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Recommended Citation
Schwab, Alex, "The Effect of Heat Treatment on the Bending Properties of a Cobalt-Chromium Orthodontic Wire" (2017). *Master's Theses (2009 -)*. 422.
http://epublications.marquette.edu/theses_open/422

THE EFFECT OF HEAT TREATMENT ON THE BENDING PROPERTIES OF A COBALT-CHROMIUM ORTHODONTIC WIRE

By

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A Thesis submitted to the Faculty of the Graduate School,
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in Partial Fulfillment of the Requirements for
the Degree of Master of Science

Milwaukee, Wisconsin

August 2017

ABSTRACT
THE EFFECT OF HEAT TREATMENT ON THE BENDING PROPERTIES OF A COBALT-CHROMIUM ORTHODONTIC WIRE

Alex Michael Schwab, DDS

Marquette University, 2017

Introduction: Elgiloy, a brand name of the original cobalt-chromium orthodontic wire, has been around for more than 50 years; yet despite this, little literature is available. Most of the literature on Elgiloy wires tends to evaluate the wires in tension. For these reasons, this study aimed to determine the bending properties of the four available tempers of Elgiloy wires and how heat treatment affects the wires' bending properties.

Materials and Methods: All four tempers of Elgiloy (red, yellow, green, and blue) were ordered in straight lengths containing 20 wires per pack that are each 0.018 inches in diameter and 14 inches in length. Two consecutive 20 mm segments were cut from each wire in all four tempers creating 40 specimens in each temper. Half of the wire segments were heat treated at 500°C for five hours and the other half remained as-received for the testing process (n=20/temper/condition). All 160 segments of Elgiloy wire were tested by a three-point bend test at 23°C (room temperature). Stiffness, flexural modulus, percent recovery, and force values were statistically compared using ANOVA ($p<0.05$).

Results: The heat treated wires showed significantly increased force values at the various deflections when compared to their as-received counterpart. Some of the different tempers for heat treated and as-received groups did have similar force values at a given deflection, but differences were observed between the tempers. The stiffness, flexural modulus, and percent recovery were also calculated for all eight groups. Heat treatment significantly increased stiffness, flexural modulus, and percent recovery for all four tempers of Elgiloy.

Conclusion: Heat treatment of Elgiloy wires led to a significant increase in stiffness, modulus, percent recovery, and force values required to deflect the wire at various deflection measurements. Despite Elgiloy wire being around for a long period of time, not a lot of literature is available. Therefore, further research and investigation is needed to determine how heat treatment of Elgiloy wires can influence their clinical use.

ACKNOWLEDGEMENTS

Alex Michael Schwab, DDS

I would like to thank my advisor, Dr. David Berzins, for all his assistance in conducting my research. I would also like to thank Dr. Dawei Liu and Dr. Bhoomika Ahuja for not only being a part of my committee but also for their dedication to Marquette's Orthodontic program that allowed me receive an excellent education in orthodontics. Finally, I cannot express how grateful I am to my wife, Kelley, who was so supportive in my decision to return back to school to pursue my dream to become an orthodontist.

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CHAPTER 1

INTRODUCTION

To be a competent orthodontist, professionals must have a thorough understanding of orthodontic wires in order to effectively and efficiently move teeth. Orthodontic wires have evolved throughout the years with each different wire providing unique mechanical properties and clinical applications.

Gold and Early Wires

In 1887 Edward Angle, known as the father of American orthodontics, initially used nickel-silver alloys in his orthodontic appliances (Quintao and Brunharo 2009). Angle later replaced those alloys with copper, nickel, zinc, and eventually gold (Kusy 2002). Type IV gold was the most widely utilized alloy in the fabrication of orthodontic accessories until the early 1930s. At the time 14 to 18-carat gold was often used for wires, bands, hooks, and ligatures. Several of the advantages to using gold were its corrosion resistance and the ability to alter its stiffness through heat treatment (Kusy 2002).

Stainless Steel Wires

Stainless steel was introduced to orthodontics in 1929 as a substitute for gold and in 1931, at the AAO Conference, it was proposed to have greater resilience with less likelihood of breakage than gold (Quintao and Brunharo 2009). Due to cost, steel soon gained worldwide acceptance over gold for use in orthodontics. Steel wires proved to be beneficial for additional reasons such as its yield strength, good corrosion resistance, elasticity, low bracket-wire friction, and the ability to solder attachments to them. Additionally, when compared to beta-titanium and nickel-titanium, stainless steel wires can produce higher forces over a shorter period of time due to their lower spring back ability and lower amount of stored energy (Kotha et al. 2014). Due to the multiple advantages and low cost, stainless steel wires are still very prevalent in modern orthodontic treatment.

Cobalt-Chromium Wires

In the 1940s a cobalt-chromium alloy was developed by the Elgin Watch Company for springs in watches. The alloy was made up of cobalt (40 wt%), chromium (20 wt%), iron (16 wt%), and nickel (15 wt%). By the 1960s, this cobalt-chromium was patented as Elgiloy and introduced to orthodontics by the company Rocky Mountain Orthodontics (Kusy 2002). Elgiloy has similar properties to stainless steel; however, Elgiloy wires must be heat treated after creating bends in order to apply their full response potential. There are four available tempers of Elgiloy wires that are formed by different amounts of cold working. Cobalt-chromium wires can be heated for as little as 7 minutes at 482^{o}C according to some studies, while the manufacturer recommends five hours, to increase the hardness (strength) to a level approximately equal to that of steel, while non-heat treated cobalt-chromium wires have a smaller spring back compared to steel (Kotha 2014). Similar to steel, cobalt-chromium wires have excellent corrosion resistance, are inexpensive, and can be soldered. Following heat treatment, Blue Elgiloy wires demonstrate increased formability, yield strength, and elasticity making them popular in clinical applications.

