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Complete contents begin on page 5A

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"Dentistry's oldest specialty"

Bending properties of superelastic and nonsuperelastic nickel-titanium orthodontic wires

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Cantilever bending properties were evaluated for several clinically popular sizes of three superelastic and three nonsuperelastic brands of nickel-titanium orthodontic wires in the as-received condition, and for 0.016-inch diameter wires after heat treatment at 500° and at 600° C, for 10 minutes and for 2 hours. A torque meter apparatus was used for the bending experiments, and the specimen test-span length was 1/4 inch (6 mm). In general, the bending properties were similar for the three brands of superelastic wires and for the three brands of nonsuperelastic wires. For the three brands of superelastic wires, heat treatment at 500° C for 10 minutes had minimal effect on the bending plots, whereas heat treatment at 500° C for 2 hours caused decreases in the average superelastic bending moment during deactivation; heat treatment at 600° C resulted in loss of superelasticity. The bending properties for the three brands of nonsuperelastic wires were only slightly affected by these heat treatments. The differences in the bending properties and heat treatment responses are attributed to the relative proportions of the austenitic and martensitic forms of nickel-titanium alloy (NiTi) in the microstructures of the wire alloys. (AM J ORTHOD DENTOFAC ORTHOP 1991;99:310-8.)

Nickel-titanium orthodontic wires have been of considerable interest to the specialty since the introduction of the original[1] Nitinol alloy somewhat more than a decade ago. The very low modulus of elasticity, considerable elastic force delivery range, and high springback of this alloy provide the orthodontist with unique advantages compared with the stainless steel, cobalt-chromium-nickel, and β-titanium wires. Within the last few years many new nickel-titanium orthodontic wire alloys have been introduced, and some of these new brands possess the property of superelasticity. Superelastic behavior was first specifically noted in the orthodontic literature for the Japanese[2] NiTi alloy. When the wire is subjected to tensile loading, appreciable activation and deactivation take place at nearly constant values of stress. Under bending conditions, this superelastic behavior is less evident, although there is a substantial region of nearly constant bending moment during deactivation. Although the term *superelasticity* was not explicitly used in the article introducing the Chinese[3] NiTi wire alloy, the bending test plots for Chinese and Japanese NiTi were very similar, indicating that the former alloy also showed superelastic behavior.

The superelastic property of some nickel-titanium wire brands has been attributed to a phase transformation from the body-centered cubic austenitic form to the hexagonal close-packed martensitic form of NiTi when the stress reaches a certain level during activation.[2] Upon deactivation, the reverse-phase transformation from the martensitic to the austenitic structure takes place when the stress is decreased to an appropriate level, which is somewhat less than that required to cause the forward transformation. It is thus necessary for the proprietary wire manufacturing processes to leave the nickel-titanium alloys largely in the austenitic structure for superelastic behavior to occur, whereas the original Nitinol alloy and other nonsuperelastic nickel-titanium wires have principally a work-hardened martensitic structure.

A clinically useful consequence of superelastic behavior is that variations in heat treatment by the manufacturer can result in differing stress levels to initiate the phase transformations in the same nickel-titanium wires. For Japanese NiTi,[2] heat treatment at 400° C had no affect on the bending plots. However, heat treatment at 500° C for periods of 5 minutes to 2 hours caused considerable differences in the constant force levels for

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superelastic behavior, and the superelastic property of this alloy was lost after heat treatment at 600° C. By using appropriate heat treatments, the manufacturer is able to offer the Japanese NiTi alloy (commercially marketed as Sentinol) in three different superelastic force ranges of light, medium, and heavy for individual wire sizes. This responsiveness to heat treatment appears to be possible for other superelastic wire brands, in principle, but vacuum or inert atmosphere conditions are required because the nickel-titanium alloys react quickly with air at elevated temperatures.

This investigation compares the bending properties of several superelastic and nonsuperelastic nickel-titanium wire brands in the size range of principal clinical interest, and it investigates the effects of heat treatment on the bending plots and superelastic behavior. Extensive studies of the metallurgical structure of the alloys have been performed by means of x-ray diffraction,[4] and these results will be presented in a separate article.

MATERIALS AND METHODS

The six brands of nickel-titanium orthodontic wires and the sizes selected for this investigation are summarized in Table I. From product information literature and private communication with the manufacturers, it was found that the Nitinol SE, Sentinol, and Ni-Ti alloys show superelastic behavior, whereas the Nitinol, Titanal, and Orthonol alloys are not superelastic. The sizes of round and rectangular wires listed in Table I encompass a variety of the most common clinical appliances.

