Nikolai, 1997). Still, the most utilized wire in orthodontics remains to be the archwire. By engaging the archwire into brackets adhered to the crowns, the orthodontist is able to activate the wire, transmitting its mechanical properties to the dentition (Nikolai, 1997). The forces delivered by the archwires causes controlled orthodontic tooth movement in all three planes of space. The edgewise appliance introduced by Dr. Edward Angle in the 1920s marked the beginning of the archwire era in orthodontics (Nikolai, 1997). Initially, archwires were composed of precious metals, such as gold (Kapila & Sachdeva, 1989; Nikolai, 1997). By the 1930s, alternative alloys were being considered due to the cost of gold wires, as well as the need for more springiness and less fracturing under tension in an archwire (Kusy, 2002). This is when stainless steel archwires were introduced to orthodontics; however, it was not until the 1960s when stainless steel archwires became widely accepted, replacing the gold wires previously utilized (Kusy, 2002). While there are only two different cross-sectional geometries of orthodontic wires, there are numerous sizes, introduction of new materials, and a variety of preformed archforms available to aid in providing the proper treatment (Nikolai, 1997). As the field of orthodontics evolves and goals of treatment change, the demand for still different archwire alloys continues.

Development of the Ideal Archwire

Development of orthodontic archwires involves critical analysis of a number of characteristics, including springback, resilience, weldability, friction, formability, esthetics, and biocompatibility (Kusy, 1997). The ideal archwire would have a large springback, low stiffness, good formability, low surface friction, high stored energy, biocompatibility, stability, and have the ability to be welded and soldered (Kapila & Sachdeva, 1989). Another characteristic important in an orthodontic archwire would be for it to be heat treatable to reduce brittleness after bends are placed (Kapila & Sachdeva, 1989; Nikolai, 1997). In fact, there is no one archwire that is ideal for use through all stages of orthodontic treatment (Kusy, 1997). As a result, different archwires are utilized in order to fulfill the varying goals of each stage of treatment. The different archwire alloys utilized offer different mechanical properties and structural composition (Kusy, 1997). Currently, the available materials for orthodontic archwires include stainless steel, nickel-titanium, beta-titanium more commonly known as titanium-molybdenum alloy, cobalt-chromium, and, more recently, esthetic composite (Nikolai, 1997; Verstrynge et al., 2006; Spendlove, 2013). Beta-titanium wires provide the orthodontists with average stiffness, good formability and weldability, and effective springback. Cobalt-chromium archwires behave similarly to stainless steel after heat treatment; however, manipulation of the wires can only occur prior to the heat treatment. Nickel-titanium archwires provide high springback, low stiffness, and flexibility. These archwires are time tested, show resistance to plastic deformation, as well as the ability to maintain a continuous light force over a long range of time, regardless of the amount of deflection (Kapila & Sachdeva, 1989; Verstrynge et al., 2006). Initial archwires, used for alignment of the dentition, need to be flexible and resilient. Nickel-titanium archwires display characteristics ideal for the initial stages of orthodontic treatment.

Stainless Steel Archwires in Orthodontics

Since its introduction to orthodontics in 1929, stainless steel has become one of the most common materials used for orthodontic archwires. When compared with the previously utilized precious metals, stainless steel proved to impose less cost to the orthodontist, as well as provide greater strength and a higher modulus of elasticity (Kapila & Sachdeva, 1989; Nikolai, 1997). These beneficial characteristics led to eventual replacement of gold, and other precious metals, with stainless steel archwires in orthodontics (Kusy, 2002). Although stainless steel archwires have many favorable properties, the force levels may be higher than ideal and the amount of springback is very low (Valiathan & Dhar, 2006). In order to overcome such forces, wires of smaller diameter or longer lengths by incorporating loops would be required clinically.

A typical composition of stainless steel wires in orthodontics ranges from 17-25 wt% chromium, 8-25 wt% nickel, 0.20 wt% carbon, and the remainder being iron. Most commonly used is 18-8 stainless steel which is composed of 8 wt% nickel and 18 wt% chromium (Proffit et al., 2012). Each element contributes important qualities to the traditional stainless steel wire used in orthodontics. The percent by weight of chromium creates an increased corrosion resistance when compared with carbon steel. Chromium forms a thin passivating oxide layer which blocks the diffusion of oxygen to the stainless steel alloy underneath (Verstrynge et al., 2006; Izquierdo et al., 2010). The incorporation of nickel is critical to ensure the stabilized austenitic nature, as well as to help improve the corrosion resistance of orthodontic stainless steel archwires (Kusy, 1997). It is known that the austenitic structure is metastable and cold-working can induce phase transformation. Low temperature heat treatment causes a reduction in internal stresses in stainless steel wires (Asgharnia & Brantley, 1986). Maintaining austenite stabilization in orthodontic wires increases the strength of the stainless steel (Izquierdo et al., 2010).

A distinctive type of steel wire, known as Australian wire, is incorporated into a number of orthodontic techniques and mechanics. It was developed to provide orthodontists with a light, flexible stainless steel wire that demonstrated high resiliency and toughness. While this wire provides benefits for the practitioner, it also poses a number of disadvantages, including brittleness and decreased formability for some tempers of Australian wire. An increased carbon content compared with traditional stainless steel may account for the rough, irregular, porous nature of the surface of Australian wires. Such characteristics may be the reason for these wires to not readily accept bends. In addition, the increased carbon content may contribute to an increase in hardness and brittleness. These qualities make Australian wire an inadequate option during sliding mechanics as there is an increase in binding. The aforementioned characteristics, along with the fact that nickel is still used in manufacturing, make Australian wire not a viable option in those with nickel sensitivity (Pelsue et al., 2009).

Austenitic Stainless Steel

As mentioned previously, in orthodontics it is important for the stainless steel archwires to remain in the austenite stabilized phase. In fabrication of stainless steels, there are three major types based on phase, or the crystal structures the iron forms. These are the ferritic, martensitic, and austenitic stainless steels. The most commonly used stainless steel in orthodontics is the austenitic grade. The main structure of austenitic stainless steels is face-centered-cubic. While chromium acts as a ferrite-stabilizing element, carbon, nickel, nitrogen, and manganese may be included at sufficient concentrations to maintain austenite stable at room temperature (Davis, 1994). Extensive plastic deformation or rapidly cooling the metal to very low temperatures can readily transform the austenitic stainless steel to martensite (Davis, 1994). Transformation to martensite stainless steel can alter the properties of the archwire. It has been suggested that this transformation can decrease the ductility and, thus, increase the tendency to fracture. In addition, the martensite phase of stainless steel has an increased hardness when compared with the austenite phase, thus, increasing the torque resistance (Izquierdo et al., 2010). As demonstrated, altering the phase of the stainless steel wires could lead to the development of undesirable properties. Maintaining the austenitic nature during the fabrication of nickel-free orthodontic wires is critical to preserving the desirable properties observed in traditional stainless steel.

Nickel Allergies in Orthodontics

Nickel allergies and sensitivities continue to rise in prevalence throughout the population. It is estimated that nickel hypersensitivity affects 4.5% to 28.5% of the population, with females being affected ten times more frequently than males (Kolokitha & Chatzistavrou, 2009). Nickel is the most common metal associated with contact dermatitis in orthodontics (Rahilly & Price, 2003). One study has indicated a nickel sensitivity prevalence of 17.2% among orthodontic patients (Pazzini et al., 2009). This reaction is a Type IV delayed hypersensitivity response occurring at least one day after introduction of the nickel-containing appliances. The leached nickel ions are capable of binding to proteins eliciting the formation of antigens that then go on to activate T lymphocytes. It is the Langerhans cells present in the oral mucosa which present the nickel allergen to memory cells, eliciting the allergic response (Bakula et al., 2011). The tissue damage or irritation noted in such a reaction is caused by activated specialized T-cells circulating in the patient's circulatory system (Kolokitha & Chatzistavrou, 2009). In patients, it typically presents itself as redness, swollen tissues, rashes, sores, or ulcers within the oral cavity (Eliades & Athanasiou, 2002; Kusy, 2004). The impact of nickel on gingival hyperplasia and periodontal health appears to be caused by the release of the cytokines, interferon λ and interleukins, IL-2, IL-5, and IL-10, induced by T lymphocytes (Pazzini et al., 2009). However, it is also important to remember that extraoral metal appliances may contain nickel. Studies conducted by Norwegian orthodontists have shown dermal reactions such as redness, eczema, itching, and desquamation due to these extraoral appliances may be observed more frequently in patients (Hensten-Pettersen, 1989; Eliades & Athanasiou, 2002).

The concern may be amplified in patients previously sensitized to nickel, most frequently due to body piercings. In these instances, one may be more likely to have an allergic response to nickel-containing orthodontic materials (Rahilly & Price, 2003). The reason for the delay in allergic response is due to the two distinct phases of the immune response. The first, or sensitization, phase is when the allergen enters the body and is recognized for the first time by the immune system. The second, or elicitation, phase is when the affected person is exposed to the allergen for a second time. It is during the latter phase in which the clinical allergic reaction is readily observed (Kolokitha & Chatzistavrou, 2009). For these reasons, stainless steel brackets and nickel-containing archwires and appliances have been of concern for orthodontists when treating patients with known nickel allergies. As long as nickel hypersensitivity issues remain prevalent in the population, orthodontists will need to provide alternative archwires and appliances for patients with known nickel allergies.

Biocompatibility Concerns with Nickel

Nickel-containing products have been utilized for a number of medical and implant procedures. These products have undergone extensive testing to ensure biocompatibility standards were achieved. However, nickel alloys in orthodontics pose a unique situation when compared with these implants. Although invasive, implanted materials form a connective tissue capsule surrounding this newly introduced foreign body. When nickel-containing stainless steel is used in orthodontic patients, the environment of the oral cavity is free to react with these wires in a continuous nature. Saliva and acidic substances increase the risk for extensive corrosion of orthodontic wires and appliances, posing a potential for more harm in those with nickel allergies (Eliades & Athanasiou, 2002). The oral environment is favorable for activity of microorganisms. In combination with hindered oral hygiene, dental biofilms accumulate in thick layers on the orthodontic appliances. This can increase the anaerobic activity of oral bacteria, stimulating further corrosion of the metal appliances (Pazzini et al., 2009). As stated previously, one of the biocompatibility concerns with stainless steel archwires is the potential of nickel release intraorally. Due to the fact that the nickel atoms are not bound strongly to form an intermetallic compound, the likelihood of slow nickel ion release over time in vivo is increased. In vitro studies have demonstrated about 40 µg of nickel ion can be released per day (Eliades & Athanasiou, 2002). Nickel ions, when tested in vitro, have been implicated as a potential cause in promoting the inflammatory response. Such processes including chemotaxis of leukocytes and calcium ion-dependent contractile activity both have been shown to be inhibited by nickel ions (Torgersen et al., 1995; Eliades & Athanasiou, 2002).

Studies have drawn varying conclusions with respect to nickel content in the saliva after the introduction of fixed appliances in orthodontic patients (Eliades & Athanasiou, 2002). For instance, in vivo investigations have revealed an increased nickel concentration in saliva after three weeks; however, individual variation and variability in number and type of fixed appliances can contribute to statistically significant differences in observed salivary nickel concentrations (Gjerdet et al., 1991). Conversely, one day to one month after insertion of orthodontic appliances did not demonstrate increased concentrations of nickel in patient’s saliva in another study (Kerosuo et al., 1997). Still, other studies have concluded that nickel released from orthodontic fixed appliances cannot be detected in saliva or blood after one week (Bishara et al., 1993). In many studies, salivary nickel concentrations are investigated over short time periods, as well as, early on in orthodontic treatment. In addition, it is difficult to use these short-term release patterns as a way to predict long-term nickel release potential. One study investigating the periodontal health in nickel allergic patients has indicated a possible cumulative effect of the nickel ions throughout orthodontic treatment (Pazzini et al., 2009). As a result, it is difficult to draw accurate conclusions about the release of nickel from appliances during orthodontic treatment (Eliades & Athanasiou, 2002). However, nickel release from orthodontic archwires and appliances should remain as a concern for orthodontists today. It is still recommended that nickel-free alloy substitutes or nickel alternatives be used in those orthodontic patients that have a history of nickel hypersensitivity.

Alternatives to Nickel-Containing Appliances

During the initial stages of orthodontic treatment, NiTi is the most commonly utilized archwire. Due to the very high content of nickel in these archwires, they are not recommended in patient with nickel hypersensitivity. There are limited alternatives to the NiTi archwire. However, there are a number of alternatives that can be used in the later stages of orthodontic treatment to replace the use of stainless steel. These alternatives may decrease the patient’s exposure to nickel. One such alternative is a nickel-free stainless steel archwire. In some instances, these are described as “nickel-lite” as the nickel content is less than 0.2% but still present. Nickel-free stainless steel variants, such as Dentaurum Noninium, mainly use manganese, molybdenum, and chromium as substitute elements (Verstrynge et al., 2006). One concern of replacing nickel is the introduction of δ–ferrite because of the ferrite-stabilizing influence caused by the elements, such as molybdenum (Davis, 1994). Research has suggested that in order to maintain the austenitic structure, nickel-lite stainless steels contain high levels of nitrogen. Introduction of nitrogen has the potential to increase the strength of these austenitic alloys (Davis, 1994). In the study conducted by Verstrynge et al., properties of stainless steel wires were investigated, including samples of the nickel-free variant by Dentaurum. Dentaurum Noninium was found to be more ductile than the traditional stainless steel wires, as well as having the lowest flexural Young's modulus (Verstrynge et al., 2006).

