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# Influence of bending mode on the mechanical properties of nickel-titanium archwires and correlation to differential scanning calorimetry measurements

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**Introduction:** Nickel-titanium orthodontic archwires are used with bonded appliances for initial leveling. However, precise bending of these archwires is difficult and can lead to changes within the crystal structure of the alloy, thus changing the mechanical properties unpredictably. The aim of this study was to evaluate different bending methods in relation to the subsequent mechanical characteristics of the alloy. **Materials and Methods:** The mechanical behaviors of 3 archwires (Copper NiTi 35°C [Ormco, Glendora, Calif], Neo Sentalloy F 80 [GAC International, Bohemia, NY], and Titanol Low Force [Forestadent, Pforzheim, Germany]) were investigated after heat-treatment in a dental furnace at 550-650°C, treatment with an electrical current (Memory-Maker, Forestadent), and cold forming. In addition, the change in $A_f$ temperature was registered by means of differential scanning calorimetry. **Results:** Heat-treatment in the dental furnace as well as with the Memory-Maker led to widely varying force levels for each product. Cold forming resulted in similar or slightly reduced force levels when compared to the original state of the wires. $A_f$ temperatures were in general inversely proportional to force levels. **Conclusions:** Archwire shape can be modified by using either chair-side technique (Memory-Maker, cold forming) because the superelastic behavior of the archwires is not strongly affected. However it is important to know the specific changes in force levels induced for each individual archwire with heat-treatment. Cold forming resulted in more predictable forces for all products tested. Therefore, cold forming is recommended as a chair-side technique for the shaping of NiTi archwires. (Am J Orthod Dentofacial Orthop 2011;139:e449-e454)

Nickel titanium (NiTi) is widely used in current orthodontic mechanics. These include archwires, springs, self-ligating brackets, and separators. By far the most common use is NiTi archwires. In contrast to other materials, NiTi alloys display unsurpassed spring back, a low module of elasticity, and relatively constant forces over large activations (superelastic behavior). These properties are particularly beneficial for archwires used in initial alignment. However, NiTi alloys are sensitive to both the composition of the alloy and the processing involved in forming the archwire. In contrast to conventional alloys such as stainless steel and beta-titanium alloy, force levels cannot be determined purely through archwire dimensions.

To date, the best method of bending NiTi archwires has not been clarified. There are 2 ways to alter the shape of the archwire: cold forming and forming with a heat source. Both techniques have been recommended for use in orthodontic practice. It is well known that NiTi alloys are highly sensitive to temperatures. Different temperatures at the time of forming and variations in intraoral temperature can lead to considerable changes in force levels. Many studies have focused on the influence of varying oral temperatures on the force levels of NiTi archwires.[1-3] Clinically, force reductions that occur with low temperatures can be used by the patient to temporarily decrease the applied force by rinsing with cold beverages. Other studies have investigated the influence of temperature to program

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or permanently form NiTi archwires.[4-10] Wide ranges of temperatures and exposure times have been used, but the results for various archwires have been inconsistent.

As a chair-side procedure, the manipulation of NiTi archwires can be achieved mechanically through cold forming. However, an overactivation of NiTi archwires during bending is necessary because a certain amount of spring back will occur. This is due to stress-induced lattice transformation from austenite to martensite. At room temperatures, the martensitic phase is stable, but, when subjected to higher temperatures comparable with the oral environment, the stress-induced martensite (low-temperature phase) will retransform to austenite (high-temperature phase). The restructuring of the austenitic lattice will result in spring back. Another possibility is to shape the NiTi archwire by using high temperatures, which induce restructuring of the lattice. This can be achieved either in a laboratory furnace[4] or with an electric current.[11-13] The latter method is more appropriate for chair-side programming of the wires. Two pliers are connected to the Memory-Maker (Forestadent, Pforzheim, Germany), and a variable electric current is transmitted through the span of wire between the pliers. Frequency and voltage can be varied so that the electric current is appropriate for the chosen archwire dimension and the intended bending.

