Mechanical Properties and Stress Relief of Stainless Steel Orthodontic Wire

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The introduction of austenitic stainless steel wire for use in orthodontic appliances has been followed by an increasing clinical acceptance of these alloy steels because of their desirable physical and mechanical properties. These alloy steels are not only nontoxic and corrosion resistant, but also possess the necessary ductility, strength, hardness and resilience to fulfill the very specialized requirements of orthodontic wire materials.

Heat treatment of stainless steel orthodontic wire appliances has been suggested to improve the elastic properties and the dimensional stability of the formed devices. Although these treatments will not allow recrystallization of the wire, a recovery process will occur in which some point and line defects in the metal structure will be eliminated in the absence of microstructural changes. Allowing the recovery to occur has a considerable significance in improving dimensional stability through its connection with residual stresses in the device.

The austenitic stainless steels used for these orthodontic wires are basically of the 18-8 type (18% CR and 8% Ni), in particular, grades 302, 304 and 316. The 316 grade, which has been introduced into dentistry recently, differs from the other two grades by having about two per cent more nickel in addition to about two per cent molybdenum. The addition of molybdenum endows the 316 grade with increased corrosion resistance.

The stainless steel wire is formed by drawing through successively smaller water-lubricated diamond dies with annealing heat treatments used during the intermediate stages of drawing to limit the strain hardening and thus permit continued reduction in cross section by further plastic deformation during the succeeding draws. An unfortunate consequence of the drawing operation is the introduction into the polycrystallic wire material of nonuniform plastic strains which persist after the applied forces on the body have been removed. The stress distribution associated with this "locked-in", nonuniform microstrain is called "residual stress". The effect of the residual stress on the behavior of the wire during arch fabrication and use can be quite significant. For example, the presence of a high tensile residual stress in an area will allow plastic flow after the application of only a small additional tensile stress. As a result the wire material may no longer be capable of delivering the desired forces required in the fabricated orthodontic appliance.

Because of the very precise control which the orthodontist wishes to have over the forces applied to move the teeth, the elastic properties and the dimensional stability of the formed wire arches must be quite predictable. In addition, the wire appliance should show maximum dimensional stability and elastic properties and, to ensure

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that there will not be any unexpected variation in these properties for a formed wire arch, a stress relief anneal has been clinically advocated at temperatures in the range from 600 to 1000°F.[1-5] At these temperatures recovery processes occur and sufficient relief of residual stress occurs[6] to avoid distortion of the arch during clinical use. The amount of residual stress relieved will, of course, depend upon state of stress, time and temperature of the heat treatment, as well as the material; relief of 25 to 40 per cent of the residual stress is reported for conventional heat treatments on austenitic stainless steel.[7] The heat treatment needed for more complete residual stress relief would be around 1600 to 1700°F for these materials,[8] but since this level of stress relief is not normally clinically desirable, the partial relief obtained at 600 to 1000°F is satisfactory.

The purpose of this research was to compare the effects of stress relief for types 302 and 316 orthodontic wires to determine how much improvement might be obtained in the dimensional stability, in the elastic modulus and yield strength of formed wire arches, as well as of the wire itself. Mechanical properties of these wires were determined both before and after heat treatment.

Materials and Methods

Heat treatment was carried out in an air atmosphere using an electric resistance furnace whose temperature was maintained using an electronic temperature controller. A measuring thermocouple was placed against the clamped end of the stainless wire specimens during the heat treatment.

The effectiveness of the heat treatments was determined using the stainless steel jig shown in Figure 1.[9] The

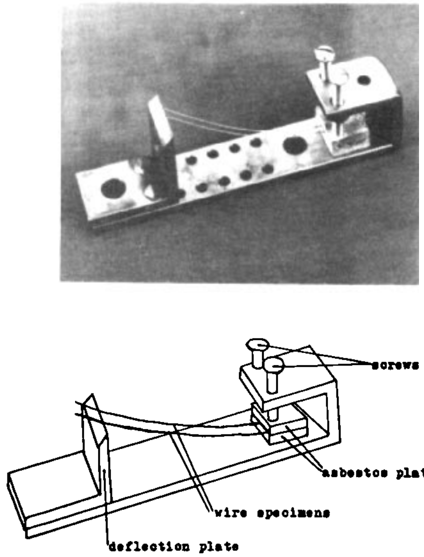

Fig. 1 **Stainless steel stress relief jig.**

.022 wire specimen was clamped at one end while the other end was deflected elastically. A constant deflection was used in all the experiments in this work. Following the high temperature annealing treatment and the subsequent cooling of the apparatus the amount of residual stress relief was determined by measuring the amount of return of the wire, if any, to the original horizontal position. The per cent relief was calculated using the expression