Currently, there is limited research available on the mechanical properties, structure, and efficacy of the nickel-free or nickel-lite stainless steel archwires available to orthodontists. It was the goal of this study to compare the nickel-free stainless steel wires offered by four manufacturers with traditional stainless steel wires containing nickel offered by the same manufacturers by investigating bending force values, activation modulus, activation stiffness, percent recovery, microstructure, and hardness.

CHAPTER 3
MATERIALS AND METHODS

For each test, nickel-free and nickel-containing wires were utilized for comparison. Round archwires of similar size were utilized for the samples. The preferred specimens were straight pieces of round laboratory wires or archwires. However, if straight wires were not available, then preformed archwires or spools of wire were used for comparison. The nickel-free and nickel-containing wires received from the same company were of the same size and shape in order to achieve the best possible comparison. Acme Monaco (New Britain, CT, USA) stainless steel archwires measuring 0.018” in diameter were compared against the ultra-low nickel stainless steel of the same diameter. Noninium straight wires by Dentaurum (Inspringen, Baden-Württemberg, Germany) with 0.2% trace nickel were tested against the company’s Remanium stainless steel archwire. Both Dentaurum wires measured 0.016” in diameter. Pozzi/Leone (Florence, Tuscany, Italy) offered Biosteel laboratory wires which consisted of 0.2% nickel traces. These were compared with Leowire, a chromium stainless steel laboratory wire, manufactured by the same company. The Leone wires were received on spools and straightened prior to three-point testing. Finally, Scheu (Iserlohn, North Rhine-Westphalia, Germany) offered Menzanium, nickel-free stainless steel straight wires which were compared against the company’s Chromium stainless steel. Leone and Scheu laboratory wires were 0.024” in diameter (Table 1).

Table 1. Manufacturers and characteristics of the orthodontic wires tested.

Company	Wire	Nickel Presence	Size (inches)
Acme Monaco	Nickel-Free	No	0.018
Acme Monaco	Stainless Steel	Yes	0.018
Scheu	Menzanium	No	0.024
Scheu	Chromium	Yes	0.024
Pozzi/Leone	Biosteel	No	0.024
Pozzi/Leone	Leowire	Yes	0.024
Dentaurum	Noninium	No	0.016
Dentaurum	Remanium	Yes	0.016

Three tests were conducted in order to determine the mechanical properties and microstructure of the nickel-free and nickel-containing stainless steel wires under investigation in this study. The investigation included the three-point bend test, Vickers microhardness test, as well as microstructure analysis. Appropriate statistical analyses were utilized for each test when indicated.

The three-point bending test allows one to analyze the bending forces for a given deflection for the eight wire products utilized. The test was conducted at room temperature. A sample size of 15 wires made up each group. A 25 mm segment of each wire was utilized. Materials were tested in the condition they were received from the manufacturer, with the exception of the Acme Monaco and Pozzi/Leone wires. In order to test the straightest portion from the preformed Acme Monaco archwires, segments were taken from the most distal segment of 15 different archwires. The two Pozzi/Leone wires were straightened by hand to straight pieces to ensure adequate placement on the testing apparatus and avoid errors. Fifteen continuous segments were cut from the spools for testing. Segments for the Scheu wires were taken from 15 different wires. A random sampling of 25 mm segments were taken from a number of the Dentaurum straight wires.

Wires were deflected with the universal testing machine (Instron, Canton, MA) at a rate of 2 mm/min to a midspan deflection of 3.1 mm (Figure 1) and then reversed. The space between lower supports was 14 mm, with the upper member being centered at 7 mm (Figure 2). Force was monitored during loading and unloading (Figure 3). Loading slope was measured from the collected data and converted to bending modulus (Segal et al., 2009; Ballard et al., 2012). In addition, elastic recovery was calculated and activation bending force values at 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, and 3.0 mm were obtained from the test for comparison. Data were compared using one-way analysis of variance (ANOVA) at a 0.05 significance level with a Tukey's HSD (honest significant difference) test post hoc analysis, where required. Statistical analysis was performed using SAS software (SAS Institute Inc., Cary, NC).

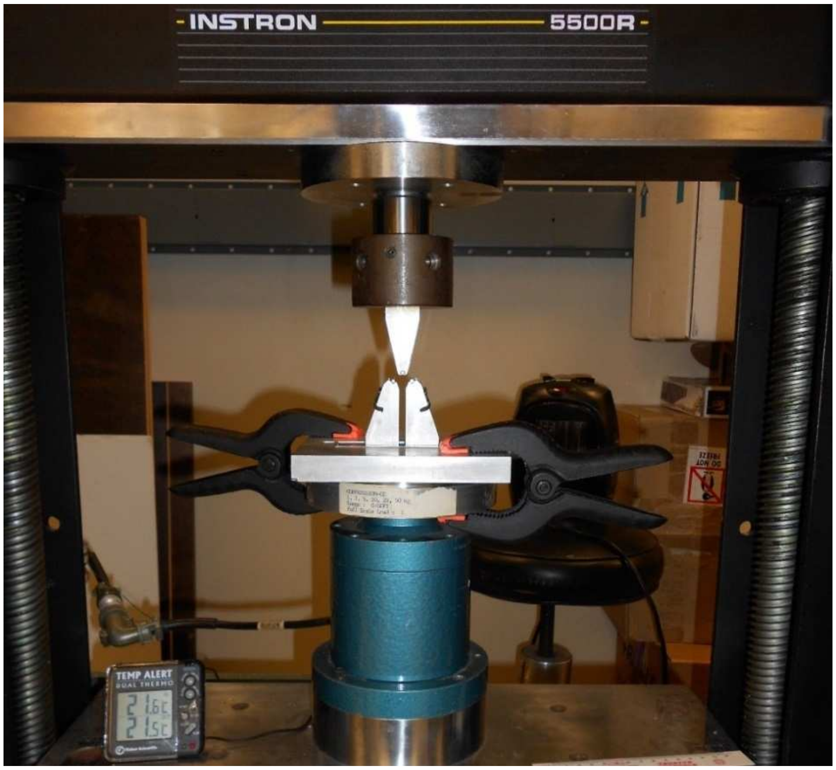

Figure 1. Instron 5500R utilized for data collection during the three-point bending test.

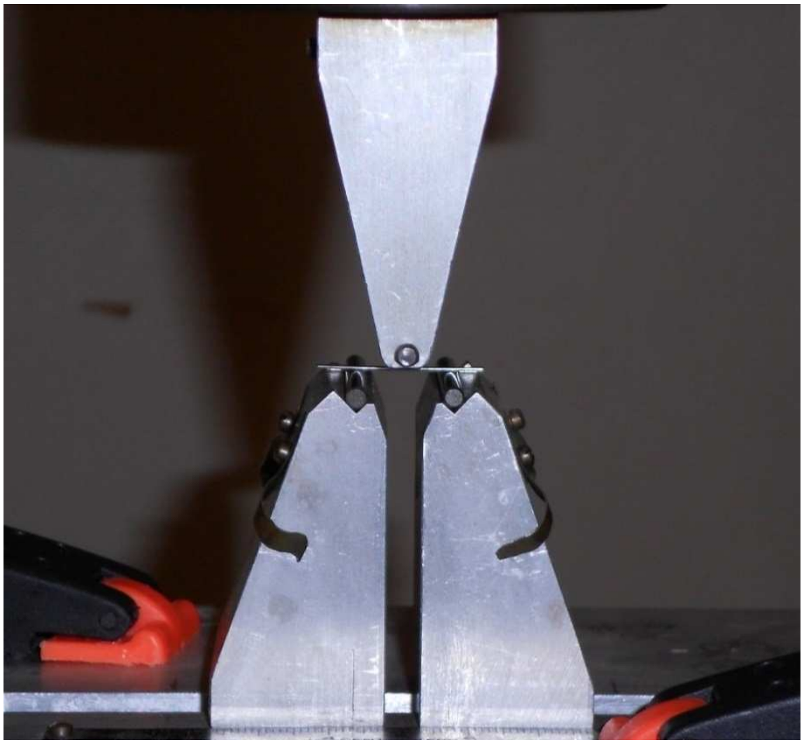

Figure 2. Testing set-up for three-point bending. A 14 mm span length between lower supports was used with the upper beam centered at 7 mm.

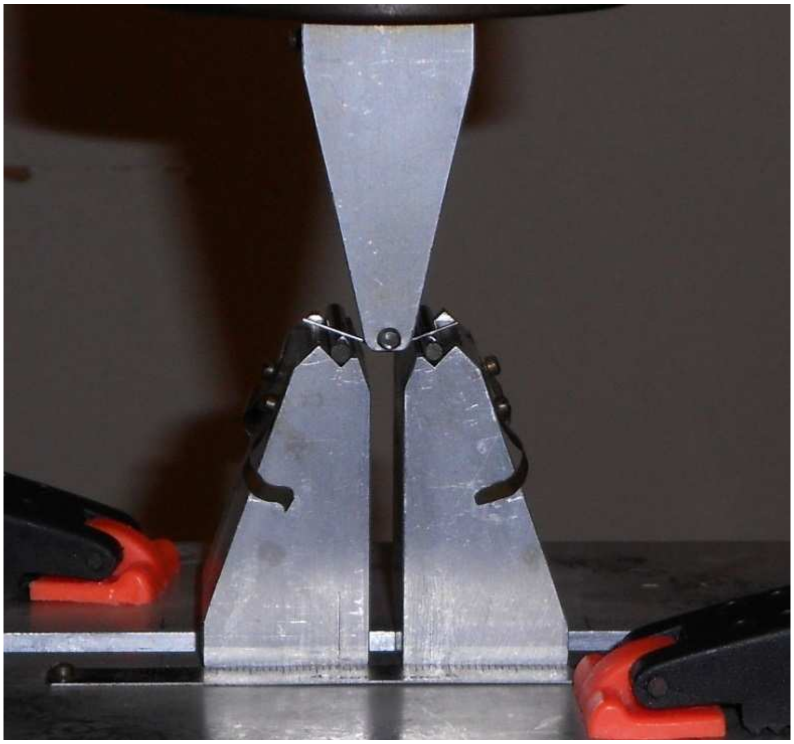

Figure 3. Three-point bending test in progress.

The Vickers microhardness test was conducted on as received wires to determine their abilities to resist plastic deformation. Five 25 mm segments of each wire group were randomly selected for testing. The cylindrical wire samples were mounted vertically in acrylic resin and prepared under standard metallographic procedures (Figure 4). A Vickers microhardness tester (Kentron; Torsion Balance Co., Clifton, NJ) was used with a 500 g load lasting 15 seconds (Figure 5). Prior to indentation, each sample was ground with SiC paper at 240, 400, 600, and 1200 grits until adequate surface smoothness was achieved (Figure 6). Each mounted wire was indented three separate times, which allowed for an average of indentations per sample to be calculated. Then, an average of all samples was generated. A Vickers microhardness number was calculated via the formula:

$$VHN=2*F*\sin(136°/2)/d^2$$

Where F is the force applied in kilograms and d is the calculated average of indentations in millimeters. Data were compared using ANOVA testing at a 0.05 significance level. A Tukey's HSD (honest significant difference) test post hoc analysis was used, when necessary. Statistical analysis was performed with SAS software.

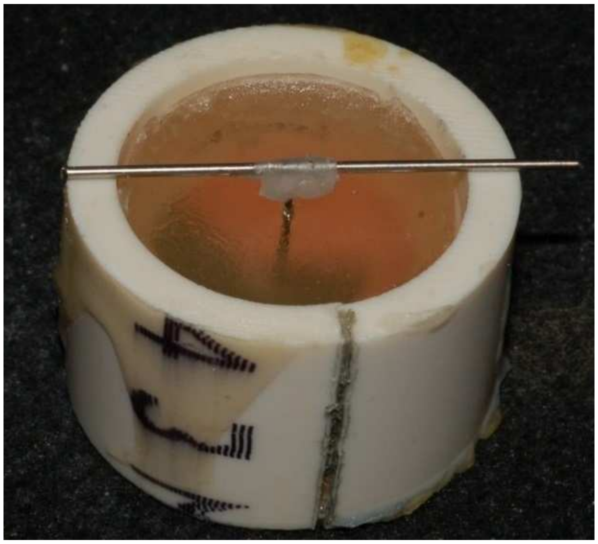

Figure 4. Sample segment of wire placed vertically in quick-set acrylic for Vickers microhardness test.

Figure 5. Kentron Vickers microhardness tester with acrylic block mounted.

