Effect of Heat-Treatment Time on Bending Properties of Cobolt-Chromium Orthodontic Wires

Melanie Hammerbeck
Marquette University

Recommended Citation
Hammerbeck, Melanie, "Effect of Heat-Treatment Time on Bending Properties of Cobolt-Chromium Orthodontic Wires" (2019). *Master's Theses (2009 -)*. 539.
https://epublications.marquette.edu/theses_open/539

EFFECT OF HEAT-TREATMENT TIME ON BENDING PROPERTIES OF COBALT-CHROMIUM ORTHODONTIC WIRES

by

Melanie Hammerbeck, DDS

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

Milwaukee, Wisconsin

August 2019

ABSTRACT
EFFECT OF HEAT TREATMENT TIME ON BENDING PROPERTIES OF COBALT-CHROMIUM ORTHODONTIC WIRES

Melanie Hammerbeck, DDS

Marquette University, 2019

Introduction: Cobalt-chromium orthodontic wires (CoCr) are made up of cobalt (40 wt%), chromium (20 wt%), iron (16 wt%), and nickel (15 wt%). Benefits of CoCr wires include customizability since the practitioner can choose different degrees of hardening, or tempers, or they can be further hardened by heat-treatment. Different protocols appear in the literature with respect to heat-treating cobalt-chromium orthodontic wires, ranging from 5 hours to utilizing a brush-flame. It is unknown if these variable treatments produce the same results. The clinical applications of these wires partly rely on the duration required to heat-treat these wires because long heat treatment times are unacceptable in a busy orthodontic practice. The objective of this research was to determine the effect of variable heat treatment time and method on the bending properties of two tempers of cobalt-chromium orthodontic wires.

Materials and Methods: Two tempers of CoCr 'Elgiloy' wires (Rocky Mountain Orthodontics), blue (B) and yellow (Y), were heat-treated for different durations. The groups (n=20/group/temper) included: 1) as-received (control); 2) brush-flame; 3) 480^{o}C for 5 secs; 4) 480^{o}C for 10 mins; 5) 480^{o}C for 2 hrs; and 6) 480^{o}C for 5 hrs. Wire segments were tested by a three-point bend test. Stiffness/flexural modulus, percent recovery, and force values at select deflections were statistically compared using ANOVA/Bonferroni post-hoc test ($p<0.05$). A T-test compared the different tempers.

Results: Longer heat-treatment (2 hrs/5 hrs) increased % recovery, flexural modulus, and force values when compared to the as-received counterparts. Heat treatment for 10 minutes resulted in intermediate increases. Using a brush-flame technique reduced elastic recovery and resulted in greater bending variability.

Conclusion: Similar mechanical properties can be achieved in just 2 hours compared to the manufacturer recommended 5 hours of heat-treatment of Elgiloy wires. Ten minutes of heat-treatment, which may be more realistic in a busy orthodontic practice, can increase bending properties 50-75% compared to the 5 hour group. The brush-flame technique used in this study is not recommended due to inconsistent heating conditions and high temperatures resulting in varying bending properties.

ACKNOWLEDGEMENTS

Melanie Hammerbeck, DDS

I would like to give a special thanks to my advisor, Dr. David Berzins, for all his assistance in conducting my research. He has helped me tremendously since my first year of dental school, when I met him as my professor in dental biomaterials. I would like to thank Dr. Dawei Liu, Dr. Bhoomika Ahuja, and Dr. Ghada Nimeri for not only being a part of my committee, but also for their dedication to Marquette's Graduate Orthodontic program. They have all helped me achieve my degree and certificate in orthodontics, and I have learned from them in both the classroom and on the clinic floor. I will be forever grateful. I would like to thank my Uncle, Dr. Mark Burbey for the passion of orthodontics he instilled in me during my own orthodontic treatment as a teenager. Finally, I would like to thank my husband Adam who followed me back to Milwaukee so I could pursue my dream of becoming an orthodontist.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

CHAPTER I – INTRODUCTION AND SIGNIFICANCE

In order to most effectively treat patients, orthodontists must have a thorough understanding of all types of wires to allow us to move teeth appropriately. Not every patient has the same treatment needs, so the orthodontist's toolbox must be diverse in order to cater to each individual. Over the years, orthodontic wires have evolved extensively. With the seemingly endless products on the market today, the orthodontist must understand the science behind, and mechanical properties of, all wires in order to properly evaluate the "latest and greatest" and therefore decide how they can fit into the practice of orthodontics. Historically and presently, the following wires have been used in orthodontics (Proffit, Fields, Sarver, & Ackerman, 2013):

1. Gold in the first half of the 20th century
2. Stainless steel or "SS" in the late 1920s (Nikolai, 1997)
3. Cobalt-chromium, "Elgiloy" or CoCr wires in mid-1950s (Nikolai, 1997)
4. Nickel titanium or "NiTi" in the early 1960s (Nikolai, 1997)
5. Beta-titanium or "TMA" in the mid-1970s (Nikolai, 1997)
6. Copper-nickel-titanium or "CuNiTi" in late 1980s (Proffit, Fields, Sarver, & Ackerman, 2013)
7. Esthetic wires currently being marketed and developed (Proffit, Fields, Sarver, & Ackerman, 2013)

Cobalt-chromium (CoCr) wires are of particular interest because they are an under-studied and misunderstood wire in the orthodontic community. These wires were developed in the 1950s by the Elgin Watch company to be used as the torsional main springs in their watches (Nikolai, 1997). Their composition is: cobalt 40 wt%, chromium 20 wt%, iron 16 wt%, and nickel 15 wt% (Kusy, Mims, & Whitley, Mechanical characteristics of various tempers of as-received cobalt-chromium archwires, 2001). There are four different tempers of CoCr wires: blue (soft), yellow (ductile), green (semi-resilient), and red (resilient) (Kusy, Mims, & Whitley, Mechanical characteristics of various tempers of as-received cobalt-chromium archwires, 2001). A major benefit of CoCr over stainless steel wires is the ability to harden CoCr wires by heat-treatment. After bends are made in the as-received soft form, they then may be heat-treated to increase stiffness, as well as enhance other desirable properties (Nikolai, 1997). Therefore, the clinician can control stiffness of the wire in three different ways – choosing different wire size, choosing varying tempers, and utilizing heat-treatment.

Heat-treatment duration of CoCr wires is poorly researched and reported in the literature. The manufacturer (Elgiloy Company, undated promotional literature, circa 1970) as well as the original patent (United States Patent No. 2524661, 1950), and other peer-reviewed literature recommends that the wires be heat-treated for as long as 5 hours (Greener, Harcourt, & Lautenschlager EP, 1972) (Kusy, Mims, & Whitley, Mechanical characteristics of various tempers of as-received cobalt-chromium archwires, 2001) (Philip & Darvell, 2016). Other authors have reported times as short as a few seconds, between 3-12 minutes at 480^{o}C (Rocky Mountain

Orthodontics, 1977) (Craig, 1978) (Philip & Darvell, 2016), 5 minutes at 649^{o}C (Fillmore & Tomlinson, Heat treatment of cobalt-chromium alloys of various tempers, 1979) or 2 hours at 480^{o}C (Philip & Darvell, 2016) (Kusy, Mims, & Whitley, Mechanical characteristics of various tempers of as-received cobalt-chromium archwires, 2001). Alternatively, a lighter (or flame) brushed along the wire until it turns a dark straw color has been mentioned as an option (Philip and Darvell, 2016) (Kusy, Mims, & Whitley, Mechanical characteristics of various tempers of as-received cobalt-chromium archwires, 2001), as well as use of the RMO Welder heating the wire to a dark straw color (Philip & Darvell, 2016). It is unknown if these variable treatments produce the same results.

Generally, there is a significant lack of research on the mechanical properties (especially bending properties) of cobalt-chromium wires in varied heat-treatment times. Past literature has focused on properties in tension, or has tested bending properties, but has not varied the duration of heat treatment prior to testing to determine how heat-treatment time affects these properties. It is unknown if these variable treatments produce the same results. The clinical applications of these wires partly rely on the duration required to heat-treat these wires because excessively long heat-treatment times may deter orthodontists from using them in clinical practice. The objective of the proposed research was to determine the effect of variable heat treatment time and method on the bending properties of two tempers of cobalt-chromium orthodontic wires.

CHAPTER II – LITERATURE REVIEW

According to Proffit (2013), the ideal orthodontic wire should possess the following properties:

1) High *strength*
2) Low *stiffness* (in most applications)
3) High *range*
4) High *formability*

Other important characteristics and considerations include: (a) ease of *soldering* or *welding* allowing use of attachments, (b) reasonable *cost*, (c) high *biocompatability*, (d) low *biohostability,* (e) highly *esthetic*, (f) low *friction*, (g) high *resilience*, (h) high *springback*, (i) *corrosion resistant* to oral fluids, (j) sufficiently *ductile* so that it does not fracture under accidental loading in the mouth or during fabrication of an appliance, and (k) the wire should be able to be fabricated in a soft state and later *heat-treated* to a hard temper (Graber, Vanarsdall, Vig, & Huang, 2017) (Kusy, A review of contemporary archwires: their properties and characteristics, 1997). In contemporary practice, no single archwire satisfies all of these requirements. Consequently, different wires must be used to accomplish specific goals in each phase of treatment (Proffit, Fields, Sarver, & Ackerman, 2013). Therefore, the clinician must understand the properties of each unique archwire to effectively use it in his or her practice.

The three major elastic properties are *strength*, *stiffness*, and *range*. These properties can be evaluated by analyzing the mechanical behavior shown in force-deflection or stress-strain plots. *Stress* and *strain* are internal characteristics that can be calculated from measurements of force and deflection (Mosby, 2007). *Stress* (σ) is defined as the internal response of a wire to the application of an external force (load) per cross-sectional areal ($\sigma = F/A$). *Strain* (ε) is the deformation or deflection of the archwire as a consequence of the stress and is defined as the dimensional change divided by the original dimension ($\varepsilon = \Delta d/d$) (Mosby, 2007). As stated previously, force-deflection curves are proportional to stress-strain curves and can be easily converted from one to another knowing the sample used in the graph. For example, load is divided by sample area to get stress and displacement is divided by sample length to get strain. From here, the derived quantity, *modulus of elasticity*, is independent of sample size and can be regarded as a true material property. *Flexural modulus* is the bending variant of *modulus of elasticity*. *Modulus of elasticity* will be described later.

Force-deflection curves allow a better understanding two major elastic properties, *stiffness* and *range* (Mosby, 2007). The *stiffness* of an orthodontic wire is given by the slope of the linear portion of the curve. Stiffness and springiness are reciprocal properties (springiness = 1/stiffness). The more horizontal the slope, the springier the wire; the more vertical the slope, the stiffer the wire (Proffit, Fields, Sarver, & Ackerman, 2013). The *range* is the distance along the x-axis to the point at which permanent deformation occurs and is measured in millimeters (which is usually taken as the *yield point*, at which 0.1% of permanent deformation has occurred, explained later). The strength is the product of stiffness and range, strength = stiffness x range. *Flexural modulus* can be determined by force-deflection curves and is the bending version of *modulus of elasticity*.

Stress-strain curves allow a better understanding of the third major elastic property, *strength* (Mosby, 2007). They also provide information on another important characteristic of orthodontic wires, *modulus of elasticity*, of which *stiffness* and *springiness* are proportional. Stress-strain curves also provide information on *proportional limit, yield strength/yield point, ultimate tensile strength*, and *failure point*. Three values (*proportional limit, yield strength*/*yield point*, and *ultimate tensile strength*) each represent, in a somewhat different way, the maximum load a material can resist; this is known as *strength*. *Proportional limit* and *yield point* represent the point at which a material transforms from acting as an *elastic* material to a *plastic* material (Proffit, Fields, Sarver, & Ackerman, 2013).

An *elastic* material is one which will return to its original shape after unloading; *plastic* behavior is the occurrence of permanent deformation in a configuration during loading. Generally, the initial linear slope represents the region in which the wire acts as an *elastic* material, load and deflection are proportionate, and any force applied to the wire in this region, when removed, the wire will rebound to its initial shape. After this point, the wire acts *plastically*, which represents the occurrence of permanent deformation (i.e. the wire will not rebound to its initial shape after unloading) (Graber, Vanarsdall, Vig, & Huang, 2017). *Proportional limit* is the most conservative measure and represents the highest point at which *stress* and *strain* will have a linear relationship. Because it can be difficult to determine this point, a more practical indicator is *yield strength*. It is the intersection of the stress-strain curve with a parallel line offset at 0.1% strain. Usually, the true *elastic limit* lies between these two points. The *ultimate tensile strength* is the maximum load a wire can sustain. This is reached after some permanent deformation, and represents the maximum force the wire can deliver if used as a spring.

As stated earlier, the *modulus of elasticity* can be determined by a stress-strain graph and is related to "*stiffness*". *Modulus of elasticity* is the slope of the initial linear region, or the amount of stress required for unit strain ($E = \sigma/\varepsilon$). The *elastic modulus* is generally reported in gigapascals (GPa) where 1 GPa = 10^9 N/m^2 = 10^3 MPa = 145,000 psi.

Orthodontic wires have evolved extensively over the history of orthodontic practice. Each wire has unique mechanical properties as described above, and varied clinical applications within the field (Proffit, Fields, Sarver, & Ackerman, 2013). The following sections provide a historical background on wires used in orthodontics.

Gold Alloys and Early Wires

The first wires used for orthodontic purposes in the first half of the twentieth century were precious metal alloys. Gold alone was far too soft for nearly all dental applications, but when combined with platinum and palladium (along with copper), it gained hardness to allow for orthodontic applications. Gold could be easily welded, and had excellent corrosion properties (Kusy, Orthodontic Biomaterials: From the Past to the Present, 2002). In addition, gold wires could be heat-treated to increase stiffness by 30%, which is comparable to today's beta-titanium alloy. To accomplish this, the gold alloy was heated at 450^{o}C for 2 minutes, cooled to 250^{o}C over a period of 30 minutes, and finally quenching to room temperature (Kusy, Orthodontic Biomaterials: From the Past to the Present, 2002). After the introduction of stainless steel, however, the use of precious metal alloys became obsolete. Today, precious metals are used in applications in which softness of the material is beneficial and casting is required, as in the fabrication of custom-fit bonding pads used for fixed lingual appliances.

Stainless Steel Wires

Stainless steel, having excellent corrosion resistance, replaced precious metal alloys due to its increased strength and springiness. The advent of stainless steel in World War I and the refinement of drawing processes to form wires in the 1930s contributed to the ability to obtain smaller cross-sectional wires than the previously used larger precious metal alloys. The "stainless" in stainless steel comes from its chromium content. Stainless steel typically consists of 18% chromium and 8% nickel (hence the "18-8 stainless steel" nomenclature commonly used in orthodontics). The elastic modulus of stainless steel is about 200 GPa (Kusy, A review of contemporary archwires: their properties and characteristics, 1997).

Cobalt-Chromium Wires

In the 1950s, the Elgin Watch Company (Elgin, IL) developed a special metal alloy, cobalt-chromium, for use in the torsional, main springs. Rocky Mountain Orthodontics gave their cobalt-chromium wires the name "Elgiloy" for that reason (Nikolai, 1997) (Kusy, A review of contemporary archwires: their properties and characteristics, 1997). Their composition is: cobalt 40 wt%, chromium 20 wt%, iron 16 wt%, and nickel 15 wt% (Kusy, Mims, & Whitley, Mechanical characteristics of various tempers of as-received cobalt-chromium archwires, 2001). Favorable characteristics of cobalt-chromium wires include: corrosion resistance, similar stiffness and strength to stainless steel wires, ability to increase strength and resilience with heat-treatment, enhanced formability prior to heat-treatment, increased ultimate strength and resilience without changing stiffness (with heat-treatment), and option of choosing different tempers. The different tempers include: blue (soft and formable), yellow (ductile), green (semi-resilient), and red (resilient, hard, high spring) (Kusy, A review of contemporary archwires: their properties and characteristics, 1997). The elastic modulus of cobalt-chromium wires is similar to stainless steel, about 160-190 GPa (Brantley & Eliades, 2001). Cobalt-chromium wires will be described in further detail in the second half of the literature review.

