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Electric Versus Furnace Heat Treatment of Cobalt Chromium Wire

Greg William Sutherland
Loyola University Chicago

ELECTRIC VERSUS FURNACE HEAT TREATMENT OF COBALT CHROMIUM WIRE

by

Greg W. Sutherland, B.A., D.D.S.

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VITA

Greg William Sutherland was born on November 24, 1950, in Kalispell, Montana.

He received his Bachelor of Arts degree from Carroll College in Helena, Montana, in 1972.

He began his dental studies at the University of Washington School of Dentistry in Seattle, Washington, in 1972, and graduated in 1976 with the degree of Doctor of Dental Surgery.

After graduation, he began graduate studies in the Department of Oral Biology at Loyola University of Chicago in July of 1976. Concurrently, he received specialty training in the Department of Orthodontics under the Chairman of Graduate Orthodontics, Dr. Milton L. Braun.

DEDICATION

To my loving wife, Raelene, and daughter, Tara, who gave me their continued support and encouragement during the course of this project.

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3. To determine if a difference in resistance to deformation exists between furnace heat treatment and electrical heat treatment for a given temperature.

4. To determine the temperature that will result in the maximum resistance to deformation for cobalt chromium wire in a dental furnace and an electrical resistant unit.

5. To measure the voltage and amperage for a constant length of wire at a given temperature in the 600 to 1400°F range.

CHAPTER I

INTRODUCTION

Heat treatment of orthodontic wire has had a confusing and controversial past. Whether it be stainless steel or cobalt chromium wire, the controversy of time and temperature is still an issue. The research in this paper deals solely with the heat treatment of cobalt chromium wire; however, the review of literature does consider stainless steel orthodontic wire.

It is well known and undisputed that heat treatment enhances the physical properties of cobalt chromium wire. Yet, there is considerable debate as to the temperature necessary to reach a maximum strength of the wire. Furthermore, no studies have been published concerning electrical heat treatment of orthodontic wire at temperatures other than 950°F.

It is the purpose of this study to explore the possibilities of electrical heat treatment on straight wires at a variety of temperatures. Although some contend that electrical heat treatment is not as uniform a heating process as the dental furnace, one would expect the maximum strength of the wire to be very similar for both methods. However, since electrical heat treatment takes only a few seconds, in contrast to three to eight minutes for a dental furnace, the former would appear to be the more expedient and convenient method. Thus, information from this study should benefit the clinical orthodontist in selecting a temperature and hence, the strength of wire he desires for a particular procedure.

CHAPTER II

DEFINITION OF TERMS

Orthodontists determine the best wire for a technique by feel and usage, i.e. by observing what happens when the wire is ligated, when in a "hook-up", how it looks after appointment intervals, etc. "Hardness" to an orthodontist means the ability of wire to exert continuous spring pressure. "Soft" means ease of bending. Engineers use "hardness" to indicate resistance to indentation and "soft" to denote low resistance to indentation. To the engineer, many "hard" wires have poor spring qualities and many "soft" wires do not bend easily. Before proceeding any further it is essential to define and explain certain key terms which will be employed and all too often are used by orthodontists in a different sense than by engineers and metallurgists.

(1) Work Hardening

When a metal is formed and shaped it becomes work hardened. This can readily be visualized by imagining that the layers of atoms have lost their regular spacing and hence, offer more resistance to slippage. When a metal is work hardened its tensile strength is increased, the metal becomes harder, and ductility is reduced. The austenitic group of alloys can be work hardened twice as rapidly as the martensitic and ferritic groups. Cobalt chromium, Elgiloy, is an alloy which readily work hardens. When 18/8 (18 percent chromium and 8 percent nickel austenitic stainless steel of either type 302 or 304) stainless steels are severely cold worked, as in a cold drawing operation like the manufacture of orthodontic wires, large internal stresses are set up which cause the wire to become brittle. These stresses can be relieved by annealing immediately after the cold drawing operation.

(2) Annealing

Annealing is a process which relieves stresses formed during cold working. The effect of annealing is to increase the ductility and, consequently, to decrease the tensile strength, proportional limit, and hardness of the strain-hardened material.

(3) Heat Treatment

Heat treatment can be considered the process of heating and cooling a metal to obtain certain desirable properties. The engineer may use the term in a variety of connotations, depending on the materials and applications intended. Orthodontists generally believe heat treatment to be a process of heating a wire to produce an increase in proportional limit, tensile strength, and hardness and, in general, an improvement in "elastic" qualities.

(4) Stress Relieving

Stress relieving is a process of reducing residual stresses in a metal object by heating the object to a suitable temperature and holding for a sufficient time.

(5) Stress

Stress is the intensity of forces produced when a load is applied. Stress is also defined as the internal force which resists an external force applied to the area. It is measured in terms of force per unit of area and is a constant for a given material. A tensile stress is the implied force which resists the deformation caused by a load which tends to elongate, e.g. a weight suspended on one end of a wire of which the other end is fixed.

(6) Strain

Strain is the amount of deformation produced by an applied load.

(7) Ductility

Ductility can be defined as the ability of a material to be deformed without rupture. The lack of ductility is commonly called brittleness.

(8) Proportional Limit

If progressive increments of weight are suspended from a steel orthodontic wire, the other end of which is fixed, it is possible to measure the amount of elongation that different weights produce in the wire. By plotting elongation against the weight which produced it, a graphical representation can be made. It is found that, up to a certain point, stressing the wire by progressive increments of weight produces a strain which is proportional to the stress. This is observed on the graph as a straight line. At a certain increment of weight the stress will no longer be proportional to the strain; this is observed on the graph as a deviation from the straight line. The point at which the stress is no longer proportional to the strain is called the proportional limit. In the actual test procedure it is difficult to locate the exact point at which the wire deviates from a straight line.

(9) Elastic Limit

Elastic limit can be defined as the maximal stress from which a material can recover, i.e. can return to its original length after the force is removed. This value is usually above the proportional limit as most materials can be stressed slightly above the proportional limit without taking a permanent set.

(10) Yield Strength

Yield strength is the maximum stress at which a material finally shows a permanent set.

(11) Ultimate Strength

Ultimate strength is the highest stress recorded before a specimen fractures.

(12) Modulus of Elasticity

Modulus of elasticity is the ratio between stress applied and deformation that results from stress.

(13) Resiliency

Resiliency is the tendency of a material to return to its original shape following the removal of a stress that has produced a strain within the elastic limit.

(14) G.S. Point*

The point at the peak of a force/deformation curve where a maximum amount of force is required to strain a constantly increasing length of wire. Since the material is stressed beyond first evidence

*G.S. Point is a term coined by the author and incorporates his initials.

of permanent deformation (Figure 7), the G.S. point measures a force greater than the yield strength. Prior to the G.S. point, an increased amount of force is necessary to cause permanent deformation. Beyond this point, less force is required to strain the wire. Since the length of wire increases the same for each test observation, the amount of increase may be considered constant. This point, to the author's knowledge, has not previously been discussed in the literature, but due to its consistent reproducibility, it is a statistically valid point for this study.

CHAPTER III

REVIEW OF LITERATURE

HISTORY OF STAINLESS STEEL

Stainless steel first appeared in the orthodontic field around 1929-1930.[1] However, Vaguelin was credited with the first discovery of chromite or chrome iron ore ($FeCr_2O_4$) in 1797.[2] Later, Brearley and Maurer in 1913, focused public attention on it by adding ferrochrome to molten mild steel, producing stainless steel.[2] In 1920, E. Hauptmeyer introduced stainless steel to the dental profession for use as a material in a dental prosthesis.[3]

Stainless steel wire has played a great role in the mechanical advancement of orthodontics. Wires are obtained by suppliers from commercial sources. The alloys are usually standard formulas based on specifications of the American Iron and Steel Institute, but are processed specifically for orthodontic use.[4] The physical properties of metals are influenced at every step in production beginning with the selection and melting of the alloy metals. After pouring the molten metal into an ingot, it is allowed to cool. The resultant granular structure determines the ultimate mechanical properties of the material. The ingot is reduced to a small diameter by rolling and to its final size by drawing. The latter refers to a precise process in which the wire is pulled through a series of progressively smaller dies until the desired demensions are achieved.[5] Thus, it is easy to see that a wire is actually a grossly distorted ingot and that different pieces of wire from the same batch may differ depending on which part of the ingot they came from.[4]

COMPOSITION OF STAINLESS STEEL

The term stainless steel is applied to all aloys of iron and carbon which contain chromium, nickel, or other elements which impart to the steel the property of resisting corrosion.[6] There are over forty stainless steel alloys whose properties vary greatly.[7] The three main groups are austenitic, ferritic, and martensitic. The steels used in orthodontics come from the austenitic group. The most widely used 18/8 alloy contains 18% chromium, 8% nickel, 0.2% carbon, and a trace of stabilizing elements.[6] All of the austenitic steels have good corrosion resistance, hardness, yield and tensile strength. Austenitic steels are non-magnetic unless heavily cold worked.[7] The types of 18/8 alloy most commonly used in orthodontics are 302 and 304.[5] Type 304 is almost identical in composition to 302, but contains less carbon (0.08 to 15% maximum). The annealed condition type 304 has slightly lower strength and hardness and somewhat higher ductility than type 302.[5]

The following elements are the major consituents of the 18/8 stainless steel. Their descriptions will help in understanding the physical and chemical properties of stainless steel wires.

(1) <u>Carbon</u> Steels containing less than 0.3% carbon are classified as low-carbon steels and include the stainless steels. In stainless steel, the carbon is present as iron carbide and remains in solid solution.[8] According to Bender,[9] the decreased corrosion resistance of stainless steel is due to the precipitation of chromium

carbide and the depletion of the chromium in the areas adjacent to grain boundaries. Decreasing the carbon content will decrease the susceptibility of steel to intergranular attack. Thus, the best 18/8 stainless steel would be produced if it could be made entirely carbon free.