Figure 6. Polished acrylic block with wire vertically positioned for Vickers microhardness test.

The final test investigated the microstructure characteristics of the sampled wires. Analysis of the microstructure of the nickel-free alternatives could provide valuable information about mechanical properties needed to determine the efficacy of these wires in orthodontic treatment. Two of the vertically mounted wires used for the microhardness testing and two randomly selected wires mounted horizontally in the same acrylic resin were prepared under standard metallurgic procedures. Grinding of the samples utilized for the microhardness test began with 120 grit SiC paper, followed by 240, 400, 600, and 1200 grits. The horizontally mounted samples, having not undergone previous testing, were prepared with 240, 400, 600, and 1200 grit SiC papers. Polishing procedures utilized a microcloth and 1.0 micron, 0.3 micron, and 0.05 micron suspensions of alumina (Figure 6). Each sample was then etched in dilute aqua regia ($HCl:HNO_3:H_2O::3:1:20$) solution for progressive time periods until the microstructure of each wire was revealed.

After grinding, polishing, and etching the vertically mounted samples used previously for the Vickers microhardness test, it was determined that horizontally mounted wires would provide more effective results for the microstructure analysis (Figure 7). A metallurgical microscope (Olympus PME3; LECO Corp., St. Joseph, MI) with a digital image acquisition device (SPOT Insight 2MP FirewireMono; Diagnostic Instruments Inc., Sterling Heights, MI) and software (SPOT Software 4.5; Diagnostic Instruments Inc.) was utilized to evaluate the specimens. Digital micrographs were obtained to display data. Magnifications using 10x, 20x, and 50x objective lenses were used for obtaining micrographs.

Figure 7. Acrylic block curing. Wire horizontally placed inside PVC mold, not visible in photograph.

CHAPTER 4
RESULTS

Three tests were conducted to investigate the microstructure and mechanical properties of a number of nickel-free and nickel-containing stainless steel wires. For data that were extrinsic measures, i.e. those differing based on the size of the wires, differences between stainless steel and nickel-free stainless steel wires were most effectively only compared against wires manufactured by the same company. In the case of this investigation, data for percent recovery, stiffness, and force values were compared in this manner. In contrast, data classified as intrinsic measures, those that do not differ with size of the wire due to normalization, could be compared amongst all eight of the stainless steel and nickel-free stainless steel wire samples. Activation modulus and hardness values were analyzed as intrinsic measures.

A number of measures were analyzed from the data collected during the three point bending test. Force values from various deflection points, percent recovery, stiffness values, and activation modulus were calculated for each of the wire products. Each of the wires was compared against each other via ANOVA and Tukey's HSD (honest significant difference) test for the analysis of activation modulus. The Dentaurum wires of Noninium and Remanium showed no statistically significant ($p>0.05$) difference with regards to activation modulus, while all other manufacturers showed statistically significant ($p<0.05$) differences between their nickel-free and stainless steel wires. There was no statistically significant difference between Scheu Chromium and Pozzi/Leone Biosteel and Leowire; however, there was a statistically significant ($p<0.05$) difference between the two Pozzi/Leone samples. The highest activation modulus at 209.6 GPa was noted for Dentaurum Noninium, while the lowest was observed for Pozzi/Leone Leowire (154.1 GPa). With regards to activation modulus, nickel-free stainless steel wires produced by 3 of the 4 manufacturers included in this study showed significantly ($p<0.05$) higher values than the stainless steel counterparts (Table 2).

Activation stiffness and percent recovery were investigated by comparing the nickel-free alternative with the traditional stainless steel manufactured by each company. Analyses did not investigate comparisons between all eight wires. The stainless steel wires produced by Pozzi/Leone and Scheu had the largest activation stiffness values because they were the largest diameter wires, whereas the Dentaurum wires had the lowest activation stiffness due to their smallest diameter. Pozzi/Leone and Acme Monaco nickel-free stainless steel wires all showed significantly ($p<0.05$) higher activation stiffness values than their respective stainless steel counterpart. Percent recovery is similarly affected by cross-sectional area of the wires. Each of the manufacturers showed statistically significant ($p<0.05$) differences between the nickel-free alternatives and the traditional stainless steel wires. For Acme Monaco and Scheu samples, the nickel-free stainless steel alternatives had slightly higher percent recovery values. Findings for Dentaurum and Pozzi/Leone samples were opposite with stainless steel wires have higher values for percent recovery.

Force deflection values were calculated at 0.25 mm, 0.5 mm, 0.75 mm, 1.0 mm, 1.5 mm, 2.0 mm, and 3.0 mm (Table 3). Nickel-free alternatives were compared with their stainless steel counterpart manufactured by the same company. In addition, a comparison was made of all eight wires and their respective force deflection curves. Dentaurum wires showed no significant differences until 1.5 mm of deflection at which

Table 2. Activation stiffness and elastic recovery during bending for the stainless steel wires.

Wire	Activation Stiffness (g/mm)	Activation Modulus (GPa)	Elastic Recovery (%)
Acme Monaco Nickel-Free	703±12 *	195.7±3.3 B	55.7±0.9 *
Acme Monaco Stainless Steel	642±14 *	178.6±4.0 C	54.9±0.7 *
Scheu Menzanium	1766±15	166.4±1.4 D	44.1±0.7 *
Scheu Chromium	1786±11	157.3±1.0 EF	43.2±0.4 *
Pozzi/Leone Biosteel	1819±82 *	160.2±7.3 E	38.2±0.4 *
Pozzi/Leone Leowire	1749±81 *	154.1±7.2 F	41.7±0.4 *
Dentaurum Noninium	470±2	209.6±0.9 A	59.7±0.2 *
Dentaurum Remanium	464±6	206.9±2.8 A	65.5±1.0 *

For intrinsic measures, within each parameter, a different letter denotes significant differences ($p<0.05$) exist between the wires. For extrinsic measures, within each parameter, * denotes significant differences ($p<0.05$) exist between nickel-free and nickel-containing stainless steel wires from the same manufacturer.

Table 3. Activation bending force values at various deflections for the stainless steel wires.

Wire	Force at 0.25 mm (g)	Force at 0.5 mm (g)	Force at 0.75 mm (g)	Force at 1.0 mm (g)	Force at 1.5 mm (g)	Force at 2.0 mm (g)	Force at 3.0 mm (g)
Acme Monaco Nickel-Free	169±5 *	342±6 *	520±9 *	671±11 *	869±10 *	950±7 *	936±21 *
Acme Monaco Stainless Steel	153±10 *	311±12 *	475±20 *	620±33 *	811±50 *	883±34 *	890±19 *
Scheu Menzanium	461±9 *	896±10 *	1264±12 *	1528±10 *	1841±12 *	1954±8 *	1883±16 *
Scheu Chromium	475±10 *	915±9 *	1316±7 *	1624±8 *	1968±7 *	2055±8 *	1983±19 *
Pozzi/Leone Biosteel	467±9 *	915±25 *	1314±54	1554±44	1779±20 *	1861±13 *	1855±26 *
Pozzi/Leone Leowire	434±9 *	865±25 *	1282±55	1586±61	1899±23 *	1988±13 *	1961±36 *
Dentaurum Noninium	113±2	229±2	342±2	435±3	573±4 *	641±4 *	643±6 *
Dentaurum Remanium	113±2	227±3	343±4	449±6	623±8 *	722±9 *	752±16 *

Within each parameter, * denotes significant differences (p<0.05) exist between nickel-free and nickel-containing stainless steel wires from the same manufacturer point the difference in force values between Noninium and Remanium were statistically significant. Data for Pozzi/Leone wires at 0.75 mm and 1.0 mm of deflection were the only other instances of nickel-free stainless steel and stainless steel wires produced by the same manufacturer to show no significant difference of force values. At all deflection points, the stainless steel samples from Scheu had larger force values than the nickel-free stainless steel samples. The opposite trend was observed with the Acme Monaco wires, with the nickel-free stainless steel demonstrating higher force values. Data collected for Pozzi/Leone wires showed a transition at 0.75 mm and 1.0 mm whereby the nickel-free stainless steel wires initially demonstrated higher force values but at larger deflection values, the stainless steel wires demonstrated larger force values. For Dentaurum, no difference in force values was found between the nickel-free and stainless steel wires until the 1.5 mm deflection mark whereupon the stainless steel delivered more force. In general, the nickel-free alternative illustrated a similar force deflection curve as the stainless steel produced by each company; however, in most instances, there was a statistically significant difference between the compared wires (Figures 8-12).

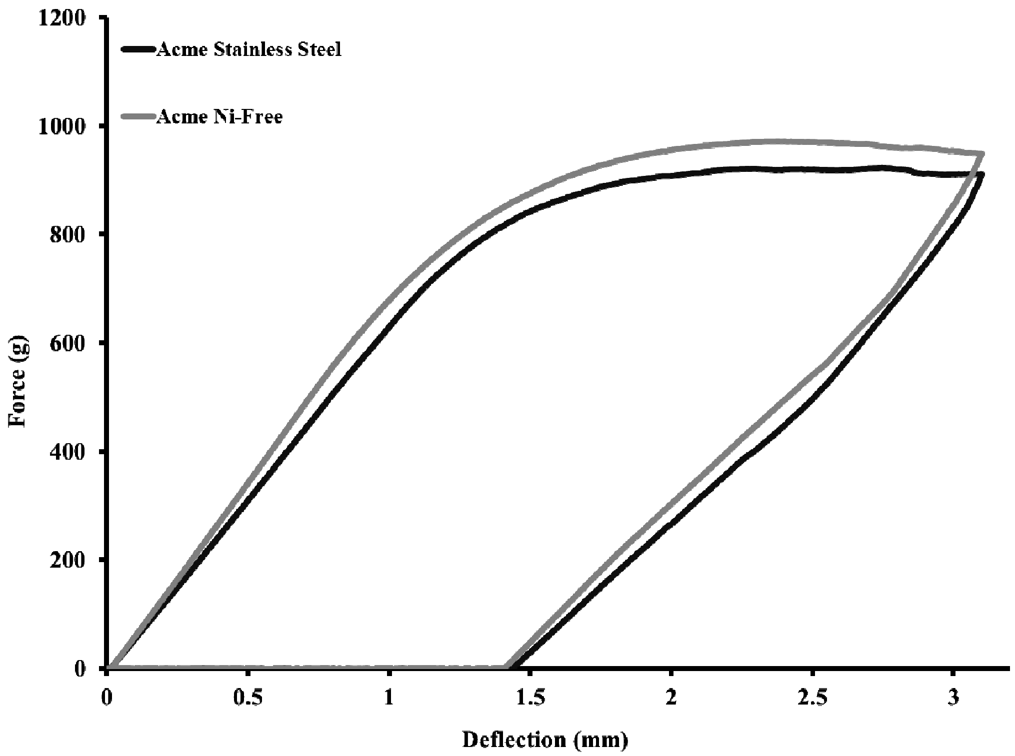

Figure 8. Comparison of typical force-deflection curves of Acme Monaco Nickel-free archwire and Acme Monaco Stainless Steel archwire.

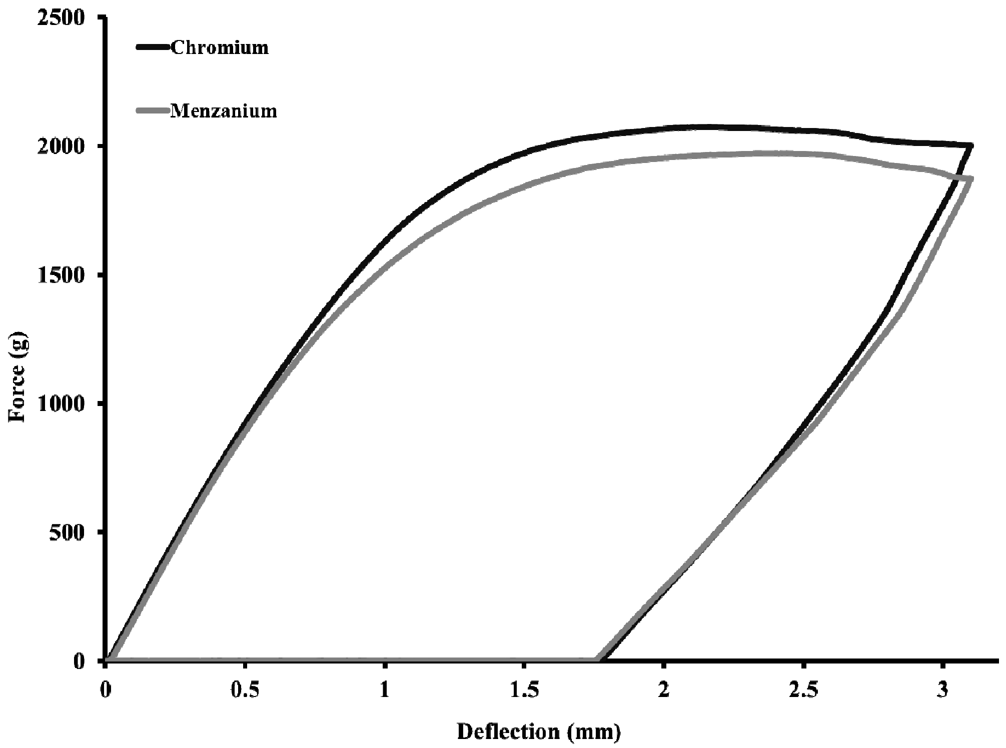

Figure 9. Comparison of typical force-deflection curves of nickel-free (Menzanium) and nickel-containing (Chromium) wires manufactured by Scheu.