A torque meter apparatus previously used for several studies[5-8] in our laboratory provided accurate and reproducible measurements of the bending moment and angular deflection. A cantilever test span of 0.25 inch (6 mm) was selected, and the bending apparatus was based on the design recommended in the original version[9] of American Dental Association specification No. 28. Two torque meters (Models 783-C-2 and 783-C-10, Power Instruments, Skokie, Ill.), with ranges of 0.05 to 2 inches · ounces and 0.5 to 10 inches per ounce, were used, depending on the maximum moment levels developed by a given group of specimens. The torque meter was operated manually, and the specimens were bent at room temperature (22° C ± 2° C) to angular deflections of approximately 80° and then unloaded. The rectangular wire specimens were subjected to second-order activation because of greater convenience with the design[9] of the specimen-gripping fixture and the direction of bending in the horizontal plane with the apparatus. The pointers on the torque meters obscured the position of zero bending moment and the initial ranges to 0.05 or 0.5 inch · ounce, and it was not possible to establish the portions of the bending deformation plots near the origin. Consequently, the graphic plots in the following section are presented as relative values of angular position or bend angle, and the horizontal axes have been shifted and labeled so that the bending curves begin approximately at the origin. These torque meters are reported by the manufacturer to be accurate to within 2%, and values of bending moment were obtained at 5° increments of angular position. Values of the relative angular deflection could be read to approximately the nearest 0.25° to 0.5° from a protractor mounted on the base of the test apparatus. There were three replications for each wire brand–size combination, and the three bending moment values at each increment of angular position were averaged and converted from inches · ounces to grams · millimeters in the preparation of a single bending plot.

Heat treatments were performed in a dental furnace (Big Brute, K.H. Huppert, South Holland, Ill.) at 500° and 600° C for 10 minutes and 2 hours on 0.016-inch-diameter segments of the six wire brands. The specimens were sealed in evacuated (approximately 0.01 to 0.1 torr) quartz capsules and placed in ceramic boats. Each capsule also contained a small piece of pure titanium that served as a "getter" of residual atmospheric gases to suppress any oxidation of the wire or incorporation of other impurities from the air. After completion of the heat treatments, the quartz capsules were

Table I. Summary of orthodontic wires used in present investigation

Wire brand	*Size (inch)*	*Manufacturer*
Nitinol SE	0.016, 0.018, 0.018 × 0.025, 0.021 × 0.025	Unitek Monrovia, Calif.
Sentinol (medium)	0.016, 0.018, 0.018 × 0.025, 0.0215 × 0.028	GAC International Central Islip, N.Y.
Ni-Ti	0.016, 0.018*	Ormco/Div. of Sybron Glendora, Calif.
Nitinol	0.016, 0.018, 0.018 × 0.025, 0.021 × 0.025	Unitek Monrovia, Calif.
Titanal	0.016, 0.018, 0.018 × 0.025, 0.021 × 0.025	Lancer Orthodontics Carlsbad, Calif.
Orthonol	0.016, 0.018, 0.018 × 0.025, 0.021 × 0.025	Rocky Mountain Orthodontics Denver, Colo.

*Only these two round wire sizes were available at the time of this investigation.

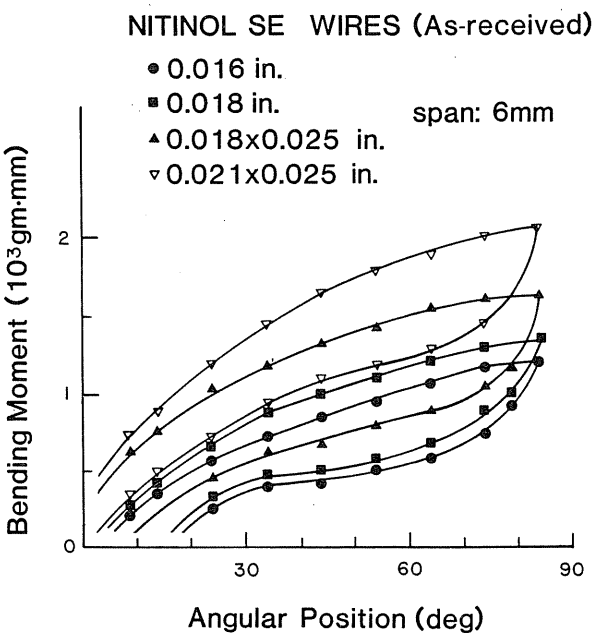

Fig. 1. Bending plots for as-received Nitinol SE wires.

