SENTALLOY®

the Story of Superelasticity

A White Paper Report

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Part Art. Part Science. All Orthodontics.

For better dentistry

DENTSPLY
GAC

Biography Dr. Alberto Teramoto DDS. Orth. Cert.

Maintains a private practice devoted exclusively to orthodontics in Mexico City. Mexico. He received his Certificate of Orthodontics from the First Department of Orthodontics of Tokyo Medical and Dental University, Japan.

Currently he is an Assistant Professor at the University Technological de Mexico and Editor in Chief of the journal Orthodontia Actual.

1. History and Basic Concepts

Introduction

Since the days of Angle many technological advances in arch wires have enhanced our specialty, increased our efficiency, reduced our chair time, and as a result, increased our profitability. However because of the great number of Nickel-Titanium alloys that actually exist, it is important to understand the historical background as well as basic concepts about them in order to visualize and recognize the clinical potential they have in Orthodontics. Although Nickel-Titanium alloys appear to be the same, there are many small differences in their composition and manufacturing process, which inevitably make the difference between ordinary and extraordinary NiTi archwires.

The beginning of NITINOL

Nickel-Titanium alloys have been found to be the most useful of all Shape Memory Alloys (SMAs), because they demonstrate the ability to return to some previous shape or size when subjected to an appropriate thermal procedure. In other words they "remember" their original shapes. Other shape memory alloys include copper-zinc-aluminum-nickel, and copper-aluminum-nickel, but they do not possess the combined physical and mechanical properties of nickel-titanium alloys. Ni-Ti is unique because of the force levels expressed when heated, its corrosion resistance, its biocompatibility, the ease with which the TTR can be set and the reasonable cost of fabricating a precise alloy. A metallurgist, Dr. William J. Buehler, doing research at Naval Ordnance Laboratory (NOL) in White Oak, Maryland, discovered the unique shape memory properties of this alloy. NITINOL is an acronym used to describe a generic family of nickel-titanium alloys. It represents the two main elements of this alloy (NiTi-Nickel and Titanium) (NOL – developed at Naval Ordnance Laboratory).

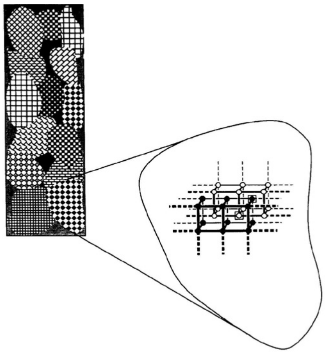
In 1958, Dr. Buehler was looking for a change in his personal life and professional career. An aerodynamics project at NOL was searching for the appropriate material for the re-entry nose cone of the SUBROC missile. Mr. Jerry Persh, the project manager, put Dr. Buehler to work assembling known property data on selected elemental metals and alloys which might be feasible. Early in the developmental stages, secondary research on Nickel-Titanium alloys led to a significant application by Raychem Corporation. They producer a product called Cryofit which was a hydraulic line coupler for the U.S. Navy's F-14 aircraft. However, this was just the beginning of a wide range of new and exciting applications in medicine, dentistry and diverse engineering areas. Dr. William J. Buehler retired from NOL in 1974 but remained involved in the development of NITINOL until 2005 at which time he moved to New Bern, North Carolina.

