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Static and Cyclic Load-Deflection Characteristics of NiTi Orthodontic Archwires Using Modified Bending Tests

Mahmoud Nili Ahmadabadi, Tahereh Shahhoseini, Mohamad Habibi-Parsa, Maryam Haj-Fathalian, Tahereh Hoseinzadeh-Nik, and Hananeh Ghadirian

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Near-equiatomic nickel-titanium (nitinol) has the ability to return to a former shape when subjected to an appropriate thermomechanical procedure. One of the most successful applications of nitinol is orthodontic archwire. One of the suitable characteristics of these wires is superelasticity, a phenomenon that allows better-tolerated loading conditions during clinical therapy. Superelastic nitinol wires deliver clinically desired light continuous force enabling effective tooth movement with minimal damage for periodontal tissues. In this research, a special three-point bending fixture was invented and designed to determine the superelastic property in simulated clinical conditions, where the wire samples were held in the fixture similar to an oral cavity. In this experimental study, the load-deflection characteristics of superelastic NiTi commercial wires were studied through three-point bending test. The superelastic behavior was investigated by focusing on bending time, temperature, and number of cycles which affects the energy dissipating capacity. Experimental results show that the NiTi archwires are well suited for cyclic load-unload dental applications. Results show reduction in superelastic property for used archwires after long-time static bending.

Keywords biomaterials, intermetallics, nonferrous metals

1. Introduction

In the early 1960s, Bohler and co-workers discovered the shape-memory effect in an equiatomic NiTi alloy with generic trade name nitinol (Ref 1).

Nickel-titanium (NiTi) orthodontic wires were introduced in orthodontics by Andreasen and Hilleman (Ref 2). NiTi orthodontic wires exhibit a lower modulus of elasticity, which is particularly useful during the early stages of fixed appliance therapy. Burstone first described the application of a superelastic NiTi wire: low deactivation forces were used to create a "physiologic" bone response (Ref 3).

Burstone and Goldberg observed beneficial characteristics such as low modulus of elasticity combined with a wide elastic working range (Ref 3, 4) that allowed wires to sustain large elastic deflections due to the very high springback quality. These wires enabled the orthodontic profession to achieve ideal tooth movement.

NiTi archwires have gained acceptance by orthodontists as initial alignment wires. Most of the information about the behavior of orthodontic wires is based on mechanical laboratory three-point bending tests that study load-deflection characteristics. Superelasticity is characterized by a load-deflection curve with a plateau during unloading. Results of three-point bending tests are load-deflection plots. These tests offer reproducibility which has facilitated comparison between studies (Ref 5-7).

Variations in model design have been shown to affect load-deflection plots. The load-deflection curves of NiTi wires alter with modifying of the test model (Ref 8-10). Modified three-point bending test which simulates wire force on the teeth in the oral conditions has more accurate results than ordinary three-point bending test. This test method provides more detailed information regarding orthodontic applications.

It is known that the NiTi alloy wire undergoes a phase transformation from an austenitic to a martensitic phase as the load increases during the loading process. Metallurgical studies have attributed these characteristics to a reversible phase transformation from the body-centered cubic structure to the monoclinic structure of Ni-Ti when the stress reaches a certain level during deformation (Ref 11).

The increasing amount of energy stored inside the NiTi wire during this process is consumed during the unloading process as the transformation is reversed, and the martensite structure reverts to austenite. Superelasticity is exhibited by unloading plateau in the reverse transformation from the martensitic phase to the austenitic phase and with low load-deflection ratios. These wires show nearly constant forces in the unloading process, a desirable physiological property for orthodontic tooth movement (Ref 12).

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Mahmoud Nili Ahmadabadi, Tahereh Shahhoseini, Mohamad Habibi-Parsa, and **Maryam Haj-Fathalian**, School of Metallurgy and Materials Engineering, University of Tehran, Tehran, Iran; and **Tahereh Hoseinzadeh-Nik** and **Hananeh Ghadirian**, School of Dentistry, Tehran University of Medical Sciences, Tehran, Iran. Contact e-mail: nili@ut.ac.ir.

According to clinical applications, unloading occurs exactly after loading; therefore, no rest period or delay should occur while loading and unloading is carried out during experimental procedure. In addition, in the oral conditions, loading is being carried out in a short period while the unloading is kept in a long period. In the clinical situation, archwires are kept deflected for a long period of time after being engaged in their brackets (Ref 13).

The purpose of this study is to investigate the load-deflection characteristics of superelastic NiTi wires with a new model design through modified bending tests in cyclic condition and when unloading was delayed for a long period of time.

2. Experiment

In this research, a new three-point bending fixture was invented and designed to determine the superelastic property in clinical conditions, where the wire samples were held in the fixture similar to an oral cavity. By means of this instrument, the three-point bending test simulates wire force on the teeth in the oral configuration.