Beta-Titanium, Nickel-Titanium, and Copper-Nickel-Titanium Wires

Although beta-titanium alloys have been known since 1952, it was not until 1979 that wire drawing technology existed to manufacture these wires for orthodontic use. The first clinical application of beta-titanium occurred in the 1980s when "high temperature" titanium, also known as "TMA" (for titanium molybdenum alloy), was introduced to market (Goldberg 1979). Around a similar time, in 1972, Unitek Corporation produced nickel-titanium alloy for orthodontic use under the trade name Nitinol after the alloy was developed earlier by the U.S. Naval Ordnance Laboratory (Miura et al. 1990). Nickel-titanium wires are composed of 55 wt% nickel and 45 wt% titanium. At this time, these wires lacked the shape memory and superelasticity that they are known for today, but were used for light forces in large activations. The modulus of elasticity for TMA wires is less than half of stainless steel, but nearly twice that of Nitinol (Verstrynge, Van Humbeeck, and Willems 2006). TMA wires have good formability, but risk breakage if bent too strongly. Good biocompatibility due to the absence of nickel and corrosion resistance are additional advantages of TMA wires; however, exposure to fluoride agents can lead to break down of the protective passive oxide layer and subsequent corrosion (Ogawa et al. 2004). Additional drawbacks of TMA include high bracket-wire friction and cost.

Later, in 1985 and 1986, researchers in China and Japan respectively developed NiTi wires with greater elastic recovery and less stiffness than traditional NiTi wires. These wires were termed "superelastic." In the mid-1990s copper was added to nickel-titanium wires (CuNiTi), which led to better defined thermal properties compared to NiTi and increased control of desired tooth movement. The

CuNiTi wires, first introduced by Ormco Corporation, presented with three transition temperatures that allow clinicians to apply forces that are appropriate to their desired treatment outcomes (Quintao et al. 2009).

When activated the same amount, nickel-titanium wires possess higher energy storage capacity than both beta-titanium and stainless steel wires (Brantley 2001). The main advantages of NiTi wires are their increased elasticity and wide activation range while delivering low forces (Huang et al 2003). On the other hand, the disadvantages of NiTi include high cost, low formability, and inability to be welded (Brantley 2009). Nickel-titanium wires also have the most bracket-wire friction when compared to beta-titanium, cobalt-chromium, and stainless steel.

Esthetic Wires

Most recently, esthetic wires were introduced in the mid-2000s to meet the demand for alternatives to the appearance of metal wires. These include wires "such as: Teflon coated stainless steel wires, stainless steel wires coated with epoxy resin, orthodontic wires comprising a nylon-based matrix reinforced with silicone fibers, and orthodontic wires made from polymer composite material reinforced with glass fiber" (Quintao and Brunharo 2009).

Application and Purpose

As technology continues to advance and provide more options for the clinician to achieve their treatment goals, it becomes essential to understand the properties of the available wires in order to achieve optimal results. No single wire is appropriate for all stages of orthodontic treatment. A thorough understanding of the unique properties different wires possess can lead to the most efficient treatment possible while at the same time minimizing any damage to the teeth and periodontal tissue.

CHAPTER II

BACKGROUND AND SIGNIFICANCE

After the Elgin Watch Company developed a cobalt-chromium alloy in the 1940s, Rocky Mountain Orthodontics introduced it to the profession of orthodontics as Elgiloy. Cobalt-chromium wires are manufactured and commercially available through Rocky Mountain Orthodontics as Elgiloy in four tempers: soft (blue), ductile (yellow), semi-resilient (green), and resilient (red). The primary make up of the wires is cobalt (40 wt%), chromium (20 wt%), iron (16 wt%), and nickel (15 wt%)(Kusy 1997). "In addition to having similar stiffness characteristics as stainless steel, the alloy is capable of having its strength, and more importantly its formability, modified by heat treatment" (Kusy 1997).

The formability prior to heat treatment allows clinicians to bend loops in the wires more easily and increases the working range of the wire as well. However, once the loops are formed resiliency is favored over formability and this is achieved through a precipitation hardening heat treatment (Callister 1994). Through this process both resilience and ultimate strength are increased. Following heat treatment, cobalt-chromium wires have improved spring back properties that are comparable to stainless steel. The manufacturer recommends heat treatment at 900^{o}F (482^{o}C) for five hours, while some studies claim as little as 7 to 12 minutes in a dental furnace (Elgiloy and Truchrome 1987) causes precipitation hardening and thus increases the deformation resistance of Elgiloy to similar levels as stainless steel (Filmore and Tomlinson 1979). Wires should be heated until they are a dark straw color. When wires are over heated, at temperatures above 1200^{o}F (749^{o}C), it leads to a rapid decline in deformation resistance of the Elgiloy wires due to partial annealing (Filmore and Tomlinson 1976).

Four tempers are available that vary in formability ranging from hard and resilient, Red Elgiloy, to soft and formable, Blue Elgiloy. The different tempers offer a range of mechanical properties for practitioners to utilize. Blue Elgiloy is the softest of the four available tempers. Due to its ability to be easily bent, Blue Elgiloy is best used when substantial bending, soldering, and welding is required. Heat treatment increases the resistance of Blue Elgiloy (Kapila and Sachdeva 1989). Yellow Elgiloy is more resilient than Blue Elgiloy, but still easily bent. Heat treatment of Yellow Elgiloy increases its resilience and spring performance (Kapila and Sachdeva 1989). Green Elgiloy is more resilient than Yellow, while Red Elgiloy is the most resilient temper available. Red Elgiloy provides high spring performance; yet, care must be taken when it is bent, as it is only able to withstand minimal working. The resilience of Red Elgiloy and chances of fracture increase greatly with heat treatment, and for this reason, all bends must be performed prior to any heat treatment.

The requirement to heat treat cobalt-chromium wires in order to achieve similar strength to stainless steel wires of comparable sizes leads many clinicians to utilize stainless steel instead when desiring higher strength. Nevertheless, cobalt-chromium wires present several advantages over stainless steel wires such as fatigue resistance, distortion resistance, and longer function as a resilient spring (Orthodontic Wires 1957). Both cobalt-chromium and stainless steel wires demonstrate good formability and high moduli of elasticity. The modulus of elasticity for these wires is twice that of beta-titanium and four times as much as nickel-titanium wires (Drake et al. 1982).

Despite Elgiloy (cobalt-chromium) wires being around since the 1960s there is little literature available on their clinical and mechanical properties. As mentioned previously, Elgiloy wires must be heat treated after creating bends in order to apply their full response potential**.** The purpose of this study was to evaluate the effects heat treatment has on the bending properties of the four available tempers of Elgiloy wire. This was achieved by comparing segments of heat treated wires to non-heat treated or as-received wires through a three-point bend test. The limited studies available on Elgiloy wires tend to evaluate their performance in tension, while there is a lack of information on their bending properties. For this reason and the greater relevance of bending over tension in clinical orthodontics, the information in this study aims to provide a better understanding of the mechanical properties of Elgiloy wires as well as how heat treatment can alter those mechanical properties.

