Stiffness Changes in Thermodynamic Nitinol With Increasing Temperature

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Load-deflection measurements on wires fabricated from a new Nitinol alloy which undergoes physical transformations affecting elastic response at body temperature.

KEY WORDS: • ELASTICITY • STIFFNESS •

Some orthodontic applications are best served by an archwire which has a low modulus of stiffness, a high resistance to permanent deformation and a wide clinical working range. The stiffness of stainless steel requires loops, multiple strands and other modifications to achieve some of these mechanical objectives. The elastic properties of Nitinol can provide advantages in such applications (ANDREASEN AND MORROW 1978, KUSY 1981, KUSY AND GREENBERG 1981, LOPEZ ET AL. 1979). Advantages noted in these earlier studies include greater working range and lower stiffness, facilitating the use of low force levels for such procedures as mass leveling.

— Purpose —

The purpose of this study is to measure and describe the physical properties of a recently-developed thermodynamic Nitinol alloy, type A-138. Wires of this alloy are limp at room temperature. When passed through its transition temperature range (TTR), which is below 100°F, it will stiffen and return toward a preset form such as an an archshape. It is this special property of "heat memory" which may be of use clinically.

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— Materials and Methods —

Samples of .017" diameter round Nitinol wire A-138 were tested for the three force parameters of stiffness, flexure yield strength, and permanent deformation, using an ADA-approved Tinius-Olsen test instrument with six inch-pounds moment capacity. The component parts of the tester include a rotating vise to grasp the sample, a bending plate over which the samples are bent, an angular deflection scale, and a load scale. All tests were conducted inside a Harris Environmental System module capable of controlling air temperature within ±0.5°F. Measurements were made at 5° increments between 75° and 100°.

The stiffness tester was placed within the environmental module and leveled so that the pendulum would be at full swing to the central bearing. A pendulum moment weight of 0.10 inch-pounds and a bending span of 12.7mm were used for all sample runs.

Each sample was clamped in the vise perpendicular to the bending plate and a drop of jewelers oil added at the bending site to minimize the influence of friction. The tester was hand-loaded to the point where the sample made initial contact with the bending plate, where the load and deflection scales set to zero.

One investigator operated the loading motor and read the load values at each 5° increment of deflection from 0° to 90°, while another monitored the temperature and recorded the load values. To minimize systematic error, the same investigator placed all specimens in the vise and calibrated the instrument prior to each test. Six samples were tested and 35 readings recorded for each sample.

Load and deflection scale readings were converted to kg/mm^2 (modulus of stiffness) by using the equation —

$E = ML/3L$, where

E = stiffness in flexure
M = bending moment
L = span length
I = moment of inertia
O = angular deflection

The bending moment (M) on the stiffness tester is the sum of moment values (indicated by the pendulum weight) multiplied by the load scale reading. The moment value for all tests was .10 inch-pounds.

The moment of inertia (I) of a specimen cross section is defined theoretically as the sum of the products of each elementary area multiplied by the square of the distance of that area from the assumed axis of rotation ($I = \pi d^4/64 = .0491 d^4$).

Both the loading and unloading modulus of stiffness were computed for each pair of load scale - angular deflection readings and recorded as kg/mm^2. An analysis of variance was performed for each 5° increment of temperature over the complete range tested.

— Results —

The working range of Nitinol A-138 (.017" round) was found to be directly related to increments of temperature increase. This increase in the working range is illustrated by the composite graphs (stress-strain curves) shown in figures 1-6, which show the force deflection curves and their flexure yield points at the six different temperatures.

The yield point is that point at which permanent deformation begins. It is labelled Y.P. on the graphs. The top line on the graph represents the loading of the wire at 90° deflection. The lower line of the graph represents the unloading cycle of the wire, showing force levels as the deflection is decreased as in an orthodontic tooth movement.