(2) Chromium Bender also states that the chromium steel derive their remarkable resistance to corrosion from the presence of chromium. Chromium content must be 12% or greater before the steel has sufficient resistance to corrosion.[9] The rate at which the steels develop passivity depends on the chromium content; steels that contain more than 20% chromium become passive in the atmosphere without developing even a slight film or rust.[10]

(3) Manganese This element has a maximum content of 2% in stainless steel.[6] Bender has assigned a dual role to manganese in steel: (1) it combines with sulphur to form manganese sulphide, and (2) it combines with oxygen to form an oxide which is less soluble in molten steel than iron oxide, thus producing an alloy of greater purity.[9] It also, in small amounts, increases the strength of the steel.[2]

(4) Nickel According to Bender,[9] nickel, when added to low-carbon steel containing 16 to 25% chromium, in the amount of 6 to 22%, has the effect of stabilizing the face centered structure in the austenitic form as it is cooled from elevated temperatures. The strength and hardness of low-carbon steel is increased by the addition of

nickel.[11] Nickel is further said to reduce the susceptibility of corrosion by non-oxidizing agents in higher chromium steels.[12]

(5) Iron The maximum content of this element in stainless steel is 68%.[7] Alloying elements are added to iron to enhance its properties because iron alone does not yield the qualities that are necessary for fine steel wire.[2]

TABLE I

COMPOSITION OF TYPES 302 AND 304 STAINLESS STEEL[5]

	Type 302	Type 304
Carbon	0.08-0.20	0.08 max.
Manganese	2.00 max.	2.00 max.
Silicon	1.00 max.	1.00 max.
Phosphorus	0.040 max.	0.040 max.
Sulphur	0.030 max.	0.030 max.
Chromium	17-19	18-20
Nickel	8-10	8-10
Iron	Balance	Balance

TABLE II

ELECTRICAL PROPERTIES OF TYPES 302 AND 304 STAINLESS STEEL[5]

Resistivity at 20°C (68°F) Ohms/cir. mil. ft.	420
Resistivity at 20°C (68°F) Microhm cm.[3]	70
Magnetic Permeability	Non-magnetic

TABLE III

PHYSICAL PROPERTIES OF TYPES 302 AND 304 STAINLESS STEEL IN THE ANNEALED CONDITION[5]

Density, gm./cc.	7.93
Density, lb./cu.in.	0.286
Tensile Modulus of Elasticity, 10^6 psi	29
Torsional Modulus of Elasticity, 10^6 psi	
(Note: Value decreases with cold-working)	12.5
Structure	Austenitic
Specific Heat, cal./°C/gm., 0-200°F	0.118
Specific Heat, cal./°C/gm., 0-100°C	0.118
Thermal Conductivity, btu./ft.^{2}hr./°F/in./	
200°F	110
1000°F	150
Linear Coefficient Thermal Expansion per °F 10^{-6}	
32-212°F	9.6
32-600°F	9.9
32-1200°F	10.4
32-1500°F	...
32-1800°F	...
Melting Point, °F	2550-2650

HEAT TREATMENT OF STAINLESS STEEL

Some investigators believe that stainless steel, because of its constitution, can be strengthened only be cold-working or plastic deformation.[7] They feel that heat treating dental stainless steel wire does not substantially improve its qualities,[13] while others advocate the contrary.[14,15,16,17,18,19,20] The advocates of heat treatment are further divided into a group that claims that any improvement is due to stress relief annealing,[14,17,18] rather than to a true heat treating transformation or carbide precipitation as Richman suggests.[8]

Kemler,[13] like Backofen and Gales, believes that the results obtained from heat treatment are due to stress relief annealing. Contrary to Funk, Gaylord, Backofen and Gales, Denver and others, he believes that the improvement obtained as a result of heat treating stainless steel wire is not sufficient to justify the procedure. He states, "It seems unlikely that a clinically demonstratable change will be noticed."[13] In addition, the Rocky Mountain Company, in referring to its 18/8 orthodontic wire, agrees with Kemler: "Since evidence of noticeable results is uncertain, we cannot endorse Tru-chrome (18/8 stainless steel) for heat treatment.[5]

Kemler did find that a low-temperature heat treatment caused an increase in the proportional limit and modulus of resilience of chrome alloy wires. He found an optimum heat treatment was five to fifteen minutes at 700 to 800°F for type 302 wire. Backofen and Gales stated that ten minutes at 750 to 820°F produced optimum results.[13]

Funk produced the most marked increase in elastic properties at 850°F for three minutes. However, he stated that good results can be obtained within a temperature latitude of approximately 200°F.[18] In each of these studies, a marked increase of as much as 40% was produced in the resiliency, with corresponding improvements in the tensile strength and proportional limit. Teetzel[21] also found that heat treatment increased the tensile strength of stainless steel wire. Kohl states that internal stress is usually unequally distributed throughout the wire after bending. Proper heat treatment relieves these stresses sufficiently to cause a reduction in the amount of breakage seen in clinical use.[7] Kohl states further that stress relief increases with increase in temperature. However, care must be taken not to approach the lower limits of the annealing range of the steel, which is approximately 1100°F. If stainless steel wires are subjected to temperatures above 1100°F, some degree of softening will occur along with a decrease in proportional limit and tensile strength.[22]

Although Callender[23] showed that heat treatment increased the elastic strength and resiliency of a wire, it produced only a slight change in the elastic modulus. That is, the heat treatments changed the degrees to which the wire may be deformed, but the force for the given deformation remained almost identical. An arch wire which has its elastic qualities increased by heat treatment will be more likely to assume its original shape after deflection.[7] Since the wire will have more resistance to permanent set after deflection than before being heat treated, maximum force will be applied during the expected range of tooth movement. This appears to be the major advantage to heat treatment of stainless steel.

Recent experiemnts of heat treatment of stainless steel wire have found eleven minutes at 750°F to be the optimum treatment for non-stabilized grades of austenitic stainless steel.[24] Ingerslev recommended 700 to 750°F for twenty to twenty-five minutes to produce optimum elastic properties in arch wires without effecting the corrosion resistance. However, he stated that since 70% of the total effect is attained after only four minutes, the time can be considerably reduced.[19] Howe et al (1968),[20] working with straight wires of types 302 and 316, found optimal yield stress was obtained in the temperature range of 700 to 950°F.

In another study by Williams,[25] thermal stress relief was performed on Australian wire which has the same chromium, nickel, and iron content as 18/8 stainless steel wire. He found that thermal stress relief at 850°F for three minutes was only partially effective on 0.016 inch Australian wire. The results obtained by Waters et al[26] suggest that the normally accepted temperature for a stress relief anneal, namely 950°F, as suggested by the Rocky Mountain Company,[5] which was adopted for their experiment, might be reduced with advantage to 925°F. They found no change for heat treatment times between one to sixteen minutes.

Denver showed that 18/8 wire heated at 900°F for three minutes with bent loops exhibited a 39% increase in resistance to permanent deformation. He also believes that where optimum properties are desired in 18/8 orthodontic iwre, it should be heat treated.[17]

In the literature, the heat treatment of stainless steel has had a controversial and confusing past. Much of this confusion is due to the different time and temperature intervals used in heat treatment, as well as large variations in sample size among the investigations. The Rocky Mountain Company has concluded that, although there was some evidence that heating stainless steel wires would increase hardness and spring qualities, the change was not usually enough to claim significance. Therefore, it was best to assume that heating stainless steel wire was primarily for stress relieving and not tempering.

No attempt was made to heat treat stainless steel wire by means of an electrical resistant unit at 850 to 950°F in any of these studies.

Finally, on the question of the influence of heat treatment or stress relieving on the warpage of a formed orthodontic arch wire, there is also a difference of opinion. The Rocky Mountain Company[5] believes that stress relieving will minimize the tendency of the formed wire to warp or spring back to its original form. Funk[18] believes heat treatment enhances stability of form. Kemler[13] believes that heat treating 18/8 stainless steel (at a temperature from 200 to 500°F and with a time variation of five to fifteen minutes) increases the warpage of formed orthodontic arches. He states, "There is a distortion of the steel wire after heat treating, inasmuch as the wire must be reformed before placing it in the mouth." Most investigators tend to agree with

Kemler. After stress relieving a wire, it tends to return to its original shape and it may need to be reformed before clinical use.

HISTORY OF COBALT CHROMIUM ALLOYS

Cobalt chromium base alloys were introduced into dentistry in 1932 when Erdle and Prang disclosed a technique for making dental castings from high melting alloys.[27] The use of cobalt alloys for cast denture bases, partial dentrues, and fixed bridgework has now become widespread.[27] In 1941, cobalt base materials were used in highly stressed gas-turbine blading. The application and modification of the alloy and the production of gas turbine blading by precision casting on an industrial scale were important wartime developments in the field of metallurgy.[28]

In the late 1940's, the Elgin National Watch Company also introduced the use of a cobalt-base alloy for the mainspring of its watches. This cobalt-base alloy, known by the trade name Elgiloy and developed by Battelle Institute for the Elgin Watch Company, proved highly suitable for many other spring applications.[27]

The excellent properties of Elgiloy has led to some unusual applications. It is used for metal drive bands in electronic fire-control systems for night aircraft. Ammunition components that operate only once, but must withstand the effects of long storage, are made from Elgiloy. Finally, a special Elgiloy spring has been inserted into a human heart to aide in the proper functioning of one of the heart valves. It is the only alloy with the necessary spring properties that is compatible with human blood and tissue.[27] After fourteen months, the spring is estimated to have functioned more than thirty-eight million times.

Rocky Mountain Elgiloy wire is produced in four different tempers, designated by a different color at the top of each wire. Red Elgiloy wire has exceptionally high spring qualities. Green Elgiloy wires are initially semiresilient and will temper comparably to high spring tempered steel wires. Yellow Elgiloy wire was developed for those who prefer greater spring qualities than that of Blue Elgiloy. Like Blue Elgiloy, it should be heat treated for maximum resiliency and spring performance. Blue Elgiloy was developed for use when the wire to be used was over 0.020 inch or when the wire required considerable bending, welding or soldering. It is frequently used in orthodontic bioprogressive therapy when rectangular wires of 0.016 x 0.016 and 0.016 x 0.022 inch are employed. For the latter reason, as well as it being the most common temper used clinically,[29] 0.016 x 0.022 inch Blue Elgiloy was the material of choice for this study.