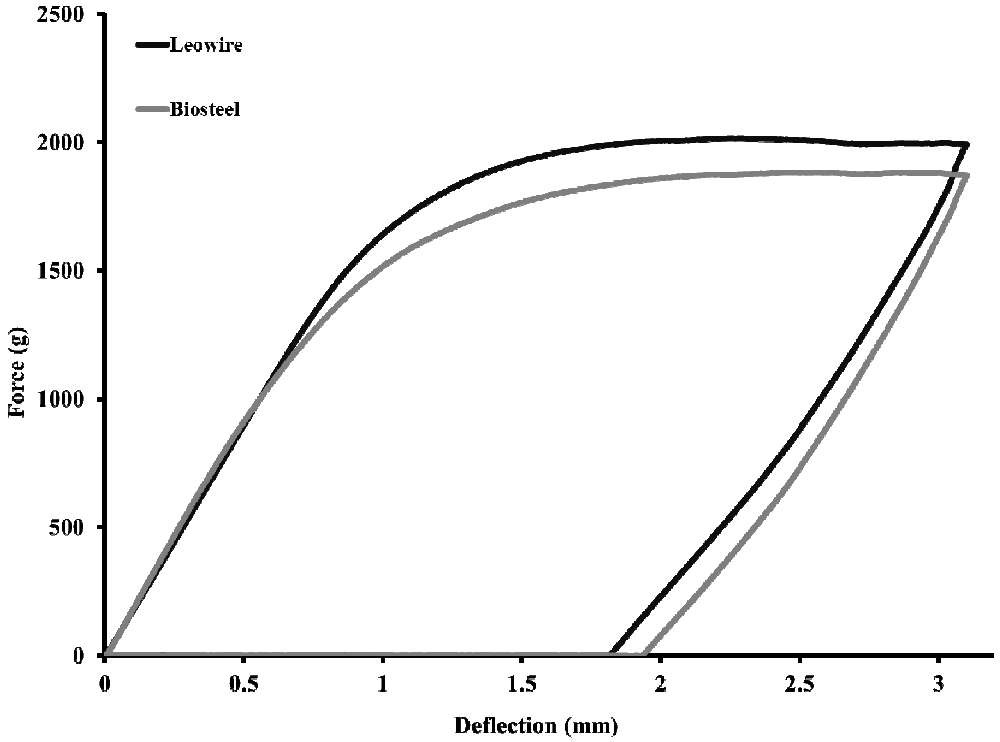

Figure 10. Comparison of typical force-deflection curves of nickel-free (Leowire) and nickel-containing (Biosteel) wires manufactured by Pozzi/Leone.

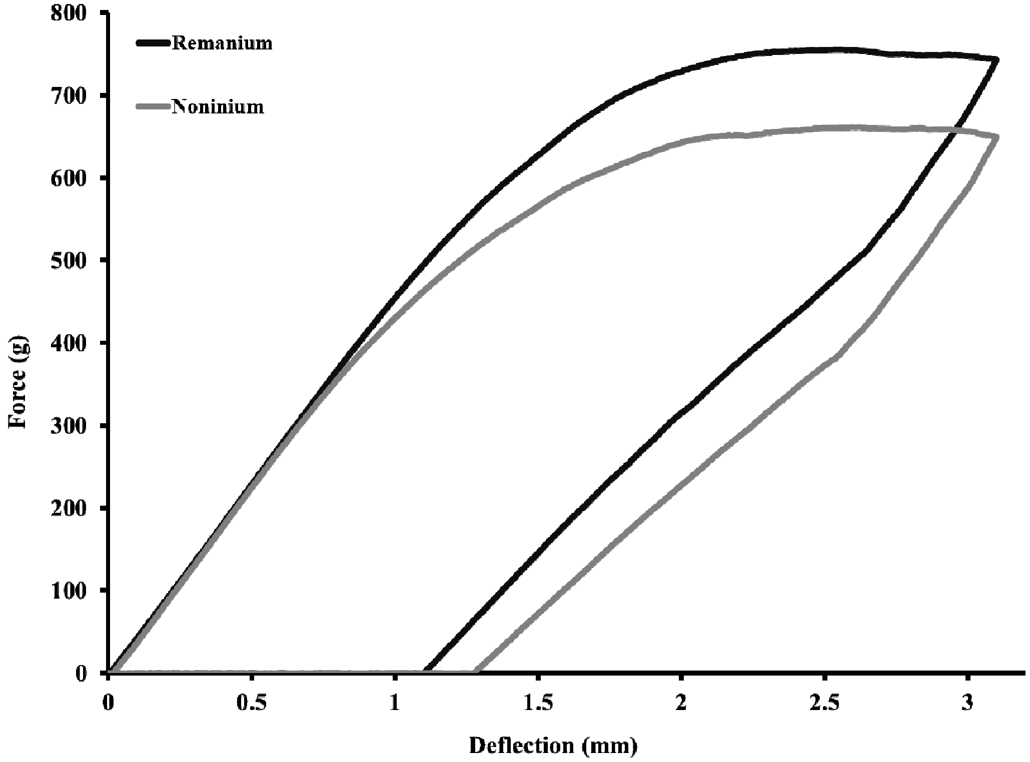

Figure 11. Comparison of typical force-deflection curves of nickel-free (Noninium) and nickel-containing (Remanium) wires manufactured by Dentaurum.

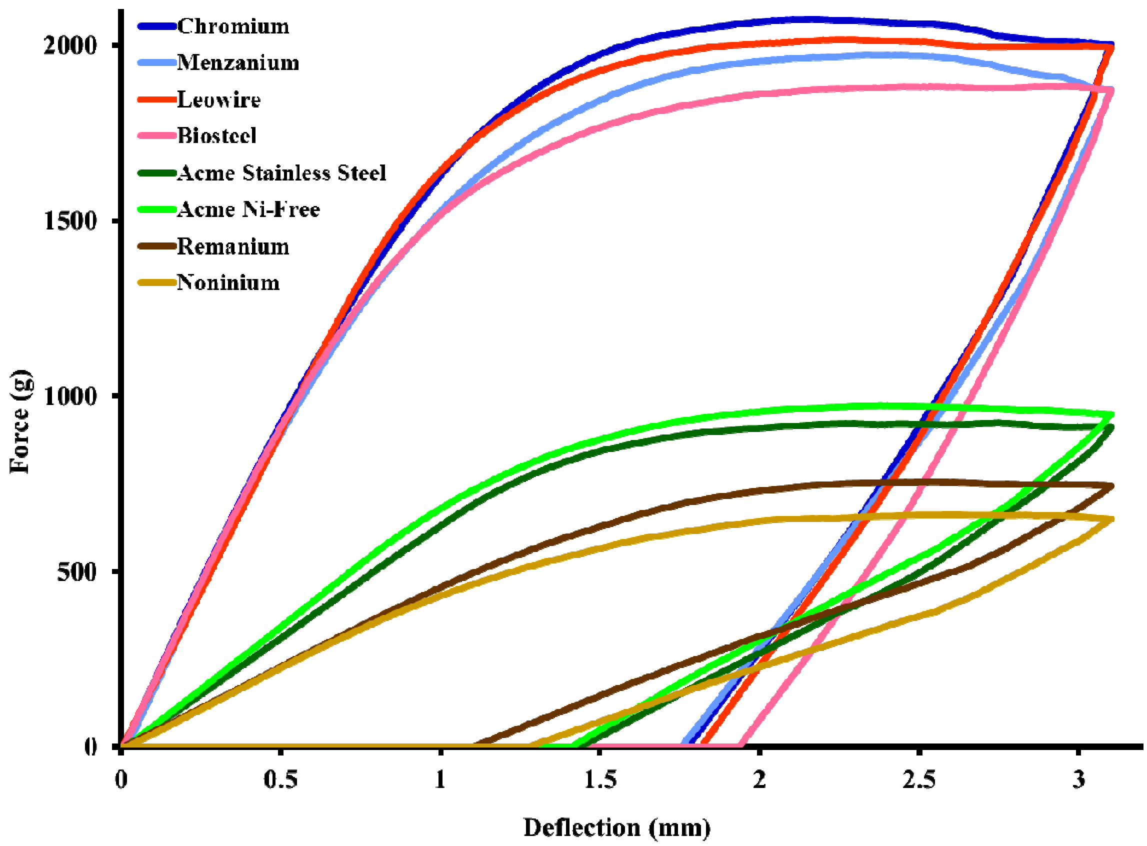

Figure 12. Comparison of typical force-deflection curves for all wires.

Mean hardness values from the Vickers microhardness test were compared amongst all eight samples, as previously stated. The ANOVA test was conducted for each calculated mean hardness value and the Tukey's HSD (honest significant difference) test post hoc analysis was conducted when necessary. Dentaurum Remanium, a stainless steel wire, was found to be the hardest wire tested. There was a statistically significant difference in hardness between Dentaurum Remanium and the other seven sampled wires. The nickel-free stainless steel wires produced by Scheu and Pozzi/Leone were numerically the softest wires tested, with statistically significant differences in hardness compared only with the stainless steel wire from Acme Monaco and Dentaurum Remanium. For the four manufacturers included in this study, the stainless steel samples demonstrated larger hardness values than their respective nickel-free stainless steel counterparts, although as mentioned it was only significant for the Dentaurum wires. Refer to Table 4 for further analysis of the tested wires and their calculated mean hardness values.

Table 4. Vickers microhardness values for the stainless steel wires.

Wire	Hardness Value (kg/mm^2)
Acme Monaco Nickel-Free	514±8 BC
Acme Monaco Stainless Steel	525±7 B
Scheu Menzanium	503±18 C
Scheu Chromium	524±11 BC
Pozzi/Leone Biosteel	503±5 C
Pozzi/Leone Leowire	504±5 BC
Dentaurum Noninium	515±7 BC
Dentaurum Remanium	568±14 A

Different letters denote significant differences ($p<0.05$) exist between the wires.

The results from the microstructure investigation indicate different grain structures and sizes for the stainless steel and nickel-free stainless steel wires produced by each manufacturer. The stainless steel archwire by Acme Monaco had flat, elongated grains whereas the nickel-free alternative had a grain structure closer to equiaxed, being roughly equal in all dimensions (Figures 13-16). Scheu stainless steel and nickel-free stainless steel wires differed mostly by grain size. Both Scheu Chromium and Menzanium wires had elongated grain structures with the stainless steel wire demonstrating grains smaller in size (Figures 17-20).The Pozzi/Leone wires differed significantly by grain structure. Biosteel, the Pozzi/Leone nickel-free stainless steel wire, had a coarse grain structure with internal texturing evident, whereas Leowire, the same company's stainless steel, had more elongated grains (Figures 21-24). Comparison of

Dentaurum Noninium and Remanium wires revealed more elongated grains in the nickel-free stainless steel (Figure 25-28). With the exception of the stainless steel wire from Acme Monaco and the nickel-free stainless steel from Pozzi/Leone, elongated grains were observed, consistent with the structure observed in wrought orthodontic wires.

