Dynamic Thermo-mechanical Behavior of Current Nickel Titanium Orthodontic Archwires

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Educational objectives:
Upon completion of this course, participants should be able to achieve the following:
• Understand the effect of phase transformation of orthodontic alloys on various mechanical properties and their potential effects on application of orthodontics forces clinically.
• Understand and differentiate shape memory alloys from non shape memory alloys based on their thermo-mechanical profiles.
• Understand the structure of NiTi Alloys and their properties.
• Understand the usefulness of low deflection wires for orthodontic force application.

Orthodontic tooth movement is achieved by the application of forces to the teeth.
Forces are created by elastically deforming an orthodontic archwire and allowing its stored energy to be released to the teeth over a period of time. Light continuous forces are physiologically desirable and produce optimum tooth movement. Typical forces are in the range of 100-150 gm. Some of the important parameters in selection of a wire are the modulus of elasticity (stiffness, load deflection rate); range (maximum elastic strain) which the distance the wire will bend/deflect elastically before permanent deformation occurs; springback (the amount, in length units, a wire will return beyond its yield point), which is the difference between a given deflection (activation) and the residual deformation after unloading to 0 gm-mm.

Various metal alloys are used in orthodontics for archwires. Stainless steel has been popular since the 1940s and replaced gold alloys. Resilience which is a measure of the amount of energy a material can absorb elastically (the potential to do “work,” the area under the stress-strain diagram, in the elastic region) (Fig. 1, see chart at right). They are still considered to be the primary alloy for orthodontic wires. They have high modulus and yield strength with adequate springback. Titanium-Molybdenum Alloy devel-
The objective of this investigation was to use dynamic mechanical analysis, thermal mechanical analysis, and mechanical deformation testing to characterize the transition temperatures, storage modulus, and hysteresis profiles of NiTi, beta-titanium, and stainless steel orthodontic archwires.

Developed in 1979 by Burstone & Goldberg has intermediate modulus and yield strength with excellent formability. Nickel-Titanium Alloys were introduced in 1971 by Andreasen as Nitinol wires. They are based on original research of Buehler in 1962 at the Naval Ordnance Laboratory. They belong to the class of materials called Shape memory alloys (SMA). They are characterized by exhibiting superelasticity, and the shape memory effect (SME). The source of the distinctive mechanical behavior of shape memory alloy materials is a crystalline phase transformation between a high symmetry, highly ordered parent phase named austenite, and a low symmetry, less ordered product phase martensite. Martensitic structure is obtained from austenite with application of mechanical load or a decrease in temperature. Upon heating or reduction of stress, the austenitic structure is recovered. Superelasticity is induced by application of stress to the austenite phase, transforming it into fully detwinned martensite. The excellent springback, low stiffness, constant stress while undergoing transformational deformation make them ideal as aligning wires. In choosing a wire for alignment of teeth, it is more desirable to have a wire with a low load of deflection rate.

Nickel Titanium (NiTi) alloys can be classified into three categories: 1) Martensite Stabilized Alloys such as Nitinol and GAC Lowland. The $A_S$ temperature is much higher than oral temperature therefore they possess a stable martensitic structure. It has no shape memory or superelasticity effects. 2) Martensite Active Alloys such as GAC Neo-Sentalloy and ORMCO CuNiTi. They demonstrate superelasticity and shape memory effect at oral temperatures. It has the Martensitic structure at room temperature and the Austenitic at oral temperatures ($A_F$ temperature is below 37°C). 3) Austenite Active Alloys such as Nitinol SE and ORMCO Superalastic OSE. The $A_F$ is much greater than 37°C. They undergo a stress induced martensitic transformation when activated and therefore display superelastic behavior but no thermoelastic behavior at oral temperatures.