The aim of this investigation was to identify the influence of cold forming and heat treatment of NiTi archwires on their mechanical properties.

## MATERIAL AND METHODS

Three-point bending tests according to ISO 15841 were performed on 3 archwires with the dimension of 0.016 × 0.022 in: Titanol Low Force (Forestadent), Neo Sentalloy F 80 (GAC International, Bohemia, NY), and Copper NiTi 35°C (Ormco, Glendora, Calif). In accordance with the ISO norm, the straight ends of the archwires were cut to a length of 30 mm and placed in the 3-point bending model with a span of 10 mm. The force was applied to the broader side of the rectangular wires. The crosshead speed was set at 7.5 mm per minute, and force levels were measured every 0.05 mm. All wires were deflected to 3.1 mm and deactivated without stopping at maximum deflection. The wires were all tested in a controlled environment: a dry temperature chamber at 36°C ± 0.5°C in a closed-air system connected to a thermostat (FS 18 HP, Julabo, Seelbach, Germany). All bending tests were performed with a testing machine (model 3344, Instron, Norwood, Mass). For each product (Titanol Low Force, Neo Sentalloy F 80, and Copper NiTi 35°C), 10 specimens were analyzed in every treatment group. The treatment groups were the following:

1. The control group, consisting of untreated archwires.
2. Heat treatment in a furnace. To evaluate the reaction to heat treatment, 6 groups with different temperatures and exposure times were tested. The heat treatments were performed in a laboratory furnace (KAVO EWL 5636, Biberach, Switzerland) at 550°C, 600°C, and 650°C for 2 and 5 seconds each. Two 1-kg steel cubes were heated to the intended temperature, the oven was opened, and the archwire was placed between the 2 steel cubes, where it remained for the time indicated. One archwire was treated every 15 minutes to allow enough time to reheat the steel cubes. The whole process from the opening of the furnace to the finished heat treatment of the wire lasted 15 to 20 seconds.
3. Heat treatment with electrical current. Programming with the Memory-Maker was conducted with an alternating current of 7 A, 50 Hz, for 5 seconds and an interplier span of 3 cm. These settings corresponded to those used clinically. The wires were not bent but only heat treated.
4. Cold forming. A permanent sweep of 30° was placed in the archwire by sliding the wire at an angle of 90° repeatedly over the edge of a plastic ruler. Once the permanent sweep was achieved and controlled by dipping the wire in hot water, the process was reversed by the same procedure. Thus, a straight section of wire, which was cold formed, was obtained.

Apart from mechanical testing, differential scanning calorimetry (DSC) measurements were taken from all wire specimens to define austenit finish ($A_f$) temperatures (MDSC 2990, TA Instruments, New Castle, Del). The heating rate was set at 10 K per minute with a temperature range of $-40°C$ to $+100°C$.

Force-deflection diagrams were recorded by measuring the force levels every 0.05 mm. Force levels at a deflection of 1.5 mm on the deactivation curve were chosen for the comparison of archwires. In addition, the mechanical properties were evaluated by the ratio of variance (Fig 1):

$$ratio\,of\,variance = \frac{midpoint\,force}{0.5\,mm\,start\,force - 0.5\,mm\,end\,force.}$$

The ratio of variance describes the inclination of the deactivation curve in relation to its force level. The force level is represented by the midpoint force at 1.5 mm. The denominator describes the gradient of the superelastic plateau, which is the subtraction of the force 0.5 mm