Nickel-Titanium and Copper-Nickel-Titanium Wires

Nickel-titanium wires were developed in the 1960s, given the name “Nitinol”, corresponding to nickel, titanium, and the Naval Ordnance Laboratory, the name at that time of the site for alloy development. They were marketed into orthodontics in the 1970s by Unitek Corporation, which is now 3M Unitek. (Brantley, Berzins, Iijima, Tufekçi, & Cai, 2017). The biggest benefit of this orthodontic alloy is its low force per unit of deactivation, or low stiffness. Furthermore, it is quite springy, delivering only one-fifth to one-sixth the force per unit of deactivation, therefore satisfying the biomechanical requirement of early stages of treatment, “light, continuous force”. A disadvantage of this wire, however, is its lack of formability, due to high springback. Martensite-stabilized NiTi has an elastic modulus of 31-35 GPa; austenite represents the high stiffness phase having an elastic modulus of 84-98 GPa (Kusy, A review of contemporary archwires: their properties and characteristics, 1997). ***Table 1*** demonstrates the major mechanical properties of the four major classes of orthodontic wires (Brantley & Eliades, 2001).

Table 1. Compositions and mechanical properties of the four major orthodontic wire alloy types (Brantley & Eliades, 2001).

Wire Alloy	Composition (wt%)	Modulus of Elasticity (GPa)	Yield Strength (MPa)[a]	Springback[b]
Austenitic stainless steel	17-20% Cr, 8-12% Ni, 0.15% C (max), balance mainly Fe	160-180	1100-1500	0.0060-0.0094 (AR) 0.0065-0.0099 (HT)
Cobalt-chromium-nickel (Elgiloy Blue)	40% Co, 20% Cr, 15% Ni, 15.8% Fe, 7% Mo, 2% Mn, 0.15% C, 0.04% Be	160-190	830-1000	0.0045-0.0065 (AR) 0.0054-0.0074 (HT)
B-Titanium (TMA)	77.8% Ti, 11.3% Mo, 6.6% Zr, 4.3% Sn	62-69	690-970	0.0094-0.011
Nickel-titanium	55% Ni, 45% Ti (approx. and may contain small amounts of Cu or other elements)	34	210-410	0.0058-0.016

[a]The values of yield strength correspond to 0.1% permanent tensile strength. [b]The terms AR and HT for the stainless steel and Elgiloy Blue alloys refer to the as-received and heat-treated conditions, respectively.

Beta-Titanium

The last major alloy to have a significant impact in modern orthodontic practice was introduced in the 1980s, stabilized beta-phase titanium-molybdenum alloys, or “TMA”, as they are commercially known. These alloys contain about 80% titanium, 11.5% molybdenum, 6% zirconium, and 4.5% tin. The stiffness of these wires varies from 99 to 127 GPa. Furthermore, the deactivation characteristics of TMA wires are about one-third that of conventional stainless steel, or twice that of conventional martensitic stabilized nitinol. For this reason, TMA wires. This alloy has several advantages over both NiTi wires and stainless-steel wires. When compared with nitinol, TMA is inherently smoother, can be welded, and has good formability. When compared with stainless steel, TMA produced greater linear forces per unit of deactivation and has substantially more range and higher springback. This seemed like the perfect solution and seemingly perfect wire. However, TMA has one major disadvantage – the coefficients of friction are the worst of any orthodontic alloy and consequently its ability to accommodate the sliding of teeth is very limited.

Cobalt-Chromium Orthodontic Mechanical Properties

Favorable characteristics of cobalt-chromium wires include: (Kusy, A review of contemporary archwires: their properties and characteristics, 1997)

- Enhanced formability versus stainless steel prior to heat-treatment
- Customizability with four different tempers
- Enhanced resistance to corrosion (Fillmore & Tomlinson, Heat treatment of cobalt-chromium alloy wire, 1976)
- Mechanical properties enhanced by heat-treatment
    - Increased ultimate strength and resilience
    - Similar stiffness and strength characteristics as stainless steel
    - Increased resiliency and elastic limit
    - Increased spring performance (Fillmore & Tomlinson, Heat treatment of cobalt-chromium alloy wire, 1976)

  - Increased resistance to permanent deformation (Fillmore & Tomlinson, Heat treatment of cobalt-chromium alloy wire, 1976)

Heat-Treatment of Cobalt-Chromium Archwires

For practitioners who wish to use loops and complex bends in their treatment mechanics, the property of formability is of high importance. Formability is required to place loops, V-bends, and various offsets into the archwire. Once deformation is complete, however, heat treatment increases the resilience of the wire by a recommended precipitation- or age-hardening process at 482°C for 7-12 minutes (Kusy, A review of contemporary archwires: their properties and characteristics, 1997). After appropriate heat-treatment, their strength and stiffness rivals that of stainless steel. Heat-treatment also then increases the resiliency and elastic limit (Graber, Vanarsdall, Vig, & Huang, 2017), capitalizing on the inherent elasticity of the material. While many alloys become softer on heat-treatment, that is, on annealing, Elgiloy shows age-hardening over a certain temperature range; the process is complex and depends on a phase transformation after cold-work (Philip & Darvell, 2016). According to Fillmore et al 1976:

> "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."

The effect of varying heat-treatment time has never been studied and published in any peer-reviewed literature. Furthermore, there is not a clear consensus on how the duration of heat treatment affects the properties of cobalt-chromium wires in bending. The following protocols have been proposed:

1) lighter (or flame) brushed along the wire until it turns a dark straw color has been mentioned as an option (Philip and Darvell, 2016) (Kusy, Mims, & Whitley, Mechanical characteristics of various tempers of as-received cobalt-chromium archwires, 2001)
2) use of the RMO welding apparatus, utilizing a manufacturer-provided special paste that indicates when the appropriate conditions of temperature of 510^{o}C (Fillmore & Tomlinson, Heat treatment of cobalt-chromium alloy wire, 1976) and time have been achieved (Brantley & Eliades, 2001)
3) use of an RMO welder, heating the wire to a dark straw color (Philip & Darvell, 2016)
4) between 3-12 minutes at 480^{o}C (Rocky Mountain Orthodontics, 1977) (Craig, 1978) (Philip & Darvell, 2016)
5) 5 minutes at 649^{o}C (Fillmore & Tomlinson, Heat treatment of cobalt-chromium alloys of various tempers, 1979)
6) 2 hours at 480^{o}C (Philip & Darvell, 2016) (Kusy, Mims, & Whitley, Mechanical characteristics of various tempers of as-received cobalt-chromium archwires, 2001)

7) 5 hours at 482°C (Elgiloy Company, undated promotional literature, circa 1970) (United States Patent No. 2524661, 1950) (Greener, Harcourt, & Lautenschlager EP, 1972) (Kusy, Mims, & Whitley, Mechanical characteristics of various tempers of as-received cobalt-chromium archwires, 2001)
8) 5 hours at 527°C (Philip & Darvell, 2016) (Elgiloy Promotional Literature, 1975)

As one can see, there is no clear consensus on the ideal heat-treatment time and temperature.

Clinical Usage of Cobalt-Chromium Archwires

There have been several reported advantages for cobalt-chromium over stainless steel: superior mechanical properties, greater resistance to fatigue and distortion, and longer function as a resilient spring (Fillmore & Tomlinson, Heat treatment of cobalt-chromium alloy wire, 1976). Furthermore, it can be electrolytically polished, easily soldered, and easily heat-treated to remove internal stress and thus improve spring performance. However, CoCr wires unfortunately tend to harden near soldered or spot-welded joints, and show faster work-hardening than other alloys. The four 'tempers' of Elgiloy are intended to allow selection flexibility as they vary a little in elastic modulus and are said to vary in their 'formability' and response to heat treatment (Philip & Darvell, 2016). High formability combined with increased elasticity and yield strength following heat treatment by 10% and 20-30%, respectively, have made Blue Elgiloy popular in clinical practice (Kotha, Alla, Shammas, & Ravi, 2014).

The tempers include: blue (soft and formable), yellow (ductile), green (semi-resilient), and red (resilient, hard, high spring) (Kusy, A review of contemporary archwires: their properties and characteristics, 1997). Blue and Yellow grades were developed between 1958 and 1961 in order to match, in their heat-treated states, the properties of the standard and extra-hard stainless steels of the day (Philip & Darvell, 2016). Blue and yellow Elgiloy wires are most commonly used in today's clinical orthodontics.

According to Kusy (2002), practitioners never exploited this alloy to its full potential. Possibly because there was not enough research on this wire, or perhaps because the heat-treatment process was never completely elucidated. Not only does heat-treatment of CoCr wires increase desirable properties of these wires, but heat-treatment also relieves residual stresses which lead to improvement in fatigue characteristics (Williams, Caputo, & Chaconas, 1978). For this reason, heat-treatment of blue Elgiloy wires for fixed lingual retainers may be beneficial for the long-term survival of this important aspect of orthodontic treatment, retention.

Prior Studies of the Effect of Heat-Treatment on Properties of CoCr Wires

Fillmore et al (1976)

Fillmore et al in 1976 compared cobalt-chromium wires heat-treated in a dental furnace versus those using an electrical resistance unit. These tests were done using 0.016" x 0.022" blue Elgiloy, bent into a pattern of loops, tested in *tension* for permanent deformation. The goal of this study was to 1) determine the temperature of heat-treatment which gave a particular temper of cobalt-chromium wire its maximum resistance to permanent deformation; and 2) quantify the increased resistance to permanent deformation due to heat treatment at various temperatures. The blue Elgiloy was bent into a pattern of loops in order to introduce a small degree of work hardening, as may be experienced in clinical procedures.

There were a total of 12 treatment groups, 6 wires in each group:

1) Nonheat-treated control
2) Heat-treatment using an electrical resistance unit using temper-indicating paste designed to flash when temperature of wire reached 510°C
3) 5 minutes at 316°C – heat-treatment using an electric dental furnace (all below)
4) 5 minutes at 371°C
5) 5 minutes at 427°C
6) 5 minutes at 482°C
7) 5 minutes at 537°C

8) 5 minutes at 593°C
9) 5 minutes at 649°C
10) 5 minutes at 704°C
11) 5 minutes at 760°C
12) 5 minutes at 815°C

Results showed that heat-treatment at temperatures up to 649°C does increase the resistance to permanent deformation of cobalt-chromium wires. A rapid decline in resistance to permanent deformation is noted in wire heat-treated at temperatures above 649°C. At 816°C, wires showed a marked increase in permanent deformation when deforming loads were greater than 350 g. Furthermore, at loads above 500 g, the wires heat-treated at 816°C permanently deformed more than wires that were not heat-treated. The reason for the poorer performance at extremely high temperatures is due to a partial annealing and overaging of the wires at these high temperatures.

This study also examined the force at which each groups of wire underwent 0.1mm permanent deformation. A percent increase in force at 0.1mm permanent deformation was calculated and it was determined that there is little increase in resistance to permanent deformation for wires heat-treated at temperatures above 593°C. Furthermore, a comparison was made that examined the linear distance of permanent deformation at 650 g. It was concluded that wires heat-treated at 593°C and 649°C showed the least amount of deformation and the wire heat-treated at 760°C showed a 7.12 mm deformation, which is more than twice as much deformation to a load of 650 g was shown by wires heat-treated at 593^{o}C, 649^{o}C, and 704^{o}C.

The wires heat-treated with the electrical resistance unit showed values of permanent deformation approximately halfway between the values of permanent deformation for wire heat-treated in the dental furnace at 427^{o}C and 482^{o}C. Since the paste is designed to flash when the wire reaches 510^{o}C, it would be expected that the wire will behave in a similar manner to halfway between the 482^{o}C and 537^{o}C. This is not the case and therefore suggests that the electric current produced uneven heating of the wire and thus variable result.

> “The electrical resistance unit cannot uniformly heat a wire and as arch length, size, and form are changed, the effects of heat treatment vary. In areas where wire segments are in close proximity as in helical loops, heat loss is reduced and the desired temperature of heat treatment is reached while other portions of the wire are below the desired temperature. Sharp bends produce highly work-hardened areas which have increased resistance to flow of electricity and thus reach the desired temperature of heat treatment before less work-hardened areas. Although this process results in wires that are unevenly heated, its convenience and ease of use make it a popular method of heat-treatment.”

The conclusions of this study include the following: temperatures of heat-treatment above 649°C show a rapid decline in resistance to permanent deformation due to partial annealing and the maximum resistance to permanent deformation occurs from heat-treatment in the temperature range of 593^{o}C to 649^{o}C.

Williams et al (1978)

Williams et al in 1978 examined the effect of heat-treatment temperature on 1) the tensile properties of CoCr wires as well as 2) bending properties of open loops, helical open loops, closed loops, and helical closed loops. Note that the bending test used for the loops was NOT a three point-bending test. For the tensile test, seven-inch sections of blue Elgiloy square wires (0.016" x 0.016") were heat-treated for 10 minutes at the following Fahrenheit (Celsius) temperatures:

1. 371°C
2. 426°C
3. 482°C
4. 510°C
5. 537°C
6. 565°C

These temperatures were chosen to bracket the 482°C suggested by the manufacturer. Ten minutes was chosen because it is practical clinically, and because previous studies have indicated that greater improvements are not obtained with longer times.

Interestingly, in the study by Williams et al, the authors stated that "greater improvements are not obtained with longer times". It should be noted that the three studies which were referenced after this statement (Backofen & Gales, 1952) (Funk, 1951) (Howe, Greener, & Crimmins, 1968) were studies involving the heat-treatment of stainless steel wires, which do not behave like CoCr wires with heat-treatment.

For the loop bending test, loops were bent consistently (to allow minimal work hardening) with a customized bending jig in blue Elgiloy wires, then heat-treated according to the optimal temperature as determined by the tensile test (510°C, described below).

Results of the straight wire tensile tests showed that heat-treatment did indeed have a pronounced effect on the mechanical properties of blue Elgiloy. The maximum values were obtained at approximately 510°C. Both yield strength and ultimate tensile strength were increased, but the most dramatic effect was an increase in yield strength of nearly 50%. The elastic modulus showed an increase of approximately 20% with heat-treatment of 10 minutes at 510°C.

Results of the loop bending tests showed that the heat-treated samples required a consistently higher force than the non-heat-treated wires to produce the same deflection. Helical open loops generate lower forces than open loop configurations, the same trend was found for helical closed loops versus closed loop configurations (helical closed loops generate lower forces than closed loop configurations). Closed loops values are lower than open loops values. At the maximum deflection, the effect of heat-treatment is greater for the open-loop configurations. At the maximum deflection the effect of heat treatment is greater for the open loops (~30%) as compared with 11% for the helical open loops. Heat-treatment effects were statistically significant at the 1% level for the open loop and the 5% level for helical open loop.

Other important points noted in this paper include the following:

- Heat treatment relieves residual stresses which lead to an improvement in fatigue characteristics
- Narrow ranges of heat-treatment temperatures produced significantly different changes in strength and modulus of elasticity, therefore control of heat-treatment parameters is important in order to produce optimal results
- For a greater long-term effect, the best results with the best force control can be obtained after heat treatment

Application and Purpose

It is apparent that there is not a definitive conclusion to the effect of heat-treatment and the bending properties (three-point bend test) on cobalt-chromium archwires. In order for the orthodontic community to better understand these under-researched wires, these crucial elements must be elucidated.

CHAPTER III - MATERIALS AND METHODS

Materials

Two tempers of Elgiloy wire (blue and yellow) were obtained from Rocky Mountain Orthodontics (Denver, CO, USA). The varying tempers for Elgiloy wires are based on their unique properties: yellow, or “ductile”, and blue, or “soft”. Both 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

Six consecutive 25mm segments were cut from each wire (20 wires) in each of the blue and yellow temper, creating 120 specimens in each temper, or 240 total specimens. Each sectioned wire had one specimen in each of the heat-treated groups, with their positions organized and maintained throughout the experiment using the Styrofoam block (***Figure 1***).