$$\frac{(dr) - (do)}{(df) - (do)} \times 100 = \text{per cent}$$

stress relief where (dr) = relaxed deflection, (do) = original position and (df) = initial deflection. The experimental temperatures chosen were 500°F and from 700°F to 1050°F in 50°F increments; the holding times used after attaining temperature were 30 seconds, 5 minutes, and 15 minutes. Because of the mass of the stainless steel jig, a thermal lag amounting to about 5 to 9 minutes, depending upon the heat treating temperature, was encountered.

TABLE I

	Modulus of Elasticity x 10^6 psi	0.2 Per Cent Yield Strength x 10^3 psi	Ultimate Tensile Strength x 10^3 psi
	TYPE 302		
Mean—Batch 1	24.8	202.8	269.6
S.D.	.283	3.39	3.67
Mean—Batch 2	24.6	246.16	285.16
S.D.	.29	3.13	2.78
	TYPE 316		
Mean—Batch 1	27.77	283.5	330
S.D.	.275	1.8	2.24
Mean—Batch 2	26.76	300.16	341
S.D.	.7	3.46	3.2

TABLE II

Elastic Modulus of Stainless Steel Wire
Following Various Thermal Cycles

TYPE 302*

	30 sec.	5 min.	15 min.
As Received	24.8 x 10^6 psi		
500°F.	25.4	25.4	26.2
700°	26.6	26.6	27.7
750°	27.0	27.7	26.6
800°	27.0	27.0	27.0
850°	27.3	27.0	26.6
900°	27.0	27.3	27.3
950°	27.0	27.3	27.0
1000°	26.6	26.6	27.3
1050°	27.0	26.6	27.0

*All values noted are results of tests of batch number one only.

TYPE 316

	30 sec. *	5 min.	15 min.
As Received	26.7 x 10^6 psi	27.7	27.7
500°F.	27.0	28.0	28.0
700°	27.0	28.8	28.8
750°	28.2	28.2	28.8
800°	27.0	28.2	28.8
850°	28.0	28.8	28.8
900°	28.0	28.0	28.0
950°	28.0	28.2	28.2
1000°	27.0	28.0	28.2
1050°	28.0	28.0	28.8

*Data gathered for the 30 second cycle was taken from batch number 2. The 5 and 15 minute data were from batch number one.

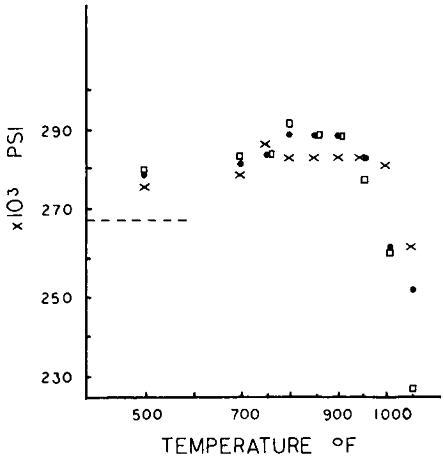

Fig. 2 Ultimate tensile strength of type 302 stainless steel orthodontic wire as a function of temperature for various heat treating times. —as received, X 30 seconds, ● 5 minutes, □ 15 minutes.

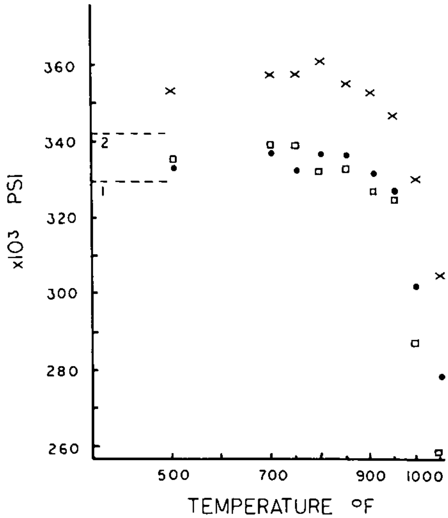

Fig. 3 Ultimate tensile strength of type 316 stainless steel orthodontic wire as a function of temperature for various heat treating times. 1 as received Batch 1, 2 as received batch 2, X 30 seconds, ● 5 minutes, □ 15 minutes.