Improved materials are constantly being proposed which sometimes increases confusion about the actual characteristics of the wires. In reality, the ubiquitous claims made by the manufacturers of improved performance are not always supported by correct information about the temperature transitional ranges (TTRs), and the mechanical properties of the wire. Previously, different parameters and experimental settings have been used to analyze the performance of alloys with different compositions and properties, and several classifications have been suggested. However, the majority of these tests and parameters were initially designed for non-superelastic or non-shape memory orthodontic materials using testing conditions that do not approximate clinical situations.

The objective of this investigation was to use dynamic mechanical analysis, thermal mechanical analysis, and mechanical deformation testing to characterize the transition temperatures, storage modulus, and hysteresis profiles of NiTi, beta-titanium, and stainless steel orthodontic archwires.

**Methods and Materials**

Six commercially available archwire products comprising of six alloy groups were studied: GAC Lowland (Martensite Stable), GAC NeoSentalloy (Martensite Active), ORMCO Cu-NiTi (Martensite Active), ORMCO Align SE 200 (Austentic Active), Unitek TMA (Titanium Molybdenum), ORMCO Stainless Steel. They had significant manufacturing and compositional differences.

Three samples of each archwire were used for the analysis. The dimensions were .016X.022 inch or .016X.025 inch with a length of 11mm.
The thermal mechanical studies were conducted with a TA Instrument DSC 2920 in standard mode. The Differential Scanning Calorimetry (DSC) measures the temperatures and heat flows associated with transitions in materials as a function of time and temperature in a controlled atmosphere. These measurements provide quantitative and qualitative information about physical and chemical changes that involve endothermic or exothermic processes or changes in heat capacity. Knowledge of the austenitic start and finish temperatures (on heating) and the martensitic start and finish temperatures (on cooling) establishes the stiffness of each archwire at ambient (25°C), and oral-cavity conditions (37°C), at the temperatures of ice cream (about 0°C), and hot coffee (about 60°C). All specimens were scanned from -30°C to 60°C. After this temperature ramp, the samples were scanned from 60°C to -30°C at the same rate. When both the specimen and the reference pans were heated at the programmable rate of 5°C per minute in the temperature-controlled chamber, changes in heat flow occurred when a phase transition happened.

The Dynamic Mechanical Analysis (DMA) instrument mechanically deforms a sample and measures the sample response as a function of temperature or time. It can measure the presence of phase transitions, elastic moduli, energy loss, and interactive effects of more than one variable simultaneously on various types of materials. Since temperature as well as stress affects the mechanical properties of shape memory alloys, DMA experiments can be designed to reflect clinical orthodontic conditions. The dynamic mechanical studies were conducted in tension mode using the TA Instruments Dynamic Mechanical Analyzer model 2980. The sample was ramped 1°C/min to 80.0°C and then ramped 1°C to -20°C. The preload force applied was .010N. Experiments were conducted with an amplitude of 5 m. All dynamic loading was carried out at 1 Hz. The data was plotted and analyzed with the Universal TA analysis software. When the phase transition is a solid-solid transformation, an endothermic absorption peak is observed on heating that begins at the austenite start (AS) temperature and ends at the austenite finish (AF) temperature (R. Kousbroek, 1984). This peak appears like other first-order transformations – e.g., melting and boiling peaks. After cooling at the same programmable rate, the transformation occurs somewhat later, and the phase change appears super-cooled. That is, the transformation of A → M occurs at the martensite start (MS) temperature, and the completion occurs at the martensite finish (MF) temperature. After we measured these four temperatures, we calculated the endothermic peaks on heating and the exothermic peaks on cooling. These peaks are proportional to the enthalpies of heating (∆H_H) and cooling (∆H_C), respectively, and were calculated using the sigmoidal tangent algorithm of Universal Analysis 2000 (TA Instruments).

The mechanical deformation studies, or stress/strain behavior during transition, were conducted in tension mode with an Endura Tec EFL 3200 Series from Bose at room temperature. Three samples of each archwire were tested with .2N/second increase in force to 75N. The 21mm sample was then ramped .2N/second to 0N. The displacement was set to 1.5mm or 15 percent.