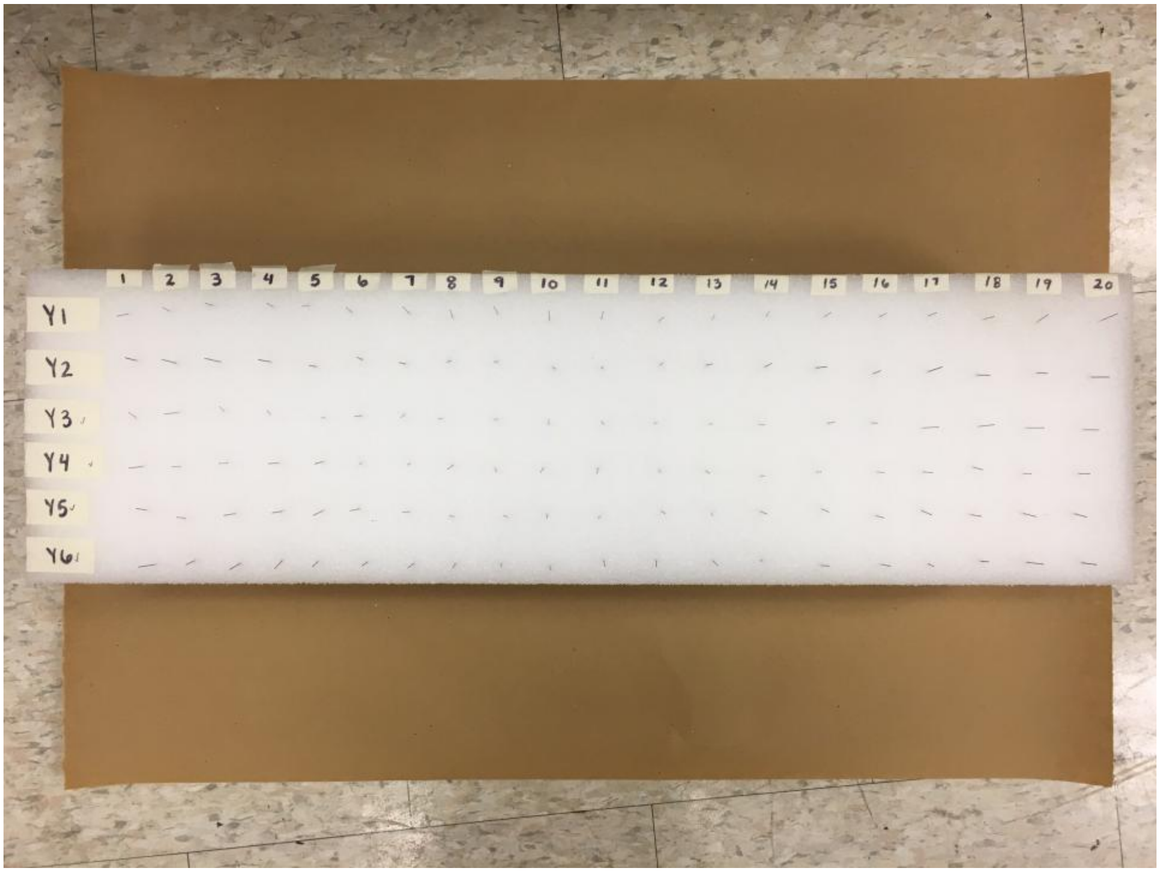


Figure 1. Wires organized on Styrofoam block prior to the three-point bend test.

The Styrofoam block was organized based on temper and heat treatment group. The groups were labeled as follows and assigned to the following groups:

Table 2. Heat-treatment grouping assignments of blue and yellow Elgiloy wires.

Blue	**n**	**Heat-treatment**	**Yellow**	**n**	**Heat-treatment**
B1	20	As-received	Y1	20	As-received
B2	20	Brush-flame	Y2	20	Brush-flame
B3	20	5 secs @ 480°C	Y3	20	5 secs @ 480°C
B4	20	10 mins @ 480°C	Y4	20	10 mins @ 480°C
B5	20	2 hrs @ 480°C	Y5	20	2 hrs @480°C
B6	20	5 hrs @ 480°C	Y6	20	5 hrs @480°C

Groups B2-B6 and Y2-Y6 were heat-treated according to their assignment listed in Table 2. Groups B1 and Y1 (40 specimens) were not heat-treated and served as the as-received controls. Groups B2 and Y2 (40 specimens) were heat-treated using the brush-flame method with a butane refillable torch (Blazer GB 2001 Micro Torch, **Figure 2**). Groups B3-B6 (80 specimens) and Y3-Y6 (80 specimens) were heat-treated at varying durations using the Neytech Vulcan Multi-stage Programmable Furnace, Model 3-130 (***Figures 3 and 4***), set at 480°C. This created a total of 240 specimens with each type of wire/temper and condition consisting of 20 specimens (n= 20/temper/condition).

Figure 2. Butane refillable torch, Blazer GB 2001 Micro Torch (Farmingdale, NY).

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

Figure 4. Heating Chamber of Neytech Vulcan Multi-stage Programmable Furnace

Heat-Treatment of Groups B2 and Y2 Using the Brush-Flame Method

A brush-flame method was used to heat-treat the wires in groups B2 and Y2 (Philip & Darvell, 2016). A butane refillable torch was used for this method (***Figure 2***). The procedure was executed as follows (**Figure 5**)

1. 1 mm of the wire was held with a direct bonding bracket holder instrument (Hu-Friedy 678-212)
2. The wire passed through the tip of the inner flame of the butane torch at a constant speed, completing one full pass of the wire in about 10 seconds.
3. At this rate, the brush-flame method caused each part of the wire to turn a dark straw-color
4. The wire was allowed to cool to room temperature prior to replacing it back into its respective position in the Styrofoam block.

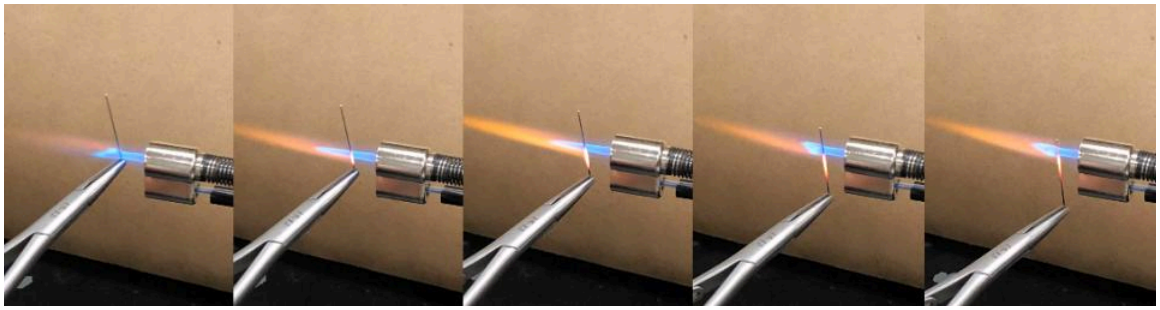


Figure 5. Brush-flame method.

Heat-Treatment of Groups B4-B6 and Y4-Y6 Using the Programmable Dental Furnace

Groups B3-B6 and Y3-Y6 were heat-treated in a programmable furnace. The specimens were loaded on the ceramic honeycomb tray, spacing out for appropriate heat dissipation (***Figure 6***). The honeycomb tray was placed atop a second ceramic platform which was designed to fit inside the furnace chamber (***Figure 4***). This was done to facilitate insertion and removal of the specimens, as the ceramic honeycomb tray was porous and wires would fall through otherwise. The temperature of the oven was set at 480°C for groups B4/Y4, B5/Y5, and B6/Y6, and subsequently heat-treated for 10 mins, 2 hrs, and 5 hrs, respectively. Group B4 was combined with Y4, Group B5 combined with Y5, and Group B6 combined with Y6; these pairings were heat-treated separately and individually. Groups B3 and Y3 were heat-treated following a different protocol due to their very short heat-treatment time of 10 seconds.

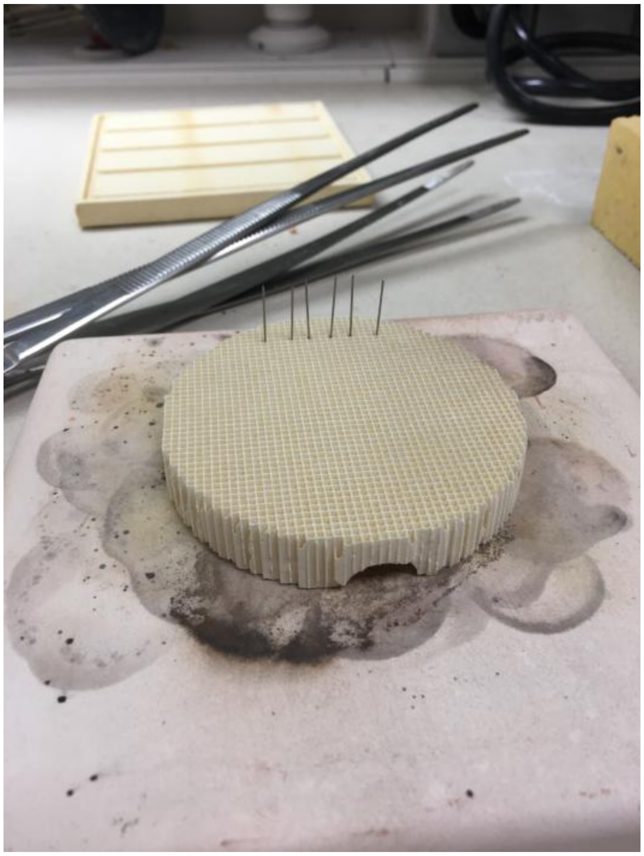


Figure 6. Samples loaded onto porous ceramic base prior to heat treatment.

Heat-Treatment of Groups B3 and Y3

Because the heat-treatment time for groups B3 and Y3 was only 5 seconds, the oven required an increased pre-heating temperature to account for the temperature drop while the chamber door was open during sample loading. After several trial runs, it was determined that the door to the chamber must be open for 5 seconds in order to load the samples. To allow the samples to be inside the chamber at exactly 480°C for 5 seconds, the oven was pre-heated to 493°C. By the time the samples were loaded, the internal chamber temperature was 480°C.

Three-Point Bend Test Protocol

The 240 segments of Elgiloy wire were tested using the three-point bending test, carried out at room temperature ($23 \pm 2^{o}C$). The wires, centered between two metal support beams at a distance of 14 mm apart, received a vertical load applied by a universal testing machine (***Figure 7***, Instron Corp, Norwood, Mass). This load was applied to the middle of each wire at a rate of 2 mm/min to a maximum deflection of 3.1 mm (***Figure 8***), and then returned to the starting position at the same rate (Chang, Berzins, Pruszynski, & Ballard, 2014). The three-point bend test was performed following American National Standard/American Dental Association specification No. 32 for orthodontic wires (ANSI/ADA Specification No. 32/ISO 15841:2006 Dentistry - Wires for use in orthodontics, 2006) as a guide. The protocol differed from the ANSI/ADA specifications in that the span between the two beams was modified to 14 mm rather than 10 mm. This was done to prevent the wire from falling from the metal support beams during deflection (***Figure 8***). In addition, following this slightly altered protocol allowed for more data to analyze as CoCr wires are normally just loaded to 0.1 mm of permanent deformation.

To record the force values, commercial software (Merlin, Instron) was used. The entire 3.1 mm of loading (activation) and 3.1 mm of unloading (deactivation) was recorded. Within the software, a “Load (kgf) vs Extension (mm)” graph was generated for each segment of wire tested.

Data Analysis

The raw data collected from each wire's three-point bend test was converted into a Microsoft Excel file to begin data analysis. The data was converted from kgf to g using formulas formatted for use within Excel. Using the information from the graph and the diameter of the wires (0.00044 m), the percent recovery, activation modulus or 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 12 different groups (B1-B6, Y1-Y6) of wires.

Statistical Analysis

Statistical analysis was performed using a two-way ANOVA with temper and heat-treatment time as factors. Due to a significant ($p<0.05$) interaction, a one-way ANOVA followed by a Post Hoc Bonferroni test was conducted ($P<0.05$). Therefore, a p-value <0.05 indicated a statistically significant difference between wires for a given measure and comparison. A T-test compared different tempers.

Statistical analysis was performed using a two-way ANOVA with temper and heat-treatment time as factors. Due to a significant ($p<0.05$) interaction, a one-way ANOVA followed by a Post Hoc Bonferroni test was conducted ($P<0.05$). Therefore, a

p-value <0.05 indicated a statistically significant difference between wires for a given measure and comparison. A T-test compared different tempers.

Figure 7. Instron Universal Testing Machine

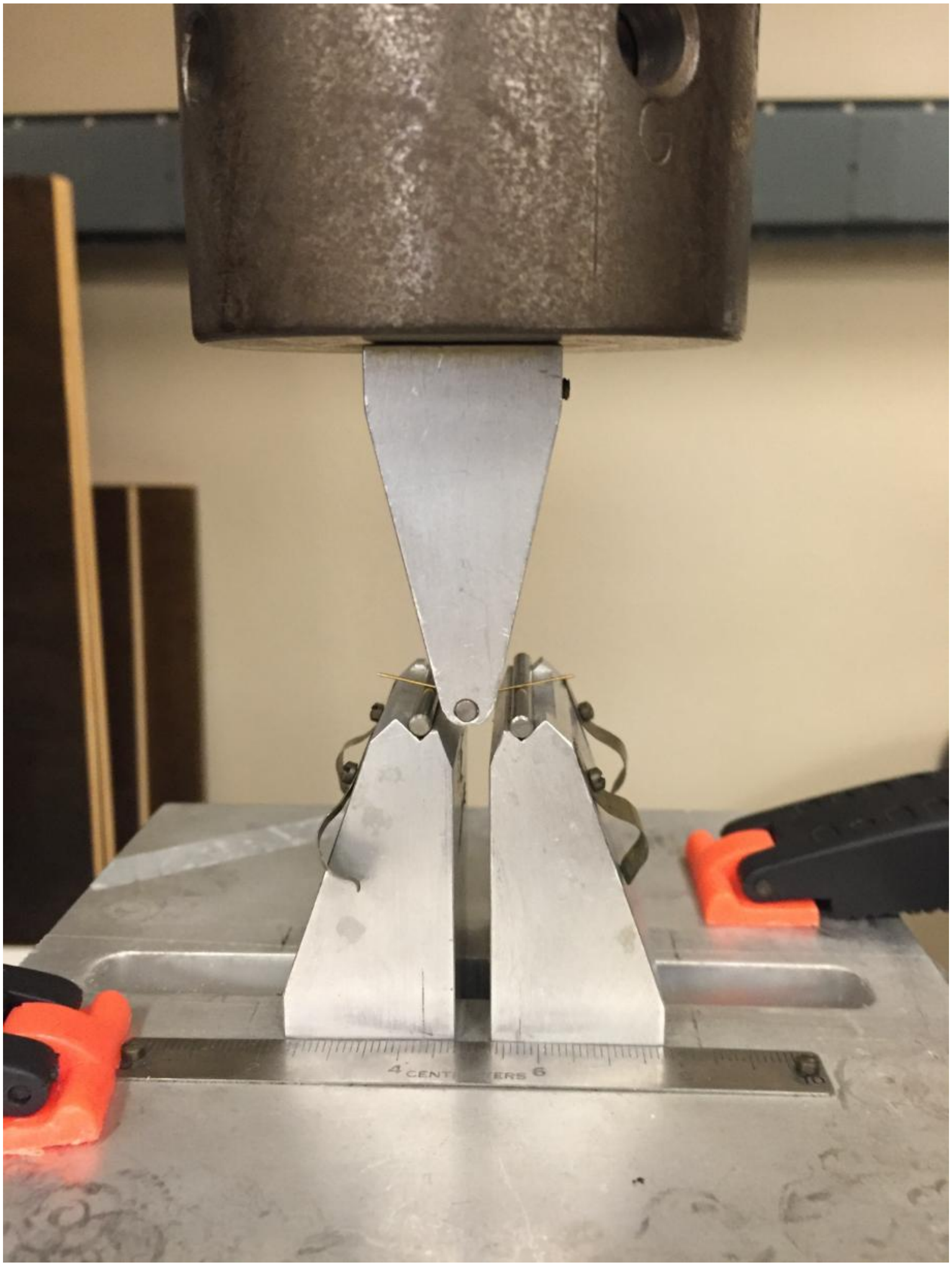
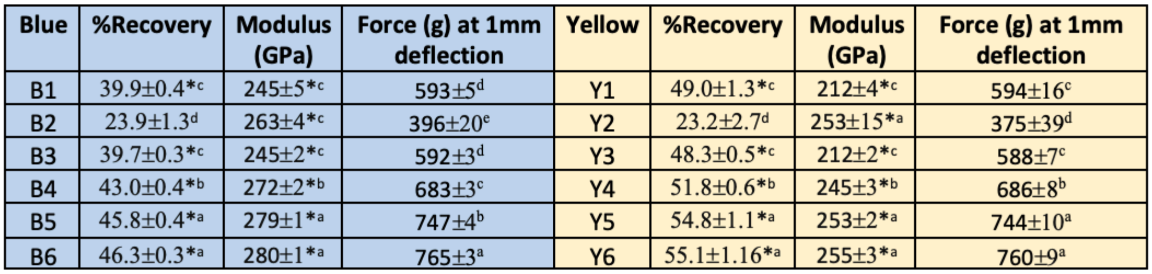


Figure 8. Instron Universal Testing Machine Performing Three-Point Bend Test

CHAPTER IV- RESULTS

In each of the blue and yellow tempers, four of the five heat-treatment groups (B2/flame, B4/10 mins, B5/2 hrs, B6/5 hrs and Y2/flame, Y4/10 mins, Y5/2 hrs, Y6/5 hrs) showed significant differences ($p<.05$) in percent recovery, modulus, and force values at 1 mm deflection versus the as-received wires (B1). Group B3 (480^{o}C for 5 secs) was not significantly different ($p>.05$) from Group B1 (as-received) for any of the three measurements (percent recovery, flexural modulus, or force at 1 mm deflection). Group Y3 (480^{o}C for 5s) was not significantly different ($p>.05$) from Group Y1 (as-received) for any of the three measurements (percent recovery, flexural modulus, or force at 1 mm deflection). However, there was one minor exception in that the B2/flame versus B1/as-received wires did not show significant differences in the flexural modulus (**Table 3**).