COMPOSITION OF BLUE ELGILOY WIRE

The composition and properties of this alloy, according to the alloy patent[30] (refer to Tables IV, V and VI), may be varied for different applications. The usual composition of this alloy is 40% cobalt, 20% chromium, 15% nickel, 7% molybdenum, 2% manganese, 0.15% carbon, 0.04% beryllium, and approximately 15% iron.[7] Although similar to 18/8 stainless steel in most of its properties, the chromium-cobalt alloy differs in that heat treatment produces a greater change in resiliency than that produced in steel.[7]

In comparison with steel mainsprings, Elgiloy mainsprings deliver 20% higher torque, 80 to 100% higher resistance to fatigue, and 275% more resistance to set.[5] Compared with 18/8 chromium-nickel steel, Elgiloy is shown to have a 9% higher ultimate strength, 8% higher yield strength, and 5% higher elastic modulus.[31] The initial patent suggests three to five hours at 600 to 1000°F to give beneficial heat treatment.[30]

Tarnish and corrosion resistance are excellent in Blue Elgiloy wire, while hardness, yield strength and tensile strength are much the same as those of 18/8 stainless steel alloys, but are less in the hardened condition.[6]

The five major elements found in 18/8 stainless steel wire are also found in Blue Elgiloy wire and perform similar functions. Cobalt and molybdenum are the major elements not found in the stainless steel wire.

(1) Cobalt According to Hodge and Bain,[12] the principle function of cobalt is that it contributes to red hardness by hardening ferrite. The cobalt is a matrix ingredient to give strength. In general, increase of strength follows with increase of cobalt, but excessive amounts produce such hardness that cold-working characteristics are unsatisfacotry, and the desired final strengths cannot be built up.

(2) Molybdenum Hodge and Bain listed the following functions of molybdenum in alloys.[12]

1. Raises the grain coarsening temperature of austenite
2. Deepens the hardening
3. Counteracts the tendency toward temper brittleness
4. Raises the hot and creep strength
5. Enhances the corrosion resistance in stainless steel
6. Forms abrasion resisting particles

Thus, molygdenum is a very effective strengthening element both for its effect in the matrix and upon aging.

TABLE IV

COMPOSITION OF ELGILOY WIRE[27]

Cobalt	40	%
Chromium	20	%
Nickel	15	%
Molybdenum	7	%
Manganese	2	%
Beryllium	0.04	%
Carbon	0.15	%
Iron	Balance	

TABLE V

PHYSICAL PROPERTIES OF ELGILOY WIRE[5]

Density- 0.300 lbs./cu. in.

Specific Gravity- 8.3

Linear Expansion- 12.7×10^{-6} per $^{\circ}$C (Range 0° to 50°C)

Thermoelasticity- 39.6×10^{-5} per $^{\circ}$C (Range 0° to 50°C)

Mean Thermal Coefficient of Expansion- 15.17×10^{-6} per $^{\circ}$C (Range 0° to 500°C)

Thermal Conductivity- 0.0298 Cal/sec/cubic cm/C

TABLE VI

MECHANICAL PROPERTIES FOR ELGILOY WIRE[5]

Ultimate Strength- 340,000 psi.

Yield Strength- 310,000 psi.

Shear Yield- 210,000 psi.

Modulus of Elasticity- 28,500,000 psi.

Torsional Modulus- 11,200,000 psi.

Hardness (Rockwell C)- 51-55

Annealing Temperature- Elgiloy 2250°F = 1230°C

Heat-treat Elgiloy- 900°F = 482°C, 7-12 minutes

HEAT TREATMENT OF BLUE ELGILOY WIRE

Rocky Mountain Blue Elgiloy wire is relatively soft in its manufactured state. It can be easily shaped with fingers and pliers. It can also be welded with a low heat capacitor wire welding heat, which is produced on the number one setting of Rocky Mountain 500 series welders or similar Rocky Mountain machines. Blue Elgiloy wire can also be soldered without embrittling. Rocky Mountain Blue Elgiloy wire is recommended for use when the diameter to be used is over 0.020 inch or when the wire requires considerable bending, welding or soldering. This wire is also excellent for use in labial arch wires employed in the edgewise technique of tooth movement, lingual arches and retainers. After fabrication, the wire should be heat treated for best results.[5]

The spring qualities of Rocky Mountain Elgiloy wire can be increased by heat treating, which does not occur in stainless steel wire. Therefore, the heat treating of Rocky Mountain Blue Elgiloy wire is desirable because it removes internal stresses and it increases the spring performance and efficiency of the wire when fabricated into an appliance.[5]

The reason that stress relieving heat treatment of Blue Elgiloy produces stress relief and hardening of the alloy is that various complex carbides and intermetallics are precipitated. Ductility changes very little in 18/8 stainless steel, but the Blue Elgiloy wire becomes less ductile or harder.[6]

Rocky Mountain states the best industrial results for tempering

Elgiloy wire are obtained by heating the wire in a special furnace for one to five hours at 900°F. This, of course, is not practical for dentistry. Effective results for Elgiloy can be produced by placing them in a dental furnace at 900°F for seven to twelve minutes.

According to Rocky Mountain, another way of heat treating Elgiloy wire is by placing Rocky Mountain adapting cables on the wire at one inch intervals. These cables, when inserted into the Rocky Mountain welder, transmit current to the wire, thus producing heat treatment of the wire. The wire will turn straw brown in color when the proper temperature has been reached.

Still another way, according to Rocky Mountain, to heat treat Elgiloy wire is to place the wire in the Elgiloy heat treating unit that fits into the Rocky Mountain welder. After insertion, a small amount of Rocky Mountain flash paste is placed on the wire. When the proper temperature is reached, the paste on the wire flashes, indicating heat treatment of the wire at 950°F.

O.E. Harder and A. Roberts suggested, in the Elgiloy patent, five hours at 900°F for a desirable combination of strength and toughness properties. They further stated that the proportional limit, yield strength, and tensile strength increase with heat treatment temperatures up to 900 to 1000°F, but this increase in strength is suggested to be accompanied by a decrease in toughness. In addition, the authors stated that overheating must be avoided because heating for five hours at a temperature of 1200°F causes a marked decrease in the strength properties. Lastly, in practice, 1200°F is the maximum useful temperature, but it is preferred to use a lower temperature wherein the time factor is not so critical.[30]

Denver[17] used a temperature of 900°F for three minutes in furnace heat treatment and found a 55 to 66% improvement in its ability to resist permanent deformation. Mutchler concluded that the optimum heat treatment for cobalt-chromium wire is three to fifteen minutes at a temperature of 900 to 1000°F in a dental furnace.[31] In addition, he stated that temperatures of 1100°F (593°C) and 1200°F (649°C) for a period of less than three minutes produced no harmful effect in the cobalt-chromium wire, but did cause a substantial decrease in the mechanical properties of the chromium-nickel wire.[31] Waters, Houston, and Stephens[26] recommended 480°C (896°F) for furnace heating cobalt-chromium wire. They found maximum elastic properties at 525°C (977°F), but stated that the properties rapidly deteriorated as the temperature was above 525°C (977°F). There was no difference in one to sixteen minute time periods. Coombe[32] suggested a stress relief anneal at a minimum temperature of 500°C (932°F), according to a quote by Waters, Houston and Stephens. The Rocky Mountain Company suggests heat treatment in a dental furnace at 900°F for seven to twelve minutes. Annealing is not recommended to allow ease of forming since Elgiloy will thereby lose its cold-work and maximum properties cannot be regained by heat treatment. However, where sections not subjected to high stress are involved annealing can be performed and a temperature of 2250°F is recommended. As noted previously, Elgiloy has a tendency to embrittle between 1100°F and 1400°F so that when a section is annealed some portion along the strip may be embrittled.

Filmore and Tomlinson state that at each temperature of heat treatment up to 1200°F there is a progressively greater resistance to permanent deformation. At temperatures above 1200°F, however, there is a rapid decline in resistance to permanent deformation due to partial annealing. The authors feel that the maximum resistance to permanent deformation occurs from heat treatment in the temperature range of 1100 to 1200°F.[29] The difference in increase in resistance to permanent deformation is approximately 95% at 900°F versus 174% at 1200°F.[29] Finally, they contend that an electrical resistant heat treatment unit with a temperature indicating paste at 950°F results in comparable resistance to permanent deformation, similar to that seen in the wires heat treated with a dental furnace at 800°F and 900°F, i.e. approximately one half of that obtained by the 1200°F treatment.

CHAPTER IV

MATERIALS AND METHODS

MATERIALS

The following materials were used in conducting this study:

1. Eighty fourteen inch strands of 0.016 x 0.022 inch Blue Elgiloy wire, cut in four and one half inch lengths (240 pieces); Rocky Mountain Products, Denver, Colorado. The softest temper was used in this study because it is the most common temper used clinically.
2. Jelenko temperature controlled oven, type TFA; 115 volts; Jelrus Technical Products Company, New Hyde Park, New York.
3. 8690-2 millivolt potentiometer; Leeds and Northrup.
4. Variable autotransformer; input 120 volts; frequency 50/60 cycles; output 0-120/140; KVA 1.4; amperage 10; type 2PF 1010.
5. Chromel-Alumel thermo couples in glass insulated tubing.
6. Seventeen bottles of Tempilaq, a temperature indicating liquid. The liquid is applied in a thin smear and allowed to dry. When the temperature of the wire reaches the stated temperature, the Tempilaq changes color and liquefies. Temperatures ranging from 600°F to 1400°F, in fifty degree increments, were monitored by this means.
7. Two hooks were formed of 0.045 inch stainless steel bent in a rectangular shape and soldered at the base. They were further reinforced by 0.021 x 0.028 inch stainless steel beams, which were vertically welded to the long axis of the 0.045 inch periphery.

Each hook was approximately thirteen millimeters wide and eleven millimeters high. They were spaced twenty-five millimeters apart. Each hook was also limited in a horizontal direction to three millimeters by vertically welded beams.

8. A small hook was formed as in step number seven. In addition, two 0.021 x 0.028 inch strands of steel were attached horizontally so, as the 0.016 x 0.022 inch Elgiloy test wire was stressed, an exact contact surface area would be known. The hook had a height of five millimeters and a width of ten millimeters. However, the movement of the test wire could only vary two millimeters due to the vertical supports on the hook. A small right angle trough was placed in a section of one-quarter inch plexiglass. Each hook was adapted closely to the right angle groove. Another one-quarter inch plexiglass was layed over the first and cemented together with Eastman Kodak 910 glue. All three hooks were then placed in a vice and allowed to set for forty-eight hours without movement.