The modulus of elasticity, yield strength and ultimate tensile strength were measured on 7 inch-long wire specimens using an extensometer and a testing machine with a cross-head speed of 0.1 in./minute. In preliminary studies the values of these mechanical properties were found to vary considerably in the as-received condition from one manufacturer's lot to another. Six samples from two batches of each wire were tested. Type 316 demonstrated higher strength properties than 302 grade material; about 10 per cent higher modulus and about 25 per cent greater yield strength as shown in Table 1.

Results and Discussion

The heat treatment cycles employed resulted in slightly increased values of modulus for both types of wire for temperatures of 700°F or more, irrespective of the holding times; type 316 showed an increase of about 3-4 per cent whereas type 302 showed about 8 per cent increase in modulus and ultimate strength (Table II and Figs. 2 and 3).

The yield strengths of both type 302 and type 316 were increased by heat treatment, the largest improvement occurring for temperatures in the range of 700° to 900°F (Figs. 4 and 5). Because of the rather wide property variations observed in the "as-received" material, no distinction can be made for the improvement in yield strength for the individual holding times although approximately a 10 per cent improvement in yield strength occurs for both the type 302 and 316 wires However, for type 316 the thermal treatment at temperatures above 1000°F causes the yield strength to drop precipitously to a value below the "as-received" value.

The stress relief tests show that generally much less than half of the residual stress is removed in the range of conventional stress relief heat treat-

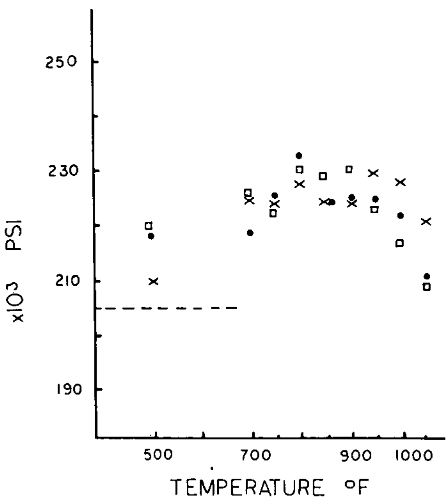

Fig. 4 0.2 per cent yield strength of type 302 stainless steel orthodontic wire as a function of temperature for various heat treating times. — as received, × 30 seconds, ● 5 minutes, □ 15 minutes.

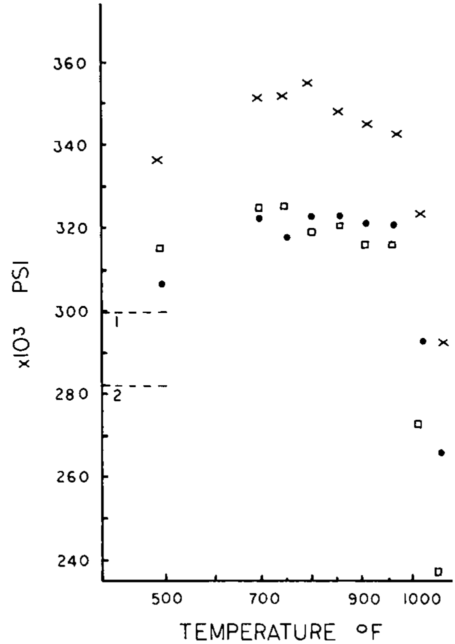

Fig. 5 0.2 per cent yield strength of type 316 stainless steel orthodontic wire as a function of temperature for various heat treating times. 1 as received Batch 1, 2 as received Batch 2, × 30 seconds, ● 5 minutes, □ 15 minutes.