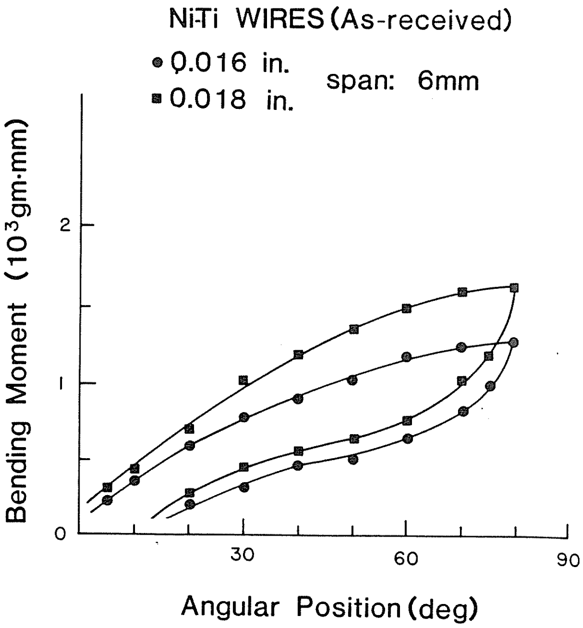

Fig. 3. Bending plots for as-received Ni-Ti wires.

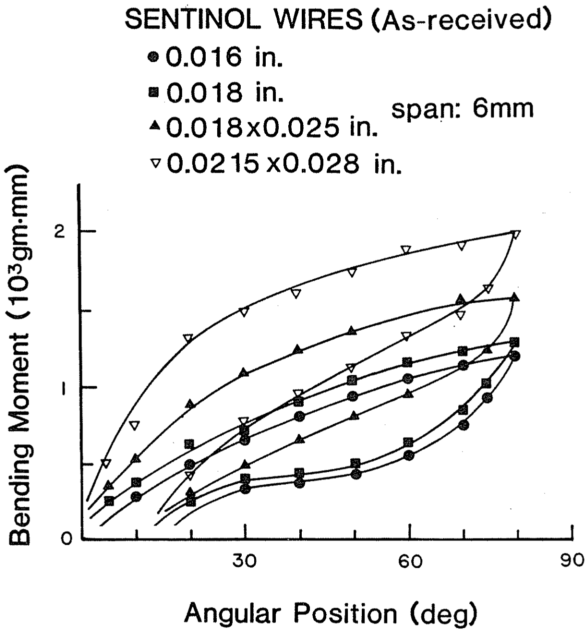

Fig. 2. Bending plots for as-received Sentinol wires.

immersed in water at room temperature and broken to quench the specimens.

RESULTS

The bending plots for the as-received superelastic alloys, Nitinol SE, Sentinol, and Ni-Ti, are shown in Figs. 1 to 3, and the bending plots for the as-received nonsuperelastic alloys, Nitinol, Titanal, and Orthonol, are shown in Figs. 4 to 6. Examination of these two sets of figures reveals that the bending curves for the three superelastic alloys were similar and that the three nonsuperelastic alloys also had similar bending curves. However, it is evident that there were considerable general differences in the bending deformation behavior for the superelastic and nonsuperelastic wires. Although it was not as apparent in the loading or activation portions of the curves, the unloading portions of the bending plots for the superelastic wires generally contained a nearly horizontal region or plateau where deactivation took place at almost constant moment values. An exception was found for the two rectangular sizes of Sentinol (Fig. 2), where the major portion of each deactivation plot had a linear region with a relatively small slope. In contrast, the activation and deactivation curves shown in Figs. 4 to 6 for the nonsuperelastic wires had much greater slopes compared to the bending plots for the superelastic wires. Another distinguishing feature of superelastic and nonsuperelastic alloys was the difference in elastic springback, which follows from the differences for the residual permanent deformation after unloading. The permanent set for the 1/4-inch test span specimens was approximately 10° to 15° for the three superelastic wires, whereas approximate values of 35° to 40° permanent deformation for Nitinol and Titanal and 20° to 30° for Orthonol correspond to much less springback for nonsuperelastic wires.