9. The Instron Universal testing device, model 1130, was set for a maximum stress load of ten pounds. The chart was adjusted to advance at a speed of two inches per minute. The gears for the chart speed were set: CX- Time and CY- Chart. A slow chart speed was desired since it produced more definite peak points on the stress curves. The crosshead speed was also programed to move at two inches per minute. The gears necessary for such a slow head speed were: IN- EX and OUT- EY. With the crosshead moving slowly

upward, it was easy to monitor and maintain the test wire in its proper position between the two lower test hooks.

METHODS

Eighty pieces of fourteen inch 0.016 x 0.022 inch Blue Elgiloy wire were cut into 240 four and one-half inch lengths. The samples were divided into three groups. The control group consisted of six four and one-half inch lengths of randomly chosen non-heat treated Blue Elgiloy wire. The experimental group was divided into the electrically heat treated and furnace heat treated groups. The electrically heat treated group had seventeen sets of wires with six four and one-half inch lengths in each set. The furnace heat treated group had nine sets with six four and one-half inch lengths in each set. Each length in the electrically tested group was coated with the temperature indicating paste. It was allowed to dry for thirty seconds and was then placed in the adapting cables that lead to the variable transformer. The transformer was set at one and one-half volts for temperatures up to 950°F and at two volts for temperatures above 950°F. (Figure 2) In Table XIII, a voltage and amperage were calibrated for each fifty degree increment between 600°F and 1400°F. As a current was passed through the wire, the temperature of the wire increased. When the temperature of the wire reached the stated temperature, the paste turned from a bright color to a darker color and liquefied. (Figures 3 and 4) Each wire was then gently and carefully scraped to remove any remaining paste residue. A one-quarter inch of wire was removed from each end of the tested specimen to make it approximately three and one-half inches in length.

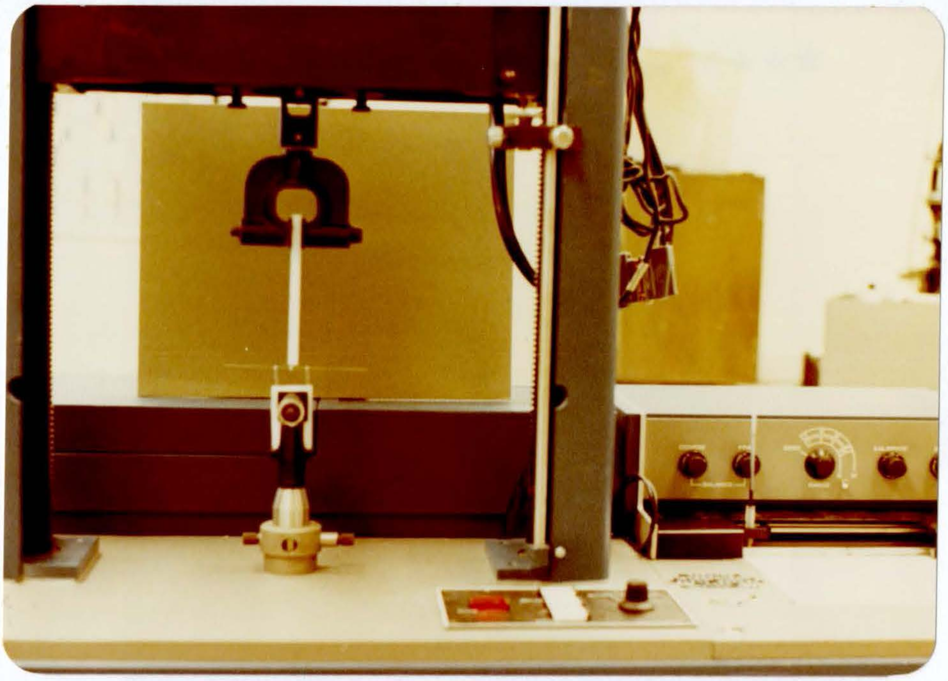


Figure 1. The Instron Universal Testing Instrument

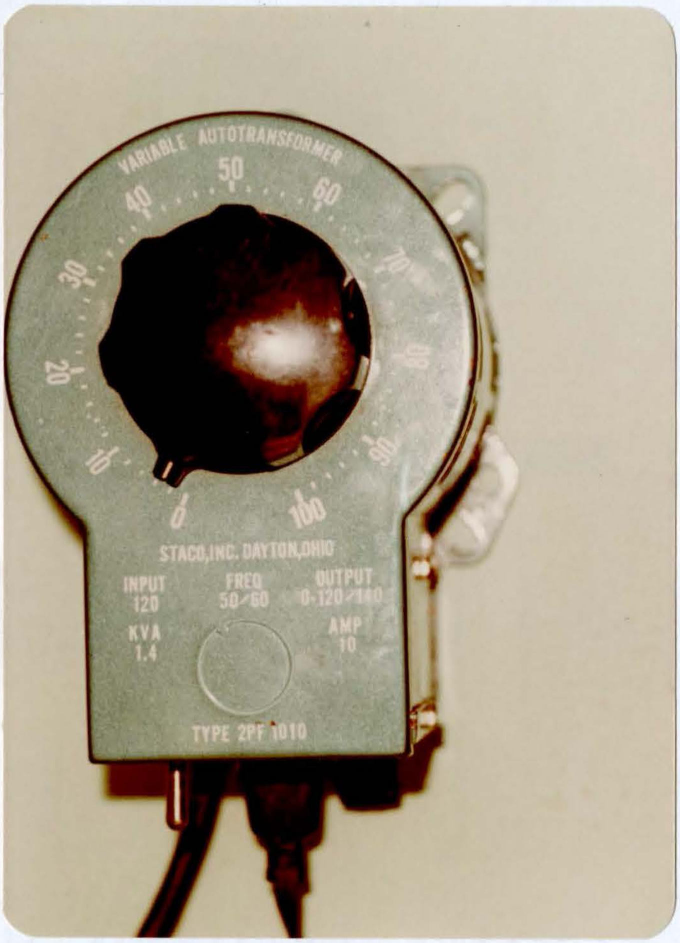


Figure 2. Variable Autotransformer

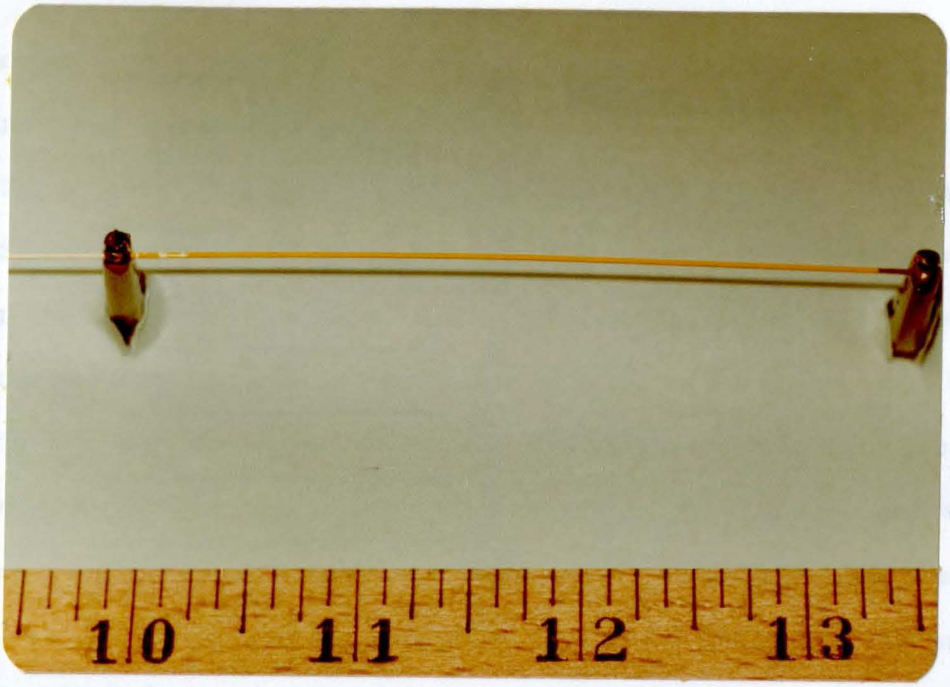


Figure 3. Wire Coated With Tempilaq Before Electrical Heating

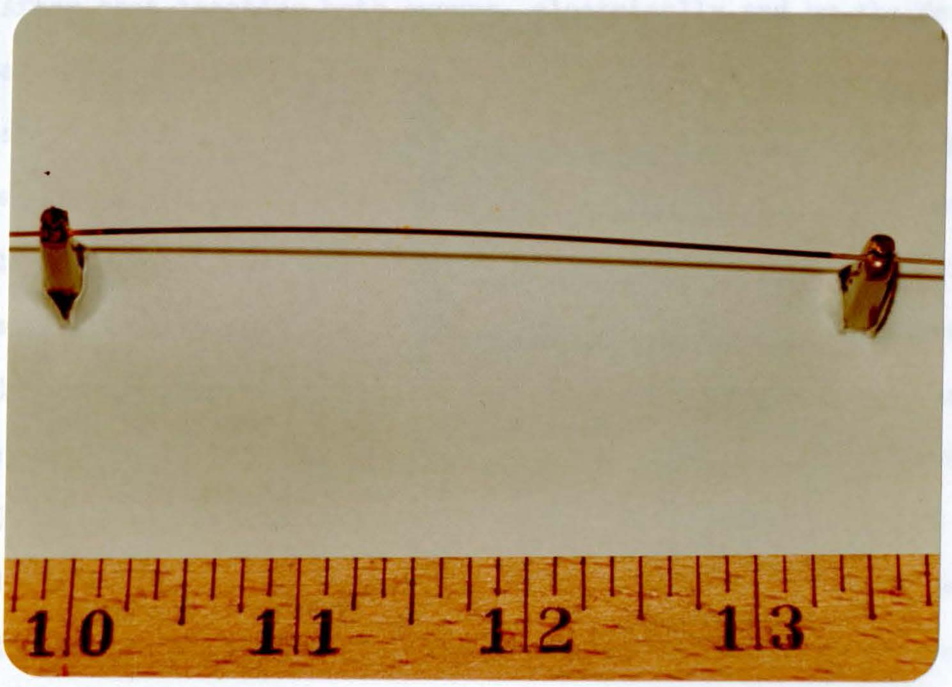


Figure 4. Wire in Figure 3 After Electrical Heating

The ends were removed to eliminate the possibility of testing a non-heat treated portion of the wire.