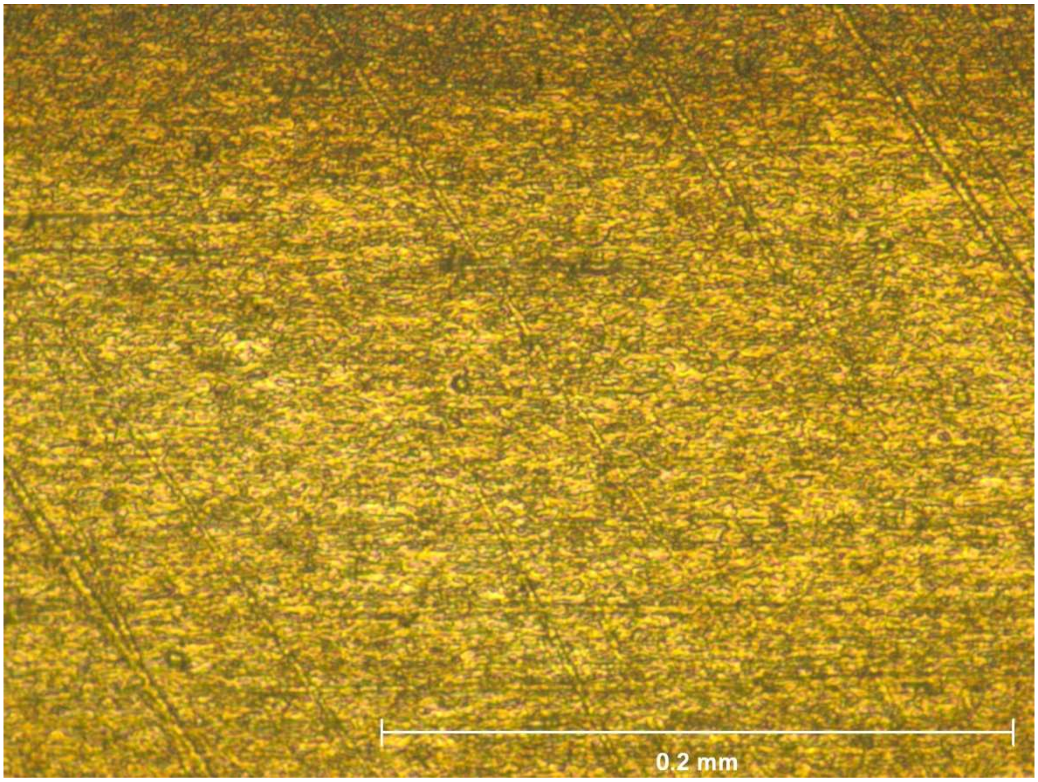

Figure 13. Optical micrograph of Acme Monaco Nickel-free archwire surface at 20x magnification

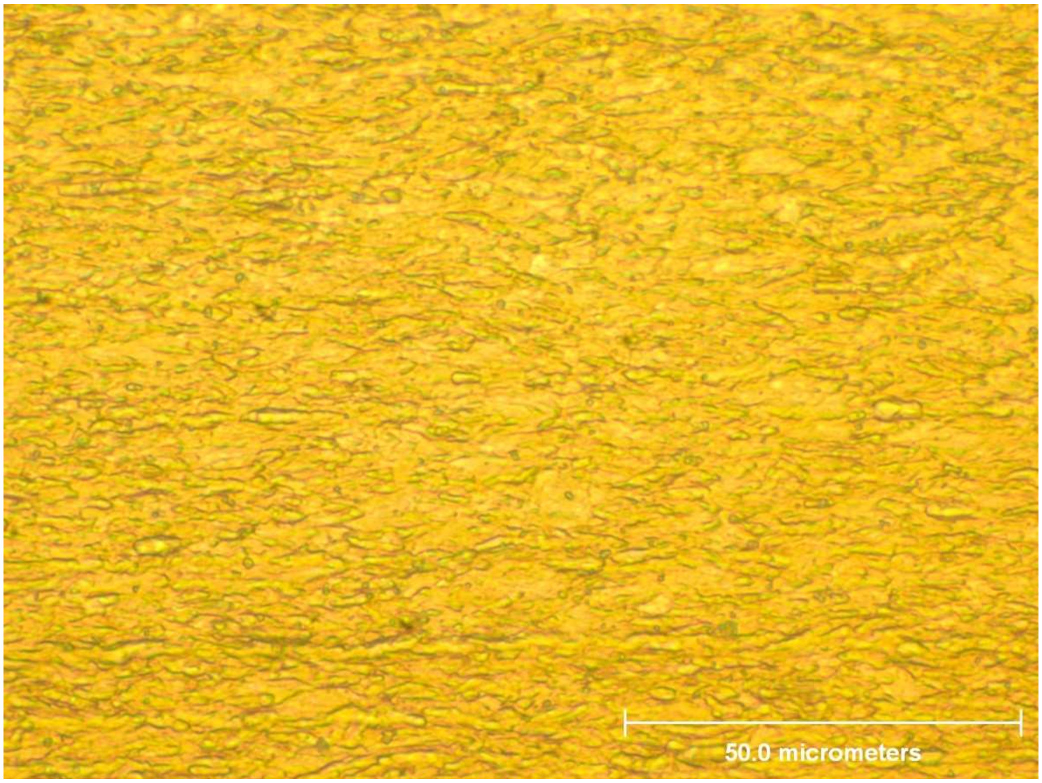

Figure 14. Optical micrograph of Acme Monaco Nickel-free archwire surface at 50x magnification

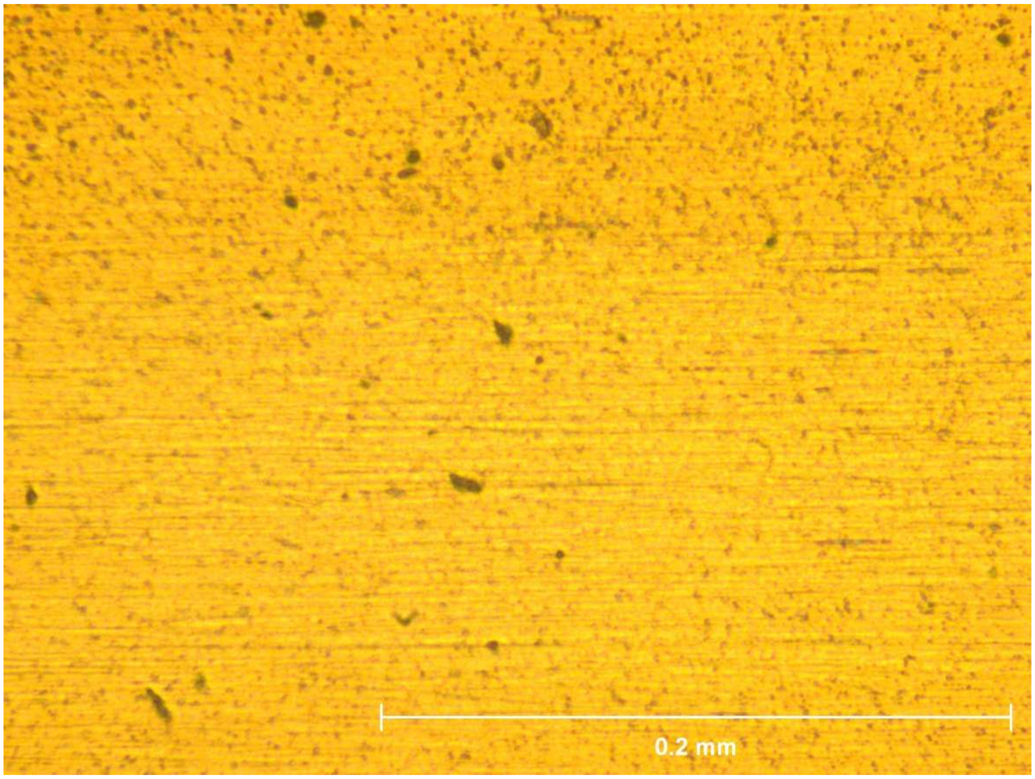

Figure 15. Optical micrograph of Acme Monaco Stainless Steel archwire surface at 20x magnification

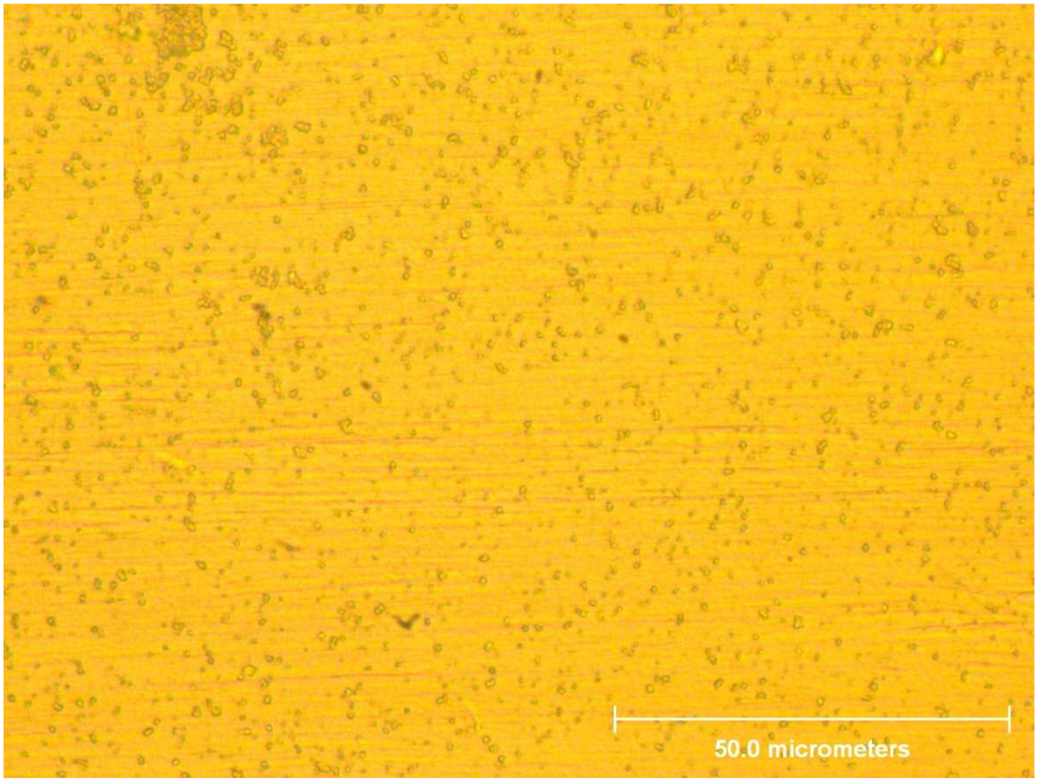

Figure 16. Optical micrograph of Acme Monaco Stainless Steel archwire surface at 50x magnification

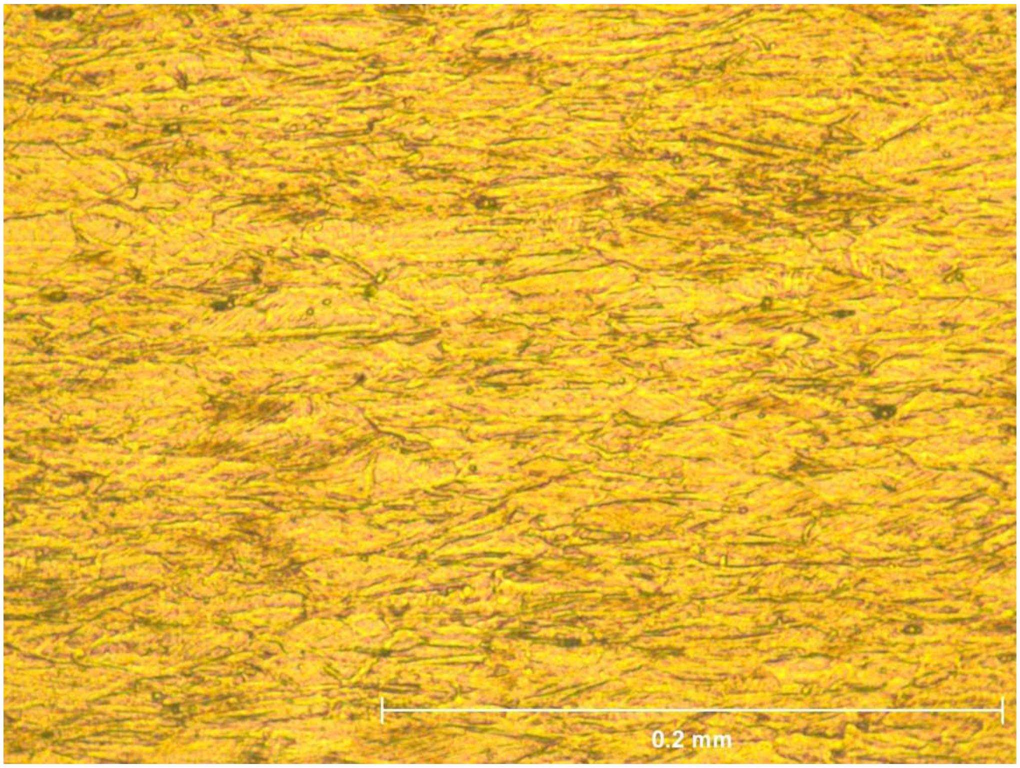

Figure 17. Optical micrograph of Scheu Menzanium wire surface at 20x magnification