(fig. 1) Metallurgist William J. Buehler

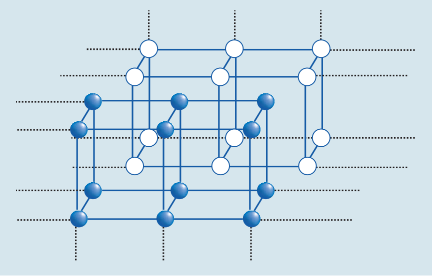
How NITINOL works

Exactly what made these metals "remember" their original shapes was in question after the discovery of the shape-memory effect. George Kauffman (Department of Chemistry of the University of Fresno) describes the process as follows: in a non-memory metal the strain of deformation is absorbed by rearrangement of the crystals, and it is impossible to get the crystals back into the original position. On the other hand in an alloy such as Nitinol the crystals stay in place: the atoms within the metal crystals rearrange themselves and the distorted object reverts to its original shape, there is no visible change in the shape of the metal, all the changes occur at the atomic level[2]. Nitinol had phase changes while still a solid, these phase changes, are named martensite (low temperature) and austenite (higher temperature). The range of transition temperature (TTR) varies for different compositions from about -50°C to 166°C by varying the nickel titanium ratio or ternary alloy with small amounts of other metallic elements. Under the transition temperature, Nitinol is in the martensite phase. In the martensite phase, this alloy can be bent into various shapes; the crystal structure is disordered body-centered cubic. To fix the "parent shape" (austenite phase), the metal must be held in position and heated to about 500°C. The high temperature "causes the atoms to arrange themselves into the most compact and regular pattern possible" resulting in a rigid cubic arrangement known as the austenite phase, the crystal structure becomes that of an "ordered" cubic frequently called a cesium chloride (CsCl) structure. Above the transition temperature, Nitinol reverts from the martensite to the austenite phase which changes it back into its parent shape.

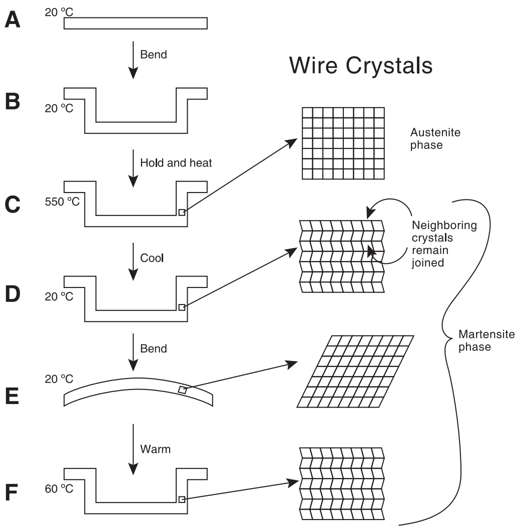
Nitinol is a conglomeration of tiny regions of single crystals called grains all of random size, shape and orientation (Fig. 2). In the austenite phase the atoms of the grains adopt an atomic structure in which each nickel atom is surrounded by eight titanium atoms at the corners of the cube and each titanium atom is like-



(fig. 2) A multicrystaline metal sample of NITINOL. Each pattern represents a different grain of random size, shape and orientation of the atom lattice. The blow-up on the right shows the structure of the austenite phase of the NITINOL atomic lattice called "body centered cubic".



(fig. 3) The cubes are intertwined such that the each corner is in the center of another cube. The distance of the center of a cube from a corner is shorter than the distance to a neighboring corner. Thus the "nearest neighbors of each nickel atoms (White balls) are titanium atoms (blue balls) not other nickel atoms and vice versa.



(fig. 4) Crystals with good neighbors.
A,B &C NITINOL wire is treated at high temperature to set the parent shape.
D When NITINOL is cooled, the phase changes from austenite to martensite because martensite crystals are slightly flexible, they can deform to accommodate bending of the wire.
E They remaining attached to neighboring crystals.
F Martensite crystals revert to their undeformed shape, and wire magically unbends.

(fig. 5) Dr. George F. Andreasen joined the Iowa dentistry faculty in 1963 and was professor and chairman of the Department of Orthodontics at the University of Iowa (1965-1975).

(fig. 6) Dr. Fujio Miura .Professor and Chairman of the 1st Department of Orthodontics of the Tokyo Medical and Dental University 1962-1991.

wise surrounded by a cube of nickel atoms (Fig. 3). In the martensite phase when the wire cools below its TTR, the grains changes which means that the nickel and titanium atoms assume a different and more complex three dimensional arrangement (Fig. 4).