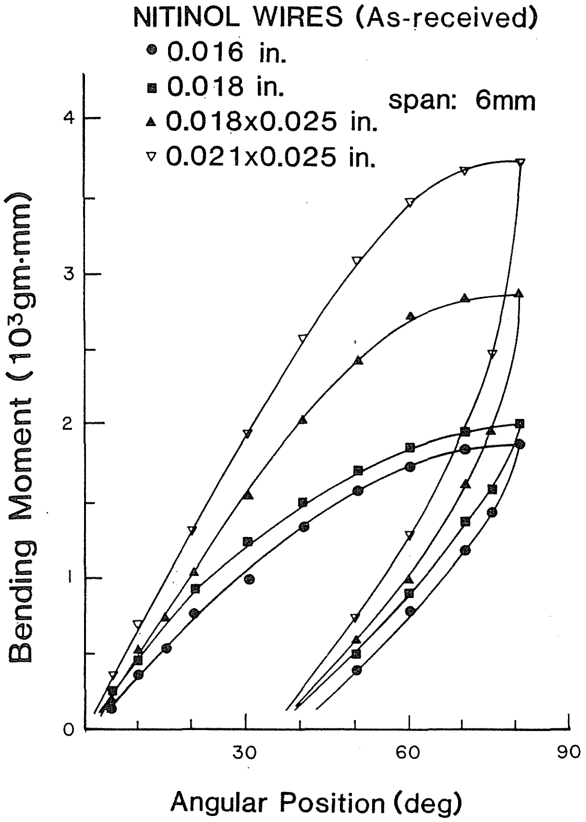

Fig. 4. Bending plots for as-received Nitinol wires.

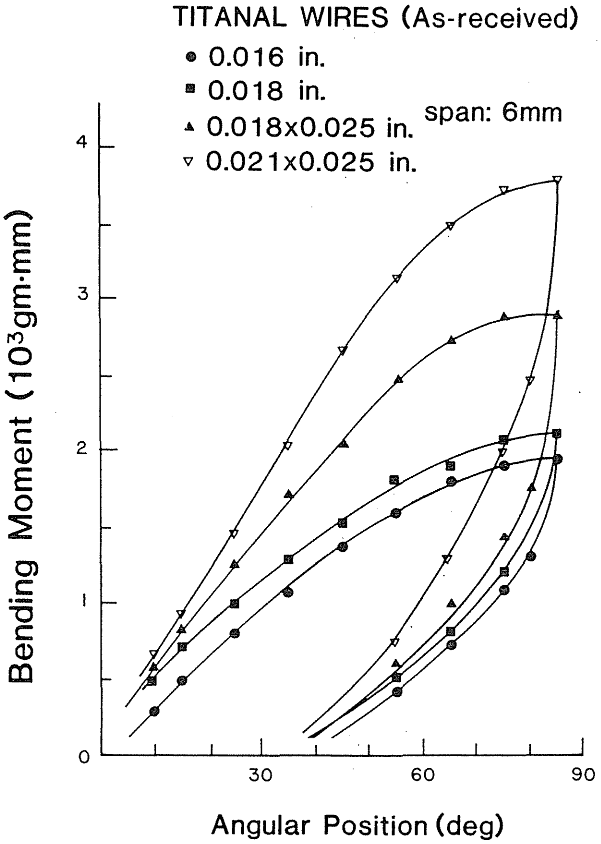

Fig. 5. Bending plots for as-received Titanal wires.

The maximum bending moment at 80° activation for the three superelastic alloys ranged from about 1200 to 2000 gm · mm as the diameter varied from 0.016 inch to rectangular specimens of either 0.021 × 0.025 inch or 0.0215 × 0.028 inch (Figs. 1 to 3). During deactivation, the bending moment for the region of superelasticity correspondingly ranged from about 400 to 1200 gm · mm. For the three nonsuperelastic alloys, the maximum bending moment at 80° activation ranged from nearly 2000 gm · mm for the 0.016-inch-diameter specimens to approximately 3800 gm · mm for the 0.021 × 0.025-inch rectangular specimens. While there were only small differences in the bending plots for the Nitinol (Fig. 4) and Titanal (Fig. 5) specimens of the same wire size, the Orthonol specimens (Fig. 6) displayed greater differences with respect to the other two nonsuperelastic alloys. The maximum bending moment delivered by the 0.021 × 0.025-inch Orthonol specimens was about 3000 gm · mm, a value considerably less than that for the corresponding Nitinol and Titanal specimens. In addition, the maximum moment for the 0.018-inch-diameter segments of Orthonol exceeded that for the 0.018 × 0.025-inch rectangular segments of this alloy in second-order activation; the maximum moment was greater for these rectangular segments of Nitinol and Titanal, compared to Orthonol. For the 0.016-inch-diameter specimens, the maximum bending moment was similar for the three nonsuperelastic alloys.

The effects of the heat treatments on the bending properties of the 0.016-inch-diameter specimens of the three superelastic alloys were very similar, as shown in Figs. 7 to 9. There was little difference between the bending plots for these wires in the as-received condition and after heat treatment at 500° C for 10 minutes. Heat treatment at 500° C for 2 hours resulted in decreases in both the maximum moment at 80° activation and the average moment for the central or superelastic portion of the deactivation curve; there was little change in the value of springback. The superelastic behavior was lost for all three alloys after the heat treatments at 600° C for 10 minutes or for 2 hours. The criteria for the loss of superelasticity were the disappearance of the plateau region in the deactivation curve and the decrease in springback. For the heat treatments of 10 minutes and 2 hours at 600° C, the permanent set for

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