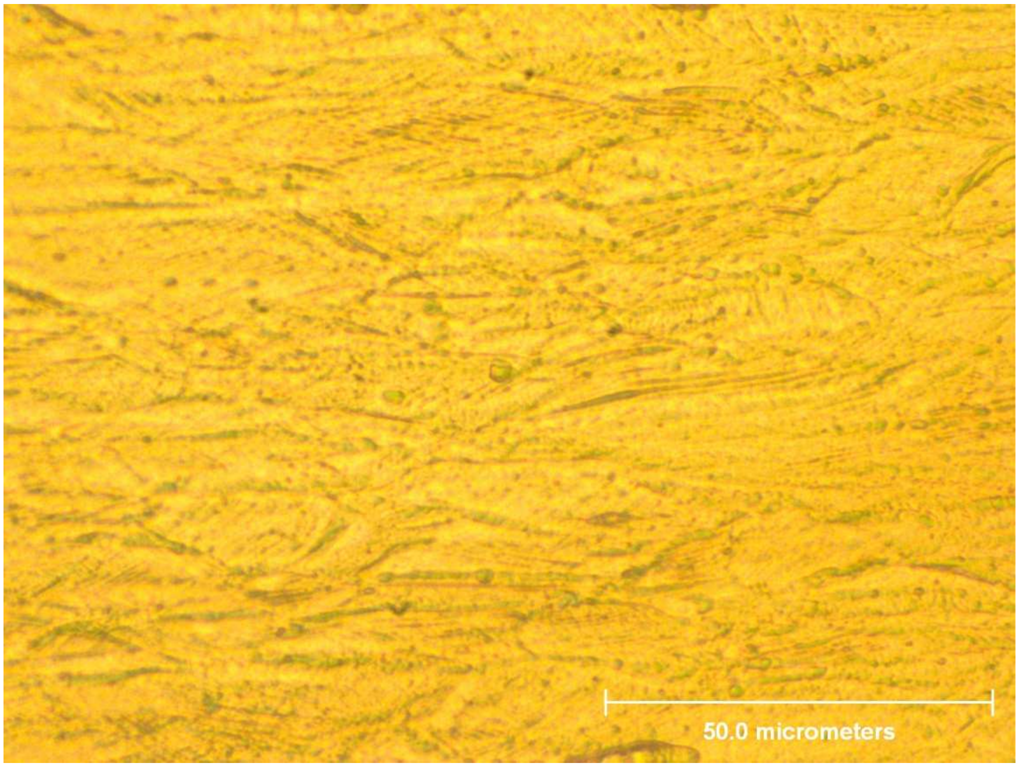

Figure 18. Optical micrograph of Scheu Menzanium wire surface at 50x magnification

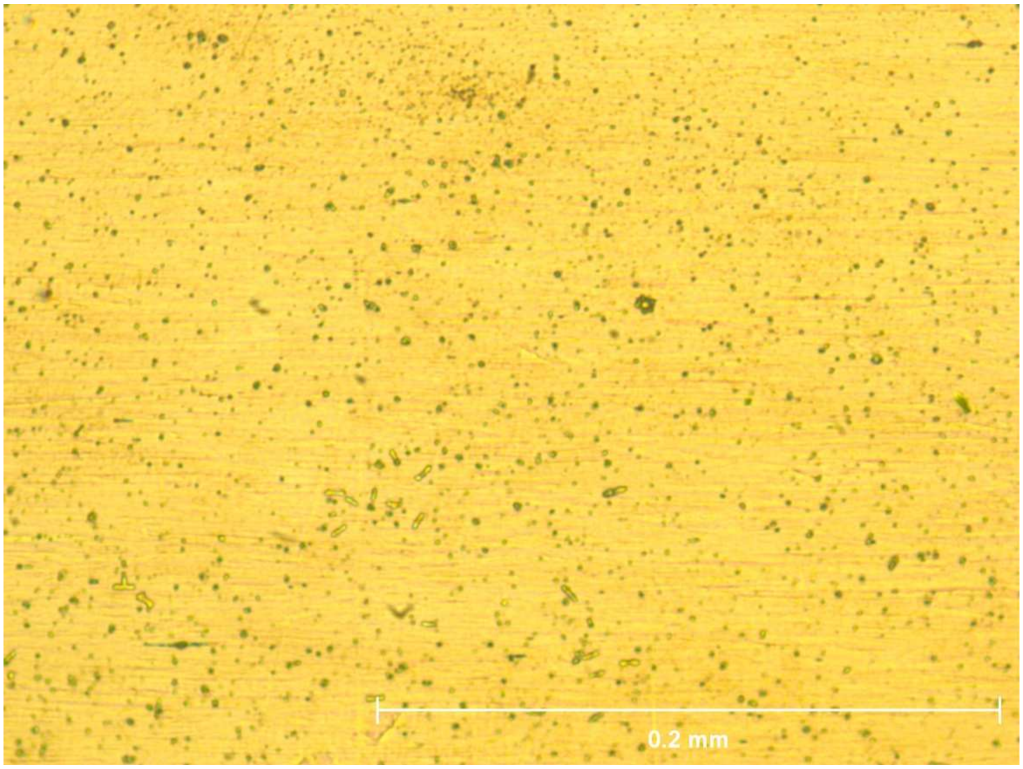

Figure 19. Optical micrograph of Scheu Chromium wire surface at 20x magnification

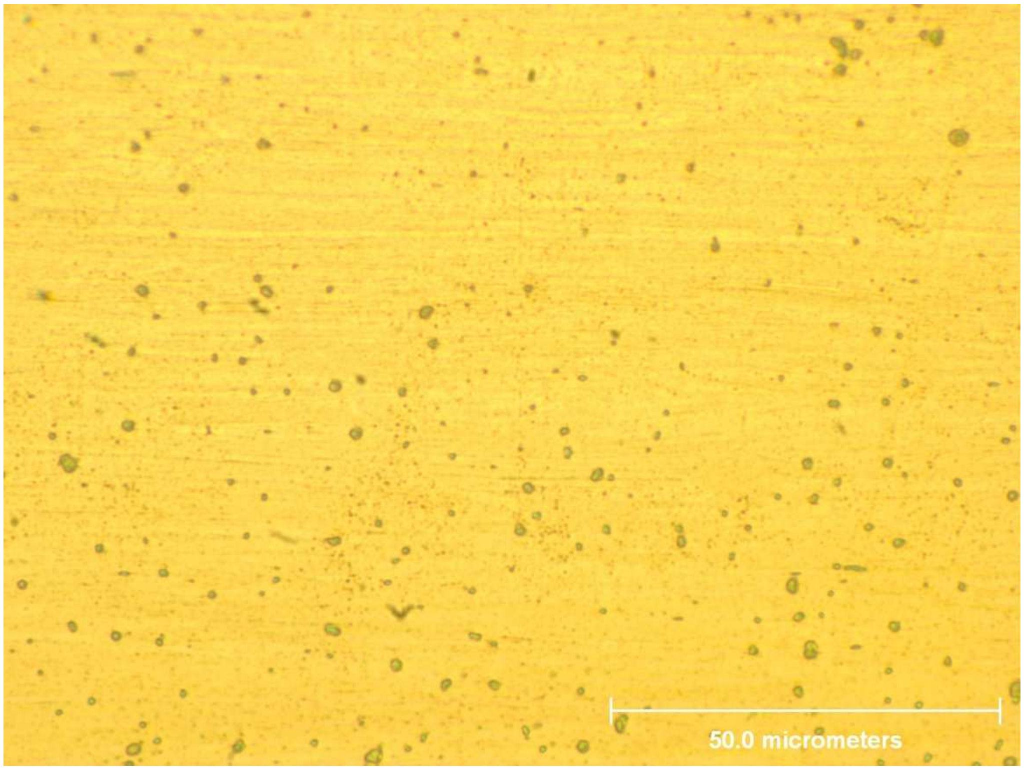

Figure 20. Optical micrograph of Scheu Chromium wire surface at 50x magnification

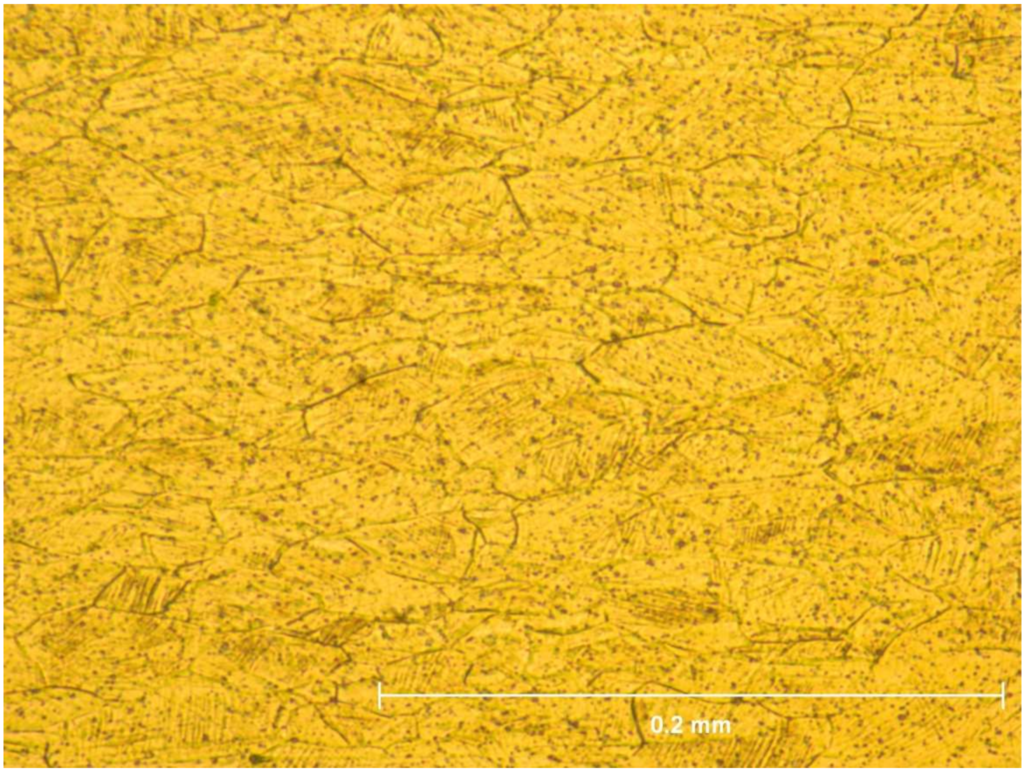

Figure 21. Optical micrograph of Pozzi/Leone Biosteel wire surface at 20x magnification

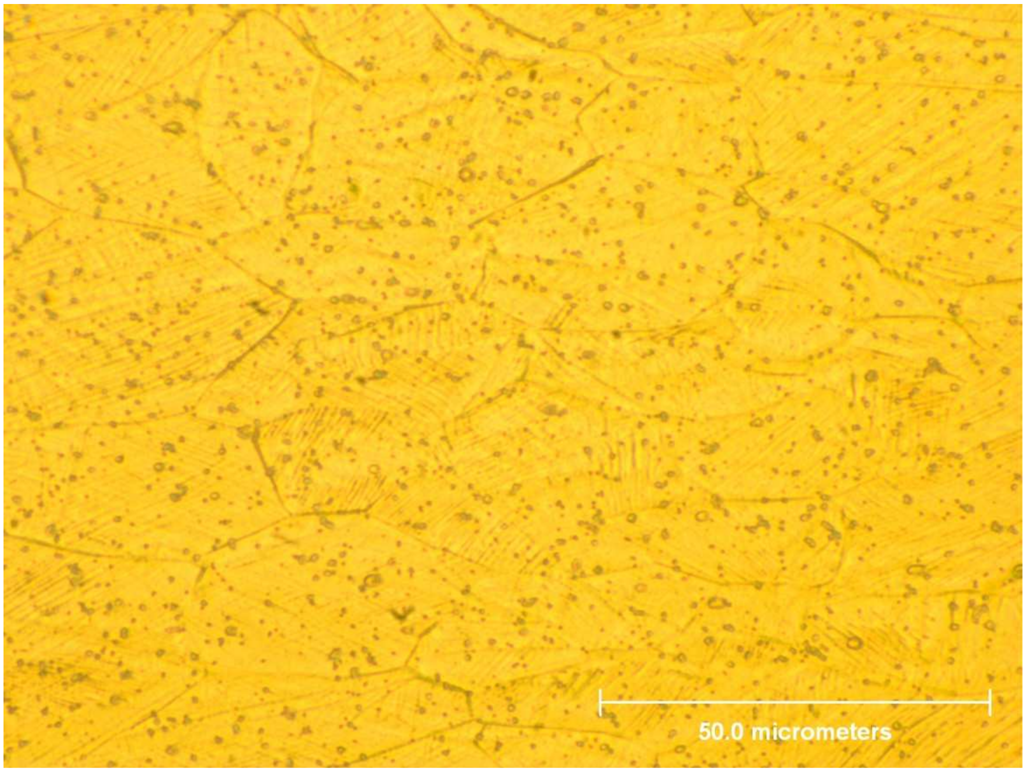

Figure 22. Optical micrograph of Pozzi/Leone Biosteel wire surface at 50x magnification