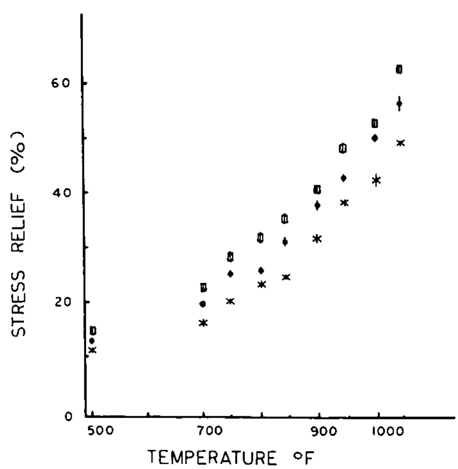

Fig. 6 Per cent stress relief of type 302 stainless steel orthodontic wire as a function of temperature for various heat treating times. × 30 seconds, ● 5 minutes, □ 15 minutes.

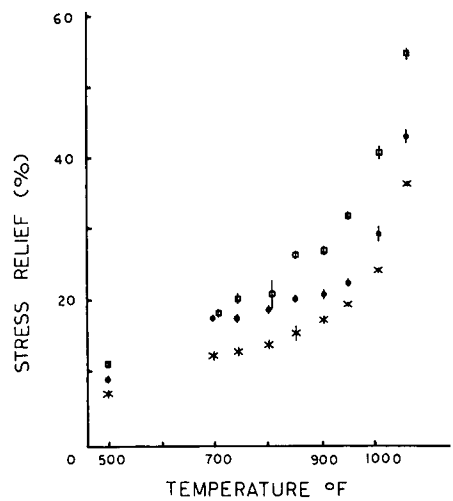

Fig. 7 Per cent stress relief of type 316 stainless steel orthodontic wire as a function of temperature for various heat treating times. × 30 seconds, ● 5 minutes, □ 15 minutes.

ment (700 to 900°F for 5-15 minutes) shown in Figures 6 and 7. In addition, one must consider that the data shown in these figures reflect somewhat longer times at temperature than would be the case if the wire arch alone were heat treated due to the thermal inertia of the test jig. The stress relief obtained should be somewhat greater than if the wire device alone were heat treated. As the figures show, the stress relief in type 302 is from 20 to 40 per cent for thermal treatment of 750° to 950°F for 30 seconds to 15 minutes; by contrast, only about 12 to 30 per cent relief is obtained for type 316 with the same heat treatment. Thus, the heat treatments needed to obtain optimum mechanical properties in these materials still allow a very large amount of the residual stress to remain in the body. Distortion of the clinical device will still be experienced to the extent that residual stresses remain.

The finding of sizeable variation in in mechanical properties from batch to batch of wire of the same grade must be considered as a possible source of difficulty, especially when these materials are used in recently introduced clinical techniques in which the wires are loaded elastically to levels near the yield point. With such variations in the basic properties a standard manipulative technique will result in variations in applied force. In addition, the residual stress distribution in the wires may cause havoc with clinical appliances unless they are sufficiently relieved.

As a result of the work reported here, the type 316 material does exhibit superior elastic properties compared to the type 302 and thus would be indicated where maximum stiffness and high resistance to deformation are required. However, a stress relief anneal is needed whether type 302 or type 316 wire is used.

On the basis of the results presented it is apparent that a more detailed specification is needed for acceptable orthodontic wires since wide variations in mechanical properties are found for materials from different suppliers even though the wire materials are classified by metallurgical grade.

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References

1. Unitek Corporation, Monrovia, California. Catalog No. 113, p. 42, 1964.
2. TP Laboratories, Inc., LaPorte, Indiana. Catalog No. 800, p. 35, 1966.
3. Thurow, Raymond C. *Technique and Treatment With the Edgewise Appliance.* St. Louis: C. V. Mosby Co., p. 94, 1962.
4. Richman, G. V. Practical Metallurgy for the Orthodontist. *Am. J. Orthodont.* 42: 573-587, (Aug.) 1956.
5. Kohl, A. W. Metallurgy in Orthodontics. *Angle Orthodont.* 34: 37-42 (Jan.) 1964.
6. Chalmers, Bruce *Physical Metallurgy,* New York: John Wiley and Sons, 1959.
7. Pollard, R. E. and Reinhart, F. M. Relief of Residual Stress in Streamline Tierod. *J. of Research Natl. Bureau of Standards,* Research paper no. 1477, 28: 755-772 (June) 1942.
8. Sangdahl, G. Stanley Stress Relief of Austenitic Stainless Steels. Metal Progress 86 No. 2: 100-104 (Aug.) 1964.