CHAPTER III

MATERIALS AND METHODS

Materials

Elgiloy wire was obtained from Rocky Mountain Orthodontics (Denver, CO, USA). The wires are manufactured in various tempers with a corresponding color that represents Elgiloy wire's unique properties: red (resilient), green (semi-resilient), yellow (ductile), and blue (soft). All four tempers were ordered in straight lengths containing 20 wires per pack that are each 0.018 inches in diameter and 14 inches in length.

Preparation of Elgiloy Wires and Heat Treatment

Two consecutive 20 mm segments were cut from each wire in all four tempers creating 40 specimens in each temper. Half of the wire segments were heat treated and the other half remained as-received for the testing process. This created 160 total specimens with each type of wire/temper and condition consisting of 20 specimens (n= 20/temper/condition).

Half of the wires (20 specimens of each temper) were heat treated in order to compare the effects of heat treatment on the bending properties of the Elgiloy wires to non-heat treated/as-received Elgiloy wires. This represented the condition of each wire. The heat treated wires were heated in a Neytech Vulcan Multi-stage Programmable Furnace (Model 3-130) at 500^{o}C for 5 hours (Figures 1 and 2). These designated 80 specimens were heat treated all at once within the same furnace.

Testing

The 160 segments of Elgiloy wire were tested using three-point bending at 23±2°C (room temperature). The wires were centered between two metal support beams that were 14 mm apart. The load was vertically applied with a universal testing machine (Instron Corp, Norwood, Mass) to the middle of each wire at a rate of 2 mm/min to a maximum deflection of 3.1 mm (Figure 3), and then returned to the starting position at the same rate (Chang et al 2014). The three-point bend test was performed following American National Standard/American Dental Association specification No. 32 for orthodontic wires (ANSI/ADA 2006) with the exception that the span between the two beams was modified to 14 mm rather than 12 mm to prevent the wire from falling from the metal support beams during deflection (Figure 4).

Commercial software (Merlin, Instron) was used to record the force required to cause deflection of the wire during loading (activation) and unloading (deactivation). A "Load (kgf) vs Extension (mm)" graph was generated for each segment of wire tested. The data for each wire test was isolated to include the recorded load in kgf at each mm increment of recorded extension. From there, the unit for load was converted from kgf to g. Using the information from the graph and the diameter of the wires (0.00044 m) the percent recovery, activation modulus or

Figure 1. Neytech Vulcan Multi-stage Programmable Furnace Model 3-130

Figure 2. Heating Chamber of Neytech Vulcan Multi-stage Programmable Furnace

Figure 3. Instron Universal Testing Machine

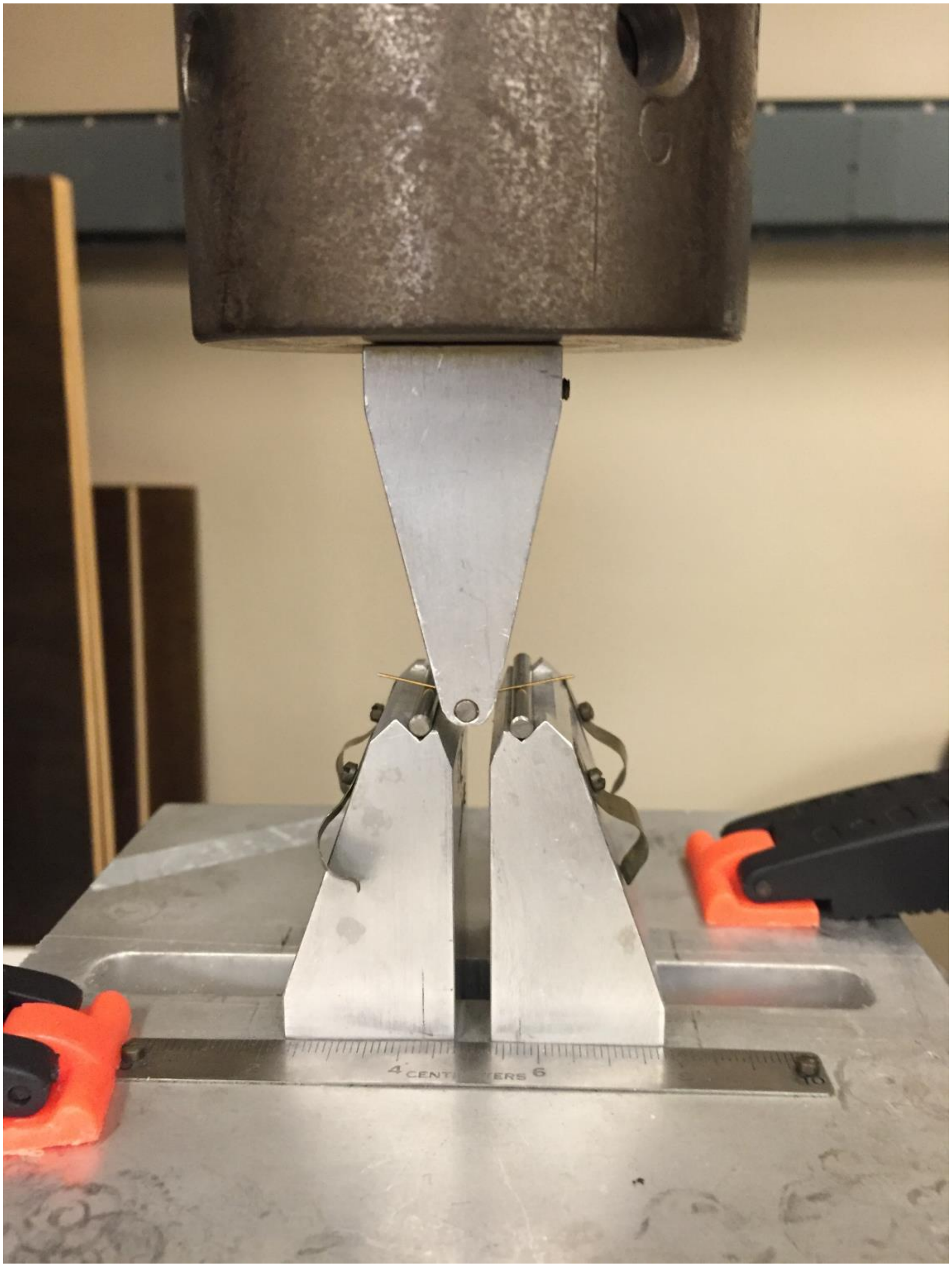

Figure 4. Instron Universal Testing Machine Performing Three-Point Bend Test

stiffness (g/mm), flexural modulus (GPa), and activation force (g) at deflection increments of 0.25 mm up to 2.5 mm were calculated. An average value and standard deviation was also determined for each of these values for all of the 8 different categories of wires.