Results

DSC test results (Fig. 2) showed no phase transformation with steel or TMA. All NiTi alloys showed AS – AF and MS – MF temperatures. In addition, all NiTi alloys, except GAC Lowland manifested the austenitic finish temperatures at oral temperature (37°C). Therefore all NiTi alloys, except for the GAC Lowland alloy were in
the austenitic form at oral temperatures. Although this would indicate that the GL should be less stiff compared to the stiffness other NiTi alloys, DMA studies show this not to be the case.

Repeated-measures ANOVA results showed a statistical significant in storage modulus (stiffness) means over each temperature points of 0°C, 25°C, 37°C, 60°C as measured with the DMA (Fig. 3). At room temperature there was no difference between CuNiTi, OSE and GNSNiTi. Between GLLNiTi and TMA. At 37°C there was no difference amongst the alloys except for steel (Fig. 4).

Differences in loading/unloading patterns, initial and final stress transformation of different superelastic alloys was seen for the mechanical deformation studies with Endura at room temperature. ORMCO – CuNiTi displayed superelastic behavior on both loading and unloading (Fig. 5a). GAC – Neo Sentalloy showed superelastic behavior on the loading, but not during unloading (Fig. 5b). The permanent deformation and inability of Neo Sentalloy to return to its original shape was due to an incomplete phase transformation at 25°C. At 25°C the alloy has both martensitic and austenitic form. ORMCO superelastic NiTi and GAC Lowland did not show superelastic behavior at 25°C.

Discussion

Our research and previous research validate the stiffness of stainless steel alloy as three times the stiffness of NiTi alloy, no phase transformation, and no superelasticity behavior as reported by previous research (Brantley, 2001).

The Storage Modulus or stiffness of beta-titanium / TMA (Unitek TMA) at 37°C was found to be comparable to the stiffness of the four NiTi alloys and one third the stiffness of steel. This was surprising because the stiffness of TMA has been reported to be twice the stiffness of NiTi and one half the stiffness of stainless steel. DSC results validated that TMA did not go through a phase transformation, and mechanical deformation tests at 25°C validated that TMA did not have a superelastic profile. We hypothesize that the low stiffness of Unitek TMA found in this study could be due to the manufacturing process of this particular beta titanium alloy. There was no phase transformation as expected.

The four NiTi alloys: ORMCO CuNiTi, GAC Sentalloy, GAC Lowland, ORMCO-superalastic NiTi, showed no statistical significance between the storage modulus or stiffness means values at 37°C. The literature reports CuNiTi austenitic finish temperatures at oral temperature (37°C). Therefore at oral temperatures, all NiTi alloys in this study are in the austenitic form except the GAC Lowland alloy. This would indicate that GL should be less stiff, however DMA studies show that the stiffness of GL alloy is similar in value when compared to the stiffness other NiTi alloys.

Mechanical deformation tests were conducted at 25°C. DCuNiTi was the only alloy tested that showed superelastic behavior and no permanent deformation at 25°C. The GAC Neo Sentalloy showed superelasticity behavior during the loading phase, however during unloading superelasticity was not observed and 1.25mm of permanent deformation was observed. Based on previous mechanical deformation
tests conducted at 25°C and 37°C by Iijima, and our DSC studies we conclude that the permanent deformation and inability of NeoSentalloy to return to its original shape was due to an incomplete phase transformation at 25°C. At 25°C the alloy is still in its martensitic form. (Iijima, 2002 #43). Further testing is need to confirm that GAC NeoSentalloy alloy may show superelasticity during unloading at lower force values or higher temperatures.

GAC Lowland which is classified as a martensitic stabilized alloy did not possess superelasticity or phase transformation at 25°C. DSC studies showed a phase transformation at 50°C.

Neither superelasticity or shape memory was seen with ORMCO superelastic NiTi (OSE) at 25°C or 37°C, although it is classified as a superelastic NiTi alloy. The phase transformation temperature occurred in the same range as the DCuNiTi, except for the $A_f$ temperature which was 5°C below room temperature. Therefore the lack of superelasticity may be due to the presence of martensitic form.