**Table.** Forces at 1.5-mm deflection, ratio of variance, and $A_f$ temperatures of the 0.016 × 0.022-in archwires with standard deviations in parentheses

| *Archwire* | *Original* | *Cold forming* | *Memory-Maker* | *550°C at 2 seconds* | *550°C at 5 seconds* | *600°C at 2 seconds* | *600°C at 5 seconds* | *650°C at 2 seconds* | *650°C at 5 seconds* |
|---|---|---|---|---|---|---|---|---|---|
| Titanol Low Force | | | | | | | | | |
| Force (N) | 2.3 (0.08) | 2.1 (0.1)<br>NS | 2.3 (0.05)<br>NS | 1.9 (0.08)<br>† | 2 (0.16)<br>NS | 2.3 (0.08)<br>NS | 2.3 (0.1)<br>NS | 1.6 (0.57)<br>‡ | 2.2 (0.12)<br>NS |
| Ratio | 2.3 (0.12) | 2.2 (0.25)<br>NS | 2.4 (0.23)<br>NS | 2.0 (0.16)<br>NS | 2.1 (0.17)<br>NS | 2.7 (0.27)<br>† | 2.7 (0.21)<br>† | 2.1 (0.11)<br>NS | 2.4 (0.38)<br>NS |
| $A_f$ (°C) | 23.6 (0.48) | 22.1 (0.74)<br>† | 27.1 (0.82)<br>‡ | 22.9 (0.71)<br>NS | 24.9 (0.54)<br>* | 23.5 (0.42)<br>NS | 17.5 (0.41)<br>‡ | 17.4 (0.32)<br>‡ | 18.7 (0.46)<br>‡ |
| Neo Sentalloy F 80 | | | | | | | | | |
| Force (N) | 0.7 (0.02) | 0.7 (0.06)<br>NS | 1.9 (0.13)<br>‡ | 0.68 (0.03)<br>NS | 0.32 (0.04)<br>‡ | 1.8 (0.2)<br>‡ | 2.1 (0.12)<br>‡ | 2.1 (0.05)<br>‡ | 1.9 (0.11)<br>‡ |
| Ratio | 0.57 (0.03) | 0.64 (0.03)<br>NS | 2.7 (0.37)<br>‡ | 0.55 (0.02)<br>NS | 0.26 (0.03)<br>‡ | 2.3 (0.31)<br>‡ | 3.1 (0.34)<br>‡ | 3.0 (0.19)<br>‡ | 2.4 (0.31)<br>‡ |
| $A_f$ (°C) | 29.2 (0.25) | 28.1 (0.2)<br>NS | 23.1 (0.89)<br>‡ | 28.4 (0.45)<br>NS | 28.9 (0.22)<br>NS | 23.4 (0.66)<br>‡ | 20 (0.63)<br>‡ | 10.7 (0.54)<br>‡ | 9.9 (0.75)<br>‡ |
| Copper Ni-Ti 35°C | | | | | | | | | |
| Force (N) | 1.7 (0.04) | 1.3 (0.06)<br>‡ | 0.82 (0.22)<br>‡ | 1.3 (0.06)<br>‡ | 1.2 (0.07)<br>‡ | 0.8 (0.1)<br>‡ | 0.6 (0.08)<br>‡ | 0.61 (0.11)<br>‡ | 0.13 (0.06)<br>‡ |
| Ratio | 3.4 (0.19) | 2.6 (0.35)<br>‡ | 1.1 (0.37)<br>‡ | 2.3 (0.29)<br>‡ | 2.0 (0.13)<br>‡ | 1.3 (0.19)<br>‡ | 0.91 (0.22)<br>‡ | 0.92 (0.19)<br>‡ | 0.17 (0.08)<br>‡ |
| $A_f$ (°C) | 27.4 (0.51) | 27.9 (0.27)<br>NS | 30.6 (0.74)<br>‡ | 27.2 (0.24)<br>NS | 27.1 (0.41)<br>NS | 27.4 (0.81)<br>NS | 27.5 (0.76)<br>NS | 28.7 (0.77)<br>* | 33 (0.55)<br>‡ |

$^{*}P \leq 0.05$; $^{\dagger}P \leq 0.01$; $^{\ddagger}P \leq 0.001$; *NS,* not significant.

from the end and start points on the deflection curve. Thus, the quality of the plateau in respect to the force level of the product can be expressed numerically.