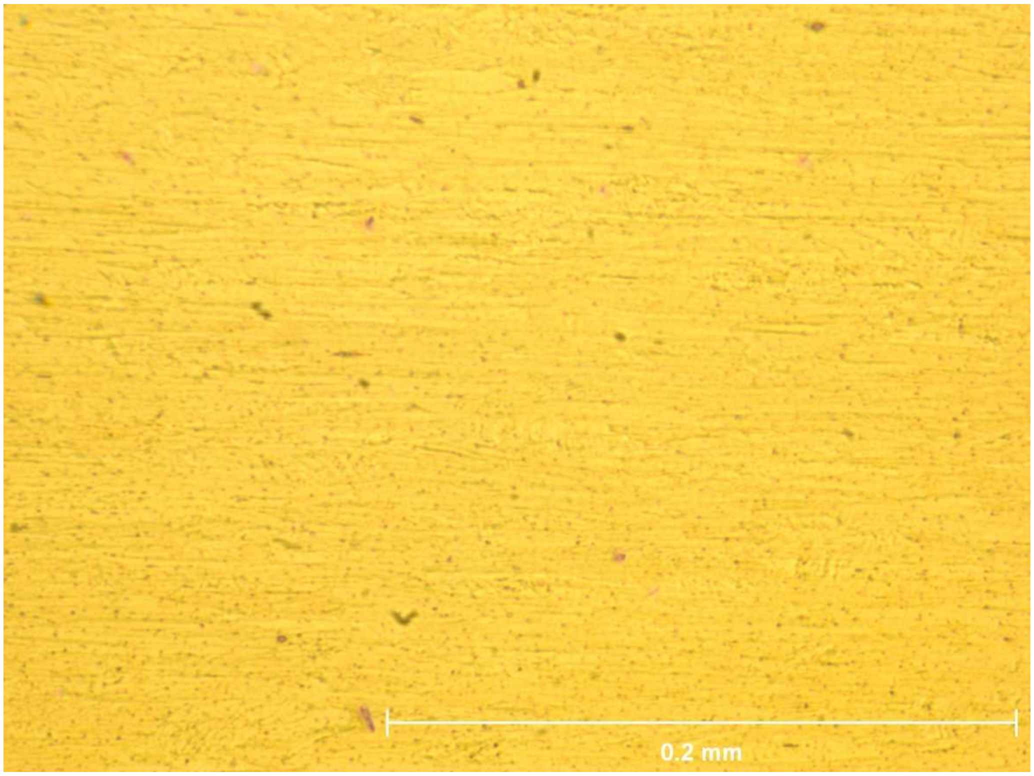

Figure 23. Optical micrograph of Pozzi/Leone Leowire wire surface at 20x magnification

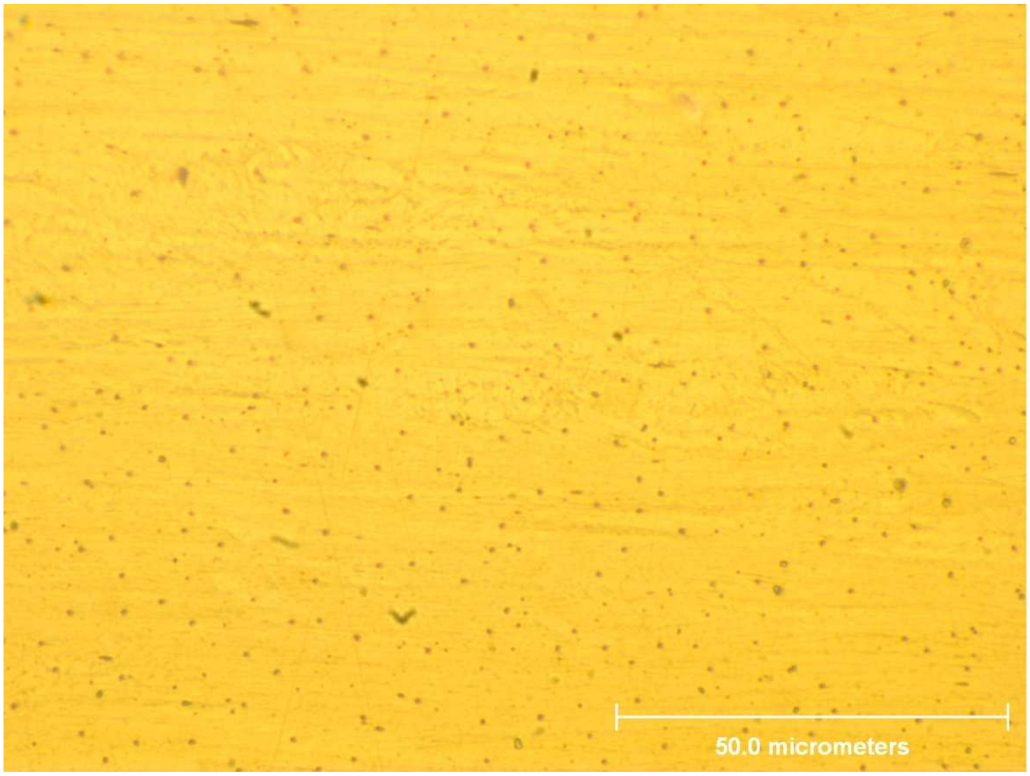

Figure 24. Optical micrograph of Pozzi/Leone Leowire wire surface at 50x magnification

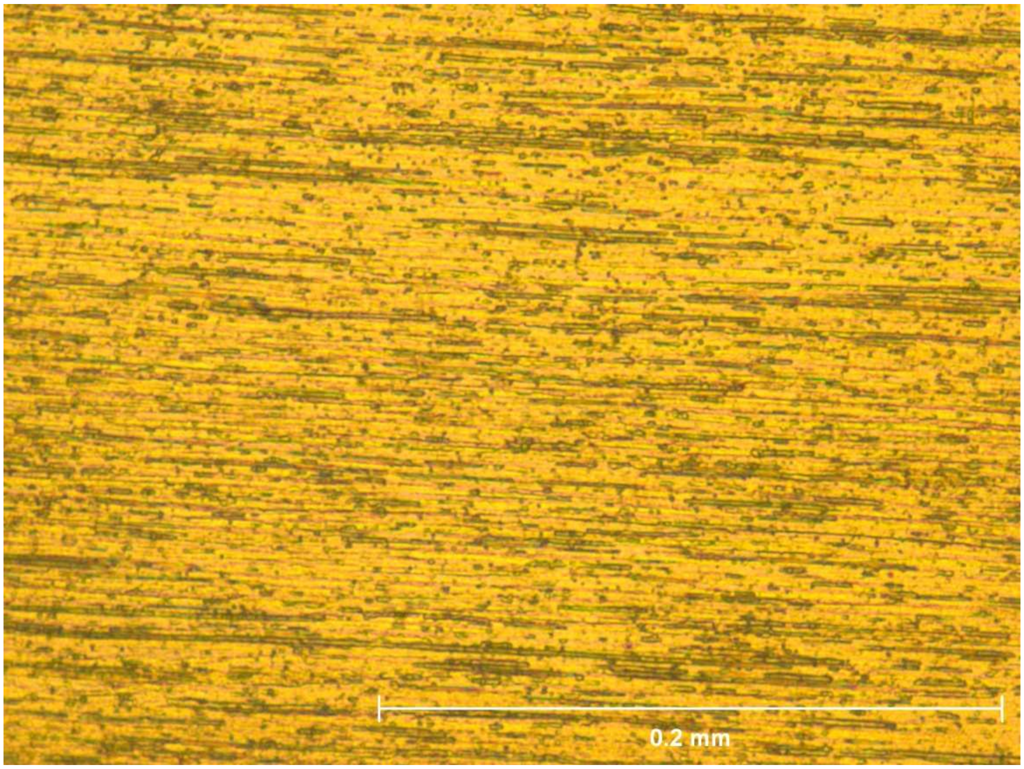

Figure 25. Optical micrograph of Dentaurum Noninium wire surface at 20x magnification

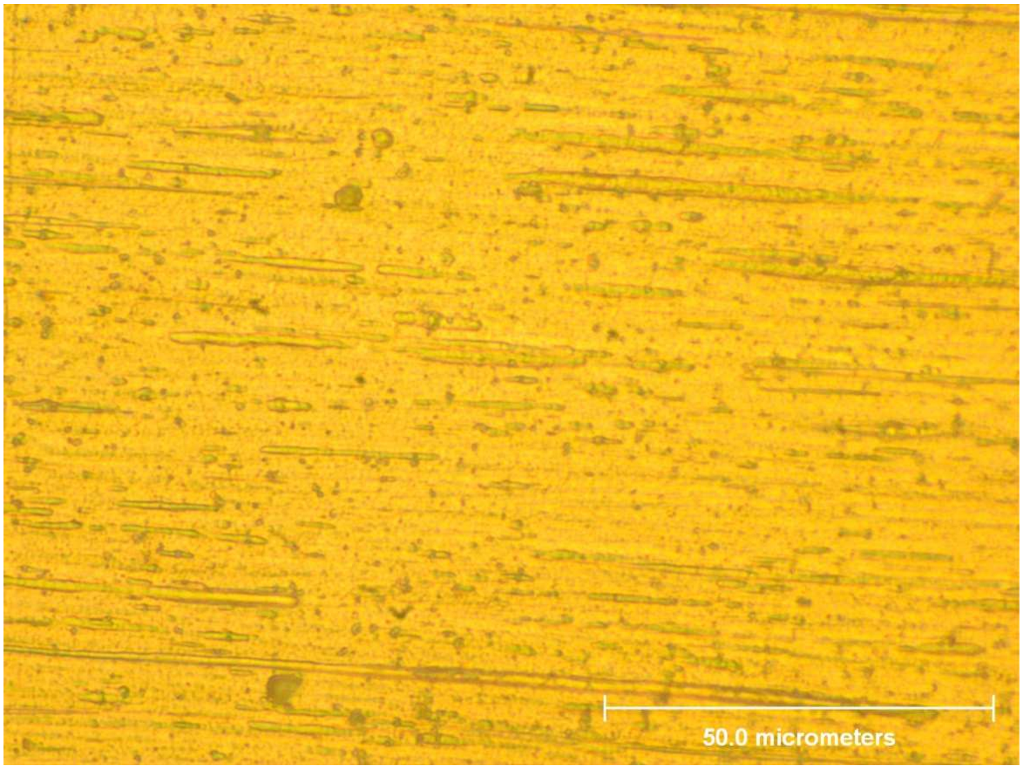

Figure 26. Optical micrograph of Dentaurum Noninium wire surface at 50x magnification

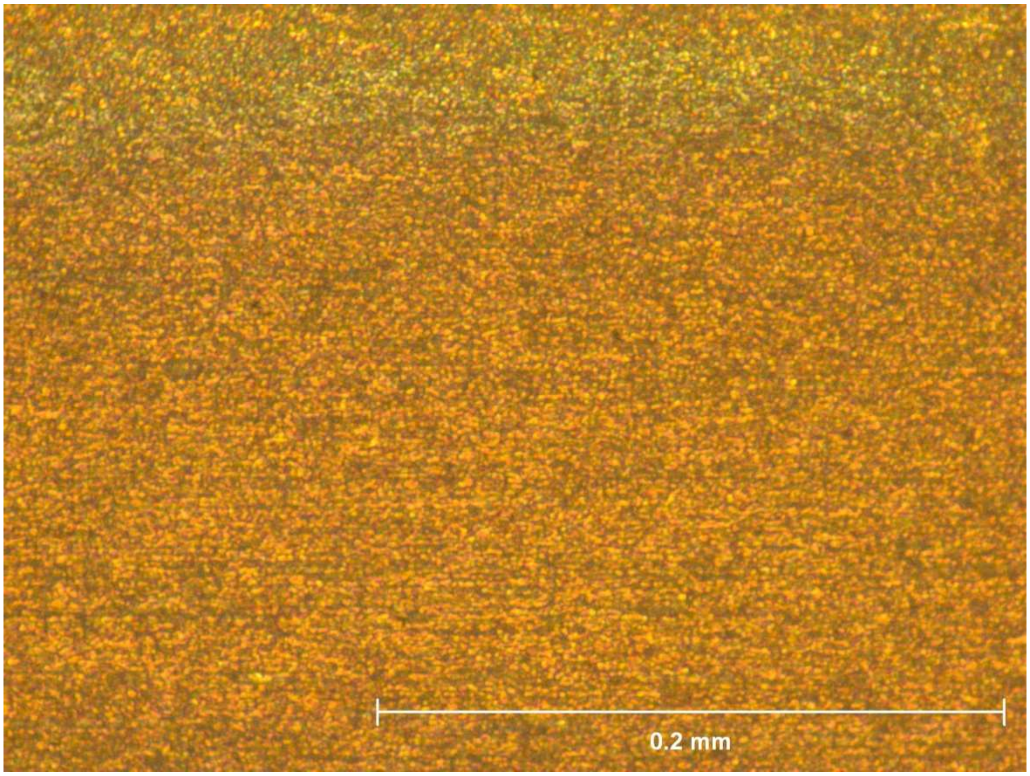

Figure 27. Optical micrograph of Dentaurum Remanium wire surface at 20x magnification