Table 3. Results.



Blue	%Recovery	Modulus (GPa)	Force (g) at 1mm deflection	Yellow	%Recovery	Modulus (GPa)	Force (g) at 1mm deflection
B1	$39.9\pm0.4^{*c}$	$245\pm5^{*c}$	593 ± 5^{d}	Y1	$49.0\pm1.3^{*c}$	$212\pm4^{*c}$	594 ± 16^{c}
B2	23.9 ± 1.3^{d}	$263\pm4^{*c}$	396 ± 20^{e}	Y2	23.2 ± 2.7^{d}	$253\pm15^{*a}$	375 ± 39^{d}
B3	$39.7\pm0.3^{*c}$	$245\pm2^{*c}$	592 ± 3^{d}	Y3	$48.3\pm0.5^{*c}$	$212\pm2^{*c}$	588 ± 7^{c}
B4	$43.0\pm0.4^{*b}$	$272\pm2^{*b}$	683 ± 3^{c}	Y4	$51.8\pm0.6^{*b}$	$245\pm3^{*b}$	686 ± 8^{b}
B5	$45.8\pm0.4^{*a}$	$279\pm1^{*a}$	747 ± 4^{b}	Y5	$54.8\pm1.1^{*a}$	$253\pm2^{*a}$	744 ± 10^{a}
B6	$46.3\pm0.3^{*a}$	$280\pm1^{*a}$	765 ± 3^{a}	Y6	$55.1\pm1.16^{*a}$	$255\pm3^{*a}$	760 ± 9^{a}

Different letters ($^{a, b, c, d}$) denote significant differences ($p<.05$) within each measurement/temper; *$p<.01$, blue versus yellow for each measurement. For example, percent recovery for the blue wires can be grouped into the following rankings based upon significance: B6=B5>B4>B3=B1>B2.

All comparisons of 2 hrs versus 5 hrs heat-treatment groups in both tempers did not show significant differences in any values except one comparison. Of the three values recorded (percent recovery, flexural modulus, and force at 1 mm deflection) in both yellow and blue tempers, the only wire and value that showed significant differences ($p<.05$) between the 2 hrs and 5 hrs groups was blue Elgiloy for the force at 1 mm (B5 = 747±4g and B6 = 765±3g).

Figures 9 and 10 show the force-deflection curves for the blue and yellow tempers separately. As heat-treatment time increased, percent recovery, flexural modulus, and force (g) at 1 mm deflection increased with increasing deflection values.

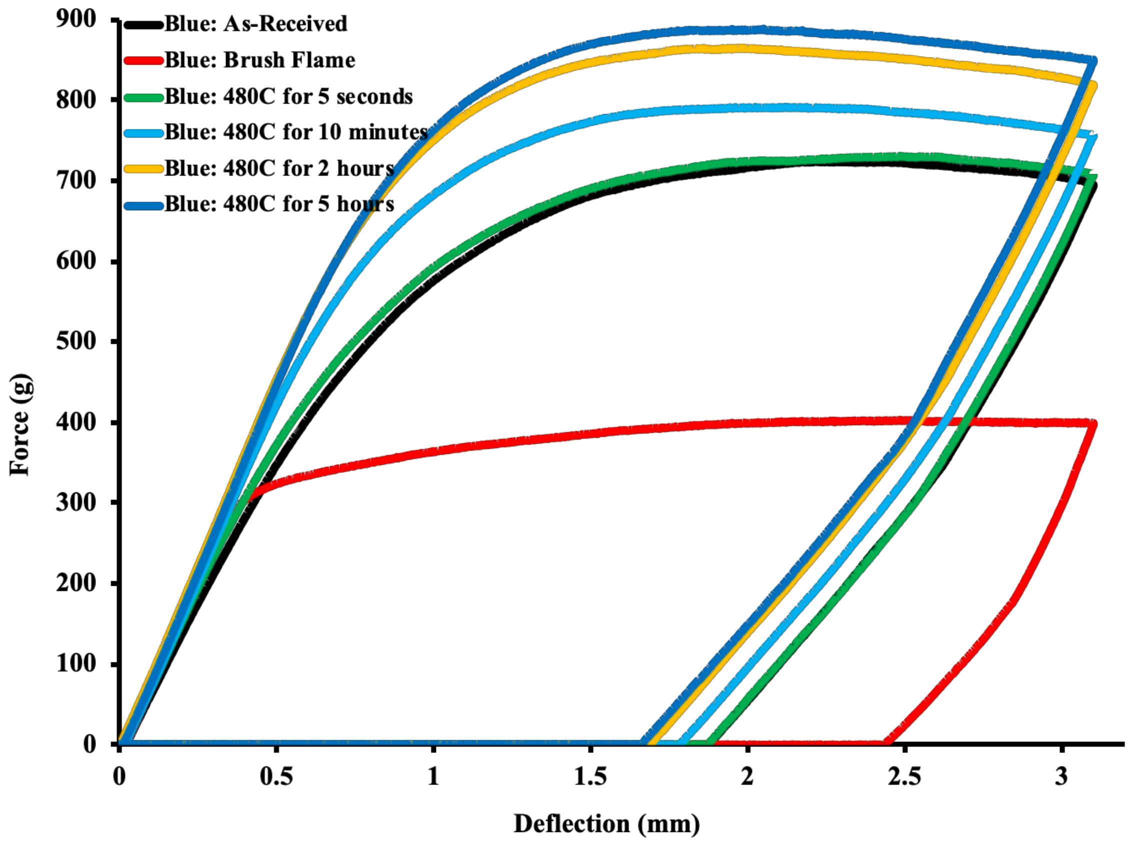


Figure 9. Comparison of force vs. deflection curves for all blue temper groups (B1-B6). Longer heat-treatment in the dental furnace led to increased percent recovery, flexural modulus, and force values in blue temper Elgiloy wires. Heat-treatment of blue Elgiloy wires with a brush-flame showed lower force values, lower percent recovery, and a generally distorted force-deflection curve versus all other groups.

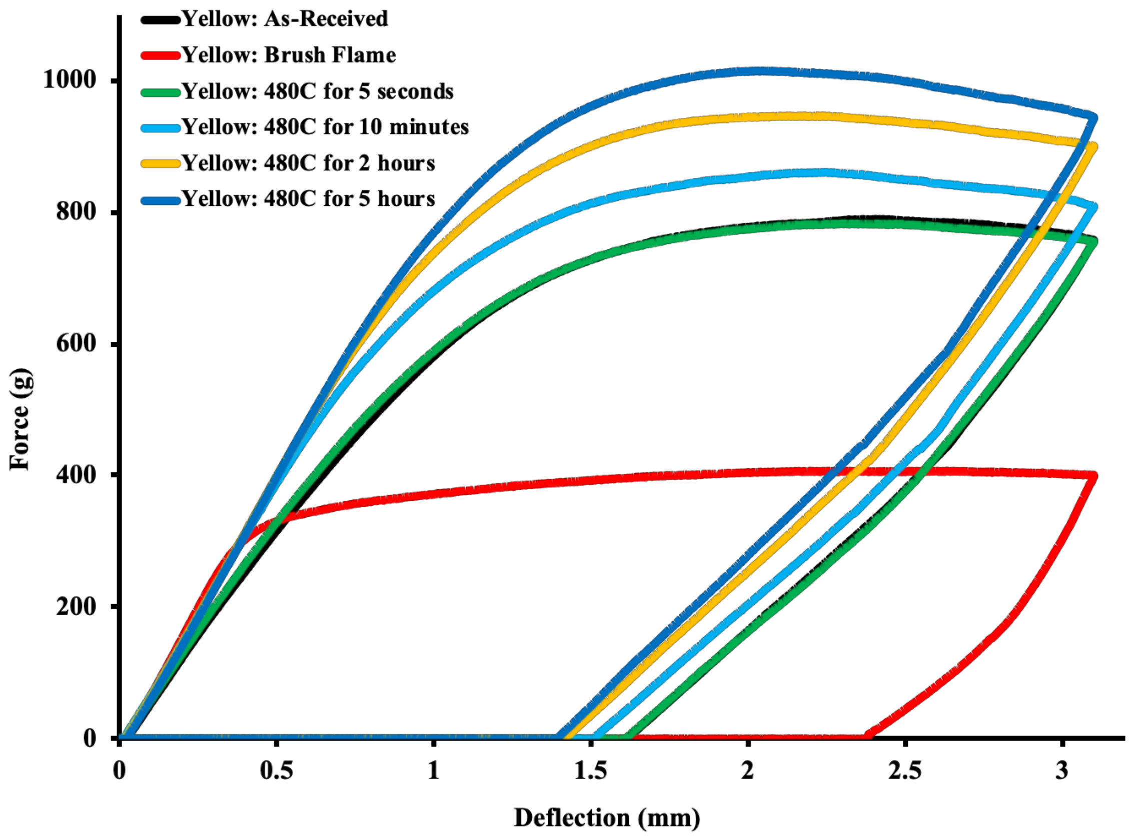


Figure 10. Comparison of force vs. deflection curves for all yellow temper groups (Y1-Y6). Longer heat-treatment in the dental furnace led to increased percent recovery, flexural modulus, and force values in yellow temper Elgiloy wires. Heat-treatment of yellow Elgiloy wires with a brush-flame showed lower force values, lower percent recovery, and a generally distorted force-deflection curve versus all other groups.

Figures 11-16 show the force-deflection curves for each heat-treatment group separately. **Figures 17-26** show the force values at various deflections for blue versus yellow Elgiloy wires. Generally (not including the brush-flame heat-treatment group), blue Elgiloy wires showed greater force values at deflection values less than 1 mm (**Figures 17-19**). At 1 mm, blue and yellow Elgiloy wires had similar force values (**Figure 20**). Beyond 1 mm deflection, yellow Elgiloy wires had greater force values (**Figures 21-26**). The blue and yellow Elgiloy brush-flame groups showed nearly identical force-deflection curves and showed similar force values at all deflection values (**Figure 12**). This force-deflection has a vastly different appearance when compared to the as-received or dental furnace heat-treated wires. **Table 4** shows the numerical force values at each 0.25 mm deflection increment.

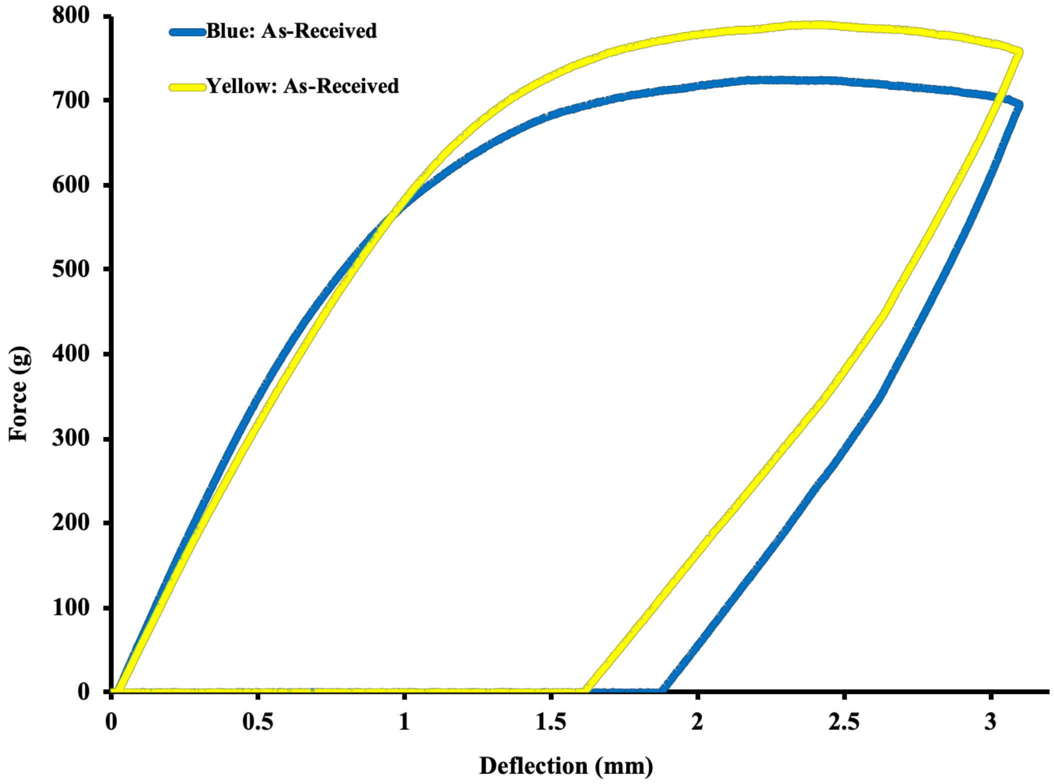


Figure 11. Force vs. deflection curves for as-received blue (B1) versus yellow (Y1) Elgiloy wires (no heat-treatment). As-received blue Elgiloy wires showed greater force (g) for deflection values below 1 mm. As-received yellow Elgiloy wires showed greater force (g) for deflection values beyond 1mm.

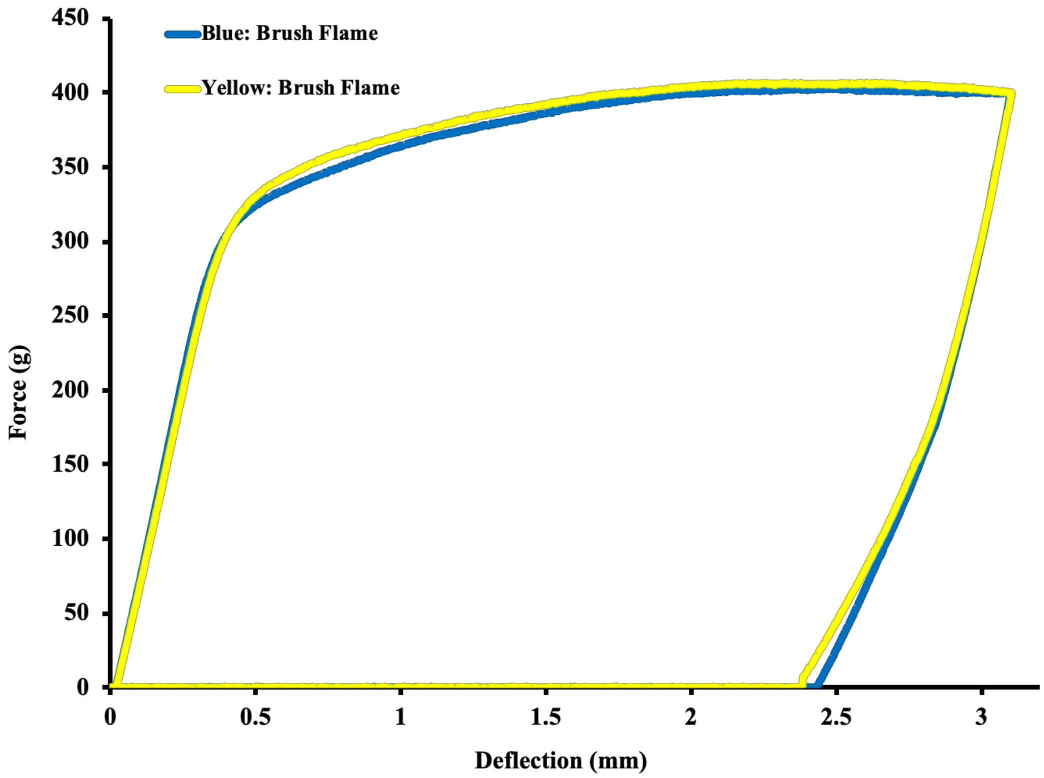


Figure 12. Force vs. deflection curves for blue (B2) versus yellow (Y2) Elgiloy wires heat-treated utilizing the brush-flame. Both brush-flame tempers showed similar force values at all deflection values. NOTE: The values on the Y-axis are much lower.