The results were analyzed by using Prism (GraphPad, San Diego, Calif). Analysis of variance (ANOVA) with a Tukey post-hoc test was performed in addition to the calculation of the descriptive statistics with means and standard deviations.

## RESULTS

The Table and Figures 2 and 3 give an overview of the mechanical behavior after thermal or mechanical treatment of the 3 archwires, including force levels and ratios.

The force levels of the untreated archwires were 2.32 N for Titanol Low Force, 1.74 N for Copper NiTi 35°C, and 0.7 N for Neo Sentalloy F 80. Cold forming led to reduced (Copper NiTi, Low Force) or similar forces (Neo Sentalloy). Heat treatment influenced force levels unpredictably. The Titanol Low Force wires showed only slightly reduced force levels (1.65 N at 650°C and 2 seconds), whereas the force levels of the Copper NiTi wires were greatly reduced (0.13 N at 650°C and 5 seconds), and the levels of the Neo Sentalloy wires were significantly increased (2.11 N at 600°C and 5 seconds). When considering the force levels in relation to treatment temperatures, an almost inverse proportion was found for Copper NiTi, no clear relationship was found for Titanol Low Force, and a sudden force increase at 600°C was observed for Neo Sentalloy. Treatment with the Memory-Maker resulted in force levels close to those achieved with a thermal treatment of 600°C for 2 seconds.

The ratio of variance was found to be in direct correlation to the force levels. The deactivation curves were almost parallel to each other, but at different force levels.

The $A_f$ temperatures measured with DSC were influenced by mechanical as well as thermal treatments (Fig 2, Table). Although the $A_f$ temperature of the Neo Sentalloy archwire reacted strongly to different temperature treatments, this influence was much smaller for Titanol Low Force and almost nonexistent for Copper NiTi. In general, an inverse relationship was found between the $A_f$ temperature and the force level. Cold forming and heat treatment at 550°C resulted in $A_f$ temperatures close to the original values.

## DISCUSSION

NiTi products are known to be highly sensitive to temperature and clinically more difficult to handle when bending is required. The aim of this study was to investigate the influence of different programming temperatures as well as cold forming on the mechanical characteristics of 3 NiTi archwires. The temperature levels and exposure times chosen were based on pretests at temperatures between 250°C and 700°C, and exposure times between 1 second and 1 hour. Most combinations resulted in either unsatisfactory programming with incomplete expression of the sweep or the elimination of the superelastic properties.

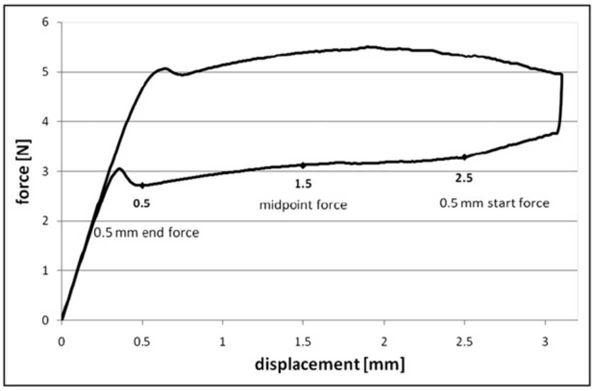

**Fig 1.** Typical graph of a superelastic Ni-Ti archwire in the force-deflection diagram. The ratio of variance compares the variance of the force levels at 2.5 and 0.5 mm with the characteristic medial force level of the product at a deflection of 1.5 mm.

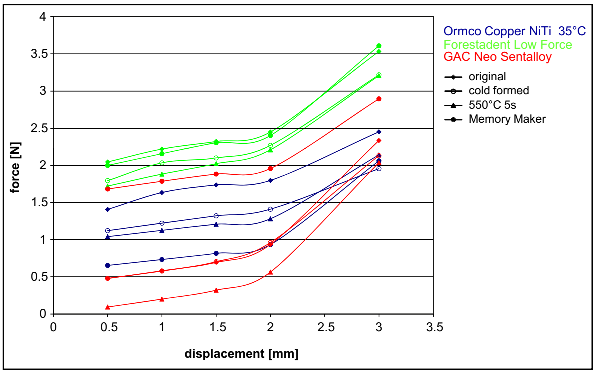

**Fig 2.** Deactivation curves of 3 archwires (0.016 × 0.022 in) after different procedures: original, cold forming, and heat treatment at 550°C for 5 seconds with the Memory-Maker. Whereas the Titanol Low Force archwire was not influenced greatly by the different procedures, the Neo Sentalloy was especially sensitive to treatment with the Memory-Maker.

