# *Bending characteristics of nitinol wire*

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Until recently only a limited group of alloys have been used for orthodontic wires, namely, gold-coper, austenitic stainless steel, and chromium-cobalt-nickle (Cr-Co-Ni) based materials. In general, the last two groups have similar mechanical properties although processing, stress-relieving, heat-treating, and minor alloying adjustments allow for small product differences. On the other hand, the gold-based wires have a modulus of elasticity approximately one half that of the other two groups. Unfortunately, the yield strength of gold alloys is less by approximately the same factor, which gives them a ratio of yield strength to modulus of elasticity that is nearly the same as that of stainless steel and Cr-Co-Ni alloys. Since springback or resilience is proportional to this ratio, all three categories of alloys are approximately the same in regard to this clinical characteristic.

When used in orthodontic appliances, wires with low moduli of elasticity in combination with high resilience aid in delivering clinically desirable low continuous forces and increased working time.[1] It is these benefits, coupled with technologic advances in metallurgy and wire processing, which have promulgated the introduction of several low-stiffness, high-springback orthodontic wires. Braided wires use traditional stainless steel but achieve their improved properties through unique design of the wire's cross section. A second approach to obtaining ''high-deflection'' wires is through the use of novel alloys, the most notable being nitinol, a nickel-titanium alloy.[2]

Nitinol was developed by William F. Buehler[3] in the early 1960's. The original alloy contained 55 percent nickel and 45 percent titanium, which resulted in a one-to-one stoichrometric ratio of these elements. The most unique feature of this NiTi intermetallic compound is the ''memory'' phenomenon, which is a result of temperature-induced crystallographic transformations.[3] Andreasen[4] suggested that these shape changes might be used by the orthodontist to apply forces. This memory principle is not used clinically, although it would appear plausible.

The commercially available nitinol orthodontic wire contains 1.6 percent cobalt to modify the transition temperature and mechanical properties. Even without the ''memory'' effect, the unusually low modulus of elasticity of $4.8 \times 10^6$ p.s.i. and high resilience offer desirable features to the orthodontist. Using a clinical model, Andreasen and Barrett[5] demonstrated that nitinol had a lower stiffness than stainless steel and could be deflected further without permanent deformation when tied into malaligned brackets. Andreasen and Morrow[6] have evaluated the bending characteristics and spring rate of

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straight sections of nitinol wire and have demonstrated its use in Class I, Class II, and Class III malocclusions.

Although nitinol cannot be formed over a sharp edge, first- and second-order bends can be placed in the wire. Because of its unusual metallurgic structure, however, it cannot be assumed, a priori, that bent-wire appliances have the same properties as unbent wires. Indeed, even stainless steel demonstrates differences in properties after a bend is placed, depending on the direction of subsequent loading. Placement of permanent bends in wires and activation in the *opposite* direction is clinically important in all orthodontic techniques, since straight wires must be modified for exact finishing detail and to deliver the necessary forces during treatment.

The purpose of this study was to characterize further the bending characteristics of nitinol wire. In addition to straight-wire sections, standardized bends were also evaluated. Finally, the time dependence of these measurements was considered.

## Materials and methods

Nitinol* and a standard austenitic stainless steel wire,† each 0.18 inch in diameter, were evaluated in three different modes. Permanent deformation versus reflection characteristics of straight-wire sections were measured with a Tinius Olsen stiffness tester‡ by the procedure outlined in the new ADA specification No. 32 for orthodontic wires.[7] Three samples of each wire were tested. A 0.25 inch span length was used to minimize the length of wire being fed into the testing span during bending. This mode of testing is illustrated schematically in Fig. 1, *A*.

A second series of bending tests was made on straight sections, but instead of the "instantaneous" loading conditions used in the procedure referred to above, samples were loaded until 60 degrees of deflection had occurred and were maintained for 0, 1, 5, 20, 40, or 60 minutes and then released. A Tinius Olsen tester was again used, and permanent deformation was measured for three different samples at each of the above-listed times, for a total of eighteen samples per material. This experiment was repeated, but the same three samples were reused at each of the indicated times, for a total of three samples per material.

The third set of tests considered the permanent deformation versus deflection characteristics of nitinol and stainless steel wire after permanent bending. Samples were first given a permanent bend of 35 degrees. Care was taken to bend in only one direction, and a template was used to ensure reproducibility. The samples were then gripped in the Tinius Olsen stiffness tester with the initial permanent bend 0.5 mm. from the edge of the vise. Standard test procedures were then followed, with the force being applied in a direction opposite that of the initial bend, as shown in Fig. 1, *B*. In another series of tests, schematically represented in Fig. 1, *C*, the wires were first permanently deformed to 90 degrees ($P_1$) and then returned to the 35 degree permanent bend ($P_2$). Samples were then tested in the same direction as the last bend, $P_2$. In Fig. 1, *F* indicates the direction of loading used during the test.