NITINOL in Orthodontics

Another early application and probably the most important for the orthodontic world was the introduction of Nitinol as an arch wire. In 1968, Dr. George F. Andreasen (Fig. 5) read about a strange alloy discovered at the Naval Ordnance Laboratory (now the Naval Surface Weapons Center). He contact William Buehler and received a number of different Nitinol compositions and in different processing stages. Andreasen did extensive clinical research and found one of these alloy to work most effectively; he called this alloy the "memory wire" because it returned to its original shape after being bent. Andreasen's 1978 article was the first to use the terms "shorter treatment times": "less patient discomfort" (light forces) and "fewer archwire changes". The wire was commercialized by Unitek Corporation and trademarked as Nitinol, identical in name to what Dr. Buehler had called it.

The first commercially available wire was 50:50% nickel to titanium and was a shape memory alloy in composition only. Cold working by more than 8-10% suppressed the shape memory effect. Nevertheless, what made it attractive compared to the competitive wires available at that time was its light force (about 1/5 to 1/6 the force per unit of deactivation)4 and its increased working range allowing it to be used in more severely maloccluded cases without taking a permanent set. Dr. Andreasen reported his research on the Thermal Dynamic Effects of Nitinol in the Angle Orthodontist in April 1985. Dr. Andreasen's work on Nitinol earned him the 1980 Iowa Inventor of the year Award. He died in 1989 at the age of 55. This was the very beginning of Nickel Titanium wires for Orthodontics.

SENTALLOY the First Superelastic NiTi Alloy

During this time, in Japan, Dr. Fujio Miura (Fig. 6) the most famous orthodontic professor in Japan's history was doing basic research on the biology of tooth movement with the objective of establishing the "Ideal Concept of Tooth Movement". They were looking for a material or device that could deliver a light and continuous force and a research project was initiated to find a material that would satisfy this requirement.

In 1982, Dr. Miura and his university team approached TOMY Incorporated (manufacture of orthodontic products) and Furukawa Electric Co. (supplier of wire material) to do joint research on a new superelastic wire (Fig. 7). This new wire was characterized by generating an optimal force for tooth movement and about 8% stress-induced-martensitic transformation (super elasticity). This new NiTi alloy was launched in 1985 under the trade name of SENTALLOY (Super Elastic Nickel Titanium Alloy). (Fig.8)

SENTALLOY had the features of super elasticity and shape memory. Dr. Miura[5] describes these unique properties as follows:

Shape Memory:

Is a phenomenon occurring in an alloy that is soft and readily amenable to change in shape at low temperature but can easily be reformed to its original configuration when heated to a suitable transition temperature. (Heat induced martensitic transformation)

Superelasticity:

Is a phenomenon that occurs when the stress value remains fairly constant up to a certain point of wire deformation. This is produced by stress, not by temperature and the phenomenon is called stress-induced martensitic transformation

He states that SENTALLOY allows a constant force to be delivered over an extended portion of the deactivation range, and is therefore more likely to generate physiologic tooth movement and greater patient comfort. Using the body temperature to transform this alloy, SENTALLOY can address tooth movement resistance during an orthodontic treatment without causing trauma to surrounding dental tissues.

Dr. Miura believed that the discovery of the "superelastic" properties of SENTALLOY wires and its use in osteoclast recruitment was a significant scientific breakthrough for the orthodontic specialty. The use of superelastic wire established a new standard of biologic treatment in clinical orthodontics[6].

(fig. 7) Dr. Fujio Miura (Left) and Dr. Masakuni Mogi (Right) Head of the Group of Dental Materials 1st Department of Orthodontics TMDU.

2. Historical Overview of Sentalloy

For more than two decades SENTALLOY wires have found a wide range of applications in Orthodontics. Many products have been developed around the philosophy of applying a physiologically correct force for tooth movement.