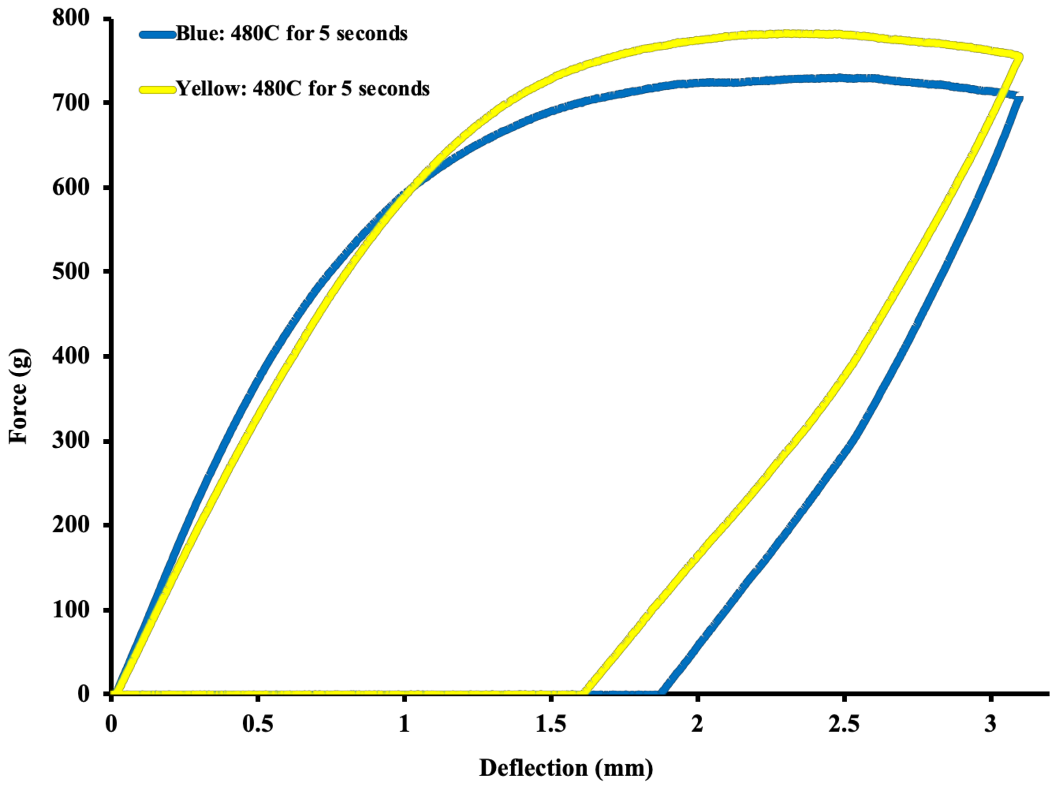


Figure 13. Force vs. deflection curves for blue (B3) versus yellow (Y3) Elgiloy wires heat-treated at 480^{o}C for 5 secs. Blue Elgiloy wires heat-treated for 5 secs showed greater force (g) for deflection values below 1 mm. Yellow Elgiloy wires heat-treated for 5 secs showed greater force (g) for deflection values beyond 1 mm.

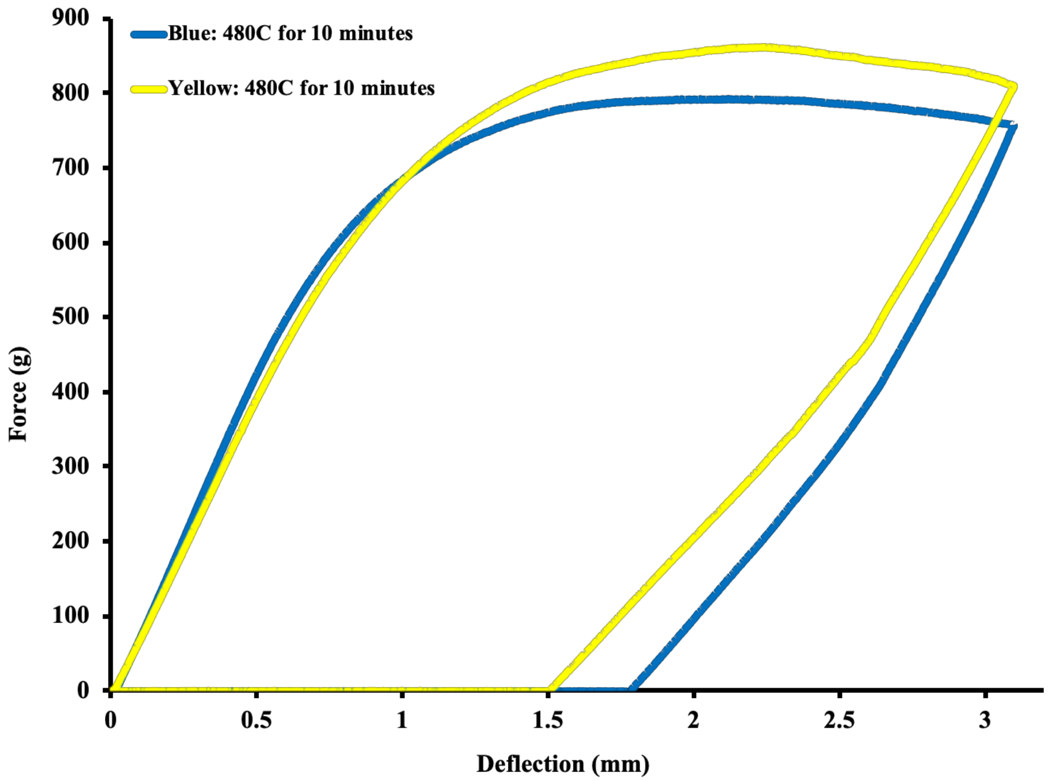


Figure 14. Force vs. deflection curves for blue (B4) versus yellow (Y4) Elgiloy wires heat-treated at 480°C for 10 mins. Blue Elgiloy wires heat-treated for 10 mins showed greater force (g) for deflection values below 1 mm. Yellow Elgiloy wires heat-treated for 10 mins showed greater force (g) for deflection values beyond 1 mm.

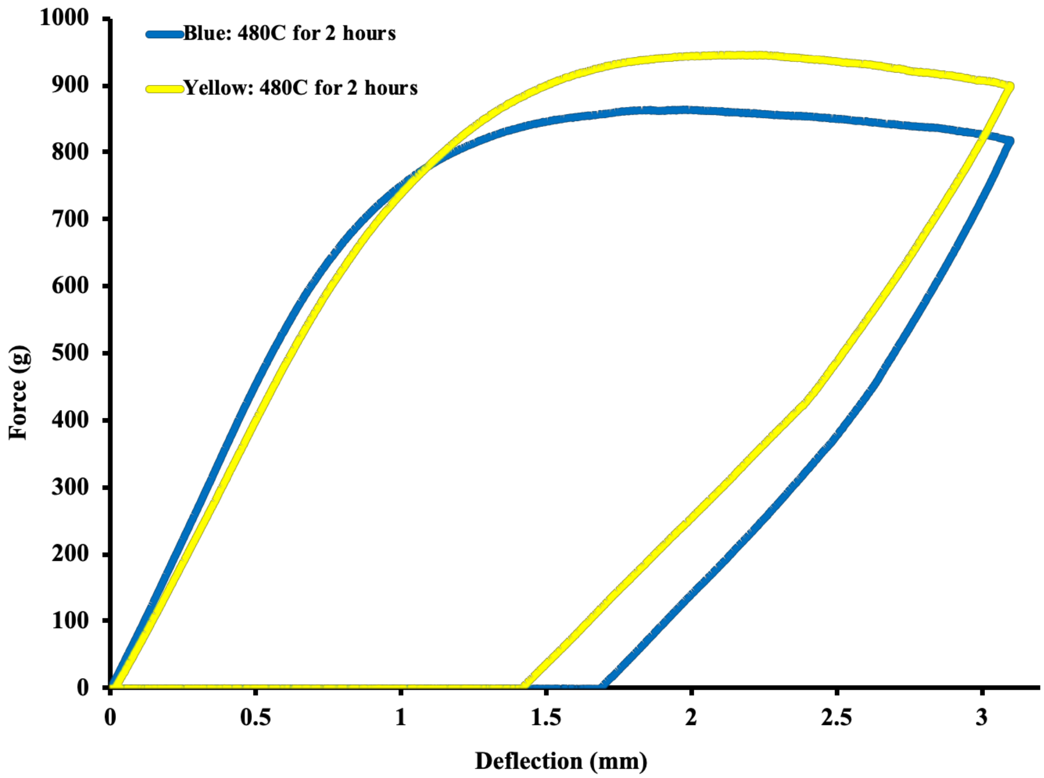


Figure 15. Force vs. deflection curves for blue (B5) versus yellow (Y5) Elgiloy wires heat-treated at 480^{o}C for 2 hrs. Blue Elgiloy wires heat-treated for 2 hrs showed greater force (g) for deflection values below 1mm. Yellow Elgiloy wires heat-treated for 2 hrs showed greater force (g) for deflection values beyond 1 mm.

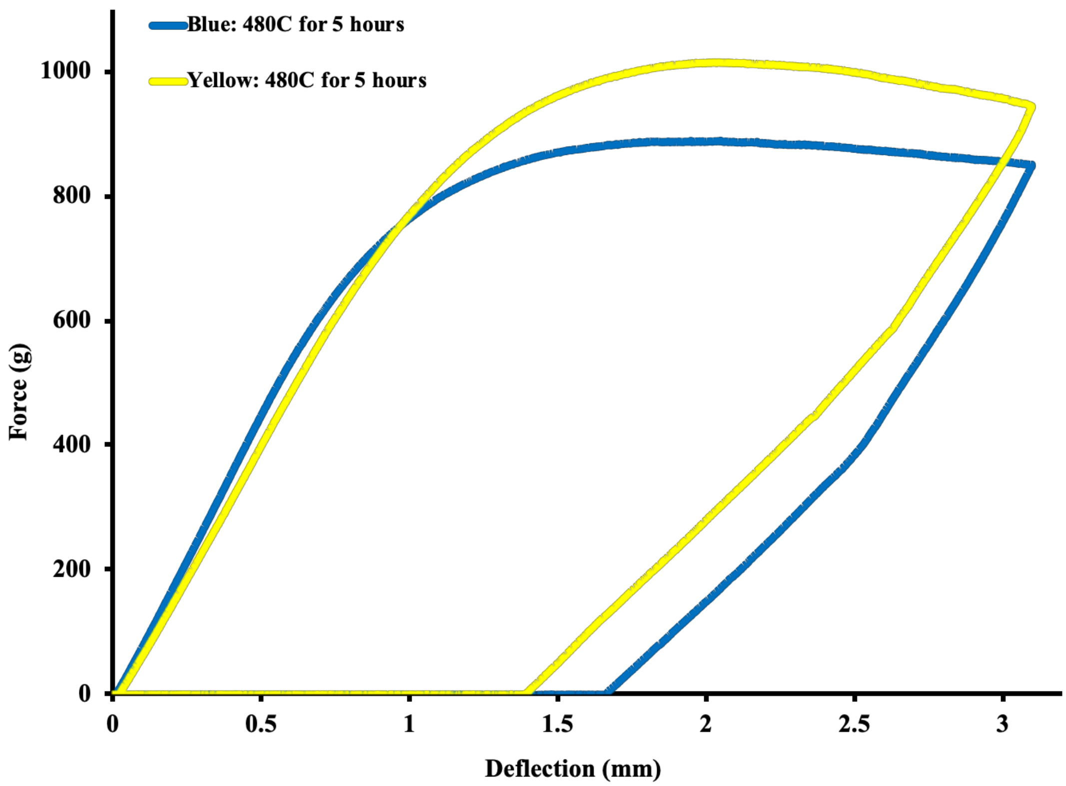


Figure 16. Force vs. deflection curves for blue (B6) versus yellow (Y6) Elgiloy wires heat-treated at 480^{o}C for 5 hrs. Blue Elgiloy wires heat-treated for 5 hrs showed greater force (g) for deflection values below 1 mm. Yellow Elgiloy wires heat-treated for 5 hrs showed greater force (g) for deflection values beyond 1 mm.

__Table 4. Force Values at Various Deflections for Elgiloy Wires.__

	Force (g) 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**
B1	192±6^{*d}	372±7^{*c}	502±7^{*d}	593±5^{d}	651±5^{*d}	689±4^{*d}	710±4^{*d}	721±4^{*d}	726±4^{*d}	724±4^{*d}
B2	217±5^{*a}	349±13^{d}	378±18^{e}	396±20^{e}	409±20^{e}	419±19^{e}	427±20^{e}	432±20^{e}	434±21^{e}	434±21^{e}
B3	194±4^{*d}	372±4^{*c}	502±3^{*d}	592±3^{d}	650±3^{*d}	688±3^{*d}	710±3^{*d}	721±4^{*d}	726±3^{*d}	726±4^{*d}
B4	201±6^{*c}	420±5^{*b}	583±3^{*c}	683±3^{c}	741±3^{*c}	773±3^{*c}	789±3^{*c}	794±3^{*c}	793±3^{*c}	788±3^{*c}
B5	213±5^{*b}	443±6^{*a}	630±5^{*b}	747±4^{b}	811±4^{*b}	845±5^{*b}	859±5^{*b}	863±5^{*b}	859±5^{*b}	851±5^{*b}
B6	209±4^{*b}	443±5^{*a}	640±4^{*a}	765±3^{a}	833±4^{*a}	868±4^{*a}	883±5^{*a}	884±5^{*a}	879±5^{*a}	872±5^{*a}
	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**
Y1	165±3^{*d}	331±7^{*c}	475±12^{*c}	594±16^{c}	676±13^{*d}	727±9^{*d}	755±7^{*d}	769±7^{*d}	774±8^{*d}	772±10^{*d}
Y2	201±5^{*a}	329±31^{c}	357±38^{d}	375±39^{d}	387±40^{e}	397±41^{e}	404±41^{e}	409±41^{e}	412±41^{e}	413±40^{e}
Y3	165±4^{*d}	329±4^{*c}	470±5^{*c}	588±7^{c}	670±8^{*d}	723±8^{*d}	753±8^{*d}	769±7^{*d}	776±7^{*d}	774±7^{*d}
Y4	183±5^{*c}	384±6^{*b}	557±5^{*b}	686±8^{b}	772±13^{*c}	824±15^{*c}	852±16^{*c}	863±16^{*c}	864±15^{*c}	858±14^{*c}
Y5	186±7^{*b,c}	399±7^{*a}	594±5^{*a}	744±10^{a}	844±16^{*b}	907±20^{*b}	940±22^{*b}	952±23^{*b}	951±22^{*b}	941±21^{*b}
Y6	189±5^{*b}	404±7^{*a}	604±5^{*a}	760±9^{a}	865±17^{*a}	932±22^{*a}	966±25^{*a}	979±26^{*a}	977±25^{*a}	967±24^{*a}

Table 4. Different letters ($^{a,\ b,\ c,\ d}$) denote significant differences (p<.05) within each deflection value/temper; *p<.01, blue versus yellow for each measurement. Heat treatment at 480^{o}C for 10 minutes or greater significantly increased force values at the various deflections.

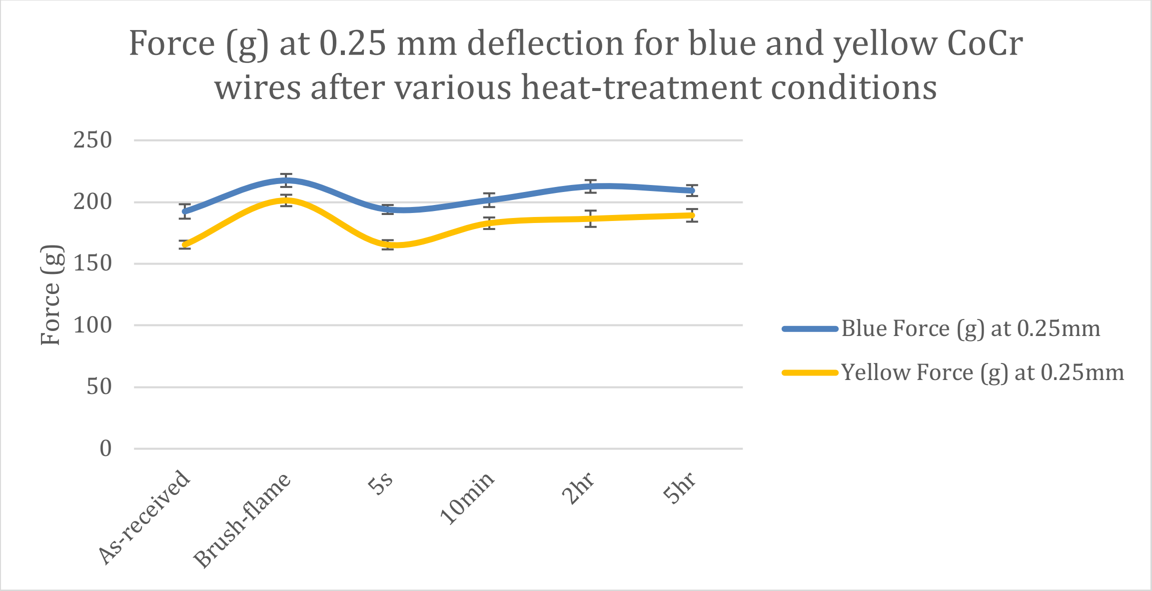


Figure 17. Force (g) at 0.25 mm deflection for blue and yellow CoCr wires after various heat-treatment conditions. Blue Elgiloy wires show greater force values for all heat-treatment conditions at 0.25 mm deflection.