The furnace heat treated group was also coated with the temperature indicating paste. Six specimens were placed in the furnace at one time. Each set remained in the furnace for a period of seven minutes to insure uniform temperature. The wires were placed on two small iron rods, so that no portion of the wires was touching the furnace floor. After heat treatment, a one-quarter inch of wire was cut from each end of the test specimen and the thermal coating was gently scraped away. The ends were cut in the furnace group to assure equal lengths of wire for both groups and to eliminate any possible temperature influence the rod may have on the test specimen.

After heat treating both groups, electrically and by the dental furnace, the wires were subjected to a strength test. As in Figure 5, the test wire was placed so that the 0.022 inch surface of the Elgiloy wire was being stressed by the 0.021 inch surface of the stainless steel hook. As the wire was deformed to its maximum resistance without permanent deformation (Figure 6), a force of 0.449 x 2 = 0.898 pounds was delivered to the 0.016 x 0.022 inch Elgiloy test specimen. As can be seen in this figure, the wire was slightly deformed, approximately 0.5 millimeters. The same wire was stressed to exceed its yield strength at 0.47 x 2 = 0.940 pounds. The resultant graph and wire are shown in Figure 7. Figure 8 shows the deformed wire on the Instron. The point at the peak of this curve where a maximum amount of force is required to deform the wire, for the purpose of this study, will be called the G.S. point. The G.S. point exceeds the proportional limit, the elastic limit, and the yield strength. As is evident in Figure 7, more than a slight amount of permanent deformation has resulted from the force needed to reach the G.S. point. After the G.S. point is reached, less force is required to deform the wire. Figures 7 and 8 illustrate the amount of deformity in the wire at the G.S. point. Figure 9 shows the G.S. point in detail. It should be noted that when the Instron pen reaches the G.S. point, a peak as in Figures 7 and 9 will consistently be reproduced. However, if not stressed to the G.S. point, the wire will spring back to nearly its original form and a graph as in Figure 6 results.

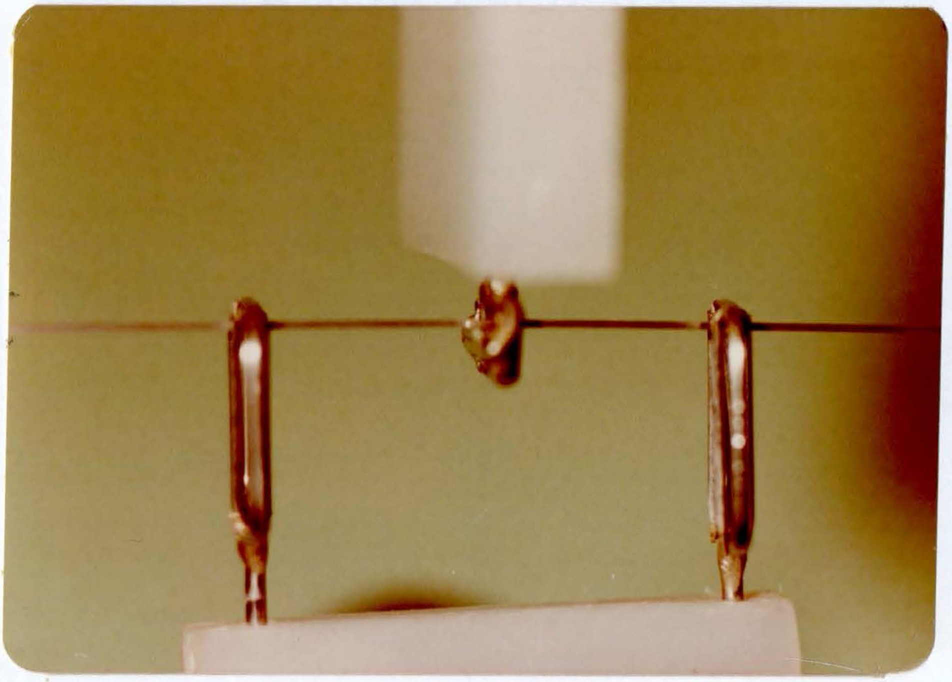


Figure 5. Wire Before Force Applied

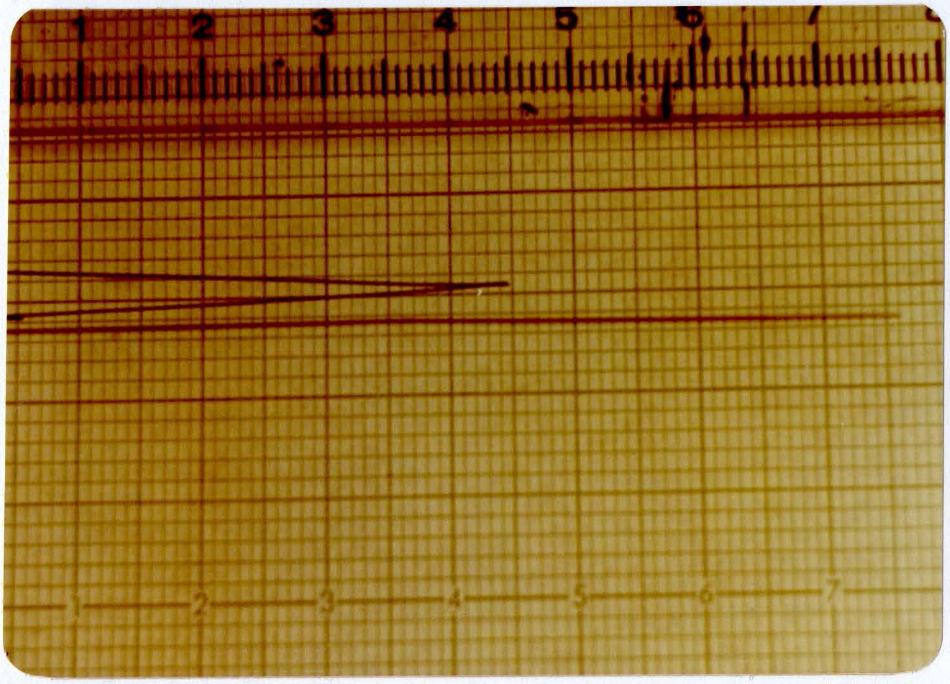


Figure 6. Wire and Graph After Load of 0.449 x 2= 0.898 lbs.

The slightly deformed wire indicates the yield strength of this wire has been approximated.

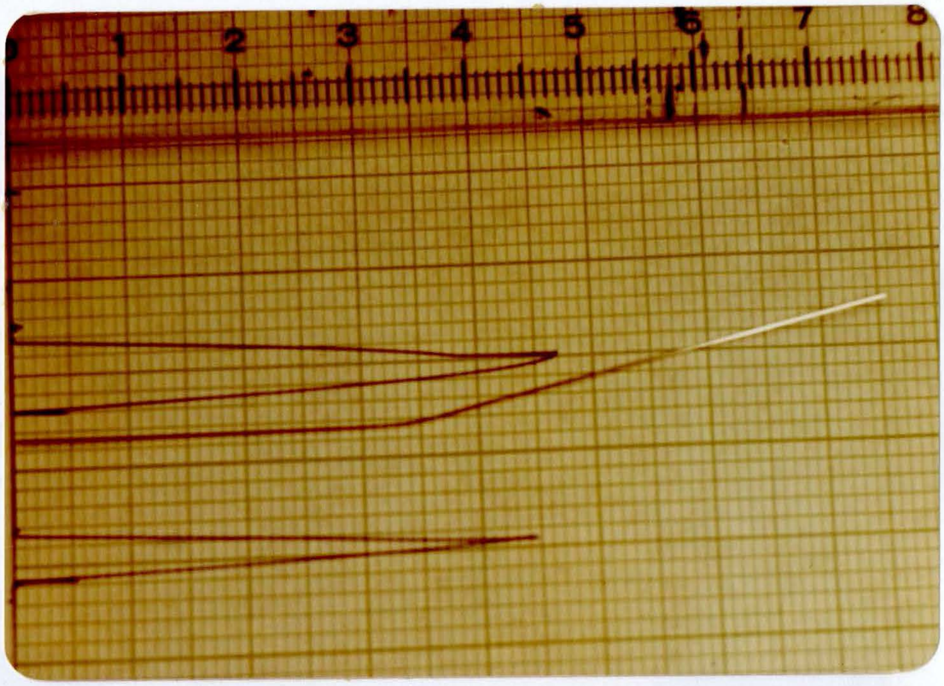


Figure 7. (a) Resultant graph and wire from Figure 6 after a peak load of 0.470 x 2=0.940 lbs. deformed the 0.016 x 0.022 Elgiloy wire. The peak point on the top of each curve is termed the G.S. point.

(b) Same graph as in Figure 6 showing the approximate force necessary to cause slight permanent deformation in the 0.016 x 0.022 inch Elgiloy wire. By definition, the yield strength for this wire has been exceeded.