*Unitek Corporation, Monrovia, Calif.
†Standard Permachrome, Unitek Corporation, Monrovia, Calif.
‡Tinius Olsen Testing Machine Corporation, Philadelphia, Pa.

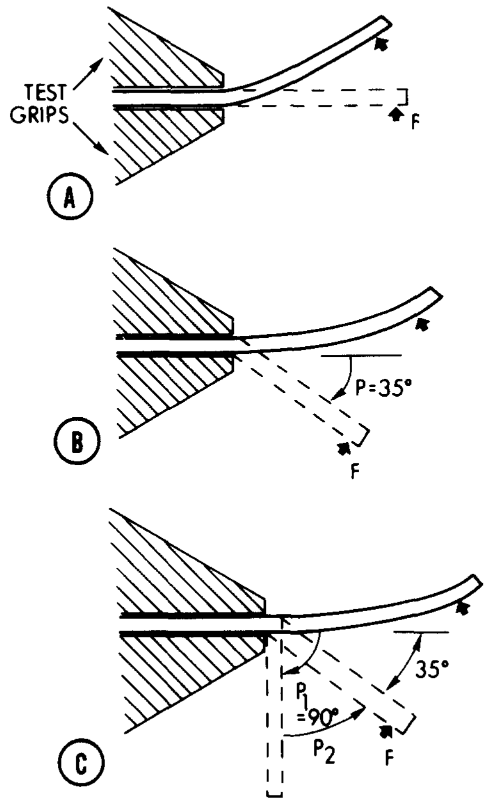


**Fig. 1.** The three modes of testing. *P* indicates the direction of bending of the configuration before loading, which is represented by dashed lines. In **C**, $P_1$ and $P_2$ show change of loading direction to produce preload configuration. *F* shows the direction of loading used during the test.

## Results

Test results for *straight-wire* sections are shown in Fig. 2, where permanent deformation is plotted as a function of deflection for the stainless steel and nitinol wires. The ability of the nickel-titanium alloy to undergo greater elastic deflections is clearly demonstrated. At any given activation, the nitinol experiences *less* permanent set. For wires 0.018 inch in diameter, the nitinol sustained approximately 23 degrees of activation and stainless steel 13 degrees before any permanent deformation was evident. These results are a further documentation of the flexibility and elasticity of nitinol described in earlier works.[2, 5, 6]

The behavior of these wires after the introduction of permanent bends is characterized in Fig. 3. The data from Fig. 2 have been replotted for comparison. The most notable feature of this figure is the large change in nitinol when tested in different modes. With respect to bending of straight sections (Fig. 1, *A*), nitinol demonstrates superior elastic properties as compared to stainless steel. However, when NiTi alloy is tested in a direction *opposite* to a *permanent* bend (Fig. 1, *B*), there is a considerable *loss* of elastic behavior. In fact, for activations of less than 40 degrees, *nitinol* exhibits *greater* permanent *defor-*