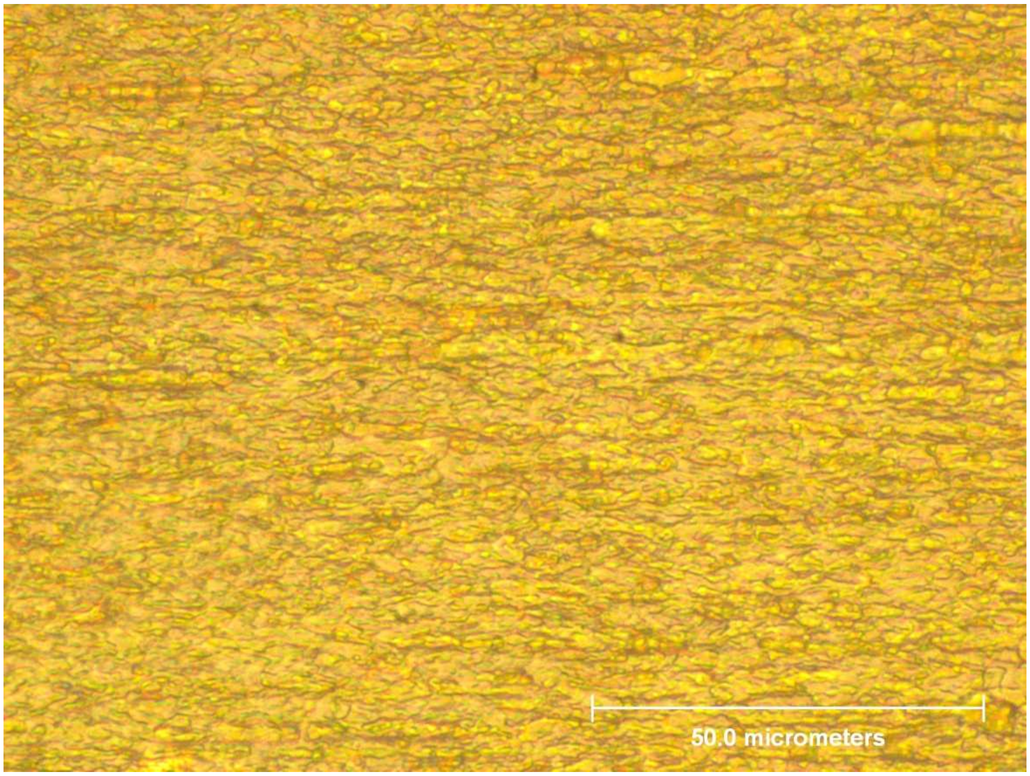

Figure 28. Optical micrograph of Dentaurum Remanium wire surface at 50x magnification

CHAPTER 5
DISCUSSION

The increasing prevalence of nickel allergies requires orthodontists to utilize nickel-free alternatives throughout treatment to avoid hypersensitivity reactions in nickel-sensitive patients. Since its introduction to orthodontics in 1977, beta-titanium alloy has been commonly utilized for patients with nickel allergies due to its excellent clinical properties and nickel-free composition (Kapila & Sachdeva, 1989; Kusy, 2002; Kolokitha et al., 2008). However, depending on the mechanics involved in treatment, the practitioner may require an archwire with different properties. For example, beta-titanium archwires have a rough surface compared with stainless steel, posing potential problems with certain sliding mechanics. Nickel-free stainless steel archwires could provide an alternative for orthodontists when treating patients with nickel allergies. In order for orthodontists to incorporate this alternative stainless steel archwire into treatment, the nickel-free stainless steel archwires must provide clinically effective mechanical properties. Another critical component in determining the properties and efficacy of nickel-free stainless steel archwires in orthodontics is to investigate the microstructure in comparison to traditional stainless steel.

In this study, the bending properties were similar between nickel-free stainless steel and traditional stainless steel orthodontic archwires. For example, the ratio of the activation stiffness between the two wires from each respective manufacturer ranged between 91 and 99%. For all of the bending force values displayed in Table 3, the ratio of forces at a given deflection between the two wires from each respective manufacturer averaged 94% and in only two instances did this ratio fall below 90% (for the Dentaurum wires at 2 and 3 mm deflections). The reason for the similarity in stiffness and applied force values between the nickel-free and regular stainless steel wires most likely involves what element was used in place of nickel in the nickel-free stainless steel. A concurrent investigation into the composition of the wires tested showed manganese (Mn) was the main element used to replace nickel. Additionally, the nickel-free wires had a few wt% more Cr and Mo, but less Fe. Manganese does not differ appreciably from nickel in atomic radius (Fe = 140 pm, Mn = 140 pm, Ni = 135 pm), thus alloy strengthening via substitutional solid solution strengthening would not be expected to be that different. Further, the Young's modulus of nickel is 200 GPa and Mn is 198 GPa, further limiting any difference in strengthening.

Despite the overall similarities in bending properties, statistical significance was frequently observed when comparing the nickel-free and regular stainless steel wires. In addition, a few general trends were noticeable. With the exception of the Acme Monaco wires, the nickel-free stainless steel, in general, delivered lower force levels than their respective stainless steel counterparts. As seen in Figure 12, wires with similar cross-sections exhibit comparable bending profiles. As expected, orthodontic archwires with smaller cross-sections deliver lower force levels throughout the entirety of deflection. Dentaurum archwires showed higher activation modulus values indicating more inherently rigid materials. Larger diameter wires produced by Scheu and Pozzi/Leone demonstrated lower modulus values. All manufacturers showed higher modulus values for their nickel-free stainless steel archwires. The reason this may not be consistent with the activation stiffness for the Scheu wires is because the Chromium wire measured 0.60 mm in diameter whereas the Menzanium wire measured 0.59 mm in diameter. Thus, the activation stiffness was greater but, when normalized for size as in the modulus determination, the nickel-free variety (Menzanium) actually had a slightly greater activation modulus. Although minimal as mentioned above, the different modulus values for the nickel-free stainless steel archwires could be a result of different composition and different processing, such as heat treatment or temperature during fabrication. In general, the nickel-free wires exhibited slightly greater activation stiffness and modulus but typically had lower force values at larger deflections. Although contradictory at first glance, it should be reiterated that the stiffness/modulus were measured between deflections of 0.25 and 0.5 mm, which lie in the elastic region of the bending curve whereas many of the forces beyond 0.75-1.25 mm, depending on wire size, resided in the plastic region. Elastic deformation and force values result from stretching of interatomic bonds whereas force levels during plastic deformation are influenced by the ease of dislocation movement. From Figure 12, it is apparent that the nickel-free wires generally experience less work hardening which shows as decreased amounts of force required to continue deflecting the wire in the plastic deformation region (greater than 0.75-1.25 mm deflections). Once again, although the effect is relatively small, it could be caused by the different composition and different processing between wires.

As would be expected with stainless steel, the archwires included in this study showed minimal percent recovery values. Scheu and Pozzi/Leone wires demonstrated less recovery than Acme Monaco and Dentaurum. While Acme Monaco and Dentaurum wires showed elastic recovery beyond 1.5 mm deflection, the larger wires by Scheu and Pozzi/Leone were permanently deformed with no further springback after returning to a deflection of 1.75 mm on deactivation. This data demonstrates the stiffer nature of larger diameter archwires and the corresponding greater permanent deformation. Less springback, as demonstrated by Scheu and Pozzi/Leone archwires, correlate to an expected increased force on teeth during orthodontic treatment for these wires. However, definitive conclusions are difficult to draw with regards to nickel-free compared with traditional stainless steel wires. Pozzi/Leone and Dentaurum stainless steel archwires had larger observed percent recovery when compared with their nickel-free counterparts, while Acme Monaco and Scheu nickel-free stainless steels demonstrated higher springback than stainless steel wires manufactured by the same companies.

Load deflection properties provide valuable information about the wires effect on biologic tooth movement during orthodontic treatment. Lower values required for deflection of the wire indicate more controlled, lighter forces to the tooth, as well as the surrounding tissues. Scheu Chromium, a traditional stainless steel archwire, consistently demonstrated the largest forces at all deflection values, indicating more force applied to the dentition compared with Scheu Menzanium. As demonstrated with stiffness, the larger wires in this study demonstrated greater force values reliably at all deflection values. It would be expected that these larger stainless steel wires would provide greater force to the teeth and surrounding tissues. This is why smaller stainless steel archwires are utilized when lesser forces are required. Acme Monaco nickel-free stainless steel showed significantly greater force levels than Acme Monaco stainless steel at all deflection points. However, similar definitive results cannot be drawn for Dentaurum or Pozzi/Leone samples. It can be pointed out that through 1.0 mm of deflection, no significant difference was observed between Dentaurum Noninium and Remanium suggesting minimal difference between the stainless steel and nickel-free alternative produced by this manufacturer.

Hardness, with regards to surface characteristics of metals, refers to the “resistance to indentation”. The Vickers microhardness test investigates the surface hardness of very small areas, such as stainless steel orthodontic archwires. The data obtained from the bending and Vickers microhardness tests provides a measure for being able to compare the nickel-free stainless steel wires to the nickel-containing stainless steel wires. Mechanical properties that contribute to surface hardness include strength, ductility, malleability, and resistance (Anuradha Acharya & Jayade, 2005). In orthodontics, hardness refers to the wear pattern of archwires. Typically, stainless steel archwires have the hardest surface, followed by beta-titanium, suggesting less wear of stainless steel during treatment (Yu et al., 2011). This study found that three of the traditional stainless steel wires had statistically similar Vickers microhardness values compared to the nickel-free stainless steel wires produced by their corresponding manufacturers. The only nickel-free alternative that tested significantly softer than its nickel-containing stainless steel counterpart was Dentaurum Noninium. Dentaurum Remanium, a traditional stainless steel, was significantly harder when compared with all other samples included in this study.

Microstructure investigation revealed differences in processing for stainless steel and nickel-free stainless steel wires produced by all manufacturers included in this study. In addition, the difference observed in grain size and shape amongst the Scheu samples could be due to a difference in laboratory processing. All wires, except the Acme Monaco and Pozzi/Leone nickel-free stainless steel archwires, showed elongated grains aligning parallel to the long axis of the wire. These findings are consistent with a wrought orthodontic wire having undergone mechanical reduction steps during processing. The Pozzi/Leone Biosteel and Acme Monaco nickel-free stainless steel archwires microstructures, differing from the typical wrought wire characteristics, indicate different intermediate manufacturing processes, such as heat treatments. As a result of these inconsistencies, no significant observations could be made from the data gathered during the microstructure analysis of the tested stainless steel and nickel-free stainless steel archwires.

While the results demonstrated by this study do not necessarily reflect the clinical situations to which orthodontic archwires are subjected intraorally, they do provide a comprehensive basis of mechanical properties in order to compare stainless steel and nickel-free stainless steel archwires. The results may provide the necessary information needed for orthodontists to assess the potential for replacing traditional stainless steel archwires with nickel-free stainless steel alternatives in those patients with known nickel allergies. The nickel-free alternative wire, beta-titanium, is currently readily available to orthodontists, providing adequate properties to act as a good archwire for intermediate and finishing stages of treatment. Beta-titanium demonstrates higher springback and lower forces than stainless steel; however, these archwires still provide clinically sufficient strength and formability (Kapila & Sachdeva, 1989; Gurgel et al., 2011; Proffit et al., 2012). One of the major disadvantages of beta-titanium archwires is the cost (Gurgel et al., 2011). For nickel-free stainless steel to become more commonplace in orthodontic offices, the characteristics of these archwires would need to be more similar yet remain as cost-effective as traditional stainless steel.

There remains debate whether nickel is released from stainless steel archwires in sufficient concentrations to cause hypersensitivity reactions in the oral cavity. Some research suggests that the way nickel is bound in a crystal lattice within stainless steel it would be unlikely that significant reactions would develop during typical orthodontic treatment (Rahilly & Price, 2003). It may be necessary to continue nickel allergy research to determine conclusively the detrimental effects of stainless steel archwires during orthodontic treatment. In those patients presenting with known nickel allergy, it would be necessary to replace all nickel-containing appliances. The archwire alone may not be deemed the major contributing factor to a hypersensitivity reaction in a patient with nickel allergies. While it is critical to find nickel-free replacements for the traditional stainless steel archwire, it is also imperative to find alternatives to brackets, bands, and other orthodontic appliances containing nickel. Determining the efficacy of nickel-free stainless steel archwires in orthodontic treatment is just one step towards providing satisfactory treatment for patients with nickel allergies.

CHAPTER 6
CONCLUSION

This study investigated the mechanical properties and microstructure of nickel-free stainless steel and traditional stainless steel orthodontic archwires produced by the same manufacturers. In general, the three-point bending test revealed nickel-free stainless steel archwires are stiffer with higher activation modulus values. With the exception of Acme Monaco, nickel-free stainless steel archwires demonstrated lower force levels than their stainless steel counterparts during deflection. Force deflection values for Acme Monaco nickel-free stainless steel were consistently larger than the corresponding stainless steel. Scheu Chromium displayed the largest force deflection values and the most similarity was noted between the two wires manufactured by Dentaurum. With regards to percent recovery, all archwires tested showed significant differences with the larger diameter archwires by Scheu and Pozzi/Leone showing earlier permanent deformation during deflection. Dentaurum Remanium was the hardest archwire tested, demonstrating significant differences when compared with all other archwires. The stainless steel wire from each manufacturer was found to be harder than its respective nickel-free stainless steel counterpart, with the only statistically significant difference found for the Dentaurum samples. The data gathered in this study suggests that, with mechanical similarities to stainless steel, nickel-free stainless steel archwires may be an adequate alternative for treatment in patients with nickel allergies. However, in order to draw more definitive conclusions about the efficacy of nickel-free stainless steel wires during orthodontic treatment, a comprehensive clinical study would need to be conducted.

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