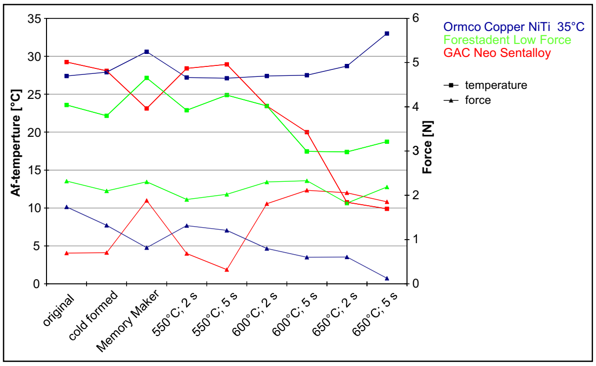

**Fig 3.** Comparison of forces and $A_f$ temperatures. In general, a change in the $A_f$ temperature induced a force level change in the opposite direction. This behavior was observed to the greatest extent for the Copper NiTi followed by the Neo Sentalloy. The Titanol Low Force archwire did not clearly exhibit this relationship.

The most promising combinations of exposure time and temperature were found at approximately 600°C for 1 to 5 seconds, which were the parameters chosen for this investigation. Although the temperature used in this study was slightly higher than those suggested in the literature, the exposure times were considerably shorter.[7-10,14] This inconsistency might be due to differences in the tested archwires from those in previous studies. Furthermore, we used a new method for heat treatment. Instead of placing the wires into a mold that was then heated to the required temperature, the archwires were placed directly into a preheated iron cast. The sharp increase in temperature might have produced the different response.

Heat treatment led to different reactions in each archwire. With Neo Sentalloy, a sharp increase in the force levels was found when treated above 600°C for 2 seconds. For Copper NiTi, a continuous decay in force levels with increasing temperatures and exposure times was observed, and there was almost no affect on Titanol Low Force. It is not clear why the archwires reacted differently to the same settings during shaping. The most likely reason for the different responses to heat treatment was the manufacturing process of the 3 wires—in particular, their different processing histories, the amount of cold work, the annealing temperatures, and their precise compositions.[15] This unpredictable behavior of NiTi alloys to temperature exposure or machining has been well documented in the literature.[4,5,16] Shape programming by heat treatment must therefore be individually adjusted for each product. This was also true for the Memory-Maker, which resulted in force levels and $A_f$ temperatures that were similar to programming at 600°C for 2 seconds. The shape of the deactivation curve was similar regardless of the exposure setting with almost parallel curves at different force levels. The parallel plots at different force levels corresponded to the ratio of variance. Shape programming that increased the force levels of the archwires increased the ratio of variance, indicating a more level deactivation curve in relation to its characteristic force level.