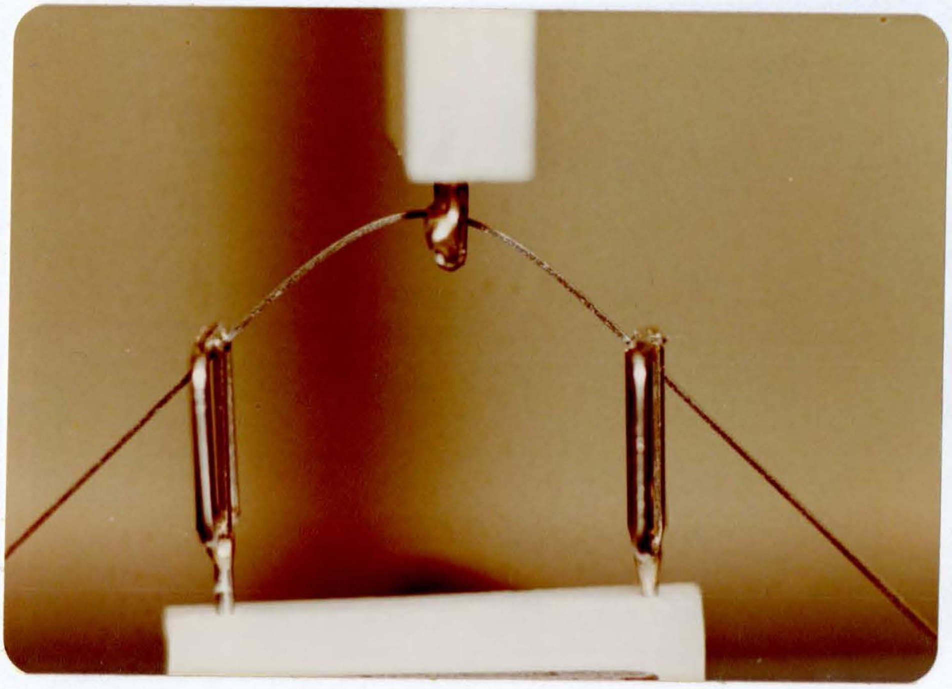


Figure 8. 0.016 x 0.022 inch wire stressed to the G.S. point, as in Figure #9.

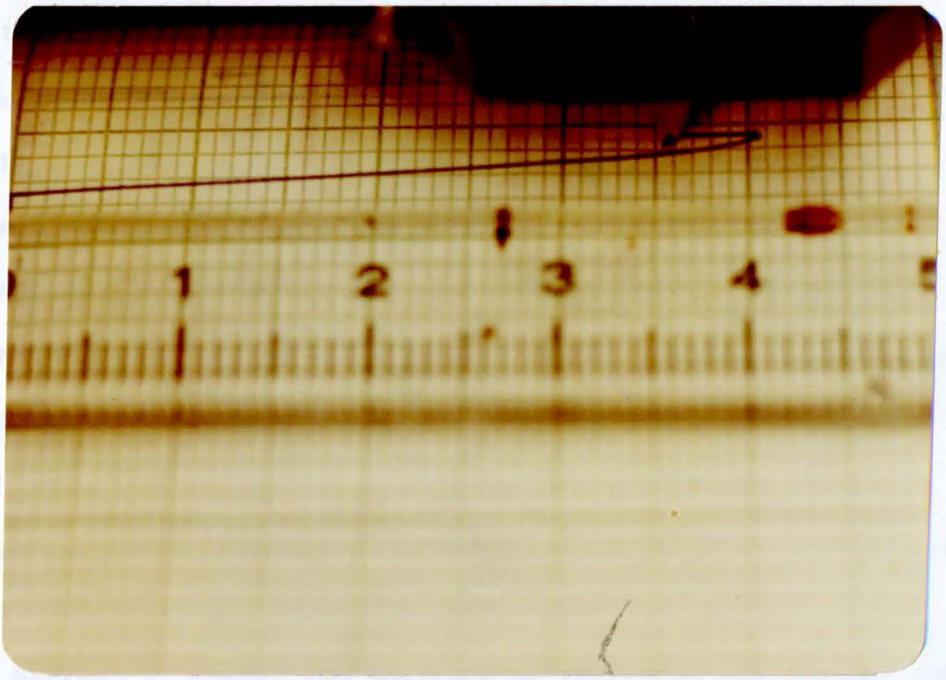


Figure 9. Close-up of the peak force load on the wire in Figure #8. This point on the peak of the graph is referred to as the G.S. point.

CHAPTER V

RESULTS

As mentioned in "Methods and Materials," the data collected were from three groups. The data shown in Tables VII through XII represent a G.S. value for a particular wire at a specific temperature. In referring to this point, it is understood that if a force greater than the mean force for the control group is needed to deform a wire to the G.S. point, then a corresponding resistance to that deformation is present in the wire due to the heat treating process. Thus, the peak of this curve, or G.S. point, gives an indication of the amount of energy contained in a wire when it is stressed beyond its yield strength. This value is related to the ability of the wire to resist permanent deformation under a dynamic (impact) force.

Eleven 'T' tests, two analyses of variance, and two 'K' tables were performed on the data. Nine 'T' tests compared furnace with electric treatment. The other two compared the two experimental groups with the control group. Tables VII, VIII, and X give summaries of means, standard deviations, and 'T' tests. Table IX gives the data for electric heat treatment from 650 to 1350°F, in one hundred degree increments. Tables XI and XII show an analysis of variance for electric and furnace heat treatment, respectively. Also tested in Tables XI and XII are significant differences in temperatures found within the respective groups at the 0.05 level.

TABLE VII

DATA SUMMARY FOR CONTROL AND ELECTRICALLY HEAT TREATED WIRES*

	CONTROL no heat	600°F	700°F	800°F	900°F	1000°F	1100°F	1200°F	1300°F	1400°F
	0.890	1.018	1.068	1.100	1.124	1.240	1.290	1.262	1.360	1.228
	0.850	1.040	1.078	1.040	1.082	1.204	1.262	1.250	1.334	1.204
	0.900	1.082	1.058	1.062	1.110	1.158	1.280	1.250	1.298	1.220
	0.880	1.052	1.072	1.084	1.098	1.178	1.242	1.270	1.342	1.242
	0.900	1.038	1.080	1.076	1.098	1.242	1.200	1.260	1.302	1.222
	0.902	1.042	1.096	1.064	1.108	1.344	1.240	1.250	1.318	1.230
MEANS	0.887	1.045	1.075	1.071	1.103	1.229	1.253	1.257	1.326	1.225
S.D.	0.0199	0.0210	0.0128	0.0206	0.0142	0.0652	0.0325	0.0084	0.0241	0.0126

* Force values measured in pounds

TABLE VIII

DATA SUMMARY FOR CONTROL AND FURNACE HEAT TREATED WIRES*

	CONTROL no heat	600°F	700°F	800°F	900°F	1000°F	1100°F	1200°F	1300°F	1400°F
	0.890	1.040	1.090	1.220	1.300	1.268	1.256	1.192	1.004	0.744
	0.850	1.060	1.074	1.150	1.260	1.282	1.270	1.180	1.018	0.736
	0.900	0.978	1.076	1.184	1.240	1.284	1.262	1.140	1.042	0.720
	0.880	0.982	1.084	1.190	1.242	1.280	1.236	1.124	1.020	0.760
	0.900	1.084	1.104	1.170	1.310	1.300	1.242	1.210	0.996	0.762
	0.902	1.078	1.100	1.196	1.322	1.284	1.268	1.162	0.936	0.784
MEANS	0.887	1.037	1.088	1.185	1.279	1.283	1.256	1.173	1.003	0.751
S.D.	0.0199	0.0468	0.0123	0.0238	0.0361	0.0103	0.0139	0.0294	0.0363	0.0225

* Force values measured in pounds

TABLE IX

DATA SUMMARY FOR ELECTRICALLY HEAT TREATED WIRES AT 650°F TO 1350°F AT 100° INCREMENTS*

	650°F	750°F	850°F	950°F	1050°F	1150°F	1250°F	1350°F
	1.056	1.024	1.118	1.160	1.268	1.248	1.228	1.402
	1.058	1.068	1.096	1.178	1.250	1.262	1.244	1.424
	1.038	1.082	1.082	1.184	1.270	1.250	1.280	1.318
	1.058	1.102	1.096	1.174	1.220	1.302	1.250	1.442
	1.058	1.122	1.080	1.194	1.192	1.208	1.280	1.408
	1.062	1.096	1.090	1.150	1.202	1.220	1.288	1.410
MEAN	1.055	1.082	1.094	1.173	1.234	1.248	1.262	1.401
S.D.	0.0086	0.0339	0.0137	0.0160	0.0337	0.0332	0.0243	0.0430

* Force values measured in pounds

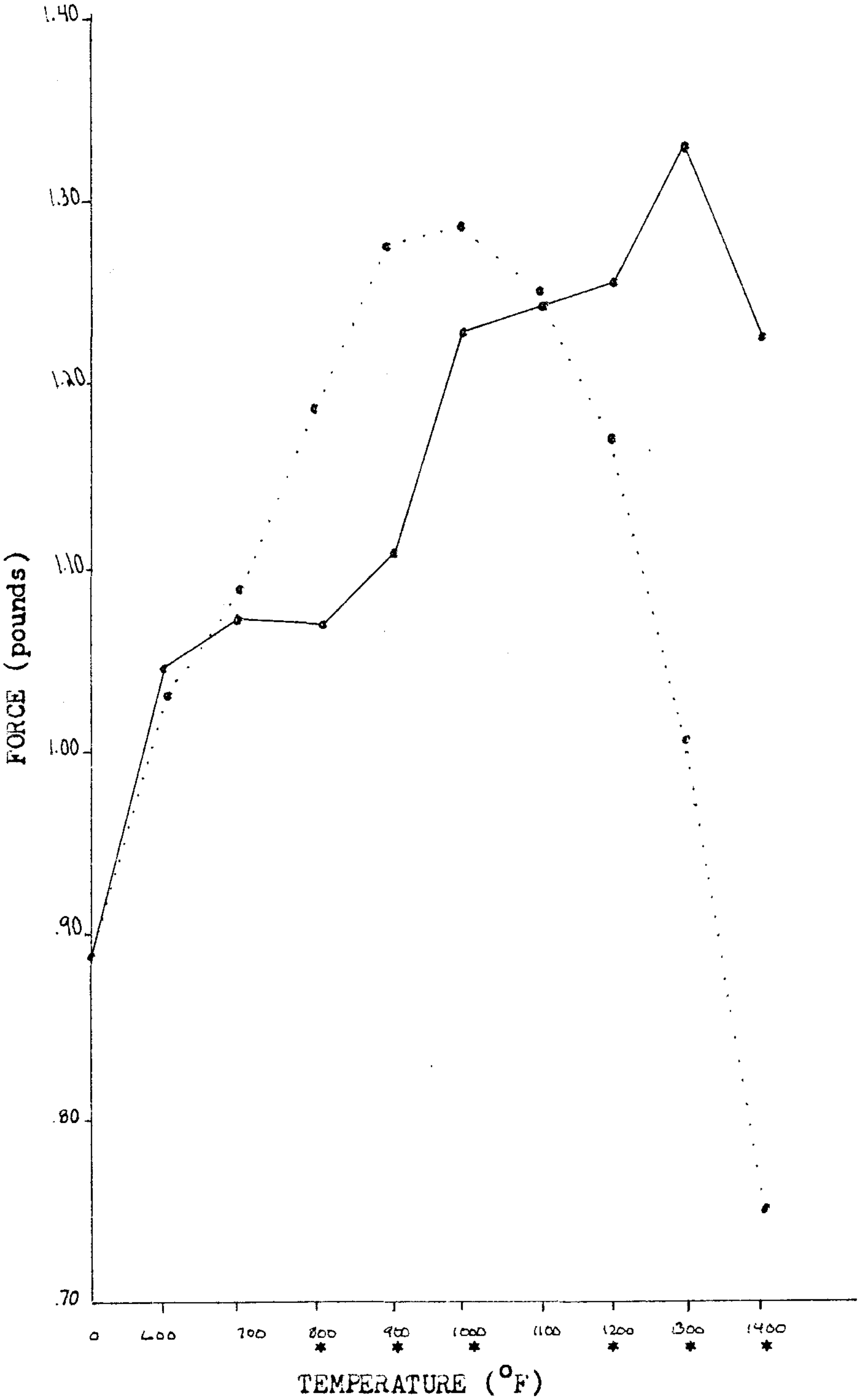
In the control group, a mean force of 0.887 pounds was necessary to deform a test wire to the G.S. point. At a heat treatment temperature of 600°F, 1.046 pounds and 1.037 pounds of force, respectively, were required to reach the G.S. point for the electric and furnace methods. Thus, approximately a 17% increase in force was needed to achieve the same peak point after heat treatment by either method at 600°F. The maximum G.S. value with the electric method occurred at 1350°F. It showed an increase of 57.8% in the resistance to deformation over the control group. In contrast, the maximum G.S. value with the furnace method showed a 44.7% increase in resistance to deformation at 1000°F.