1958 Dr. William J. Buehler began experimental work on NITINOL at Naval Ordnance Laboratory in the United States. (Fig. 2.1)

1976 Dr. George Andreasen develops the first NiTi alloy for Orthodontics. (Fig. 2.2)

1986 Dr. Fujio Miura develops SENTALLOY the first Super-elastic Nickel-Titanium Alloy. (Fig. 2.3)

1987 GAC International introduces the first superelastic Open and Close Coil Springs. (Fig. 2.4a & 2.4b)

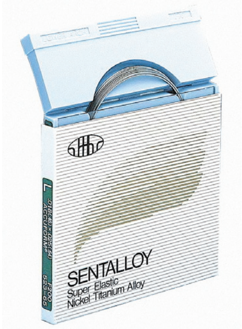
1988 DERHT - A method for bending Sentalloy wire was developed under the trade name of ARCH-MATE. (Fig. 2.5)

1990 NEO SENTALLOY appears and for the first time that it was possible to use a full size rectangular wire as an initial wire. The clinician could choose a wire that generates 100, 200 or 300 grams. (Fig. 2.6)

1992 BIOFORCE is introduced as the only superelastic wire that starts with low, gentle force for anteriors and increases to the posteriors. (Fig. 2.7)

1993 GAC International created BioForce & NeoSentalloy with IonGuard, A new Nickel Titanium wire which underwent an Ion implantation process (reducing friction). (Fig. 2.8)

1993 SENTALLOY MOLAR MOVER is created for molar distalization. (Fig. 2.9)



(fig. 8) SENTALLOY. Super Elastic Nickel Titanium Alloy.

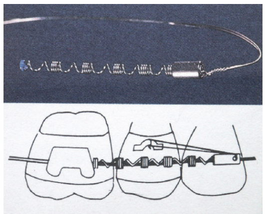
(fig. 2.4 & 2.5)

(fig. 2.5)

(fig. 2.6)

(fig. 2.7)

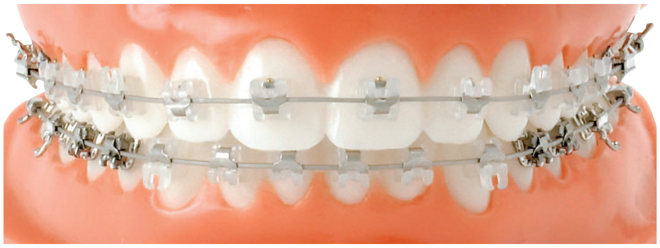
(fig. 2.8)



(fig. 2.9)

(fig. 2.10)

(fig. 2.11)



(fig. 2.12)

1995	TOMY Inc. introduces SENTALLOY STLH a new Static Thermoactivity Low Hysterisis Nickel-titanium wire. (Fig. 2.10)
2000	GAC PAKs were developed to enhance aseptic storage and the dispensing of individual wires. (Fig. 2.11)
2008	High Aesthetic Archwires: Sentalloy and BioForce. A rhodium coating process provides low reflectivity for reduced visibility while providing the same outstanding performance as regular Sentaloy wires. (Fig. 2.12)

3. Evaluation of Mechanical & Physical Properties of Sentalloy

There exist basically three types of laboratory tests used to study the mechanical properties of orthodontic wires; they are bending, tension and torsion. Two additional tests are used to evaluate physical properties; they are Differential Scanning Calorimeter (DSC) and X Ray Diffraction. Although these tests do not necessarily reflect the clinical situations to which wires are usually subjected, they provide a basis for comparison of these wires. In all of these tests SENTALLOY has shown superior results indicating that it is the only biologically correct arch wire.

The next section describes some of these examples.

A) Three point bending test

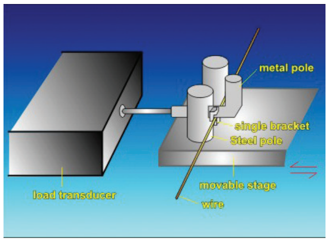
In 1986, in order to demonstrate the difference between the first Nitinol wire (Unitek Corp.) and the Super Elastic nickel-titanium alloy (SENTALLOY) a three-point bending test was introduced by Miura[5]. This test was designed to clarify the relationship between the loading and deflection by determining the nature of the force being delivered during orthodontic treatment. This method is acceptable to demonstrate the spring back properties.

On the other hand, when using a cantilever bending test, wires with good springback properties appear to have superelastic properties even if the wires do not possess this feature. The three-point bending test was designed because it would accurately differentiate the wires that do not possess superelastic features. At the same time, the three-point bending test more closely simulates the application of a wire force on the teeth in the oral cavity.