The purpose of the ratio of variance was to enhance the comparability of the different products. Unlike traditional alloys such as stainless steel or beta-titanium alloy, which can be compared according to their modules of elasticity, NiTi archwires show a complex force-deflection pattern. To numerically express the quality of NiTi archwires, the slope on the deactivation curve must be related to their force level. With the same midpoint force, a higher value for the ratio of variance must be due to a flatter plateau, indicating a higher quality product. If products of a different force level are compared, it must be considered that archwires at a characteristic force level of 2 and 0.5 N, and with identical slopes of their superelastic plateaus, are not of the same quality. Whereas a deviation of 1 N from the start to the end points on the deflection curve represents a 50% variance for a midpoint force of 2 N, it would represent a 200% variance for a midpoint force of 0.5 N. Although a force variance of 50% from the clinically intended force level might be acceptable, it can be argued that an archwire with a force variance of 200% is not clinically appropriate, even though both slopes of the deflection curves are identical. Therefore, the inclination of the deactivation curve for a lower-force archwire must be flatter to indicate an archwire of equal quality. This relationship of a characteristic midpoint force of an archwire and its force variance is numerically expressed by the ratio of variance. High values represent high-quality archwires with a low percentage of force variance with respect to their characteristic force level. Therefore, even products with different force levels can be compared by using the ratio of variance. The correlation of the DSC measurements and the force levels found in this study are in good agreement with previous investigations.[9,10] A reduction in $A_f$ temperature causes a change in the crystal structure that results in proportionally greater austenite. This means that the force, as shown by the deactivation curve, is increased with decreasing $A_f$ temperatures. This behavior was most pronounced for Neo Sentalloy, for which the greatest influence of temperature on $A_f$ temperature was found. Similar force levels between programming with the Memory-Maker or exposure to temperatures of 600°C for 2 seconds were also mirrored in similar $A_f$ temperatures for both programming techniques.

Shape programming at varying temperatures and exposure times in a dental furnace is inappropriate as a chair-side procedure. Therefore, for clinical use, the implications of cold forming and the use of the Memory-Maker on the properties of the wires in comparison with their original properties are important. Cold forming did not lead to statistically significant changes in force levels for Neo Sentalloy, and it led to decreases of 9.5% for Titanol Low Force and 24% for Copper NiTi. However, although the use of the Memory-Maker resulted in a 169% increase in the force levels for Neo Sentalloy, no significant change for Titanol Low Force and a decrease of 53% for Copper NiTi were observed. Standard deviations for both techniques were similar, and the deflection curves were parallel to the untreated wires on the force-deflection diagram. Although this result was expected for the Memory-Maker as another form of heat treatment, it was not clear how mechanical deformation would influence the behavior of the alloy. It appears that the lattice structure of the NiTi archwires did not alter with cold forming. Cold forming resulted in DSC measurements with values similar to those of the original wires. Overall, both techniques can be used clinically. However, whereas a slight reduction of forces in NiTi archwires is predicted for cold forming, the influence of the Memory-Maker is more variable. When using the Memory-Maker, it is essential to know the individual reaction of the chosen archwire to heat treatment. Moreover, the level of heat application with the Memory-Maker depends on the treatment time, the distance between the pliers conducting the electric current, and the voltage and frequency settings of the Memory-Maker. Although the optimal force levels of archwires with respect to tooth movement, root resorption, and histologic reactions remain to be accurately defined, it would be wise to choose products and forming methods that deliver the most predictable force levels.[17-19] Therefore, cold forming is recommended in clinical practice.

## CONCLUSIONS

The mechanical behavior of NiTi archwires after exposure to varying temperatures between 550°C and 650°C led to unpredictable force levels in 3-point bending tests. Only temperature and time settings of 550°C and 2 seconds led to values close to the untreated archwires. In general, $A_f$ temperatures were indirectly proportional to the force levels.

Chair-side programming with the Memory-Maker resulted in different force levels from cold forming. Whereas force levels after cold forming were always slightly lower than those for the original archwires, they were either similar, strongly increased, or decreased after treatment with the Memory-Maker. Therefore, cold forming is the recommended method for chair-side forming of NiTi archwires.

## REFERENCES

1. Iijima M, Ohno H, Kawashima I, Endo K, Mizoguchi I. Mechanical behavior at different temperatures and stresses for superelastic nickel-titanium orthodontic wires having different transformation temperatures. Dent Mater 2002;18:88-93.
2. Meling TR, Odegaard J. The effect of short-term temperature changes on superelastic nickel-titanium archwires activated in orthodontic bending. Am J Orthod Dentofacial Orthop 2001;119:263-73.
3. Sakima MT, Dalstra M, Melsen B. How does temperature influence the properties of rectangular nickel-titanium wires? Eur J Orthod 2006;28:282-91.
4. Khier SE, Brantley WA, Fournelle RA. Bending properties of superelastic and nonsuperelastic nickel-titanium orthodontic wires. Am J Orthod Dentofacial Orthop 1991;99:310-8.