Statistical Analysis

Statistical analysis was performed using a two-way ANOVA with temper and condition as factors. Due to a significant ($p<0.05$) interaction, a one-way ANOVA followed by a Post Hoc Tukey HSD test was conducted. A p-value <0.05 indicated a statistically significant difference between wires for a given measure.

CHAPTER IV

RESULTS

All four tempers, Red Elgiloy (Fig. 5), Yellow Elgiloy (Fig. 6), Green Elgiloy (Fig. 7), and Blue Elgiloy (Fig. 8), showed a statistically significant ($p<0.05$) difference between the heat treated and as-received wires within each temper. The heat treated wires showed significantly ($p<0.05$) increased force values at the various deflections when compared to their as-received counterpart (Table 1). Some of the different tempers for heat treated and as-received groups did have similar force values at a given deflection (Table 1). For example, at 0.25 mm of deflection there were six statistically distinct groups of wires of the eight groups tested where AR was less than AG & AY, AG & AY were less than HR, HR was less than HG & AB, HG & AB were less than AB & HY, and AB & HY were less than HB. At deflections of 0.75 mm, 1.25 mm, 2.0 mm, and 2.25 mm there were eight statistically different groups, while the remaining deflections showed similarities of force values between some wires. The stiffness, flexural modulus, and percent recovery (Table 2) were also calculated for all eight groups. There was a significant difference ($p<0.05$) between all eight groups of Elgiloy wires for all three measures. Heat treatment significantly increased stiffness, flexural modulus, and percent recovery for all four tempers of Elgiloy. The four heat treated tempers (Fig. 9) and four as-received tempers (Fig. 10) were also graphically compared together to evaluate the different force properties of each temper.

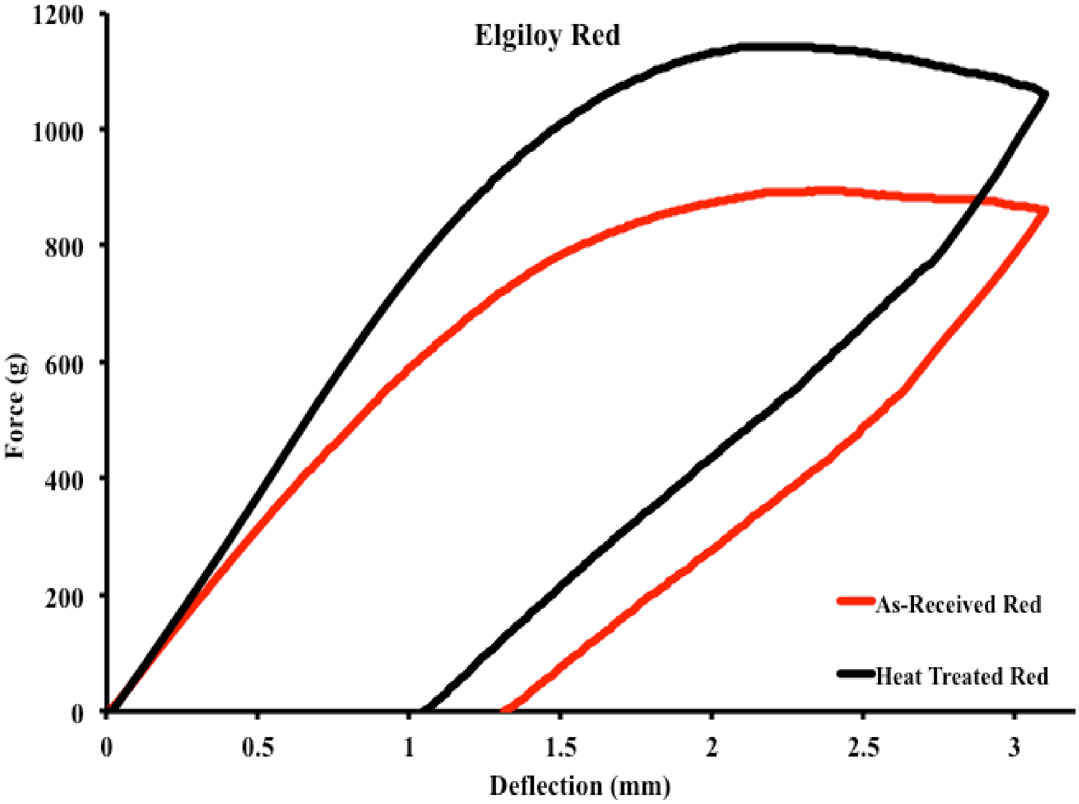

Figure 5. Force versus Deflection for Heat Treated and As-Received Red Elgiloy Wire. Heat treatment led to an increase in force values at the various deflections.