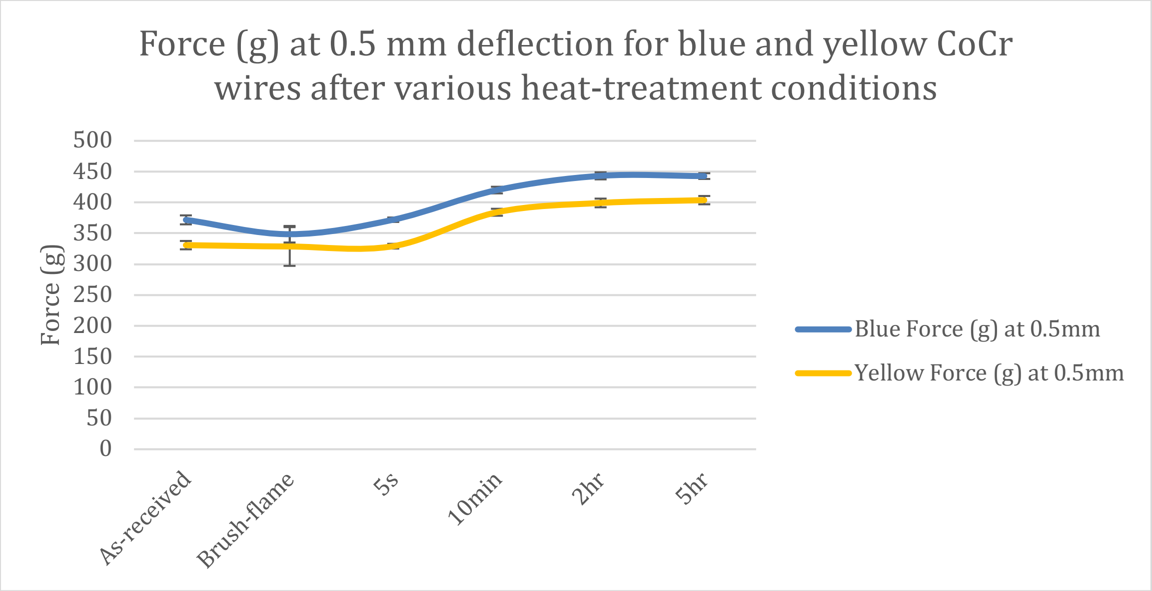


Figure 18. Force (g) at 0.5 mm deflection for blue and yellow CoCr wires after various heat-treatment conditions. Blue Elgiloy wires show greater force values for all heat-treatment conditions except brush-flame at 0.5 mm deflection.

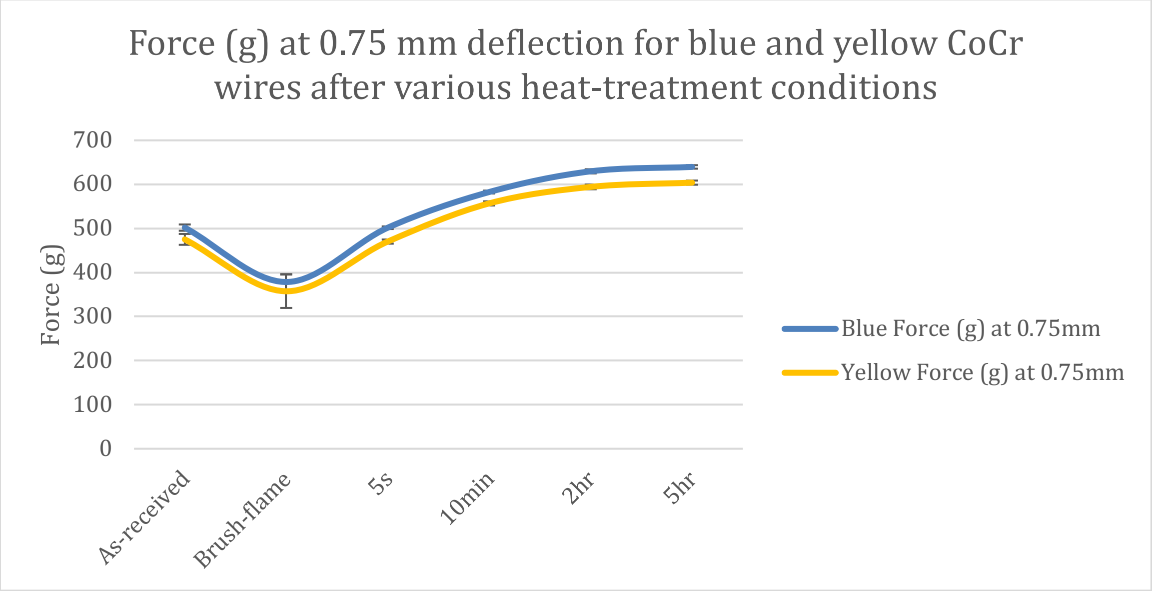


Figure 19. Force (g) at 0.75 mm deflection for blue and yellow CoCr wires after various heat-treatment conditions. Blue Elgiloy wires show greater force values for all heat-treatment conditions except brush-flame at 0.75 mm deflection.

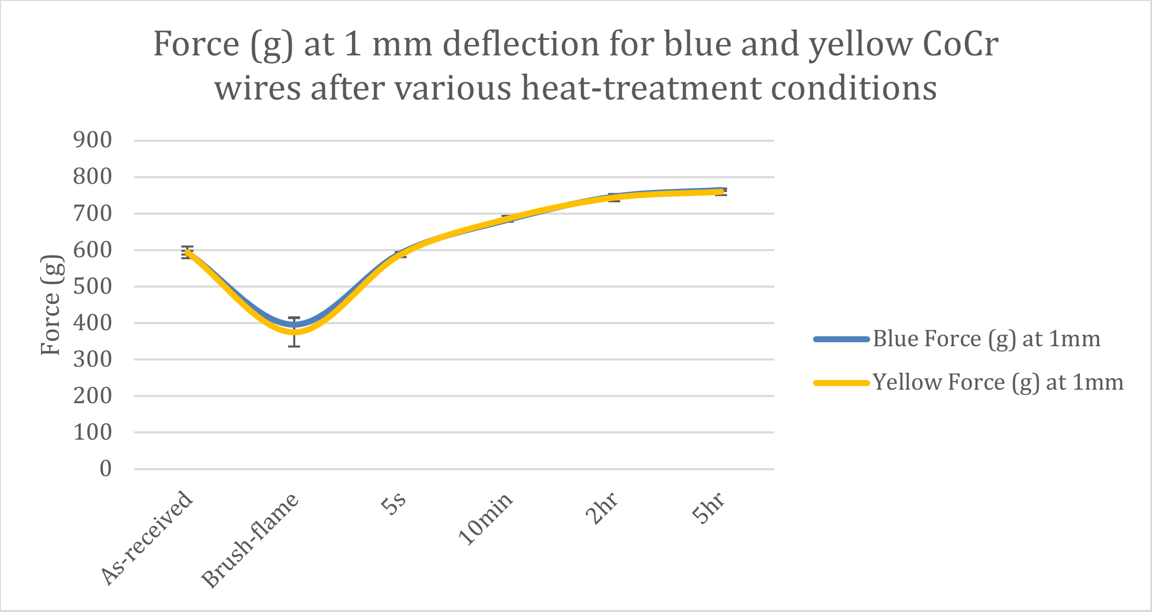


Figure 20. Force (g) at 1 mm deflection for blue and yellow CoCr wires after various heat-treatment conditions. No significant difference exists among different heat-treatment conditions for blue versus yellow Elgiloy wires at 1 mm deflection.

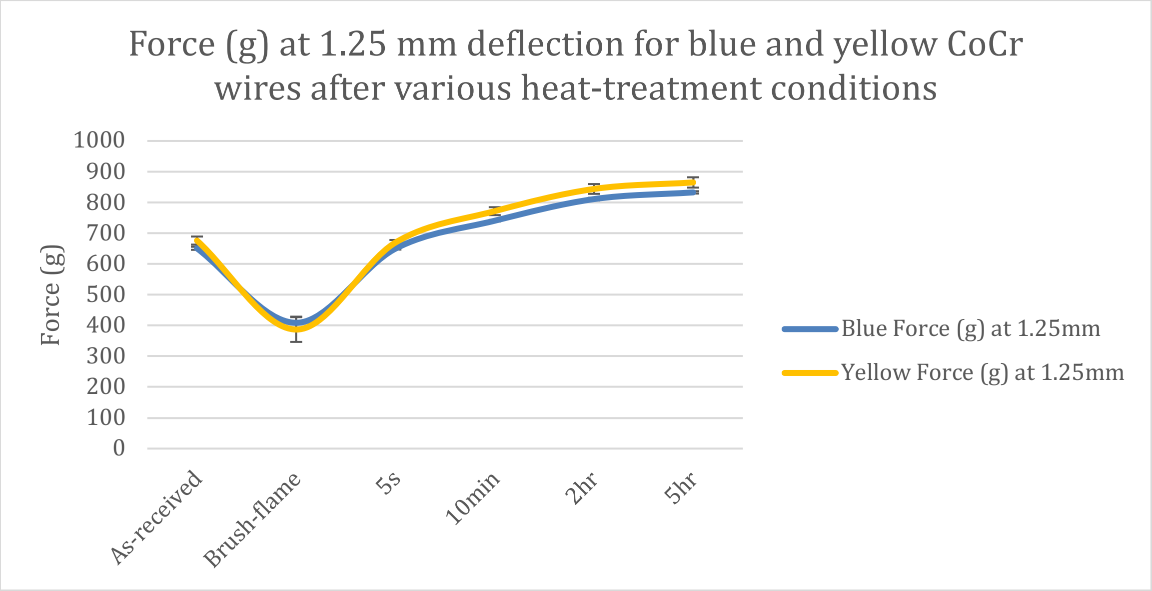


Figure 21. Force (g) at 1.25 mm deflection for blue and yellow CoCr wires after various heat-treatment conditions. Yellow Elgiloy wires show greater force values for all heat-treatment conditions except brush-flame at 1.25 mm deflection.

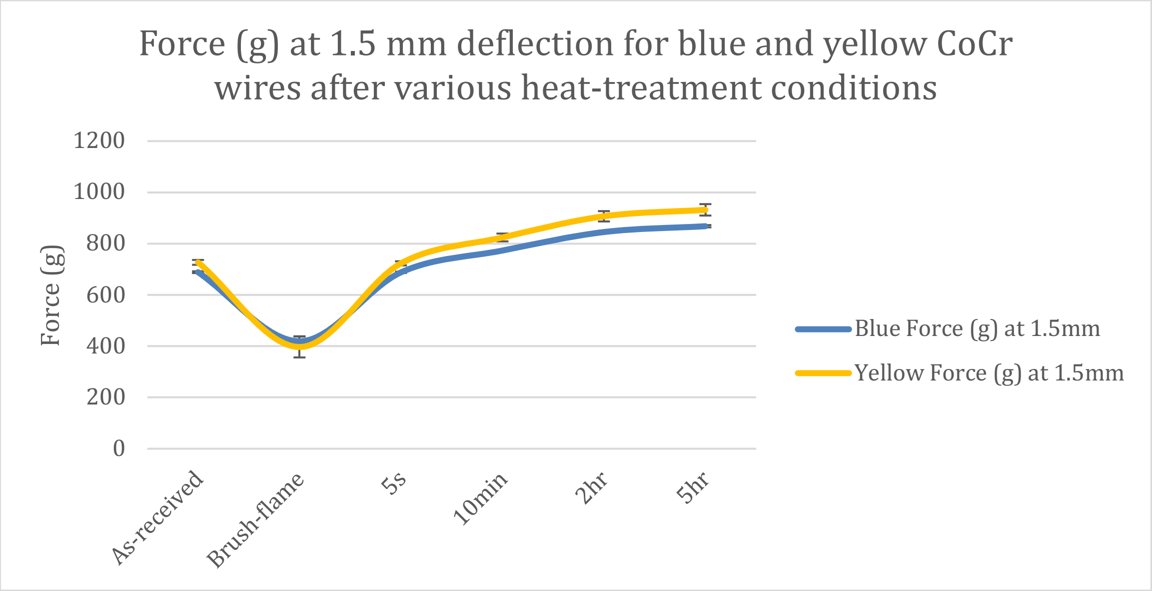


Figure 22. Force (g) at 1.5 mm deflection for blue and yellow CoCr wires after various heat-treatment conditions. Yellow Elgiloy wires show greater force values for all heat-treatment conditions except brush-flame at 1.5 mm deflection.

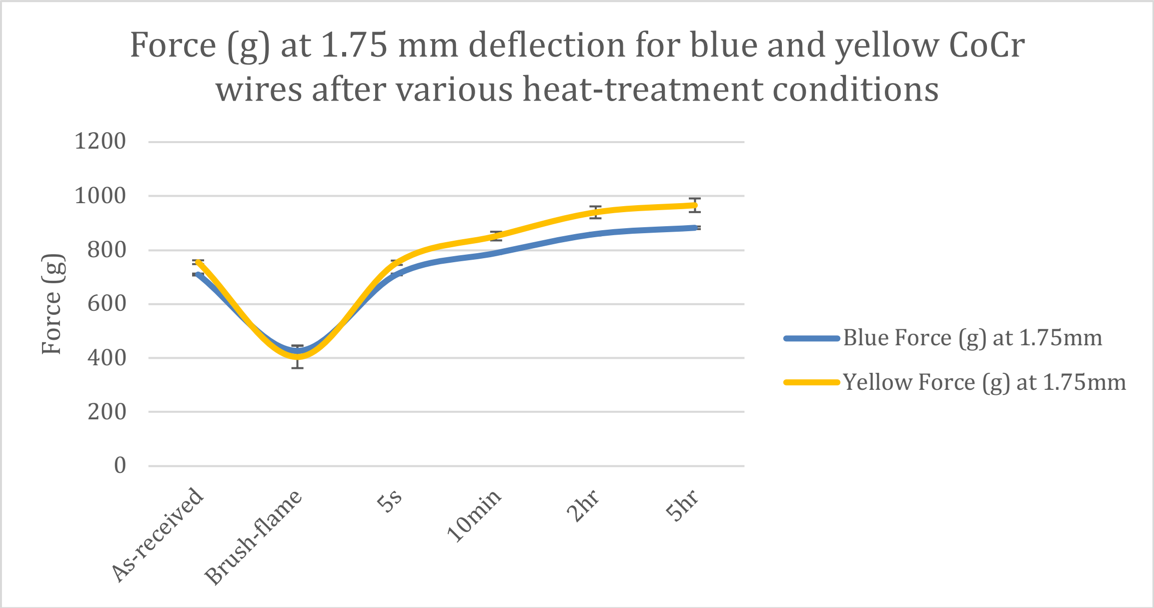


Figure 23. Force (g) at 1.75 mm deflection for blue and yellow CoCr wires after various heat-treatment conditions. Yellow Elgiloy wires show greater force values for all heat-treatment conditions except brush-flame at 1.75 mm deflection.

