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Force delivery of NiTi orthodontic arch wire at different magnitude of deflections and temperatures: A finite element study

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ABSTRACT

NiTi arch wires are used widely in orthodontic treatment due to its superelastic and biocompatibility properties. In brackets configuration, the force released from the arch wire is influenced by the sliding resistances developed on the arch wire-bracket contact. This study investigated the evolution of the forces released by a rectangular NiTi arch wire towards possible intraoral temperature and deflection changes. A three dimensional finite element model was developed to measure the force-deflection behavior of superelastic arch wire. Finite element analysis was used to distinguish the martensite fraction and phase state of arch wire microstructure in relation to the magnitude of wire deflection. The predicted tensile and bending results from the numerical model showed a good agreement with the experimental results. As contact developed between the wire and bracket, binding influenced the force-deflection curve by changing the martensitic transformation plateau into a slope. The arch wire recovered from greater magnitude of deflection released lower force than one recovered from smaller deflection. In contrast, it was observed that the plateau slope increased from 0.66 N/mm to 1.1 N/mm when the temperature was increased from 26 °C to 46 °C.

1. Introduction

Orthodontic treatments involve the movement of tooth in various directions and orientations at different stages. These stages are divided into alignment and leveling, correction of molar relationship and space closure, and finishing treatment. Movement of tooth is induced by force generated from a pre-deformed wire hooked to the bracket on the tooth. The design of bracket is supposed to allow the arch wire to slide at negligible friction, thus tooth movement is achieved only by the bending force generated by the pre-deformed wire. Most brackets are made of stainless steel and arch wire is secured onto it by using ligation ties. For alignment and leveling stage, orthodontist starts with round light wire that can be bent easily and subsequently replaces it with a thicker wire with rectangular shape (Kim et al., 2008). This sequence of wires usage is important to gain light forces throughout the orthodontic treatment, as tooth moves effectively at force below 1.0 N (Proffit et al., 2014).

For decades, the use of superelastic nickel-titanium (NiTi) wire is preferred against stainless steel wire during the early stage of orthodontic treatment, with a goal of bringing the teeth into alignment (Duerig et al., 2013). NiTi arch wires are chosen due to its unique properties of superelasticity, which permits recovery of very large strain of approximately 6–8% without permanent deformation (Otsuka and Wayman, 1999). This superelastic behavior is found to be suitable for aligning and leveling treatment, in which it provides a constant magnitude of force for effective tooth movement. As the arch wire slides to recover its original straight shape, it pulls the teeth to a better position (Singh, 2015). It is well documented that superelastic NiTi material yields this large strain over a stress plateau by manifesting its stress-induced martensitic (SIM) transformation (Jiang et al., 2009).

Even though NiTi arch wires are widely used, its real performance in bracket configuration is still unclear since most of the force-deflection studies focused on three point bending test (Kaphoor and Sundareswaran, 2012; Varela et al., 2014). The force-deflection behavior deduced from three point bending test is not directly transferable to the oral clinical setting due to the absence of sliding resistance consideration during the test. In order to obtain realistic clinical force, Nucera et al. (2014) have included bracket engagement in their bending test to consider the influence of sliding resistance towards the bending behavior of NiTi arch wire. They found that the force released by the 0.36 mm round NiTi arch wire during recovery increased linearly from 3 mm to 1 mm, which completely defies the believe of constant and

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continuous force delivery of NiTi arch wire in orthodontic treatment.

The sliding resistance in arch wire-bracket configuration was categorized by Kusy and Whitley (1999) into two components, classic friction (F_L) and binding (F_{BI}). Classic friction refers to sliding resistance created by elastomer ligatures when it drives the arch wire against the base of the bracket slot. Meanwhile, binding is developed when the arch wire is bent, with the magnitude of friction increases as the curvature of the bend increases. Since arch wire slides through the slot of the adjacent brackets during leveling treatment, a portion of the released force (F_R) from the NiTi arch wire is used up to overcome the generated binding and classical friction at the wire-bracket interface (Baccetti et al., 2009).

Researchers have developed various constitutive models of shape memory alloy using different state variables to describe the phase transition characteristics such as, reorientation of martensite, martensite volume fraction and energy dissipation. A few macro scales constitutive models of shape memory alloy have been proposed in literature but feature only the superelastic (Auricchio and Taylor, 1997) or both shape memory effect and superelastic behavior (Boyd and Lagoudas, 1996). The superelasticity model by Auricchio and Taylor (1997) is employed for the generation of UMAT/Nitinol subroutine available in Abaqus FEA. In recent years, a few studies have utilized this built-in subroutine and successfully predicted the true behavior of shape memory alloy under its operating conditions (Pelton et al., 2013; Robertson et al., 2015; Weafer et al., 2016).