The lower section of the fixture is a rail fabricated from steel with a special movable base and a curved canal assembled over the rail. The upper section was designed to simulate teeth arrangement and curvature: a stainless steel disk (316L, Ø80 mm, h10 mm) with 12 rods (316L, Ø5 mm, h10 mm) were welded to the points representing the centers of teeth on the disk (Ref 14). The center points of teeth were located on the medium upper standard arc. Distances between the center points of the teeth (interbracket distance) were similar to the Wilkinson model (Ref 8). A fillet face was machined on the rod surface parallel to the standard arc. Brackets were fixed on the flat face of rod using superglue and orthodontic wire attached to the fixed appliance (Fig. 1). The modified three-point bending tests were conducted by the instrument as shown in Fig. 2 and 3. By rotating the steel disk over the fixture, different locations of teeth with different wire curvatures were selected for dynamic loading. The position of tooth 5 (left) was selected and forced to 2 mm deflection (Fig. 1). The fixture was extended for holding 10 wire samples in a dynamic three-point bending test. Consequently, two stainless steel disks were selected and longer steel rods (Ø5 mm, h150 mm) were welded to the points representing center of teeth on the disks. Ten series of brackets were fixed on the flat face of the rods (Fig. 3). This fixture was developed for static bending in a saliva bath at a defined temperature. The saliva was composed of KCl (1.21 g/L), NaCl (0.4 g/L), NaH_2PO_4 (0.78 g/L), and urea (1 g/L). The pH of saliva bath was kept at 7 by means of NaOH. Tests were carried out on the Ø0.016 inch Trueflex (Orthotechnology) archwires with a Zwick universal testing machine fitted with 2.5 kN load cell and at a speed of 1 mm/min.

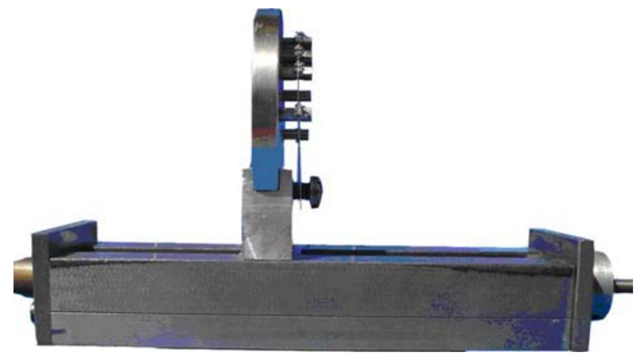

Fig. 2 Three-point bending fixture

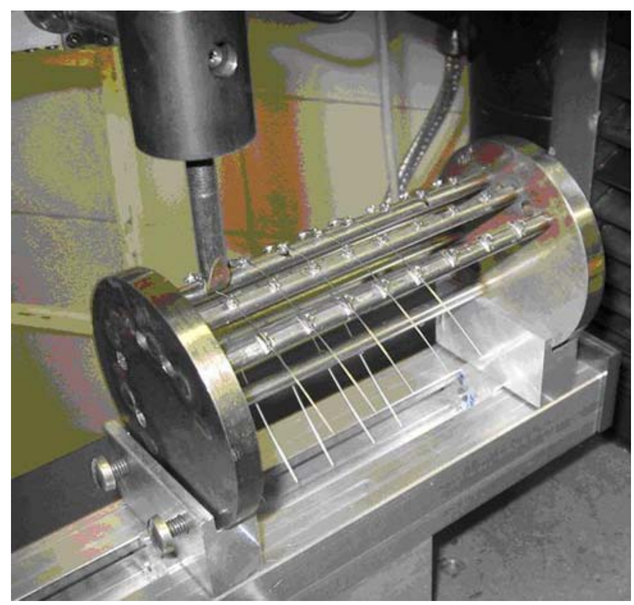

Fig. 3 Extended fixture

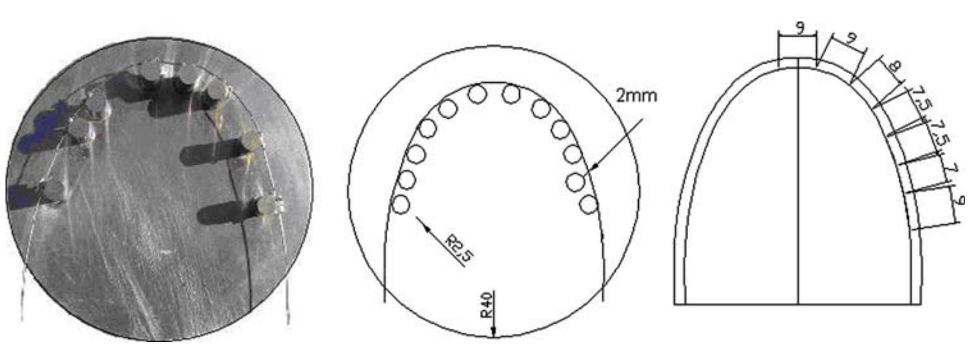

Fig. 1 The points of teeth on the medium standard arc on the upper section of test instrument