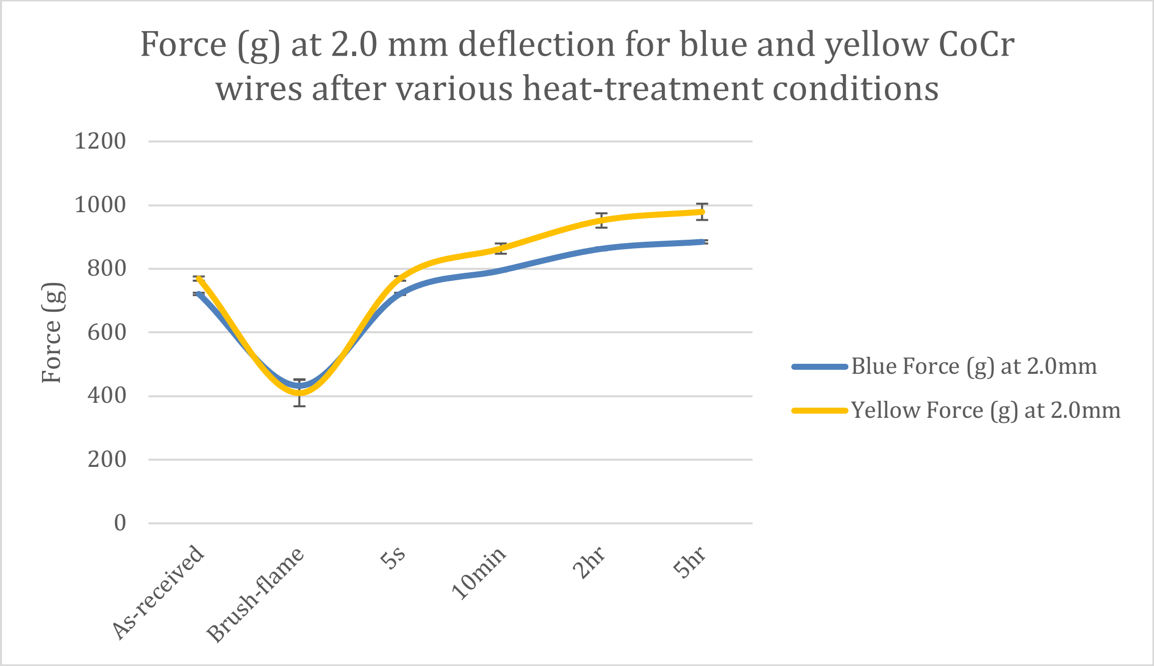


Figure 24. Force (g) at 2.0 mm deflection for blue and yellow CoCr wires after various heat-treatment conditions. Yellow Elgiloy wires show greater force values for all heat-treatment conditions except brush-flame at 2.0 mm deflection.

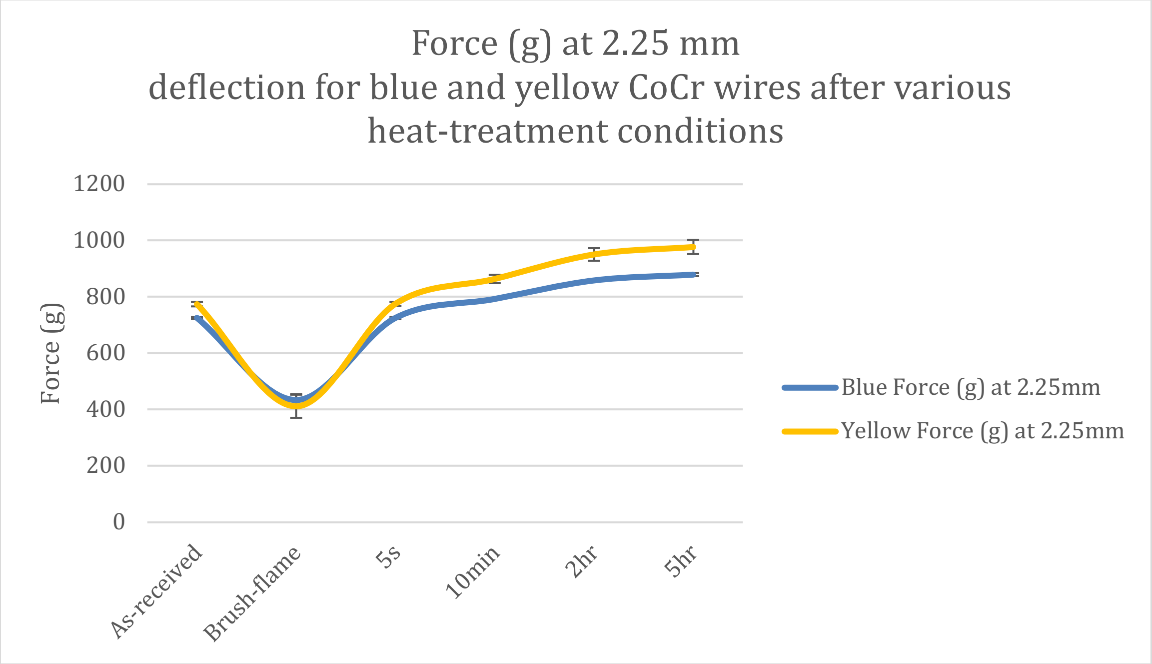


Figure 25. Force (g) at 2.25 mm deflection for blue and yellow CoCr wires after various heat-treatment conditions. Yellow Elgiloy wires show greater force values for all heat-treatment conditions except brush-flame at 2.25 mm deflection.

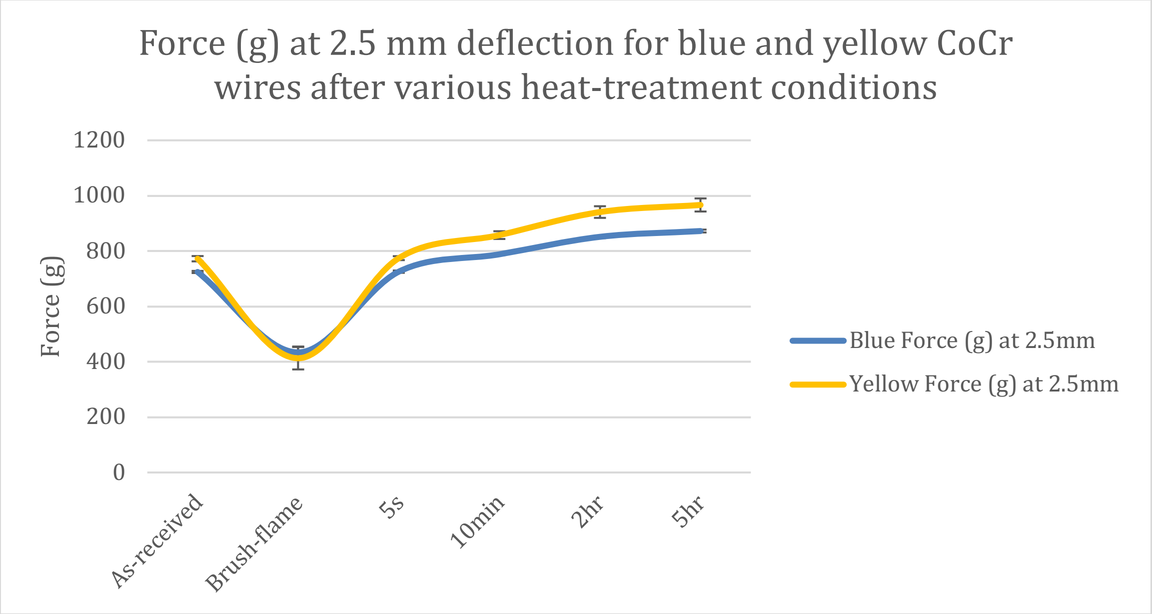


Figure 26. Force (g) at 2.5 mm deflection for blue and yellow CoCr wires after various heat-treatment conditions. Yellow Elgiloy wires show greater force values for all heat-treatment conditions except brush-flame at 2.5 mm deflection.

Figure 27 shows the percent recovery values for blue versus yellow Elgiloy wires for each heat-treatment group. **Figure 28** shows the flexural modulus for blue versus yellow Elgiloy wires for each heat-treatment group.

Heat-treatment increased both flexural modulus and percent recovery (**Table 5**). For blue Elgiloy wires: heat-treatment for 5 hrs increased flexural modulus by 14.3% and percent recovery by 16.0%; heat-treatment for 10 minutes increased flexural modulus by 11.0% and percent recovery by 7.8%. For yellow Elgiloy wires: heat-treatment for 5 hrs increased flexural modulus by 20.3% and percent recovery by 12.4%; heat-treatment for 10 minutes increased flexural modulus by 15.6% and percent recovery by 5.7%.

Similar mechanical properties can be achieved in just 2 hours compared to the manufacturer recommended 5 hours of heat-treatment of Elgiloy wires. The 5 hour heat-treatment group value was assumed to be the "ideal" value of the wire of the various parameters (percent recovery, flexural modulus, and force values). To determine the "percentage to ideal" of the 5 secs, 10 mins, and 2 hrs heat-treatment groups, the following formula was followed:

$$\% \; to \; ideal \; at \; 5 \; secs, 10 \; mins, or \; 2 \; hrs \; heat \; treatment \; duration$$

$$= \frac{\text{mean value of 5 secs, 10 mins, or 2 hrs heat treatment} - \text{mean value of as received wire equivalent}}{\text{mean value of 5 hrs wire equivalent} - \text{mean value of as received wire equivalent}}$$

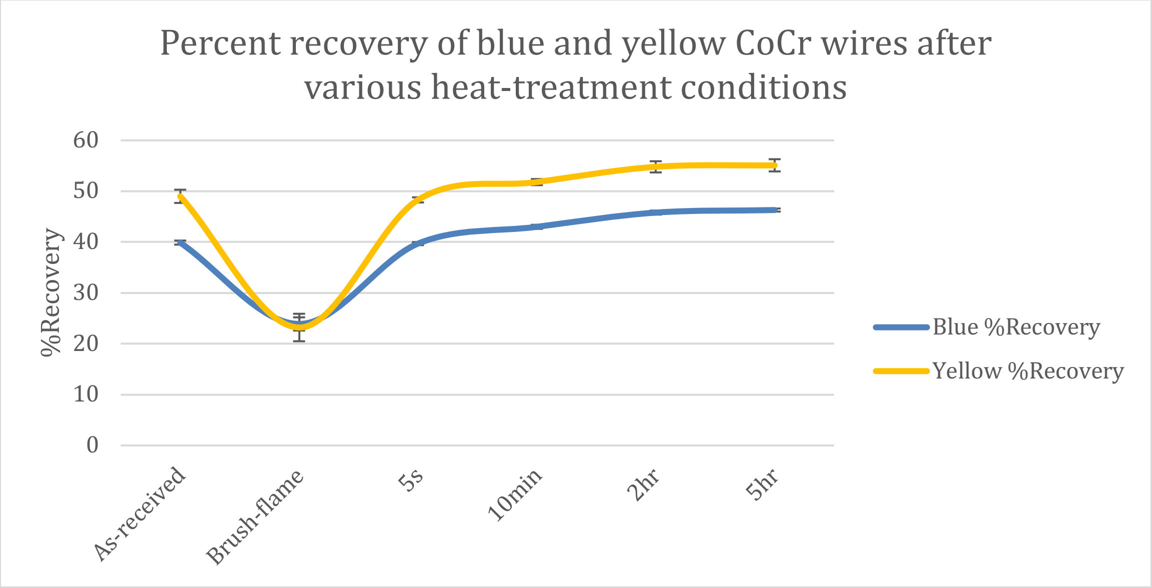


Figure 27. Percent recovery of blue and yellow CoCr wires after various heat-treatment conditions. Yellow Elgiloy wires show greater percent recovery for all heat-treatment conditions except brush-flame.

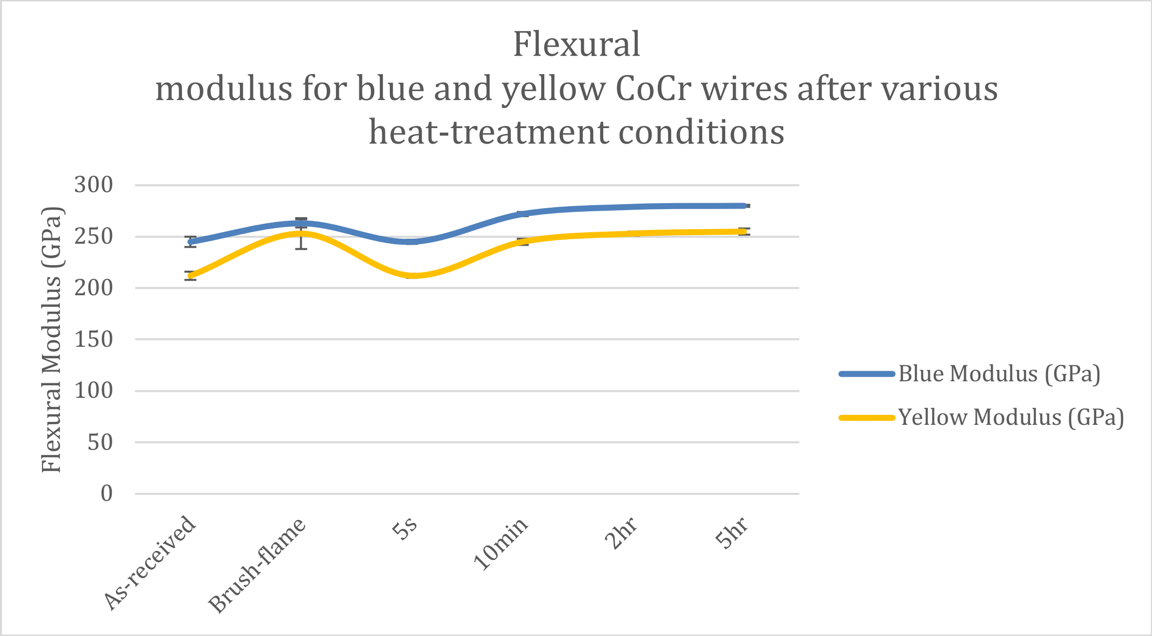
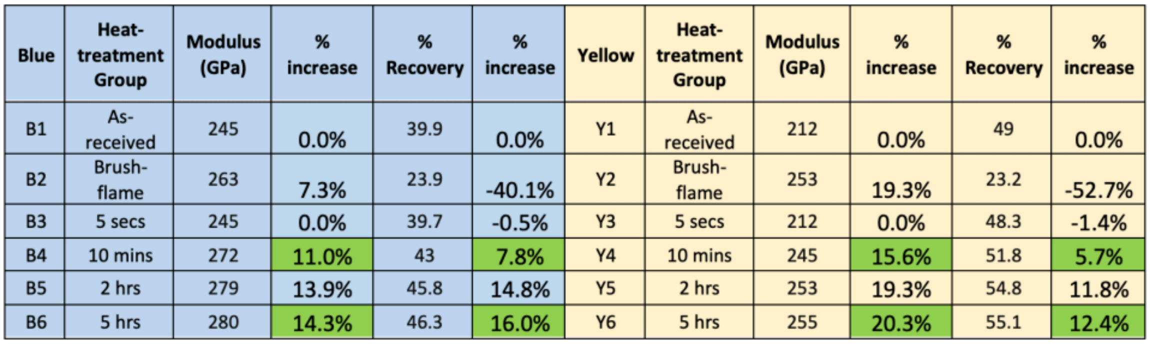


Figure 28. Flexural modulus for blue and yellow CoCr wires after various heat-treatment conditions. Blue Elgiloy wires show greater flexural modulus for all heat-treatment conditions except brush-flame.

Table 5. Percent increase in flexural modulus (GPa) and percent recovery with varying heat-treatment conditions of blue and yellow Elgiloy wires.

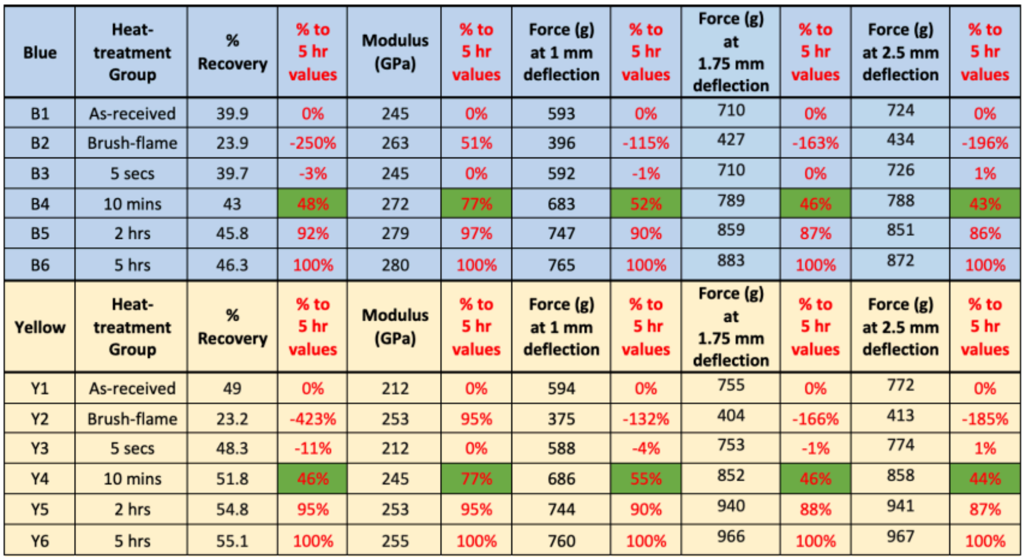


Blue	Heat-treatment Group	Modulus (GPa)	% increase	% Recovery	% increase	Yellow	Heat-treatment Group	Modulus (GPa)	% increase	% Recovery	% increase
B1	As-received	245	0.0%	39.9	0.0%	Y1	As-received	212	0.0%	49	0.0%
B2	Brush-flame	263	7.3%	23.9	-40.1%	Y2	Brush-flame	253	19.3%	23.2	-52.7%
B3	5 secs	245	0.0%	39.7	-0.5%	Y3	5 secs	212	0.0%	48.3	-1.4%
B4	10 mins	272	11.0%	43	7.8%	Y4	10 mins	245	15.6%	51.8	5.7%
B5	2 hrs	279	13.9%	45.8	14.8%	Y5	2 hrs	253	19.3%	54.8	11.8%
B6	5 hrs	280	14.3%	46.3	16.0%	Y6	5 hrs	255	20.3%	55.1	12.4%

Table 5. For blue Elgiloy wires: heat-treatment for 5 hrs increased flexural modulus by 14.3% and percent recovery by 16.0%; heat-treatment 10 minutes increased flexural modulus by 11.0% and percent recovery by 7.8%. For yellow Elgiloy wires: heat-treatment for 5 hrs increased flexural modulus by 20.3% and percent recovery by 12.4%; heat-treatment for 10 minutes increased flexural modulus by 15.6% and percent recovery by 5.7%.