In Table X, a significant difference at the 0.001 level is demonstrated for the control versus the experimental groups. The 'T' tests at the 0.001 level of confidence produced a difference between the electric and furnace methods for the following temperatures: 800°F, 900°F, 1000°F, 1200°F, 1300°F, and 1400°F. (Table X)

At 1100°F, both methods give comparable results. (Figure 10) However, the furnace method, at temperatures over 1100°F, shows a dramatic decrease in the force necessary to reach the G.S. point. In contrast, the electrical method requires an increase in force to reach the G.S. point up to 1350°F. In the electrical method, temperatures greater than 1350°F need less force to produce the same point. Figure 10 graphically displays the fact that over 1100°F the electric method yields higher G.S. values than the furnace method. However, at

FIGURE 10

MEAN G.S. POINTS FOR ELECTRICAL VS. FURNACE TREATMENT



—— Electrical treatment

... Furnace treatment

* Significant difference between mean G.S. points at 0.001 level

TABLE X

'T' TEST BETWEEN ELECTRIC AND CONTROL;

FURNACE AND CONTROL; ELECTRICAL AND FURNACE

	N	Mean (lbs)	S.D.	'T' Value	Significant at .05,.01,.001	Significant at .1
Control	6	0.887	0.0199	36.9	yes	yes
E 600°F	6	1.045	0.021			
Control	6	0.887	0.0199	21.2	yes	yes
F 600°F	6	1.037	0.0468			
E 600°F	6	1.045	0.0468	1.57	no	no
F 600°F	6	1.037	0.0210			
E 700°F	6	1.075	0.0128	2.12	no	yes
F 700°F	6	1.088	0.0123			
E 800°F	6	1.071	0.0206	41.3	yes	yes
F 800°F	6	1.185	0.0238			
E 900°F	6	1.103	0.0142	36.8	yes	yes
F 900°F	6	1.279	0.0361			

TABLE X (continued)

'T' TESTS BETWEEN ELECTRIC AND CONTROL;

FURNACE AND CONTROL; ELECTRICAL AND FURNACE

	N	Mean (lbs)	S.D.	'T' Value	Significant at .05,.01,.001	Significant at .1
E 1000°F	6	1.229	0.0659	9.14	yes	yes
F 1000°F	6	1.283	0.0103			
E 1100°F	6	1.253	0.0325	1.04	no	no
F 1100°F	6	1.256	0.0139			
E 1200°F	6	1.257	0.0084	6.73	yes	yes
F 1200°F	6	1.173	0.0294			
E 1300°F	6	1.326	0.0241	130	yes	yes
F 1300°F	6	1.003	0.0363			
E 1400°F	6	1.225	0.0126	253	yes	yes
F 1400°F	6	0.751	0.0225			

temperatures lower than 1100°F, the furnace method produces significantly higher G.S. values.

Tables XI and XII give a summary of an analysis of variance for the electrical and the furnace methods.

The data for the electrical method shows a significant difference in G.S. points obtained at the various temperatures. That is, 1300°F was found to yield significantly higher G.S. values than 600°F, 700°F, and 800°F at the 0.05 confidence level. Results further showed a difference between 1300°F and 600°F at the 0.01 confidence level.

The data for the furnace method also shows a significant difference in G.S. points obtained at the various temperatures. 900°F, 1000°F, and 1100°F yield significantly higher G.S. values than 1400°F at the 0.05 level of confidence.

TABLE XI

ANALYSIS OF VARIANCE FOR THE ELECTRICALLY HEAT TREATED GROUP

SOURCE	DF	S.S.	M.S.	'F' VALUE
Between	8	73.0949	9.13680	21,549.2
Within	45	0.01910	0.000424	

Null Hypothesis: No difference in G.S. points among electrically treated wires at different temperatures.

Since 'F' computed (21,549.2) is greater than 'F' table value (2.18), reject the null hypothesis.

Conclusion: There is a difference in G.S. points among electrically treated wires at different temperatures.

'K' TABLE LISTINGS

Significantly different temperatures

0.05 level:

$1300^\circ F \neq 600^\circ F$

$1300^\circ F \neq 700^\circ F$

$1300^\circ F \neq 800^\circ F$

0.01 level:

$1300^\circ F \neq 600^\circ F$

TABLE XII

ANALYSIS OF VARIANCE FOR THE FURNACE HEAT TREATED GROUP

SOURCE	DF	S.S.	M.S.	'F' VALUE
Between	8	66.9820	8.37262	4406.68
Within	45	0.08652	0.00190	

Null Hypothesis: No difference in G.S. points among furnace treated wires at different temperatures.

Since 'F' computed value (4,406.68) is greater than 'F' table value (2.18), reject the null hypothesis.

Conclusion: There is a difference in G.S. points among furnace heat treated wires at different temperatures.

'K' TABLE LISTINGS

Significantly different temperatures

0.05 level:

$1400^{\circ}F \neq 900^{\circ}F$

$1400^{\circ}F \neq 1000^{\circ}F$

$1400^{\circ}F \neq 1100^{\circ}F$

TABLE XIII

APPROXIMATE CURRENT AND VOLTAGE READINGS

FOR ELECTRICALLY HEAT TREATED WIRES

°F	CURRENT (amps)	VOLTAGE	COMPUTED RESISTANCE (ohms)
600	4.0	2.4	0.60
650	4.2	2.9	0.69
700	4.3	2.9	0.67
750	4.5	3.0	0.66
800	5.0	3.0	0.60
850	5.1	3.2	0.63
900	5.2	3.5	0.67
950	5.3	3.5	0.66
1000	5.7	3.8	0.67
1050	6.0	3.9	0.65
1100	6.1	4.0	0.66
1150	6.2	4.1	0.66
1200	6.3	4.1	0.65
1250	6.4	4.2	0.66
1300	6.5	4.3	0.66
1350	6.5	4.5	0.70
1400	6.5	4.8	0.74

CHAPTER VI

DISCUSSION

In the Review of Literature, it was established that Blue Elgiloy wire should be heat treated to remove internal stresses and to increase the spring performance and efficiency of the wire. The purpose of this study is to determine if a difference exists between two clinically acceptable methods of heat treatment, electrical and furnace. Furthermore, if a difference does exist, which temperatures within each method yield the greatest strength for the wire.

To determine the resistance to deformation of Elgiloy wire, the peak point on a force/deformation curve was chosen as the reference base. It is understood in referring to this point, that if a mean force greater than the mean force for the control group is needed to deform a wire to the G.S. point, then a similar resistance to that deformation has been incorporated into that wire, due to the heat treating method and/or temperature. The G.S. point, in light of the extremely small standard deviations in each group (Table X) and the very large 'F' computed values (Tables XI and XII), is a consistently reproducible, statistically valid point for this study.

As seen in Table X, a significant difference exists between experimental and control groups. A 'T' test value of 36.9 showed a significant difference at the 0.001 level between the electrical and the control methods. The electrical method at 600°F (1.045 pounds) showed an increase of 17.8% in resistance to deformation over the control group. At 1350°F (1.401 pounds), the electrical method showed an increase of 57.8% in resistance to deformation. As expected and discussed earlier, electrical heat treatment does improve the qualities of Elgiloy wire.

A 'T' value of 21.2 showed a significant difference at the 0.001 level between the furnace and the control methods. A furnace temperature of 600°F increased the resistance of the wire to deformation by 16.9%. At 1000°F, an increase of 44.6% was noted.

A comparison between the data from the electrical and the furnace methods yields some surprising conclusions. The nine 'T' tests in Table X demonstrate a significant difference between the electrical and the furnace methods for the same temperatures. It was found that the following temperatures yielded different strengths of wires at the 0.001 probability level: 800°F, 900°F, 1000°F, 1200°F, 1300°F, and 1400°F. Acknowledging that a difference in methods exists for these temperatures, it is possible to identify the method that will give the maximum strength at a specific temperature.

The furnace method gives substantially higher G.S. points for the low temperature heat treating. That is, at 800°F, 900°F, and 1000°F, the furnace method produces greater wire strength. However, at higher temperatures of 1100°F, 1200°F, 1300°F, and 1400°F, the electrical method yields higher strengths for the test specimen. The maximum resistance to deformation is reached by the electrical method at 1350°F. (Table IX) Temperatures of 600°F, 700°F, and 1100°F do not show a difference between methods. Hence, wires treated by either method at these temperatures would produce similar wire strengths.