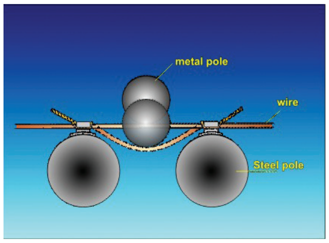
Materials

Four round 0.016 wires were selected; Stainless Steel, Co-Cr-Ni, Work-hardened NiTi and Sentalloy NiTi wires. In order to simulate an oral cavity environment the wires and the steel poles were set in a controlled temperature chamber at 37°C.

The midpoint of the wire was deflected 2 mm at a speed of 0.1mm/min, under a pressure from a metal pole 5 mm in diameter. (Fig. 3.1 & 3.2)



(fig. 3.1)

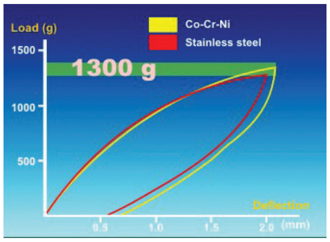


(fig. 3.2)

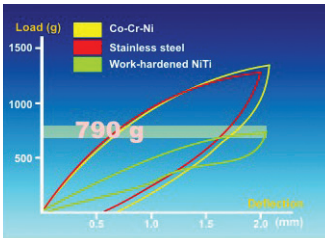
Findings

Both Stainless steel and Co-Cr-Ni wires showed a linear relationship on the load deflection curve. At 2 mm of deflection the load was recorded around 1300 g. (Fig. 3.3) As the deflection was removed both wires showed a permanent deformation. With the cold worked Nitinol the load deflection curve was almost linear; and when the deflection of 2.0 mm was reached the load was 790 g. (Fig. 3.4)

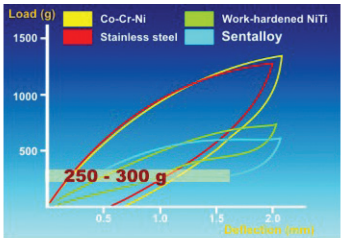
When the Sentalloy wire was tested a load of 650 g. was recorded at 2.0 mm of activation, however, when the deflection was reduced the load was decreased to



(fig. 3.3)



(fig. 3.4)



(fig. 3.5)

much smaller values around 250-350 g. and constant between 1.6 to 0.6 mm. No permanent deformation was recorded. (Fig. 3.5)

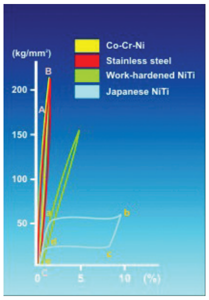
By evaluating the test results, we see that Sentalloy wire shows a superelastic property which is physiologically compatible to the tooth movement because it provides a light continuous force for a long period of time during deactivation.

B) Tensile Test

According to Miura, superelasticity is produced by stress and not by a temperature difference; this is called a stress-induced martensitic transformation. Uniaxial tensile testing was performed on all specimens; they were all stretched using an Instrom universal testing machine.

Materials

Four round 0.016 wires were again selected; Stainless Steel, Co-Cr-Ni, Work-hardened NiTi and Sentalloy NiTi. They were attached to a steel plate with epoxy resin at 37°C. In this figure, the Y axis represents the force generated by the wire and the X axis shows the Strain that the specimens were stretched. (Fig. 3.6)



(fig. 3.6)

Findings

For the Stainless steel and Co-Cr-Ni wires the elastic modulus was 170-220 Kg/mm2. These wire showed very high values and a stress-strain curve that was almost straight during the activation and deactivation phase.

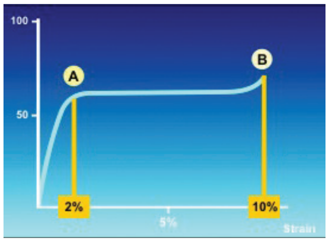
The elastic modulus of Work-hardened Nitinol was 150-160 Kg/mm2 and again the stress-strain curve was almost straight.