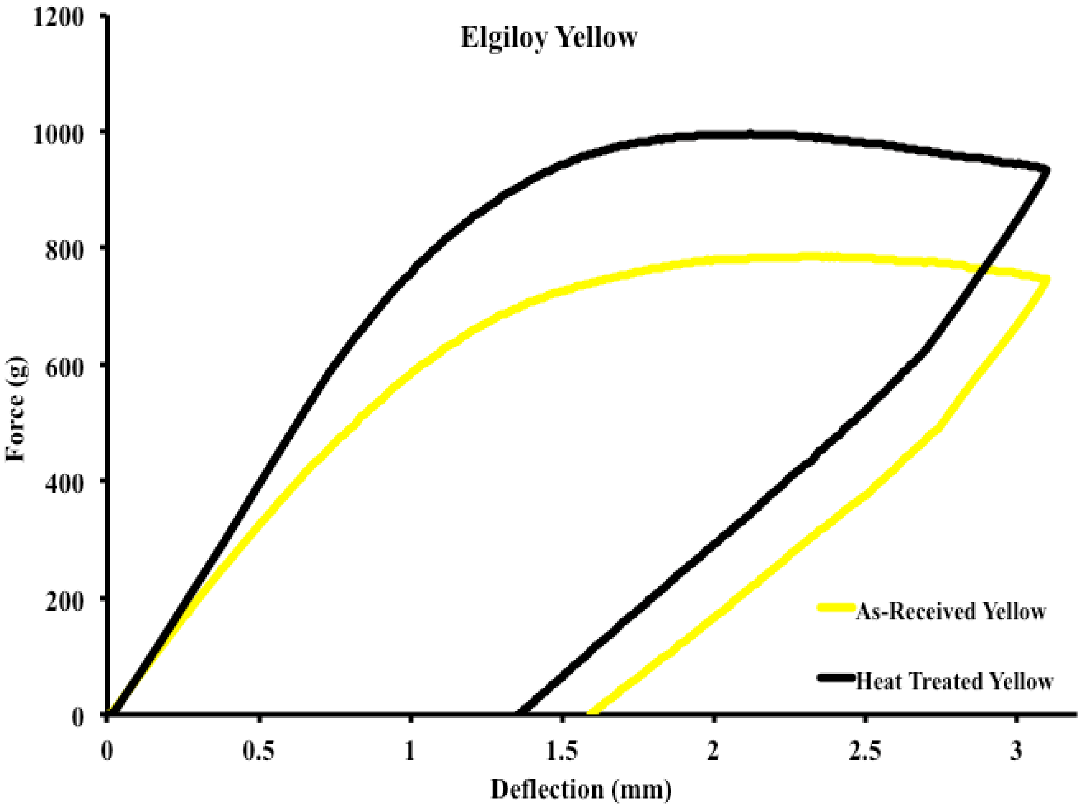

Figure 6. Force versus Deflection for Heat Treated and As-Received Yellow Elgiloy Wire. Heat treatment led to an increase in force values at the various deflections.

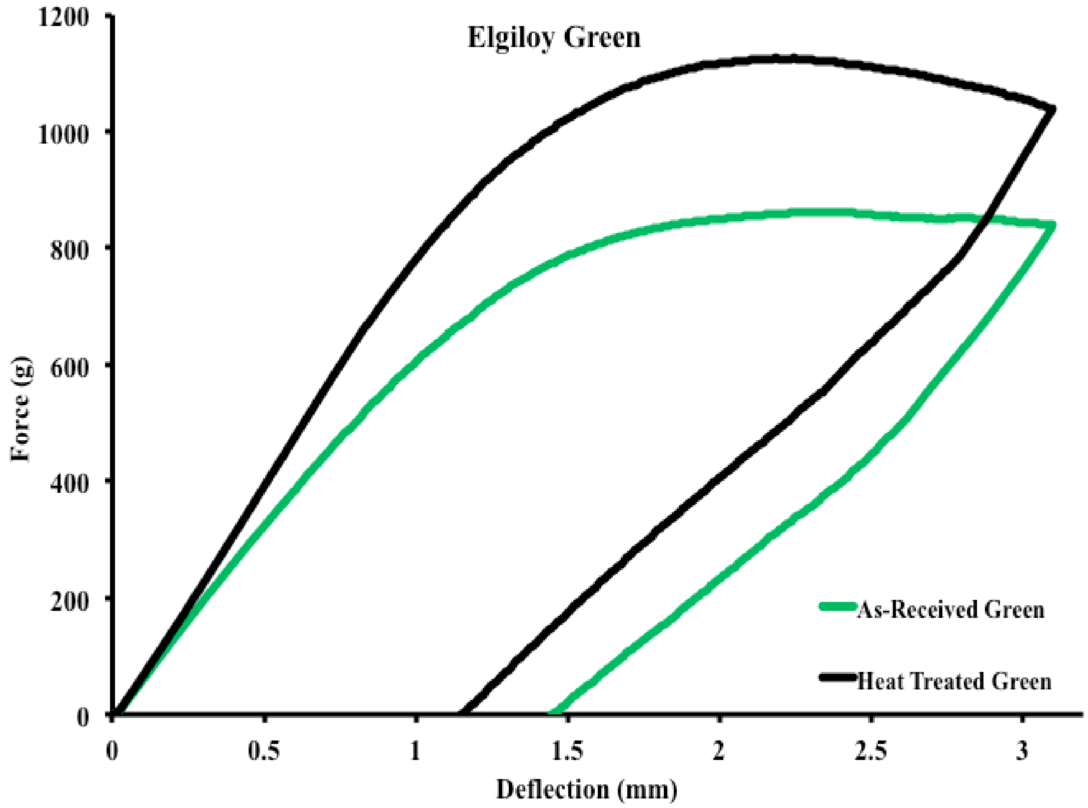

Figure 7. Force versus Deflection for Heat Treated and As-Received Green Elgiloy Wire. Heat treatment led to an increase in force values at the various deflections.