To explain the results obtained in this study, it becomes necessary to deal with the most fundamental makeup of the material. Cobalt chromium wire, in common with other metals, exhibits the property of atomic diffusion. At room temperature, this migration is negligible. However, on raising the temperature, the rate of diffusion increases because of the higher internal energy.[4] Orthodontic wire, as received from the manufacturer, is not in a state of equilibrium.[4] Stresses have been introduced into the alloy during the rolling stages and also during the final drawing of the ingot through dies. Since the grains have elongated in the drawing process, a distorted space lattice is produced with individual atoms in irregular positions. The cold-drawn, strain-hardened wire is in a highly stressed state. The latter produces a metal with a higher yield strength, surface hardness, and proportional limit, but with a ductility that is greatly reduced. To obtain different gradients of ductility in Elgiloy wire, it is possible to stress relieve the wire. The ultra-spring, brittle Red Elgiloy has had very little stress relief, while the soft, pliable Blue Elgiloy has had substantially more.

Cobalt has a unique phase transformation that allows cobalt alloys an increase in strength after heat treatment. More specifically, pure cobalt has a close-packed hexagonal crystal structure (h.c.p.) at a temperature below 785°F. At temperatures above 785°F (some say 842°F),[27] the hexagonal crystal structure transforms into a face-centered cubic structure (f.c.c.). By increasing the temperature of the wire, the h.c.p. structure is easily transformed into the f.c.c. structure. However, the reverse low temperature allotrophic transformation reaction of f.c.c. to h.c.p. is very sluggish.

It must be appreciated that mixing elements with cobalt will effect the properties of the cobalt. In the first place, the alloys directly modify the properties of the cobalt and, secondly, they influence the rate of transformation from h.c.p. to f.c.c.. Thus, by alloying cobalt, the temperature of transformation is increased. In Elgiloy, seven elements are present to directly effect the physical properties and rate of transformation. The transformation temperature of 842^{o}F for pure cobalt is undoubtedly low for Elgiloy, considering the influence of the other alloys.

The results of this study suggest that the temperature for phase transformation varies between the electrical method and the furnace method. This is due, in part, to the different exposure times of the wire to a given temperature. In resistance heating, the wire reaches a desired temperature almost instantaneously and then rapidly cools off. This is in contrast to furnace heat treatment where the wire is gradually heated and then maintained at a constant temperature for several minutes. Even if the temperatures of the wires are the same, the energy levels are quite different. In resistance heating, low temperatures are inadequate to provide maximum phase transformation. The higher temperatures, however, impart enough energy from a high current source to allow maximum atomic diffusion to the f.c.c. form. The reverse reaction of f.c.c. to h.c.p. does not begin until the transformation temperature is again reached, if the wire is rapidly heated.[27] In a sense, the f.c.c. structures are "locked" into their atomic positions due to the quick energy release and rapid cooling. The latter could help to explain why resistance heating ultimately produced a higher wire strength. That is, in a dental furnace the wire heats more slowly and it is less difficult for f.c.c. to transform back to h.c.p.. Hence, more h.c.p. exists at the end of the heat treatment process compared with the electrical method.

In the low temperature ranges, time proved to be a critical factor. The longer time exposures in the dental furnace provided adequate energy for maximum atomic diffusion to occur. Consequently, the furnace method yielded higher wire strengths in the lower temperature ranges, as compared to the electrical method.

It may be theorized from the results of this study that the energy necessary for stress relief of the strain-hardened Elgiloy and to achieve different temper gradients is less than the energy necessary to achieve maximum atomic diffusion. While increasing the temperature of the wire resulted in greater strength, a relieving of internal stresses also took place. A complicating and variable factor in determining the cause of the increase in wire strength is the magnitude of residual stress produced by each heat treating method. Acknowledging that a sudden intense thermal change would correspondingly produce a thermal expansion due to the increased vibration of atoms at high temperatures; and, furthermore, realizing that residual stresses are produced by uneven or very rapid cooling of metals, the possibility of residual stress contributing to the strengthening process, due to rapid cooling of a very small wire in ambient air, cannot be denied.

To the author's knowledge, a minimum temperature for phase transformation in Elgiloy wire has not been established. However, an empirical guide for maximum atomic diffusion in the electrical heat treating method should approach a temperature of 1350°F. A temperature of 1000°F for seven minutes in a dental furnace should also produce maximum phase transformation.

Resembling the results obtained by Fillmore and Tomlinson,[29] this study suggests that electrical heat treatment at 950°F (G.S. 1.172) yields comparable resistance to deformation as furnace heat treatment at 800°F (G.S. 1.186). A 'T' value of 1.22 denies any difference between the two temperatures at the 0.05 confidence level. However, in contrast to Fillmore and Tomlinson's conclusion that 1200°F by the furnace method yields the greatest resistance to deformation, this study shows that 1000°F to 1100°F gives the maximum wire strength for this method. The latter temperature is comparable to 1100°F to 1200°F for the electrical method. In addition, 1350°F ultimately gives the highest results for electrical heat treatment, which are 9.2% greater than for furnace heat treatment. This increase in strength is in dramatic contrast to previous reported studies on electrical heat treatment.

A thorough analysis of heat treatment of Elgiloy wire would not be complete without a discussion of the advantages and disadvantages of heat treatment. The advantages of heat treatment, in general, include the ease of fabrication of complex appliances and the fewer fractures which result. There is less internal stress in the wire, hence, more uniform properties and better fatigue properties, improved elastic properties, and consequently, less likelihood of distortion in the mouth. As for electrical heat treatment, it is fast, convenient, and easy to use, and can be hooked up to a welder present in most orthodontic offices. The biggest advantage to furnace heat treatment is that it provides a uniform temperature to all portions of the wire.

The disadvantages of heat treating, in general, are that it takes time and trouble. A suitable oven or welder is required. An elastic recoil of approximately 0.1% strain occurrs, which necessitates further adjustment of the appliance.[26] The appliance will be more susceptible to fracture if subjected to repeated adjustment. The color of the wire is effected unless polished; and, corrosion resistance may also be effected. A disadvantage of electrical heat treatment is lack of a uniform temperature in the loops bent into the wire. Also, sharp bends produce highly work-hardened areas which have increased resistance to the flow of electrons, and thus, reach the desired temperature during heat treatment before less work-hardened areas. This produces a wire that is unevenly heated. A disadvantage of the furnace method is the length of time required for heat treating the wire. Another is the poor economics of a dental oven in an orthodontic office for the sole purpose of heat treatment.

SUMMARY

Eighty fourteen inch lengths of 0.016 x 0.022 inch Blue Elgiloy wire were acquired from the Rocky Mountain Products Company. Each length was cut in three, four and one-half inch lengths.

The wires were divided into three groups. The non-heat treated method consisted of one group with twelve specimens. The electrical heat treated method had seventeen temperature groups with six specimens per temperature, or a total of one hundred and two specimens. The furnace method had nine temperature groups with six specimens per temperature, for a total of fifty-four test specimens.

The control group received no heat treatment. The electrical group of wires was heated by means of a variable autotransformer and the temperature was indicated by Tempilaq, a temperature indicating liquid. The furnace group was heat treated by placing the wires in a dental furnace for seven minutes at a constant temperature.

After all the wires were treated in the described manner, they were placed on the Instron testing device for evaluation of their resistance to deformation. Measurements were recorded on a graph, with the peak of the force/deformation curve representing the comparative reference base for wire strength. This point, as referred to herein, is called the G.S. point.

'T' tests revealed a significant difference between the electrical method and the control method. A significant difference between the furnace method and control method was also noted, as was between the

electrical and furnace methods at a variety of temperatures. The furnace heat treatment method yields higher strengths in the 800°F, 900°F, and 1000°F temperature ranges. However, the electrical method showed a significant difference between methods at the 1200°F, 1300°F, and 1400°F ranges and, ultimately, higher strengths. At 600°F, 700°F, and 1100°F no difference existed between the two methods. In the electrical method, temperatures of 600°F, 700°F, and 800°F gave significantly lower G.S. points than 1300°F. In the furnace method, temperatures of 900°F, 1000°F, and 1100°F gave significantly higher G.S. points than 1400°F. A listing of amperage, voltage, and resistance for temperatures of the electrical method may be found in Table XIII.

CONCLUSION

From the results obtained in this study, the following conclusions were drawn:

1. Electrical heat treatment of straight four and one-half inch strand of 0.016 x 0.022 inch Blue Elgiloy wire at a temperature of 1350°F increases its resistance to deformation 57.8% over the non-heat treated method.

2. The electrical method at 1350°F increases Blue Elgiloy's resistance to deformation 9.2% over the furnace method at 1000°F for seven minutes.

3. The electrical method yielded its highest strength at 1350°F (an increase of 57.8% over the non-heat treated wire), while the furnace method's highest strength was at 1000°F (an increase of 44.7%).

4. A 'T' value of 6.83 exists between furnace treatment at 1000°F and electric treatment at 1300°F, giving a statistical difference at the 0.01 confidence level between the two methods.

5. The furnace method gives greater wire strength in temperatures less than 1100°F; but, in excess of 1100°F, the electrical method yields ultimate higher strengths.

In conclusion, the electrical method, which is the most convenient and expedient method for heat treating straight wire, also yields the highest resistance to deformation at a temperature of 1350°F. Although both methods give acceptable results on straight wires in the low temperature range, there clearly is a statistical difference between the two methods in the high temperature ranges.

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APPROVAL SHEET

The thesis submitted by Greg Sutherland has been read and approved by the following committee:

Dr. James L. Sandrik, Director
Chairman, Department of Dental Materials, Loyola.

Dr. Joseph Gowgiel
Chairman, Department of Anatomy, Loyola.

Dr. Bill Petty
Associate Clinical Professor, Orthodontics, Loyola.

The final copies have been examined by the director of the thesis and the signature which appears below verifies the fact that any necessary changes have been incorporated and that the thesis is now given final approval by the Committee with reference to content and form.

The thesis is therefore accepted in partial fulfillment of the requirements for the degree of Master of Science.

April 12, 1978
Date

James L. Sandrik
Signature of Director