For the loading cycle of the wire, the flexure yield point remained approxi-

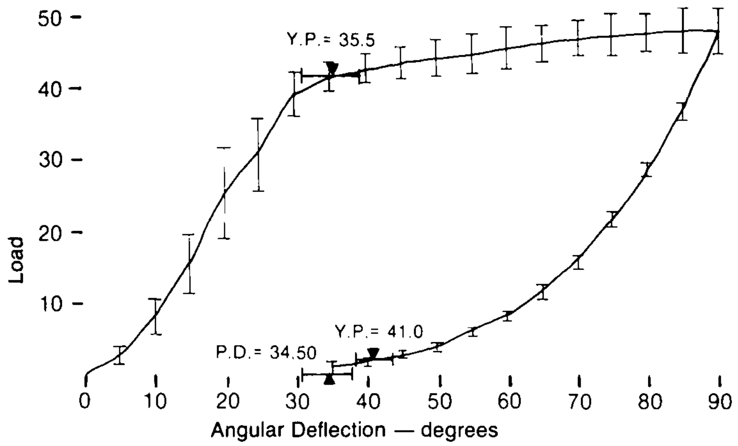

Fig. 1 Composite load-deflection curve for Nitinol Wire A-138 at 75°F. Load scale is in arbitrary units. Flexure yield points (Y.P.) in loading and unloading cycles are shown in degrees of angular deflection. Yield point under loading, 35.5° ±4.4°; under unloading, 41.0° ±2.8°. Permanent deformation is 34.5° ±3.5°.

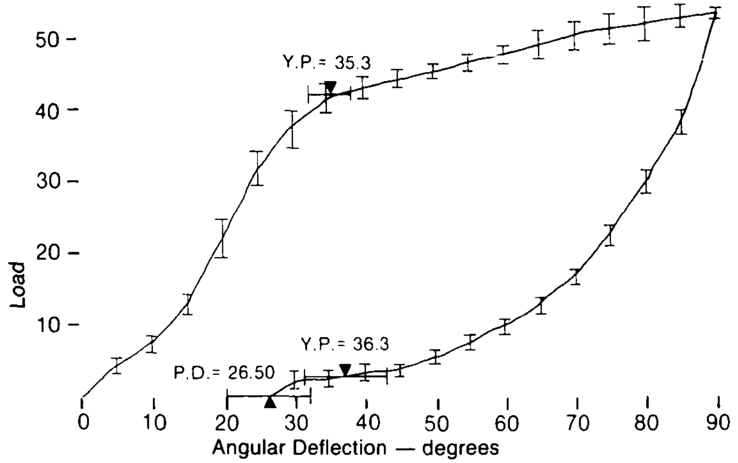

Fig. 2 Composite load-deflection curve for Nitinol Wire A-138 at 80°F. Load scale is in arbitrary units. Flexure yield points (Y.P.) in loading and unloading cycles are shown in degrees of angular deflection. Yield point under loading, 35.3° ±3.9°; under unloading, 36.3° ±4.9°. Permanent deformation is 26.5° ±5.9°.

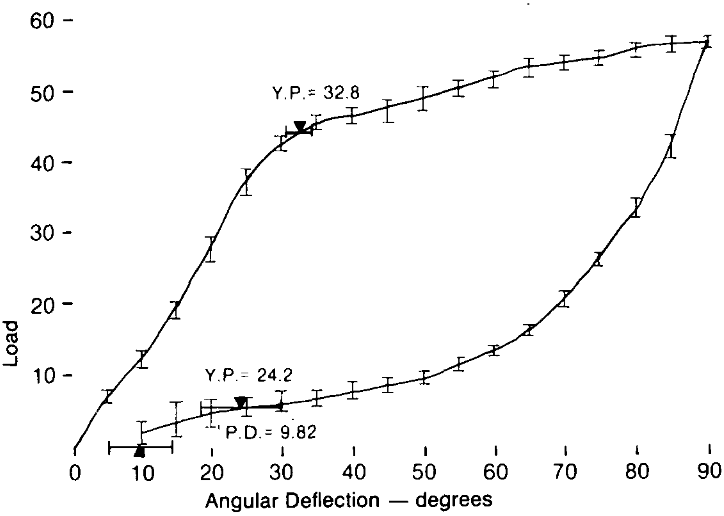

Fig. 3 Composite load-deflection curve for Nitinol Wire A-138 at 85°F. Load scale is in arbitrary units. Flexure yield points (Y.P.) in loading and unloading cycles are shown in degrees of angular deflection. Yield point under loading, 32.8° ± 1.9°; under unloading, 24.2° ± 5.8°. Permanent deformation is 9.8° ± 4.5°.