Conclusions

Nickel-titanium alloys used for orthodontic archwire exhibit complicated and unexpected mechanical properties due to manufacturing and processing of the alloy. DMA results show that the stiffness value means of the four NiTi alloys are similar. Current classification of Niti alloys may need to be reviewed and take into account their working properties, which are clinically relevant.

References


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Author’s Bio

Dr. Anil Ardeshna was previously trained in England, receiving his Bachelor in Dental Surgery (B.D.S.) from the University of Wales, U.K. in 1981. His training included a general dental residency and an oral surgery residency. His Doctor of Dental Medicine degree was received from the University of Connecticut Dental School in 1986, where he also earned is certificate of specialty in Orthodontics and a Masters in Dental Science in 1989.

He is the post graduate orthodontic program director at the New Jersey Dental School, University of Medicine and Dentistry of New Jersey, and in part-time private practice. He was previously an assistant professor of orthodontics at the University of Connecticut. Dr. Ardeshna is a diplomat of the American Board of Orthodontists and president of the New Jersey Indian Dental Association. He was voted as one of the top orthodontists in New Jersey by the New Jersey Monthly magazine in 2005.

Dr. Ardeshna lectures on Diagnosis and Treatment Planning, Biomechanics of Tooth Movement and Appliance Design, Biomaterials, Segmented Arch Technique and the MBT Technique.

Disclosure: Dr Ardeshna declares that neither he nor any member of his family have a financial arrangement or affiliation with any corporate organization offering financial support or grant monies for this continuing dental education program, nor does he have a financial interest in any commercial product(s) or service(s) he will discuss in the presentation.
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1. Optimum tooth movement requires
   a. Light continuous forces
   b. Light intermittent forces
   c. Heavy prolonged forces
   d. Heavy intermittent forces

d. Elgiloy Alloy

e. Steel Alloy

2. The Modulus of Elasticity
   a. Describes the resistance to elastic deformation
   b. Determines the magnitude of force delivered by a wire
      activated within the elastic range.
   c. Same as Stiffness
   d. Same as Load-Deflection Rate
   e. All of the above

3. In choosing a wire for alignment of teeth, it is more desir-
   able to have a wire with
   a. A high load of deflection rate
   b. A small working range
   c. A high modulus of elasticity
   d. A low load of deflection rate
   e. A low springback

4. When attempting to increase the magnitude of an applied
   orthodontic force, an orthodontist will have the most signif-
   icant effect by:
   a. Using nitinol wire
   b. Using stainless steel wire
   c. Using titanium molybdenum alloy wire
   d. Using a multistrand steel wire
   e. Using a gold wire

5. The wire made out of the following material will have best
   formability
   a. Copper Nickel Alloy
   b. Nickel Titanium Alloy
   c. Titanium Molybdenum Alloy

6. Nickel Titanium alloys belong to a class of materials called
   a. High performance alloys
   b. Shape memory alloys
   c. Flexible alloys
   d. Super elastic alloys
   e. Orthodontic alloys

7. Superelasticity is due to
   a. high stiffness
   b. shape memory
   c. phase transformation
   d. martensite change from twinning to detwinning form
   e. austenitic changes

8. Both shape memory and superelasticity was seen with the
   following alloy archwire.
   a. Unitek Titanium Molybdenum Alloy
   b. GAC Lowland
   c. Ormco Superelastic OSE
   d. Stainless Steel
   e. Ormco Cu Niti

9. Titanium Molybdenum alloy undergoes phase transforma-
   tion with change in temperature
   a. True
   b. False

10. The austenite phase of nickel titanium alloy exists at
    a. Higher temperature than martensite
    b. Does not respond to stress
    c. Is softer than martensite
    d. Lower temperatures compared to martensite
    e. Can be transformed to martensite by application of heat

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