Archwires were subjected to bending tests up to 2 mm deflection. The three-point bending tests were conducted in different conditions:

1. Cyclic bending test: As-received arch wire subjected to cyclic bending test at 22 °C (20 cycles).
2. Three-point bending tests: These tests were carried out on the new wire samples at 22 °C (tests were repeated five times with specimen wires changed for every test).
3. Static deflection: Two groups of 15 wires each were subjected to the static deflection for 30, 60, and 90 days in fixture, in an incubator at 37 °C (5 wires for each holding time). Group 1 held in saliva bath and group 2 held dry. The saliva bath was topped up during the long-term studies for the group 1. The amount of deflection in static bending was 2 mm.
4. Dynamic bending: After static deflection, three-point bending tests were carried out on the wires. To maintain similar conditions as for the new wires, dynamic three-point bending tests at this step were performed at 22 °C. All tests were repeated five times in both conditions with specimen wires being changed for every test.

Cyclic bending test was performed by means of the single wire fixture. Other tests were carried out by the extended fixture. Load-deflection graphs show load-unload values (N) versus deflection (mm). Comparisons were made in the following aspects:

- Change in force level and hysteresis range during cycling at loading and unloading sequences.
- Load-deflection curve characteristics between the tests for the static long-time bending and for those with immediate unloading.
- The effect of time on the load-deflection characteristics of orthodontic wires when they were unloaded after 30, 60, and 90 days delay before unloading.
- Force levels and amounts of hysteresis between static bending tests in saliva bath and dry atmosphere.

3. Results

Figure 4 shows cyclic load-deflection plots for as-received archwire at 22 °C. This figure indicates that the stress plateaus associated with loading and unloading decrease with increasing cycle number. Test results indicate wires produced a low slope force at unloading process (lower plateau) at 22 °C. Lower plateau indicates deactivation forces enabling effective tooth movement. Average of force in lower plateau is about 1.5 N (Fig. 4). At 22 °C during increasing number of cycles, level of forces at both load and unload plateau slightly decreased. At this temperature, the hysteresis range is near to constant with increasing cycle number (Ref 14).

During the loading process, NiTi archwire undergoes a phase transformation from austenite to a martensite as the load increases. The increasing amount of energy stored inside the NiTi wire during this process is consumed during the unloading process as the transformation is reversed, and the martensite structure reverts to austenite (Ref 13).

The hysteresis range is equal to the difference between the amount of energy consumed by the reverse transformation and the amount of energy stored in the transformation. The range of the hysteresis observed after cyclic deformation showed energy dissipation. This is accompanied by considerable softening. Softening phenomenon is due to the build-up of residual stresses which may arise from the formation of interstitial dislocations (Ref 15).

Martensitic transformation is a displacive transformation which dislocations accelerated this type of transformation. In the first cycle of bending, a few dislocations remain. In the latter cycles, these dislocations decrease nucleation energy for martensitic transformation. Dislocations work as autocatalyst by aggregation in the austenite-martensite interface and assist nucleation of new martensite blade. Eventually, softening phenomenon occurs due to dislocation-assisted transformation.

Figure 5 represents load-deflection plot for as-received Orthotechnology archwires (mean value of five samples). Figure 6 shows load-deflection plots for archwires after static bending in body temperature. Results show decrease in plateau force levels associated with loading and unloading after 30 days static deflection (Fig. 6) in comparison with new wires (Fig. 5). After a long-time bending, the hysteresis was increased. Also in comparison with new wires (Fig. 5), the force level in loading increased but decreased in the unloading sequence (Fig. 6). This phenomenon has been discussed in relation to stress relaxation. It is a decrease of internal stress over time due to localized flow of solid metal under strain (Ref 13). According to Fig. 6, loading and unloading plateau