Finally, in contrast Sentalloy showed a non linear stress-strain curve of great significance that clearly illustrates its superelastic properties.

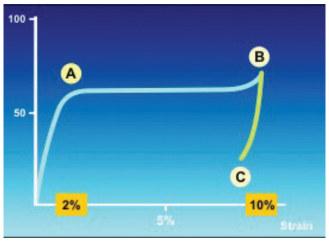
When Sentalloy was stretched, the stress-strain curve was straight up to 2% of its original length. Beyond 2% it produced stresses between 55-58 Kg/mm2 up to a 10% strain (A to B). (Fig. 3.7) This diagram shows how the martensitic transformation begins at the 2% strain level and the transformation continues up to the 8 to 10% point. When the first martensitic transformation is completed the whole specimen is transformed into the martensitic phase. (A to B). (Fig.3.7) When this occurs the stress increases because of the elastic deformation. Martensitic transformations occur in both the loading and unloading directions.

When the strain is removed (B to C) the stress decrease is linear because the elastic deformation occurs in the martensitic phase. (Fig. 3.8) The next step (Fig. 3.9) illustrates a reverse martensitic transformation towards the austenitic phase while generating a continuous force (C to D) (Fig. 3.9). In the final step, the martensitic transformation is completed and the wire is again in the austenitic phase (D to E). This elastic deformation occurs in the austenite phase and the stress decrease is linear. (Fig. 3.10)

The preceding metallurgical analysis indicates that Sentalloy possesses superelastic properties (A to B



(fig. 3.7)



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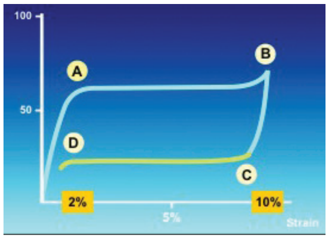

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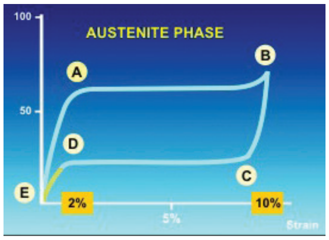

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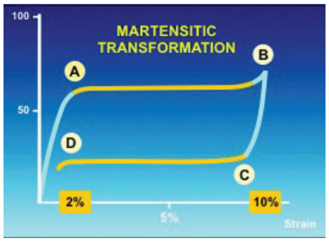

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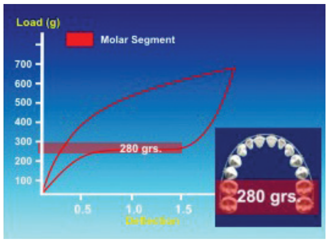

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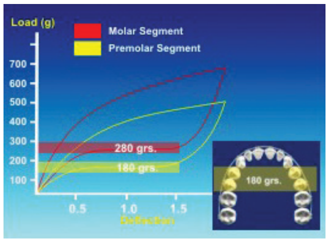

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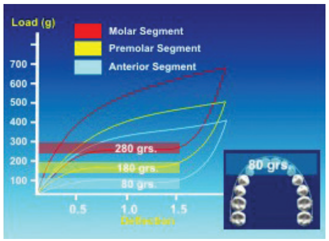


(fig. 3.14)

range) and (C to D range) in the stress-strain curves. (Fig. 3.11)

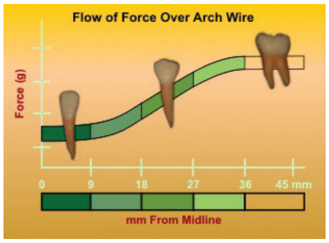
The deformation of NiTi alloys and temperature changes induce martensitic transformations. These transformations are either stress (deformation) related or temperature related. Heating the alloy will induce the martensitic change (martensite to austenite) and removal of heat (cooling)(austenite to martensite) will return the wire to its original shape.

BioForce

Miyazaki[8] reported that a specific type of heat treatment (unlike the moderate temperature changes noted above) of Sentalloy at 500°C would permanently and significantly alter the force plateau during unloading on a three-point bending test. This procedure created the possibility to manufacture Sentalloy with three different levels of force.