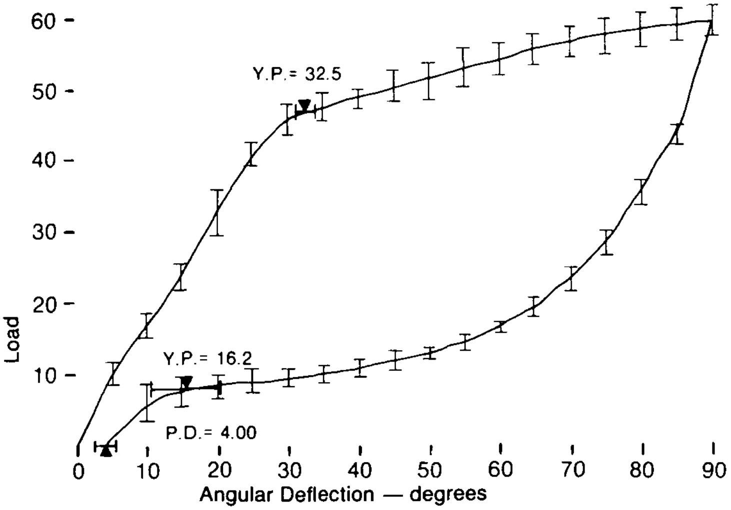

Fig. 4 Composite load-deflection curve for Nitinol Wire A-138 at 90°F. Load scale is in arbitrary units. Flexure yield points (Y.P.) in loading and unloading cycles are shown in degrees of angular deflection. Yield point under loading, 32.5° ± 1.6°; under unloading, 16.2° ± 4.9°. Permanent deformation is 4.0° ± 1.6°.

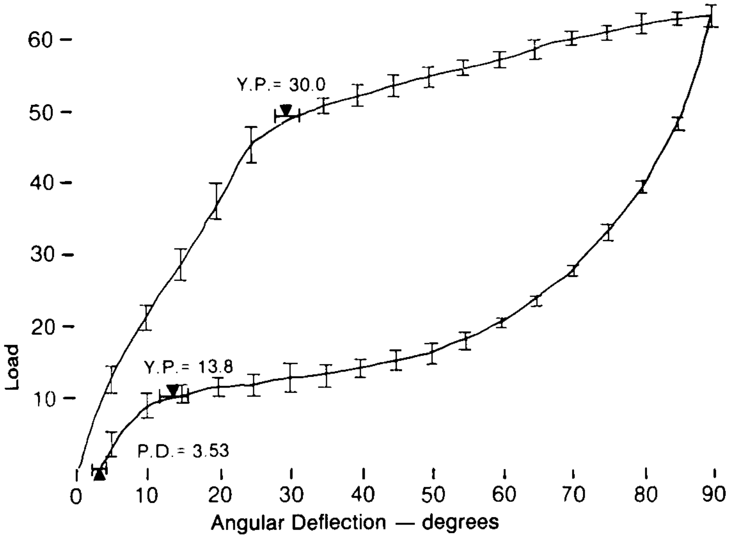

Fig. 5 Composite load-deflection curve for Nitinol Wire A-138 at 95°F. Load scale is in arbitrary units. Flexure yield points (Y.P.) in loading and unloading cycles are shown in degrees of angular deflection. Yield point under loading, 30.0°±1.8°; under unloading, 13.8°±1.8°. Permanent deformation is 3.5°±1.1°.

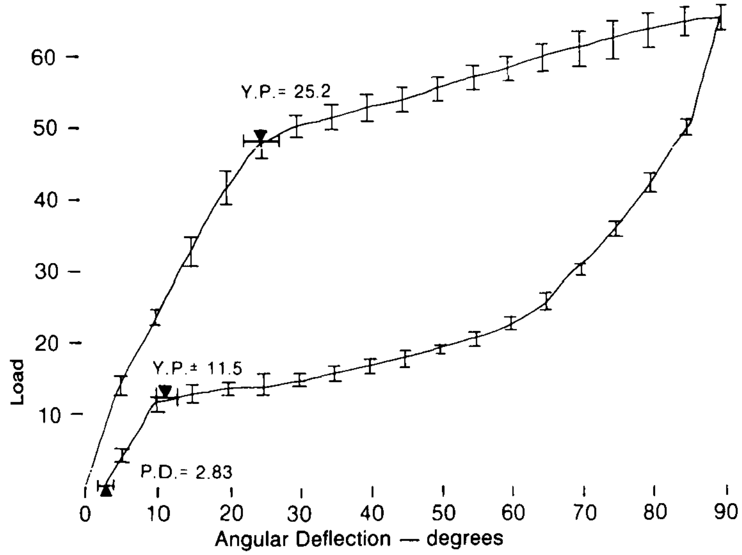

Fig. 6 Composite load-deflection curve for Nitinol Wire A-138 at 100°F. Load scale is in arbitrary units. Flexure yield points (Y.P.) in loading and unloading cycles are shown in degrees of angular deflection. Yield point under loading, 25.2°±2.4°; under unloading, 11.5°±1.5°. Permanent deformation is 2.8°±1.2°.