Table 6 shows the "percentage to ideal" values for each of the parameters and various heat-treatments for each yellow and blue Elgiloy wires. For example, heat-treatment of blue Elgiloy wire for just 10 minutes resulted in a 77% increase in flexural modulus from the as-received wires to the 5 hrs heat-treatment group. Overall, heat-treating the wires for just 10 minutes caused an increase of a range of 43 to 77% of the values from as-received to 5 hrs heat-treatment. Heat-treating the wires for 2 hrs vs 5 hrs caused an additional increase in values in the range of just 3-14%. Therefore, there was not much additional benefit to heat-treating beyond 2 hrs at 480^{o}C. This is also supported by the non-significant findings in the values of 2 hrs vs 5 hrs heat-treatment groups in both blue and yellow Elgiloy wires (**Table 3**).

Table 6. Calculation of % to the mean values obtained via heat-treatment for 5 hours.



Blue	Heat-treatment Group	% Recovery	% to 5 hr values	Modulus (GPa)	% to 5 hr values	Force (g) at 1 mm deflection	% to 5 hr values	Force (g) at 1.75 mm deflection	% to 5 hr values	Force (g) at 2.5 mm deflection	% to 5 hr values
B1	As-received	39.9	0%	245	0%	593	0%	710	0%	724	0%
B2	Brush-flame	23.9	-250%	263	51%	396	-115%	427	-163%	434	-196%
B3	5 secs	39.7	-3%	245	0%	592	-1%	710	0%	726	1%
B4	10 mins	43	48%	272	77%	683	52%	789	46%	788	43%
B5	2 hrs	45.8	92%	279	97%	747	90%	859	87%	851	86%
B6	5 hrs	46.3	100%	280	100%	765	100%	883	100%	872	100%
Yellow	**Heat-treatment Group**	**% Recovery**	**% to 5 hr values**	**Modulus (GPa)**	**% to 5 hr values**	**Force (g) at 1 mm deflection**	**% to 5 hr values**	**Force (g) at 1.75 mm deflection**	**% to 5 hr values**	**Force (g) at 2.5 mm deflection**	**% to 5 hr values**
Y1	As-received	49	0%	212	0%	594	0%	755	0%	772	0%
Y2	Brush-flame	23.2	-423%	253	95%	375	-132%	404	-166%	413	-185%
Y3	5 secs	48.3	-11%	212	0%	588	-4%	753	-1%	774	1%
Y4	10 mins	51.8	46%	245	77%	686	55%	852	46%	858	44%
Y5	2 hrs	54.8	95%	253	95%	744	90%	940	88%	941	87%
Y6	5 hrs	55.1	100%	255	100%	760	100%	966	100%	967	100%

Table 6. Heat-treatment for 10 minutes resulted in values intermediate to the as-received versus 5 hour heat treatment time.

CHAPTER V - DISCUSSION

Elgiloy is a unique orthodontic wire in which the desirable mechanical properties can be greatly enhanced by heat-treatment. Prior to heat-treatment, however, this wire has the benefit of increased bendability into complex loops and bends. Fillmore and Tomlinson (1976) described how heat-treatment causes changes in mechanical properties:

> "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."

The heat-treatment of Elgiloy wires causes an age-hardening over a particular temperature range, but this process depends on a phase transformation following it being cold-worked (Assefpour-Dezfuly & Bonfield, 1984). As described in the textbook *Materials Science for Dentistry 9th Edition* by Darvell, heat-treatment of Elgiloy wires can be explained on a molecular level:

> "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."

For this reason, the changes in mechanical properties of Elgiloy wires following heat-treatment in this study can be explained; there was an increase in percent recovery, flexural modulus, stiffness, and force values at various deflections.

The ability to heat-treat Elgiloy creates for numerous advantages and increased clinical use of the wire. Heat treatment:

- Makes the wire more resistant to masticatory forces (Williams, Caputo, & Chaconas, 1978)
- The relief of residual stress through heat treatment leads to improved fatigue characteristics (Williams, Caputo, & Chaconas, 1978)
- 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, Elgiloy wires are highly resistant to corrosion, easily soldered, and able to be electrolytically polished (Fillmore & Tomlinson, Heat treatment of cobalt-chromium alloy wire, 1976).

The results of this study showed that blue Elgiloy is stiffer (greater flexural modulus) than yellow Elgiloy. These results are consistent with past studies (Asgharnia & Brantley, 1986), (Kusy, Mims, & Whitley, Mechanical characteristics of various tempers of as-received cobalt-chromium archwires, 2001), (Schwab, 2017).

Greater stiffness/flexural modulus of the blue Elgiloy wire (**Figure 28**) explains why this temper showed greater force values during the elastic phase, at deflections less than 1mm (**Figure 17-19**). At 1mm both blue and yellow Elgiloy wires had the same force values (**Figure 20**). Beyond 1mm, yellow Elgiloy wires showed greater force values (**Figure 21-26**). However, yellow Elgiloy wires have greater percent recovery (**Figure 27**).

This study was conducted to investigate how varying heat-treatment modality and duration affects stiffness, flexural modulus, force delivery, and percent recovery of the two of the most commonly used Elgiloy wires, blue and yellow, in a three-point bend test. Stiffness is represented by the elastic modulus on a force versus deflection graph within the elastic range. The more horizontal the slope, the springier the wire; the more vertical the slope, the stiffer the wire (Proffit, Fields, Sarver, & Ackerman, 2013). Clinically, the flexural modulus relates the tendency for an archwire to bend, for example when placed into a bracket, and this value is determined by a three-point bend test, as performed in this study.

Many previous studies on cobalt-chromium wires have been performed in tension, for example: Philip and Darvell, (2016), Fillmore et al 1976, Fillmore et al 1979, and Williams 1978. However, 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." Therefore, the testing parameters of utilizing a three-point bend test better determines the clinically applicable mechanical properties.

The manufacturer recommends 5 hours at 527°C for Elgiloy wires (Elgiloy Promotional Literature, 1975). Other sources have recommended heat treatment ranging from 480 to 510°C for 3 to 12 minutes. One study found the maximum mechanical properties were reached when the Elgiloy wires were heat-treated in the range of approximately 593 to 649°C (Fillmore & Tomlinson, Heat treatment of cobalt-chromium alloy wire, 1976). It is apparent that there is no universally accepted heat-treatment protocol for these wires. Therefore, heat-treatment time was varied in this study to determine its effect on the mechanical properties of cobalt-chromium wires.

A previous study by Schwab (2017) found a statistically significant increase in stiffness, flexural modulus, and percent recovery of all four tempers of Elgiloy wires following heat treatment for five hours at 500°C. Similar results were found in this study (**Table 3**). This study served as a follow-up to his study which called for "further studies need to be done to evaluate how these alterations can be utilized clinically in an efficient manner. The 3-12 mins 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. 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."

After heat-treatment, the flexural modulus increased by 14.3% in the blue Elgiloy wires and 20.3% in the yellow Elgiloy wires. Past studies found a 20% increase in flexural modulus after heat-treatment for 5 minutes at 950°F (510°C) (Williams, Caputo, & Chaconas, 1978). This study found similar values to the

Williams study for yellow Elgiloy only. It must be remembered that the Williams study tested wires in tension with complex loop and helical bends rather than a three-point bend test used in this study.

Based on the results, it was determined that the brush-flame technique used in this study is not recommended most likely due to inconsistent heating conditions, in addition to high temperatures reached within the wire, resulting in varying bending properties. Flexural modulus increased by only 7.3% (**Table 5**) (versus 10 mins increased by 11.0%). In the study by Williams et al, increasing dental furnace temperature beyond 510^{o}C caused decreases in flexural modulus beyond their highest values. In the study by Fillmore (1976), at loads above 500g, the wires heat-treated at 816^{o}C permanently deformed more than wires that were not heat-treated. The reason for the poorer performance at extremely high temperatures is due to a partial annealing and overaging of the wires at these high temperatures.

The portion of the flame used to heat-treat the wire can reach high temperatures (1200^{o}C). Due to the inherent high temperature of the flame used in the methods to heat-treat the wire with the brush-flame technique, the temperature of the wire most likely increased beyond ideal conditions, causing a "dead soft" or partial annealing phenomenon. However, it must be noted that the design of this study followed the brush-flame technique outlined in previous studies. These previous studies failed to mention the exact temperatures that were reached within the flame, or within the wire. These parameters are very difficult to measure. Furthermore, the standard deviations of percent recovery, flexural modulus, and force values had a significantly larger range, which suggests inconsistent

Heat-treatment for 10 minutes resulted in intermediate increases. This may be more realistic in a busy orthodontic practice and can increase bending properties by 50-75% compared to the 5hr group. Ten minutes of heat-treatment during clinical hours is reasonable, but further studies should be conducted at shorter durations and higher temperatures to determine the effects on mechanical properties.

CHAPTER VI - SUMMARY AND CONCLUSIONS

Blue and yellow Elgiloy wires of 0.018'' diameter were tested in a three-point bend test after being assigned to the following groups: 1) as-received (control); 2) brush-flame; 3) 480^{o}C for 5 secs; 4) 480^{o}C for 10 mins; 5) 480^{o}C for 2 hrs; and 6) 480^{o}C for 5 hrs. Force values were recorded throughout the three-point bend test in order to calculate percent recovery, flexural modulus, and force values at each 0.5mm increments of deflection. Varied heat-treatment times could then be compared to each other, as well as their as-received counterpart. It was concluded that:

1. Longer heat-treatment (2 hrs/5 hrs) increased percent recovery, flexural modulus, and force values when compared to the as-received counterparts.
2. Greater stiffness/flexural modulus of the blue Elgiloy wire explains why this temper showed greater force values during the elastic phase, at deflections

less than 1mm. At 1mm both blue and yellow Elgiloy wires had the same force values. Beyond 1mm, yellow Elgiloy wires showed greater force values

3. Yellow Elgiloy wires have greater percent recovery.
4. Similar mechanical properties can be achieved in just 2 hours compared to the manufacturer recommended 5 hours of heat-treatment of Elgiloy wires.
5. Heat-treatment for 10 minutes resulted in intermediate increases. This may be more realistic in a busy orthodontic practice and can increase bending properties 50-75% compared to the 5-hour group.
6. Using a brush-flame technique reduced elastic recovery and resulted in greater bending variability.
7. The brush-flame technique is not recommended due to inconsistent heating conditions resulting in varying bending properties.

BIBLIOGRAPHY

ANSI/ADA Specification No. 32/ISO 15841:2006 Dentistry - Wires for use in orthodontics. (2006). ANSI/ADA.

Asgharnia, M. K., & Brantley, W. A. (1986). Comparison of bending and tension tests for orthodontic wires. *American Journal of Orthodontics, 89*(3), 228-236.

Assefpour-Dezfuly, M., & Bonfield, W. (1984). Strengthening mechanisms in Elgiloy. *Journal of Materials Science, 19*(9), 2815-2836.

Backofen, W. A., & Gales, G. F. (1952). Heat treating stainless steel for orthodontics. *American Journal of Orthodontics, 38*, 755-765.

Brantley, W. A., & Eliades, T. (2001). *Orthodontic materials: Scientific and clinical aspects.* New York: Thieme.

Brantley, W., Berzins, D., Iijima, M., Tufekçi, E., & Cai, Z. (2017). *Orthodontic applications of biomaterials: a clinical guide. Chapter 1: Structure/property relationships in orthodontic alloys.* (T. Eliades, & W. A. Brantley, Eds.) Duxford, United Kingdom: Woodhead Publishing of Elsevier.

Chang, J.-H., Berzins, D. W., Pruszynski, J. E., & Ballard, R. (2014). The effect of water storage on the bending properties of esthetic, fiber-reinforced composite orthodontic archwires. *Angle Orthodontist, 84*(3), 417-423.

Craig, R. G. (1978). *Dental materials: a problem-oriented approach.* St. Louis: CV Mosby.

Darvell, B. W. (2009). *Materials Science for Dentistry, 9th ed.* Cambridge: Woodhead.
Elgiloy Company. (undated promotional literature, circa 1970). Elgiloy: the cobalt-nickel alloy. Elgin, IL: Elgiloy Company.

Elgiloy Promotional Literature. (1975). *High Tech Alloys*. Retrieved June 2019, from High Tech Alloys: http://www.hightechalloys.de/pdf/Elgiloy_Flyer.pdf

Fillmore, G. M., & Tomlinson, J. L. (1976, April). Heat treatment of cobalt-chromium alloy wire. *Angle Orthodontist, 46*(2), 187-195.

Fillmore, G. M., & Tomlinson, J. L. (1979, April). Heat treatment of cobalt-chromium alloys of various tempers. *Angle Orthodontist, 49*(2), 126-130.

Funk, A. C. (1951). The heat-treatment of stainless steel. *Angle Orthodontist, 21*, 129-138.

Graber, L. W., Vanarsdall, R. L., Vig, K. W., & Huang, G. J. (2017). *Orthodontics: Current Principles and Techniques, Sixth Edition.* St. Louis: Elsevier.

Greener, E. H., Harcourt, J. K., & Lautenschlager EP. (1972). *Materials science in dentistry.* Baltimore: Williams & Wilkins.

Harder, O. E., & Roberts, D. A. (1950, October 3). *United States Patent No. 2524661.*

Howe, G. L., Greener, E. H., & Crimmins, D. S. (1968). Mechanical properties and stress relief of stainless steel orthodontic wire. *Angle Orthodontist*(38), 244-249.

Kotha, R. S., Alla, R. K., Shammas, M., & Ravi, R. K. (2014). An overview of orthodontic wires. *Trends in biomaterials and artificial organs, 28*(1), 2014.

Kusy, R. P. (1997). A review of contemporary archwires: their properties and characteristics. *Angle Orthodontist, 67*(3), 197-207.

Kusy, R. P. (2002). Orthodontic Biomaterials: From the Past to the Present. *Angle Orthodontist, 72*(6), 501-512.

Kusy, R. P., Mims, L., & Whitley, J. Q. (2001). Mechanical characteristics of various tempers of as-received cobalt-chromium archwires. *American Journal of Orthodontics and Dentofacial Orthopedics, 119*(3), 274-291.

Mosby. (2007). *Mosby's Review for the NBDE Part II.* St. Louis: Mosby Elsevier.

Nikolai, R. J. (1997, September). Orthodontic Wire: A Continuing Evolution. *Seminars in Orthodontics, 3*(3), 157-165.

Philip, S. M., & Darvell, B. W. (2016). Effect of heat treatment on the tensile strength of 'Elgiloy' orthodontic wire. *Dental Materials, 32*(8), 1036-41.

Proffit, W. R., Fields, H. W., Sarver, D. M., & Ackerman, J. L. (2013). *Contemporary Orthodontics Fifth Edition.* St. Louis, Missouri, USA: Elsevier Mosby.

Rocky Mountain Orthodontics. (1977). Elgiloy and tru-chrome stainless steel: orthodontic treatment wires. . Denver: RMO.

Schwab, A. (2017, August). The effect of heat treatment on the bending properties of a cobalt-chromium orthodontic wire. Milwaukee, WI.

Williams, B. R., Caputo, A. A., & Chaconas, S. J. (1978). Orthodontic effects of loop design and heat treatment. *Angle Orthodontist, 48*(3), 235-239.