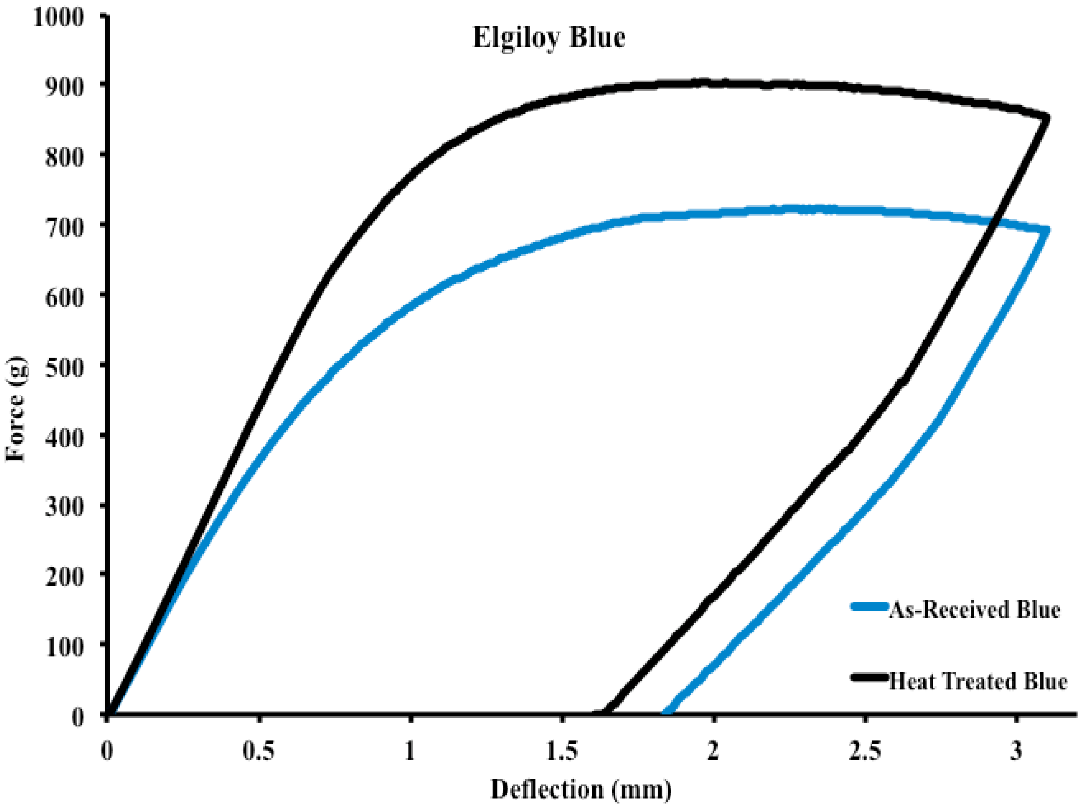

Figure 8. Force versus Deflection for Heat Treated and As-Received Blue Elgiloy Wire. Heat treatment led to an increase in force values at the various deflections.

Wire	**Force (grams) at Deflection**									
	0.25 mm	**0.5 mm**	**0.75 mm**	**1.0 mm**	**1.25 mm**	**1.5 mm**	**1.75 mm**	**2.0 mm**	**2.25 mm**	**2.5 mm**
Green (As-Received)	160±5 E	320±5 F	474±5 F	604±5 D	708±4 E	785±4 E	830±3 D	854±2 F	864±2 F	865±4 E
Green (Heat Treated)	182±5 C	386±6 C	599±6 C	776±5 A	916±5 A	1019±6 A	1081±8 A	1112±9 B	1117±9 B	1107±9 B
Blue (As-Received)	188±5 B/C	357±4 E	490±3 E	579±3 E	639±2 H	680±3 G	703±3 F	716±3 H	722±3 H	722±3 G
Blue (Heat Treated)	203±9 A	427±9 A	633±7 A	762±6 B	836±5 D	876±5 D	893±5 C	898±5 D	895±5 D	887±6 D
Yellow (As-Received)	163±5 E	320±5 F	466±4 G	582±5 E	667±6 G	724±5 F	754±5 E	772±5 G	779±6 G	779±7 F
Yellow (Heat Treated)	189±6 B	396±5 B	605±6 B	764±6 B	875±11 C	949±14 C	987±15 B	1001±15 C	999±14 C	989±13 C
Red (As-Received)	149±9 F	304±8 G	454±7 H	582±7 E	691±6 F	780±5 E	836±4 D	870±4 E	885±5 E	885±5 D
Red (Heat Treated)	174±5 D	369±5 D	575±5 D	753±4 C	895±4 B	1007±4 B	1077±5 A	1119±7 A	1133±5 A	1125±5 A

Table 1. Force Values at Various Deflections for Elgiloy Wires. Different letters indicate a statistically significant ($p<0.05$) difference exists between wires for a given measure. Heat treatment significantly increased force values at the various deflections.

Wire	Stiffness (g/mm)	Flexural Modulus (GPa)	% Recovery
Green (As-Received)	648±4 F	197±1 F	53.8±0.5 E
Green (Heat Treated)	829±6 C	252±2 C	62.6±0.7 B
Blue (As-Received)	689±6 E	210±2 E	40.4±0.3 H
Blue (Heat Treated)	910±6 A	277±2 A	47.2±0.6 G
Yellow (As-Received)	638±6 G	194±2 G	48.6±0.3 F
Yellow (Heat Treated)	839±6 B	256±2 B	56.2±0.5 D
Red (As-Received)	630±4 H	192±1 H	57.7±0.5 C
Red (Heat Treated)	794±5 D	242±1 D	66.3±0.9* A

Table 2. Stiffness, Flexural Modulus, and Percent Recovery for Elgiloy Wires. Different letters indicate a statistically significant ($p<0.05$) difference exists between wires for a given measure. * Six of twenty Red (Heat Treated) wires fractured and are not included in the % recovery. Heat treatment significantly increased stiffness, modulus, and percent recovery.