In this study, a three dimensional numerical modeling of wire-bracket system was developed to anticipate the bending behavior of superelastic NiTi arch wire. The model adopted the concept introduced by Auricchio and Taylor (1997) and a nonlinear finite element procedure was incorporated into it. The objective of this work is to evaluate the influence of binding friction towards force-deflection characteristics of NiTi arch wire with respect to various magnitudes of deflection and oral temperatures. The evolution of normal stress and martensite fraction in the finite element model is subsequently analyzed to understand the utilization of superelastic behavior during bending. This new knowledge may assist orthodontist to quantify the true mechanical response of NiTi arch wire in brackets configuration whilst improving current installation practices.

2. Materials and methods

2.1. Experimental testing

In this study, three types of experimental analyses were carried out; uniaxial tensile, modified three point bending and calorimetric test. The uniaxial tensile test was conducted to quantify the mechanical behaviors parameters of NiTi wire for defining the superelastic behavior in the material subroutine. Modified three point bending test was executed by considering three brackets engagement during the test. The result of bending test was used to validate the force-deflection curve generated from the numerical model. The calorimetric test was done to measure the transformation temperatures of the arch wire, in specific the austenite finish (A_f) temperature. The specimen used for all analyses was superelastic NiTi arch wire with a rectangular cross section of 0.4 mm × 0.56 mm.

20 mm uniaxial specimens were cut from the straight end section of the arch wire. The specimens were elongated to 1.7 mm at a displacement rate of 1 mm/min in the direction of its length before unloaded at similar rate. This test was conducted on an Instron model 3367 universal testing machine. The uniaxial test was carried out at three different temperatures of 26 °C, 36 °C and 46 °C. A small chamber was used to control the environmental temperature of the specimen during tensile test, with an accuracy of ± 1 °C. The desired temperature was achieved by continuous flow of heated air through inlet and outlet vents. The testing procedure and settings followed the standard of ISO 15841: Dentistry-Wires for use in Orthodontic. This uniaxial test was repeated for three times with a new specimen used for each test. The average value measured from the stress-strain curves at 26 °C was used for the determination of material properties.

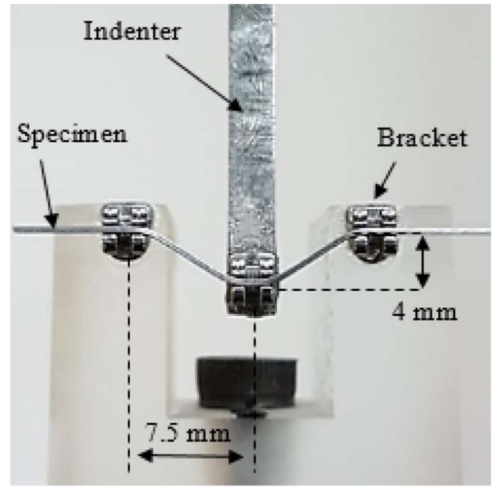

Fig. 1. NiTi arch wire bent on modified three point bending setup.

The modified three point bending test was conducted using the same universal testing machine with a customized compressive loading jig, as shown in Fig. 1. The lower load-cell capacity of 500 N was installed for this test to increase the sensitivity of load reading. The clinical scale of three brackets apparatus was set up by setting the distance between the brackets to be 7.5 mm, thus resembling the average distance of adjacent teeth (Nucera et al., 2014). Three brackets with 0.56 slot height and 2.80 mm slot width were used with respect to its zero torque and angulation design. The brackets were glued to the movable indenter and mounting base using cyanoacrylate adhesives. No ligation tie was installed during the placement of wire inside the bracket slot. Next, the specimen was deflected to 4 mm at 26 °C by setting the indenter to move vertically downward and upward at a displacement rate of 1 mm/min. This bending test was repeated for two times, and the validation was done by comparing the experimental and numerical result directly. In this study, the coupling of 0.4 mm × 0.56 mm wire with the 0.56 mm-slot bracket reflects the common wire-bracket combination used during the leveling treatment (Lombardo et al., 2012). In fact, this 0.16 mm clearance is sufficient to permit sliding of the arch wire along the bracket slot (Proffit et al., 2014).

The phase transformation temperatures of the specimens were determined using TA-Q20 differential scanning calorimeter. The specimen size was 7.86 mg and the heating and cooling rate was 10 °C/min. The transformation temperatures were determined by the intersection of tangent lines on the peaks as described in ISO 15841.

2.2. Constitutive model of shape memory alloy

To simulate the superelasticity of the NiTi arch wire, a built-in user material subroutine (UMAT/Nitinol) in Abaqus 6.12.2 was employed. This subroutine was established by Auricchio and Taylor (1997), based on a generalized plasticity theory that decomposes strain components into purely elastic and transformational strains. The change in linear elasticity from the parent austenite phase to the stress-induced martensite phase was achieved by adopting a rule of mixtures. The change in the stress level to induce phase transformation shifts linearly with temperature. This model was chosen over other viable macro scales constitutive models for its good agreement with experimental result involving bending type deformation (Nematzadeh and Sadrnezhaad, 2012).

The material data used in the subroutine are tabulated in Table 1. These data are generated from the uniaxial test of equiatomic NiTi, deformed at room temperature.