5. Li Z, Cheng X, ShangGuan Q. Effects of heat treatment and ECAE process on transformation behaviors of TiNi shape memory alloy. Mater Lett 2005;59:705-9.
6. Liu Y, McCormick PG. Thermodynamic analysis of the martensitic transformation in NiTi–I. Effect of heat treatment on transformation behaviour. Acta Metall Mater 1994;42:2401-6.
7. Novak V, Sittner P, Dayananda GN, Braz-Fernandes FM, Mahesh KK. Electric resistance variation of NiTi shape memory alloy wires in thermomechanical tests: experiments and simulation. Mater Sci Eng A 2008;481-482:127-33.
8. Wang Z, Zu X, Feng X, Dai J. Effect of thermomechanical treatment on the two-way shape memory effect of NiTi alloy spring. Mater Lett 2002;54:55-61.
9. Yamamoto M, Kuroda T, Yoneyama T, Doi H. Bending property and phase transformation of Ti-Ni-Cu dental casting for orthodontic application. J Mater Sci Mater Med 2002;13:855-9.
10. Yoneyama T, Doi H, Hamanaka H, Yamamoto M, Kuroda T. Bending properties and transformation temperatures of heat treated Ni-Ti alloy wire for orthodontic appliances. J Biomed Mater Res 1993;27:399-402.
11. Hempowitz J, Sander FG, Wichelhaus A, Frank RP, Edrich J. Heat treatment of NiTi-archwires, simulated with nonlinear coupled finite element analysis. Proceedings of the second international conference on shape memory and superelastic technologies; 1997 Mar 2-6; Pacific Groove, CA, USA. SMST; 1997. p. 497-501.
12. Miura F, Mogi M, Ohura Y. Japanese NiTi alloy wire: use of the direct electric resistance heat treatment method. Eur J Orthod 1988; 10:187-91.
13. Wichelhaus A, Sander FG, Hempowitz H. The transformational behaviour of wires in the elastic and plastic range in dependence upon temperature-treatment. Proceedings of the second international conference on shape memory and superelastic technologies; 1997 Mar 2-6; Pacific Groove, CA, USA. SMST; 1997. p. 449-54.
14. Stamm T, Hohoff A, Wiechmann D, Sütfeld J, Helm D. Accuracy of third-order bends of nickel-titanium wires and the effect of high and low pressure during memorizing heat treatment. Am J Orthod Dentofacial Orthop 2004;126:476-84.
15. Drexel MJ, Selvaduray GS, Pelton AR. The effects of cold work and heat treatment n the properties of nitinol wire. Proceedings of the second international conference on shape memory and superelastic technologies; 2006 May 7-11; Pacific Groove, CA, USA. SMST; 2006. p. 447-54
16. Adujudom DM, Thoma PE, Fariabi S. The effect of cold work and heat treatment on the phase transformations of near equaitomic NiTi shape memory alloy. Mater Sci Forum 1990; 56-58:565-70
17. Ren Y, Maltha JC, Kujpers-Jagtman AM. Optimum force magnitude for orthodontic tooth movement: a systematic literature review. Angle Orthod 2003;73:86-92.
18. Owman-Moll P, Kurol J, Lundgren D. The effects of a four-fold increased orthodontic force magnitude on tooth movement and root resorption. An intra-individual study in adolescents. Eur J Orthod 1996;18:287-94.
19. Von Böhl M, Maltha J, Von den Hoff H, Kuijpers-Jagtman AM. Changes in the periodontal ligament after experimental tooth movement using high and low continuous forces in beagle dogs. Angle Orthod 2004;74:16-25.