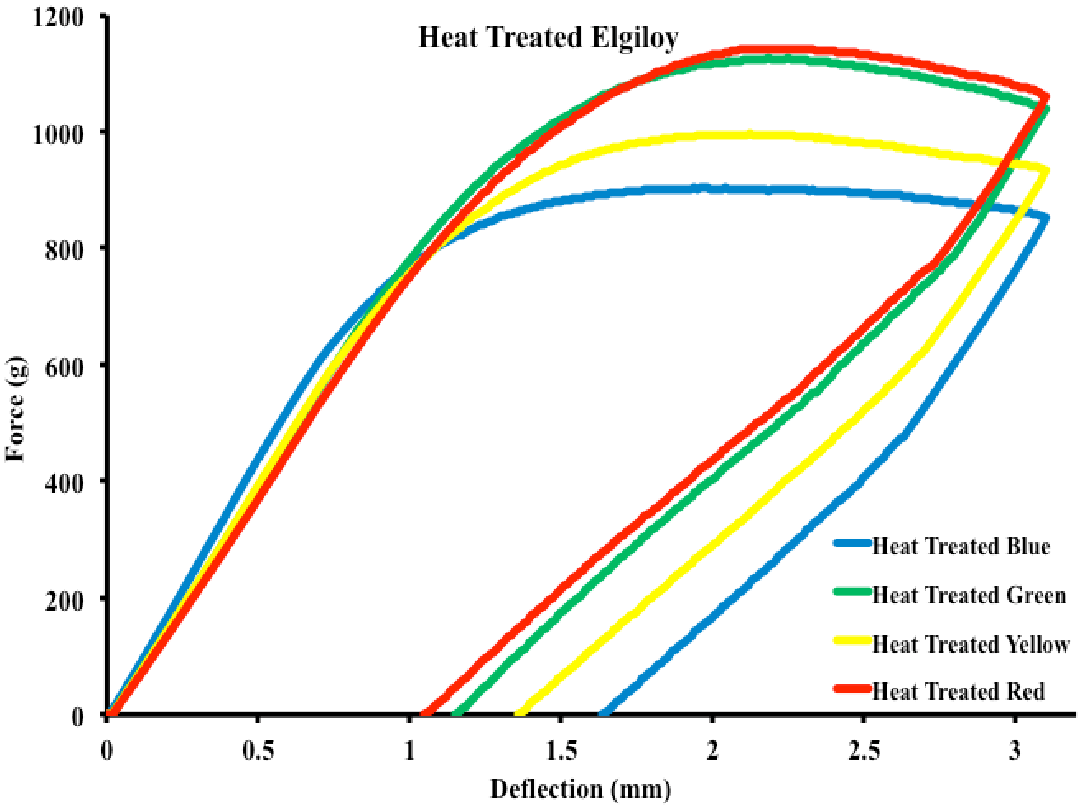

Figure 9. Comparison of Force Versus Deflection Curves in Four Tempers of Heat Treated Elgiloy Wire

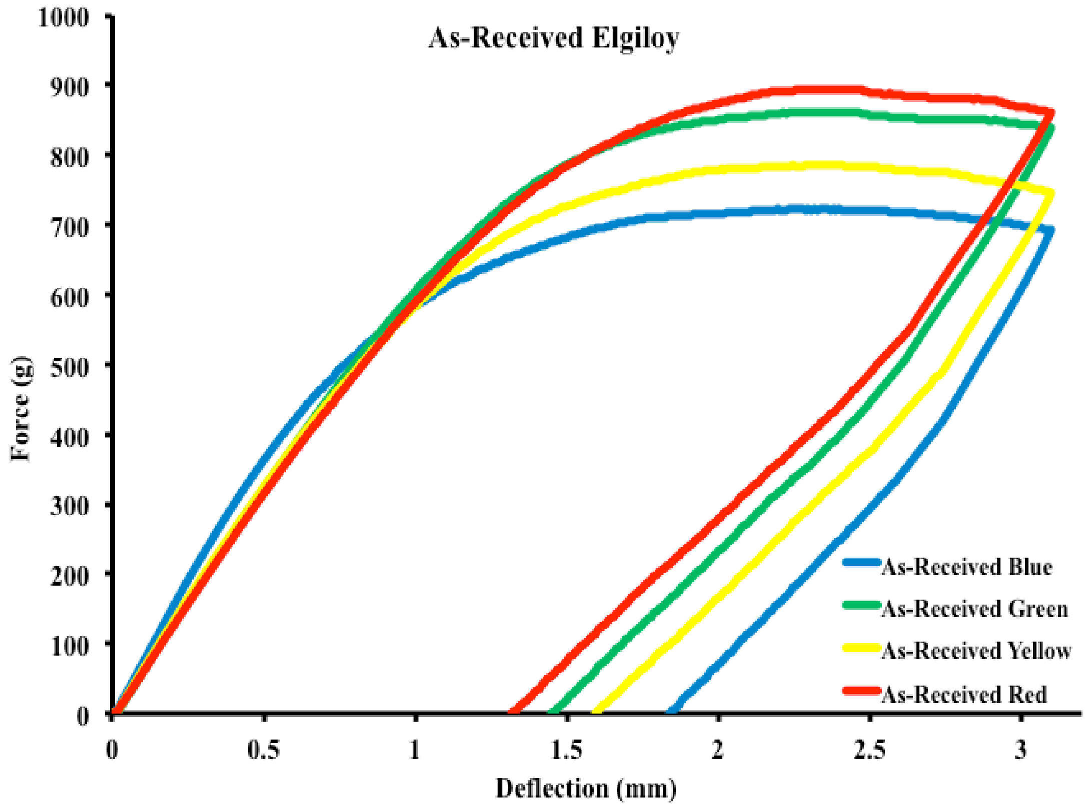

Figure 10. Comparison of Force Versus Deflection Curves in Four Tempers of As-Received Elgiloy Wire

CHAPTER V

DISCUSSION

Elgiloy is an orthodontic wire made of cobalt-chromium provided in four tempers in order to deliver flexibility for their range of use in orthodontics. The advantage of Elgiloy wires is that they are supplied in a more formable state where bends can easily be made and then the wires can be hardened through heat treatment to equivalent levels of stainless steel. Fillmore and Tomlinson described how heat treatment procedures are able to alter mechanical properties of wires:

> In many alloys increases in strength and hardness are seen following certain heat-treatment procedures. These changes are produced by at least two phenomena. First, some increase in strength following heat treatment is due to a partial relief of the internal stresses retained from cold working. Second, other increases in strength and hardness may be due to precipitation hardening of the alloy system. (Fillmore and Tomlinson 1976)

This study was conducted to investigate how heat treatment affects stiffness, flexural modulus, force delivery, and percent recovery of all four available tempers of Elgiloy following a three-point bend test. Stiffness is represented by the elastic modulus on a bending moment (force) versus deflection graph within the elastic range. The steeper the slope is in the linear portion of the graph, the greater the stiffness of the material. Stiffness or load deflection rate can also be thought of as “the force magnitude delivered by an appliance and is proportional to the modulus of elasticity” (Kapila and Sachdeva 1989). Clinically, the flexural modulus relates the tendency for a material or archwire to bend, such as in the three-point bend test that was performed in this study. Flexural modulus can also be thought of as the ratio of stress to strain or the slope of a stress versus strain curve and uses the units of force per area (Pascal).

This study had similar testing conditions as the study carried out by Philip and Darvell where Elgiloy wires were tested in tension at 23°C following heat treatment at 500°C for five hours; however, this study evaluated Elgiloy wires through a three-point bend test. As Asgharnia and Brantley (1986) stated, "the mechanical properties of orthodontic wires are typically determined under bending conditions because this mode of deformation is considered more representative of clinical use than the conventional tension test".