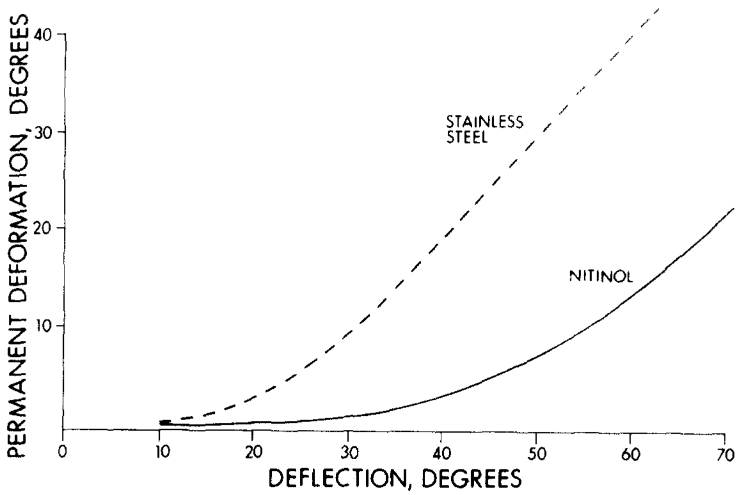


**Fig. 2.** Permanent deformation versus deflection for straight-wire sections, mode *A* in Fig. 1.

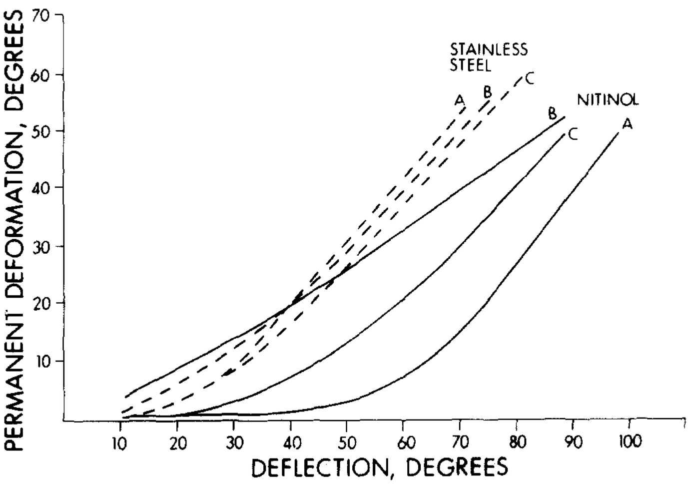


**Fig. 3.** Permanent deformation versus deflection for the three modes of testing illustrated in Fig. 1.

*mation* than stainless steel, their relative performance switching for activations larger than 50 degrees. When the nitinol wire was bent to 90 degrees and returned to 35 degrees prior to testing (Fig. 1, *C*), it again demonstrated the desirable low permanent deformation, although its performance was not comparable to the straight-wire test.

The magnitude of change associated with testing of stainless steel in different modes was not nearly as large as that of the NiTi alloy. The changes which did occur, however, document the desirability of *overbending* stainless steel. Even with small activations of 10 to 35 degrees, stainless steel in straight and overbent sections showed less permanent deformation than the samples tested in a direction opposite the last permanent bend.

The time dependence of nitinol and stainless steel is illustrated in Fig. 4, where

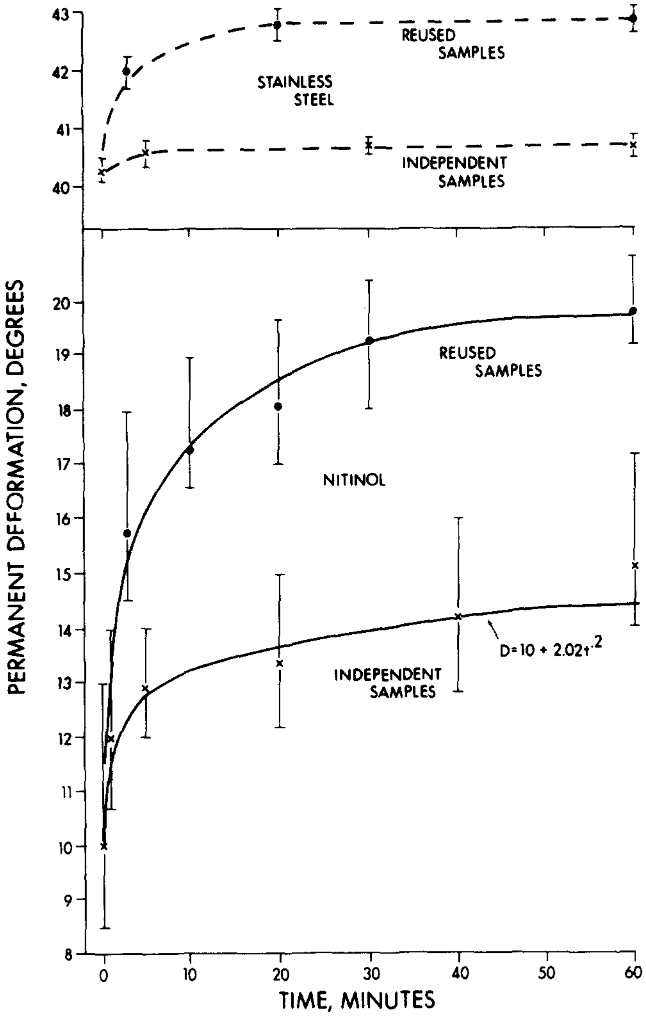


**Fig. 4.** Permanent deformation versus length of time samples held at a 60-degree bend. *x-x-x* represents data obtained with three independent samples at each time interval. ·-·-· represents data obtained with the same three samples reused at each time interval. Range of values obtained at each data point is indicated.

permanent deformation is plotted as a function of the length of time the samples were maintained at a 60-degree bend. Two curves are shown for each material. The lines labeled "independent samples" resulted from three replications at times of 0, 1, 5, 20, 40, and 60 minutes, new specimens being used for each test. Each line labeled "reused samples" was obtained with a total of three samples, each one being retested at the time intervals indicated.

The unexpected result was the *time dependency of nitinol,* even when independent samples were used. The nitinol experienced approximately 5 degrees of additional *permanent* set over 60 minutes, most of which occurred within the first 5 minutes. A one-way

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