mately the same after the first 5° rise in temperature (Fig. 1). Above 80°F there was a steady decrease in the flexure yield point through the next 15° of temperature rise (Figs. 2-5). The 5°F increase in temperature from 95°F to 100°F produced the greatest decrease (approximately 5°) in angular deflection (Fig. 6).

In the unloading cycle, first 5° temperature rise resulted in a decrease in flexure yield point from 41° to 36.3° angular deflection. The greatest decrease in the flexure yield point (12.1°) was seen between 80° and 85°, diminishing to 8°, 2.4° and 2.3° angular deflection in the increments between 85°F and 100°F.

The angle at which permanent deformation of the wire occurred became smaller at higher temperatures, from 34.5° ± 3.5° angular deflection at 75°F to 2.8° ± 1.2° at 100°F. The most dramatic decrease in the angle of deflection at which permanent deformation occurred was seen between 80°F and 85°F, where this 5°F increment of temperature resulted in a 16.7° decrease, compared to only 7° decrease over the next 15°F rise in temperature.

— Discussion —

The stress-strain curve for any orthodontic wire reveals how much force is needed to move a tooth a given distance. From a practical viewpoint, the loading cycle represented by the upper curve shows the forces applied to a tooth when the clinician deflects a wire and ties it into a bracket. The lower curve representing the unloading cycle shows potential tooth movement as the wire returns to its original shape. The flexure yield points for Nitinol wire represent points of "temporary permanent deformation."

Typical stress-strain curves for most metals, including stainless-steel archwires, show varying flexure yield points on the loading cycle, with the unloading cycle dropping rather rapidly to zero force at 40° to 60° angular deflection. The return of A-138 Nitinol wire to within 12° deflection of its original shape upon heating through its TTR indicates a working range approximately 40% to 50% greater than that of stainless-steel wire. As seen in the composite graphs, the slope on the loading cycle for A-138

Table 1

Means and Standard Deviations
of Composite Graphs
(in degrees of angular deflection)

Temperature	Permanent Deformation	Flexure Yield Point	
		Loading	Unloading
75°F	34.5±3.5	35.5±4.4	41.0±2.8
80°F	26.5±5.9	35.3±3.9	36.3±4.9
85°F	9.8±4.5	32.8±1.9	24.2±5.8
90°F	4.0±1.6	32.5±1.6	16.2±4.9
95°F	3.5±1.1	30.0±1.8	13.8±1.8
100°F	2.8±1.2	25.2±2.4	11.5±1.5

Nitinol becomes steeper at higher temperatures, which means that more force is applied to the wire for each unit of bend. This demonstrates that there is an increase in the modulus of elasticity or stiffness as the wire warms to mouth temperature.

Clinically, the fact that the transition temperature range (TTR) of Nitinol A-138 corresponds to body temperature may be of practical use. It is in the TTR that A-138 Nitinol stiffens and assumes its altered state of elasticity. If the wire could be engaged into the appliance while still limp, clinical application could be facilitated in situations requiring extreme adjustments, or short working spans as in some lingual appliances. The small permanent angular deformation at 100°F demonstrates its ability to return to nearly original shape when heated to approximate mouth temperature.

— Summary and Conclusions —

The purpose of this study was to measure and describe the physical properties of a recently-developed thermodynamic Nitinol alloy, type A-138, at intervals of temperature between room and body temperatures.

The properties of stiffness, flexure yield strength and permanent deformation were measured, demonstrating that the working range of Nitinol A-138 is directly related to increases in temperature between 75°F and 100°F.

As stiffness of the .017″ round A-138 Nitinol wire increases, the yield point decreases. In the loading cycle, yield points dropped from 36° angular deflection at 75°F to 25° at 100°F. In the unloading cycle, the yield point at 75°F was 41° of deflection, with force dropping to zero at 35°; at 100°F, yield point was only 12° and force did not drop to zero until unloaded to 3° angular deflection.

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