The temperature for heat treatment (500°C) in the study carried out by Philip and Darvell was chosen "because of the confusion between the heat treatment temperature advised by the alloy's manufacturer (Elgiloy, Elgin, IL, USA), and the temperatures apparently used or recommended in dentistry, 500°C was chosen as a compromise" (Philip and Darvell 2016). The manufacturer recommends 5 hours at 527°C for Elgiloy wires (Promotional Literature Elgiloy). Other sources have recommended heat treatment anywhere from 480 to 510°C for 3 to 12 minutes, while one study found the maximum resistance to permanent deformation for Elgiloy wires when heat treated in the range of approximately 593 to 649°C (Fillmore and Tomlinson 1976). Nevertheless, inability to adhere to the recommended times leads to unpredictable properties of the wires. The five hours for duration of heat treatment and three-point bend test in 23°C degree Celsius (room temperature) were followed per manufacturer recommendations.

With the information provided by the three-point bend test, calculations were made to be able to evaluate stiffness, flexural modulus, and percent recovery for the as-received and heat treated Elgiloy wires of all four tempers. Following heat treatment, all wires showed a statistically significant ($p<0.05$) increase in stiffness, flexural modulus, and percent recovery. The increase in stiffness ranged from 26.0% for Red Elgiloy to 32.1% for Blue Elgiloy with Yellow Elgiloy and Green Elgiloy showing a 31.5% and 27.9% increase, respectively. The percent increases for flexural modulus were the same as that for stiffness because it is derived from stiffness but takes into account wire dimensions. Although all four tempers of Elgiloy wires demonstrated an increase in percent recovery with heat treatment, it was not as large of an increase when compared to stiffness and flexural modulus. Blue Elgiloy showed a 16.8% increase in percent recovery with heat treatment followed by Green with a 16.4% increase, Yellow with a 15.6% increase, and finally Red with a 14.9% increase. This study was able to demonstrate that when Elgiloy wires are heated at 500°C for five hours, there is a statistically significant increase in stiffness, flexural modulus, and percent recovery compared to their as-received counterparts when performing a three-point bend test.

Through the heat treatment process Elgiloy wires demonstrate age-hardening over a particular temperature range and the process depends on a phase transformation following it being cold-worked (Assefpour-Dezfuly and Bonfield 1984). As explained in the textbook *Materials Science for Dentistry 9th Edition* by Darvell: “Cold-work in this class of alloy causes a partial martensitic transformation of the initially quenched face-centered cubic α-phase solid solution. It is this precipitation of the low-temperature β-phase that causes the rapid work-hardening of Elgiloy that can cause difficulties. The β-phase can be made to grow in extent on heating below the α-β transus temperature." This is able to explain the process by which all tempers of Elgiloy wires showed a significant increase in flexural modulus, stiffness, and percent recovery following heat treatment in this study.

There are some limitations to the study when attempting to use this information for clinical purposes. The recommendation to heat treat the wires for five hours at 500^{o}C is going to be a major limiting factor for clinicians. Not only would it be difficult or nearly impossible to spend over five hours on the preparation of a particular wire, but also purchasing the necessary equipment to execute this heat treatment process will be a major limiting factor in carrying out these recommendations. The 3-12 minute timeline followed in previous studies would be much more practical to follow; however, further studies are required to evaluate how this short of time frame of heat treatment affects mechanical properties compared to the manufacturer recommended five hours. Additionally, in this study 6 of the heat treated Red Elgiloy wires failed during the three-point bending test. The wires that failed were excluded from the results leading to a smaller sample size for that group; however, all the results were consistent allowing conclusions to still be drawn from this sample of wires. The failure of the Red Elgiloy wires follows the mechanical properties that these wires are the most resilient, which increases with heat treatment. Red Elgiloy wires are thus only able to withstand minimal bending and fracture easily following heat treatment; therefore, any adjustments to the wire should be made prior to any heat treatment.

Nevertheless, the ability to heat treat Elgiloy creates for numerous advantages and increased clinical use of the wire. As stated in a previous study, although not directly related to the intended use for heat treatment of Elgiloy wires, heat treatment makes the wire more resistant to masticatory forces (Williams, Caputo, and Chaconas 1978). Also, the relief of residual stress through heat treatment leads to improved fatigue characteristics. Prior to heat treatment Elgiloy wires are easily formable and once heat treated they demonstrate similar mechanical properties to stainless steel (Proffit 2000). Elgiloy wires even have some properties that are superior to stainless steel such as greater resistance to fatigue, longer function as a resilient spring, and greater resistance to distortion (Philip and Darvell 2016). Additionally, they are highly resistant to corrosion, easily soldered, able to be electrolytically polished, and easily heat treated to remove internal stresses thus improving spring performance (Fillmore and Tomlinson 1976).

Even though this study was able to demonstrate a statistically significant increase in stiffness, flexural modulus, and percent recovery of all four tempers of Elgiloy wires following heat treatment for five hours in 500^{o}C, further studies need to be done to evaluate how these alterations can be utilized clinically in an efficient manner. The requirement to heat the wire for five hours following the placement of bends eliminates efficiency for patient appointments in an orthodontic office. Further studies need to be done to evaluate if the duration of time can be reduced to one that would be more practical in a clinical setting while still maintaining the desired mechanical properties of the Elgiloy wires.

CHAPTER VI

SUMMARY AND CONCLUSIONS

All four available tempers of Elgiloy wire of 0.018" diameter underwent heat treatment at 500°C for five hours to compare the effects to untreated wires through a three-point bend test. Measurements were recorded in order to be able to calculate stiffness, modulus, percent recovery, and the given force at specified deflections throughout the three-point bend test. Heat treated Elgiloy wires could then be compared to their as-received counterpart as well as the different tempers. It was concluded that:

1. Heat treatment of Elgiloy wires led to a significant increase in stiffness, flexural modulus, percent recovery, and force values required to deflect the wire at various deflections.
2. In order of least to greatest for both stiffness and flexural modulus for the different tempers of Elgiloy the order was Red < Green < Yellow < Blue. The order for percent recovery was the exact opposite with Blue < Yellow < Green < Red.
3. Despite Elgiloy wire being around for a long period of time, not a lot of literature is available. Therefore, further research and investigation is needed to determine how heat treatment of Elgiloy wires can influence their clinical use.

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