This same technology allowed a single wire size to have three different force levels. The optimal super elastic wire now offered light forces in the anterior section, medium force in the bicuspid area and a heavier force in the molar region. In a three point bending test, the Superelastic properties of the wire expressed a constant force of 280 g in the molar region. (Fig. 3.12) In the premolar region a constant force of 180 g. (Fig. 3.13) and in the anterior segment the wire demonstrated a plateau force of 80 g. (Fig. 3.14)

Altering the Superelastic characteristics of the wire in designated areas created the possibility of manufacturing one wire with the biologically appropriate force to move specific teeth. This should all but eliminate patient trauma and require fewer arch wire changes. (Fig. 3.15)



(fig. 3.15)

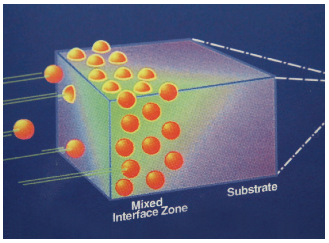
BioForce with Ionguard

To minimize friction, GAC created a Nickel-Titanium wire which underwent an Ion implantation process but did not affect the unique Superelastic properties of BioForce and Neo Sentalloy.

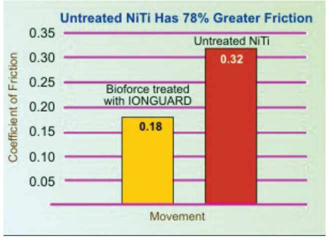
Ion implantation was originally developed for use in semiconductor applications. At low temperature, a high energy beam of ions are used to modify the surface structure and chemistry. The ion implantation is not a layer on the surface therefore, it does not affect the dimensions or properties of the material and can be applied to virtually any material. Ion implantation improves wear resistance, surface hardness, resistance to chemical attack, and most importantly reduces friction. (Fig. 3.16)

Ryan[9] showed that the ion-implantation process reduces the frictional forces produced during tooth movement and tends to increase stress fatigue, hardness and wear, regardless of the composition of the material. Stainless steel wire produce the least frictional force during in-vitro tooth movement followed by treated nickel-titanium, treated beta-titanium, untreated nickel-titanium and finally untreated beta titanium. There were statistically significant differences in the amount of movement seen with the ion-implanted wires compared to their untreated counterparts. (Fig. 3.17)

In an in-vitro study, Bedolla & Teramoto[10] showed differences to the study done by Ryan. BioForce with Ionguard showed the smoothest surface (Fig. 3.18) and generated the least frictional force followed by stainless steel and untreated NiTi. The combination of BioForce Ionguard with In-Ovation-R brackets showed the lowest frictional forces. (Fig. 3.19 & Fig. 3.20)



(fig. 3.16)



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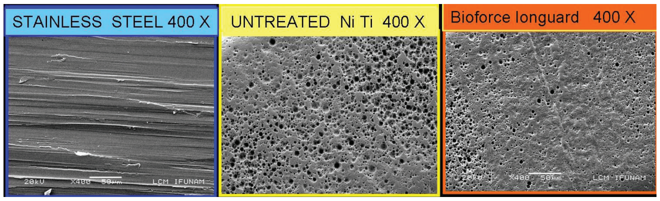

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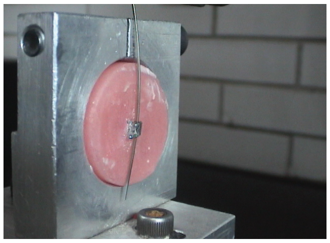
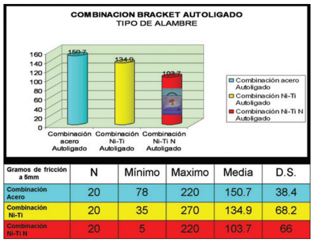


(fig. 3.19)



Gramos de fricción a 5mm	N	Mínimo	Maximo	Media	D.S.
Combinación Acero	20	78	220	150.7	38.4
Combinación Ni-Ti	20	35	270	134.9	68.2
Combinación Ni-Ti N	20	5	220	103.7	66

(fig. 3.20)

Differential Scanning Calorimetry

In the last decade, DSC has been used to study phase changes in nickel-titanium alloys. In conventional DSC two small pans, one containing the material to be analyzed and the other an inert reference material such as indium are heated at the same rate, typically 5°C or 10°C per minute. The changes in the thermal power difference for the two pans are related to changes in the heat capacity. This is useful for studying phase transformations in nickel-titanium arch wire alloys.

