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Effect of heat treatment on the tensile strength of 'Elgiloy' orthodontic wire

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ABSTRACT

Objective. Elgiloy is the trade name of a cobalt–chromium–nickel superalloy that is offered for orthodontic use as wire. Despite some years of use, there is very little information in the dental literature on its mechanical properties, and especially on the effect of the hardening heat treatment (HT), that may be used after forming, on the tensile strength (TS) in relation to the four 'tempers' that are available.

Methods. Straight lengths of round wire of the four available tempers, Blue, Yellow, Green and Red, were tested in direct tension at 5 mm/min in air at 23 °C to fracture, both as-supplied (AS) and with HT at 500 °C for 5 h, in air. HT was done in a high-uniformity, three-zone tube furnace in an alumina boat. The wires were then allowed to cool to room temperature in the boat, outside the furnace. The nominal (original cross-sectional area) peak stress was calculated.

Results. TS varied from 1.4 to 2.1 GPa, AS, and 1.6 to 2.8 GPa HT, according to temper, but with appreciable variation within tempers. Even so, the TS plot of HT *vs.* AS was very straight and of narrow distribution (intercept: -0.638 ± 0.064 GPa, slope: 1.575 ± 0.036, r^2: 0.994918, $n = 12$, $F = 1957.7$, $p \sim 8 \times 10^{-13}$).

Significance. The strengthening due to HT was highly regular and TS can be reliably predicted on the basis of the AS value, but this of course cannot be known without specific batch testing. However, the unexpectedly large variation in the AS values within tempers renders such a prediction of lower reliability and usefulness in practice. Indeed, the distinction between tempers can be negligible, making selection according to application demands problematic, and differential property expectation less than certain. No such product data are provided commercially. Quality control is not as tight as might be expected. The implications for treatment need to be explored.

1. Introduction

Orthodontic treatment is dominated by the use of wire-based devices, and is likely to remain so, especially for circumstances where removable plastic aligners are unsuitable. Until the 1960s, archwires were principally of gold alloy but were then largely supplanted by stainless steel on grounds of cost. At about this time, a patented [1] cobalt–chromium (CoCr) alloy, of the class known as stellites, was introduced [2], having been developed during the 1950s, and used particularly for watch springs. With the trade name Elgiloy, it was taken up for

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dental use in wire form by Rocky Mountain Orthodontics (RMO). Originally the alloy was formulated with beryllium, but this is now no longer deliberately present (pers. comm.; Elgiloy Corporation), in contradiction of other sources, *e.g.* [3].

It is not the purpose here to elaborate on the various properties and advantages of the wide range of alloys now used for archwires, matters which are dealt with extensively elsewhere, but rather to note two factors that are of great practical importance. The first is that of the modulus of elasticity (*E*), which in the context of the flexural rigidity, EI_z, where the effect of the cross-section (size and shape) of the wire is manifest through the second moment of area, I_z [Chap. 23, 4], controls the forces which may be applied. The second is the formability: the ease with which a wire can be shaped as desired. Essentially, this refers to deformation after the elastic limit, σ_e, otherwise known as the yield point. The problem is that the lower the value of the elastic limit the less the elastic range (otherwise known as 'maximum flexibility' or 'springback'): $\varepsilon_{\max} = \sigma_e/E$, making the approximation that the elastic and proportional limits are indistinguishable (which might be assumed to be fair in the context).

Elgiloy for orthodontic use is supplied in four color-coded 'tempers': Blue, Yellow, Green, Red, said to be of increasing yield point value, which depends on the cold work done, as measured by the area reduction in drawing the wire from the fully solution-treated condition (*i.e.* by heating above the β–α transus temperature).

Strangely, reported values for the yield point (and ultimate tensile strength) are sparse and erratic, and until recently this also applied to the elastic modulus [5]. Generally, such data are commonly tabulated to enable the proper selection of a wire for a treatment, although in practice this cannot be done as a rule in the present case, especially since in this instance RMO were not in possession of such data. While there are some values quoted in various sources for the same alloy under a variety of conditions, these data cannot be assumed to be applicable to the dental context because the thermomechanical history of the wires supplied is, in fact, kept secret. An attempt at a critical compilation would not be worthwhile. The originators of the alloy, likewise cannot help, not knowing what has been done to the material after it has left their hands.

The advantages claimed for cobalt-chromium wire over stainless steel are said to be superior mechanical properties, greater resistance to fatigue and distortion and longer function as a resilient spring [6]. Also, it can be electrolytically polished, it is easily soldered, and said to be easily heat-treated to remove internal stress and thus improve spring performance [7]. However, problems affecting the orthodontic use of cobalt-chromium wire include the tendency to harden near soldered or spot-welded joints, and faster work-hardening than other alloys [7]. The four 'tempers' of Elgiloy are intended to allow selection flexibility as they vary a little in elastic modulus [5] and said to vary in their 'formability' and response to heat treatment [8,9]: Red – hard, resilient; Green – 'semi-resilient', shaped easily with fingers; Yellow – ductile; Blue – softest. 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 [10–12].

While formability is required to place loops, V-bends and other shapes in an archwire, low yield point is a disadvantage for springs intended to move teeth. Instead, high resilience (*i.e.* maximum stored energy) is required [13]. 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 [14]. Cold-work in this class of alloy causes a partial martensitic transformation of the initially quenched face-centered cubic α-phase solid solution [Chap. 28, 4]. It is this precipitation of the low-temperature β-phase that causes the rapid work-hardening of Elgiloy that can cause difficulties. This β-phase can be made to grow in extent on heating below the α–β transus temperature [Chap. 28, 4]. The alloy manufacturer recommends 5 h at 527 °C for this wire (but 482 °C for strip) [15]. Heating above the transus would amount to a solution heat treatment, returning the alloy to its fully-soft condition. It has been said that embrittlement [16] (a general problem with carbides and σ-phase in cobalt–chromium alloys [Chap. 19, 4]), can be caused by excessive heat treatment, although it is not clear what that would amount to, but it may not be immediately relevant to Elgiloy in dentistry as the temperature required for this is very high (>700 °C) [14]. Ordinarily, heat treatment does not appreciably change the modulus of elasticity of alloys [17].

That recommended 5-h heat-treatment time-scale appears to be unacceptable in dental practice contexts [18], although no information on the heat-treatment to be used for Elgiloy is present, it would seem, on the RMO website [19], because elsewhere some 3–12 min at ~480–510 °C is suggested [2,12,20–22], or even "a few seconds" [18]. Indeed, it has been said:

> *Unfortunately, the heat treatment was often improperly applied by clinicians who could not adhere to the recommended time-temperature scheme. As a consequence, [the properties] of the heat-treated wire were unknown.* [18]

Supposedly, the required heat treatment can be performed easily with the aid of an electrical resistance-welding apparatus [23], with a paste to show when the appropriate conditions of temperature and time have been achieved. A furnace heat treatment for 10 min was said to achieve the same result. [23] In fact, RMO used to sell a "temper paste" that would flash when the desired temperature was reached. This product has been discontinued. RMO have advised [Leon Laub, pers. comm.] alternative treatments:

1. RMO Welder: heat to dark straw color;
2. 900 °F (482 °C) for 7–12 min; 2 h will result in "greater resiliency";
3. Brush flame: use a lighter or brush flame, moving it back and forth under the wire; heat to dark straw color.

Methods 1 and 3, as well as the resistance heating method, clearly only involve a very short time at temperature, as well as being rather localized or uneven.

A number of other companies now market cobalt–chromium orthodontic wires, but no studies of their mechanical properties and the results of heat treatment have apparently been reported [23].