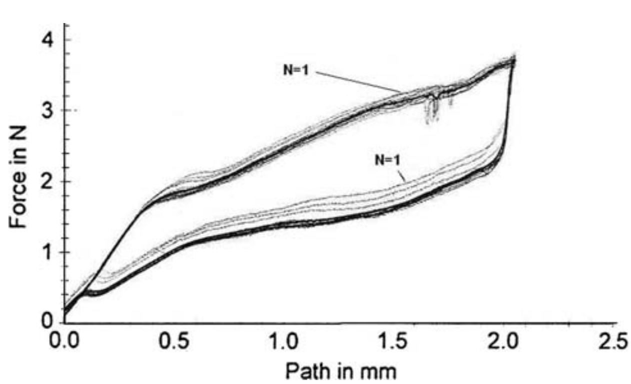

Fig. 4 Cyclic load-deflection plots for as-received archwire at 22 °C

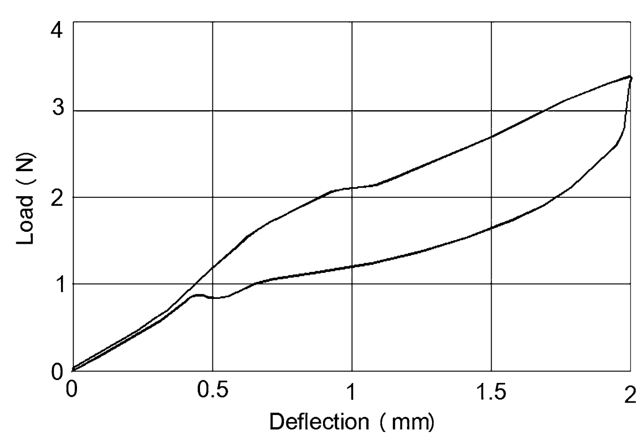

Fig. 5 Load-deflection plots for new archwires (mean value of five samples)

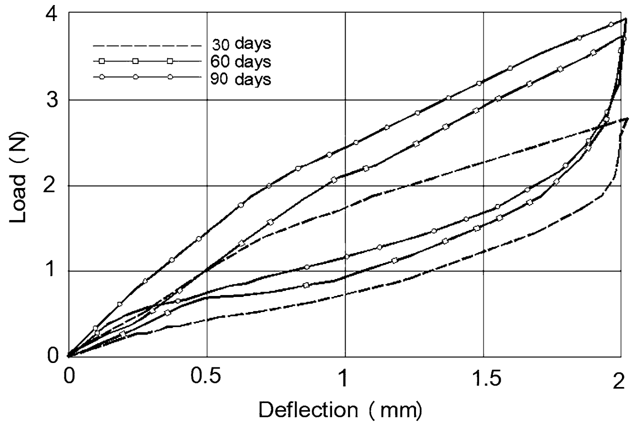

Fig. 6 Load-deflection plots for archwires after 30, 60, and 90 days static bend in body temperature (each curve represents mean value of five samples)

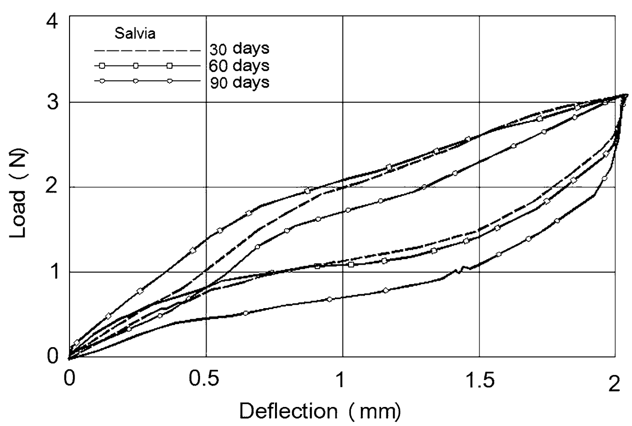

Fig. 7 Load-deflection plots for archwires after 30, 60, and 90 days static bend in body temperature at saliva bath (each curve represents mean value of five samples)

level increase as time in static bend mode increased; however, the magnitude of the increase in load across the loading plateau is greater than the magnitude of the increase in load across the unloading plateau as static bend time increase.

Figure 7 indicates load-deflection plots for archwires after static bending in body temperature in saliva bath. According to Fig. 7, the stress plateaus associated with loading and unloading decrease with increasing static bending in saliva bath. Force levels of both loading and unloading plateaus decrease by increasing holding time in saliva. The hysteresis range is near to constant with increasing holding time.

Usually, hysteresis phenomenon does not occur in the elastic limit. After long-time static bending, the unloading curve runs below the loading curve (under 0.8 N load and 0.4 mm deflection). In other words, the elastic limit is vanished (Fig. 6 and 7). This behavior is probably due to dislocations pile up which prevents reverse transformation after long-time bending.

4. Conclusions

Modified load-deflection tests agreed with tension-compression results and simulated load conditions in an oral cavity. At 22 °C, during cyclic load-unload with increasing number of cycles, level of forces at both load and unload plateau slightly decreased. The range of the hysteresis observed during cyclic load-unload showed energy dissipation. Load relaxation was observed in the wires subjected to long-term static deflection at 37 °C. Load relaxation increased in saliva bath environment and decreased in dry environment as static deflection time increased. The increase of load relaxation in salvia is supposedly due to some interactions between salvia and wires. Hysteresis range in dry wires showed increase after long-term deflection while this range is near to constant with increasing holding time in saliva at 37 °C.

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