The important phase transformations for nickel-titanium alloys are:

Ms - Martensite-start: the temperatures at which the transformation to martensite begins upon cooling;

Mp or Mf - Martensite peak or Martensite-finish: the temperature at which the transformation is completed;

As - Austenite-start: the temperature at which the transformation to austenite begins upon heating;

Ap or Af - Austenite peak or Austenite-finish: the temperature at which the transformation to austenite is complete.

In some cases an intermediate R-phase (Rhombohedral crystal structure) may form during this transformation process.

DSC studies ([11]) have been helpful in explaining the differences in phase transformation for major types of nickel-titanium wires. The major findings of one such study are explained in the next section.

MATERIAL AND EQUIPMENT

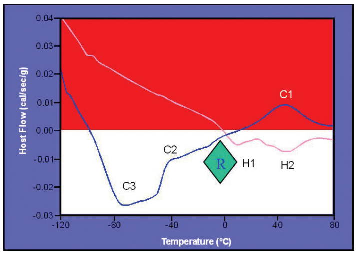
Wires tested

Four different Upper 016X022 NiTi arch wires were tested.

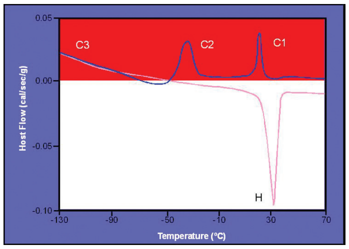
- Nitinol-SE (3M UNITEK)
- Copper-NiTi 35 (ORMCO)
- Neo-Sentalloy F 80 (DENTSPLY GAC International)
- Bioforce-Sentalloy (Anterior section) (DENTSPLY GAC International)

Equipment

Differential Scanning Calorimeter (DSC) for measuring the Austenite transformation temperature (Af point) were performed using a SII-DSC6220 Seiko Instrument (Fig. 3.22) and a Thermal Analyzer LN2 vessel was connected to DSC for cooling (Fig. 3.23).



(fig. 3.22)



(fig. 3.23)

Oral temperature

Sublingual temperature is routinely used as an indicator of oral temperature. It is approximately 37°C for most individuals, while not forgetting that many factors have been shown to affect the temperature in the oral cavity.

Temperature data should be considered during the manufacture and clinical use of temperature sensitive orthodontic materials like the nickel titanium wires. According to Moore[12] if a single oral temperature were to be selected for the investigation of the in- vitro properties of orthodontic wires, 35.5°C would be more appropriate than 37°C.

RESULTS

NITINOL SE

With Nitinol SE the complete transformation to austenite (Af) occurs at about 60°C which is considerably above the temperature of the oral environment.

COPPER NITI 35

A single peak on the heating DSC curve which corresponds to the martensite to austensite transformation indicates that the Af temperature (29.1°C) is under oral cavity temperature for Copper NiTi 35

NEOSENTALLOY

Neo Sentalloy has a completely austenitic structure close to the temperature of the oral environment (32.7°C).

There is also considerable hysteresis for the TTR in the forward and reverse directions for the complete transformation (martensite to austenite).

BIOFORCE (Anterior section)

Just like Neosentalloy, in the anterior section of Bioforce we see the complete transformation occurring very close to body temperature 32.5 °C.

Summary

Sentalloy arch wires were the first reported Superelastic Nickel Titanium arch wire in Orthodontics5.

They are body heat activated and are capable of producing excellent treatment results because they deliver a light and constant force for a long period of time; which is considered physiologically desirable for tooth movement.

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