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Assessment of the Force-Deflection Behavior of Aged NiTi Archwires in Various Inter-Bracket Distance Configurations

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ABSTRACT

The aim of the study was to determine the force-deflection behavior of aged nickel-titanium (NiTi) archwires when subjected to bending within a bracket model featuring different inter-bracket distances. The flexural behavior of commercial 0.016 × 0.022-inch NiTi archwires was modified by subjecting them to different ageing temperatures. The archwire with the lowest unloading force during bending in a three-point bending arrangement was chosen for force-deflection evaluation at various inter-bracket distances. The findings indicate that subjecting the commercial as-received NiTi archwires to an ageing treatment at a temperature of 490 °C effectively decreased the magnitude of the unloading force from 2.0 N to 1.3 N. It was also discovered that NiTi archwires displayed unloading force in the form of a slope over the deflection course when narrow inter bracket distances of 7.0 mm and 7.5 mm were used. The force slope exhibited a significant decrease and approached a nearly constant force trend when the inter-bracket distance was increased to 8.5 mm and 9.0 mm. The unloading force of 490 °C aged NiTi archwires exhibited a progressive increase from 1.7 N to 3.4 N as the spacing between the brackets was altered from 7.0 mm to 9.0 mm. The ageing treatment approach might be useful for reducing the bending force released by commercial rectangular NiTi archwires at different inter-bracket distance settings.

Keywords: 3-5 Ageing treatment, Flexural behavior, Inter-bracket distance, NiTi archwires

1. INTRODUCTION

Orthodontic treatment is a process of improving the appearance of human teeth by shifting them into a better position. Orthodontic treatment normally takes 6 to 30 months to complete, depending on the initial irregularity of the teeth. The force required to initiate tooth movement is generated by the archwire's spring-back potential. Previous research has indicated that spring back forces within the range of 0.5 to 1.0 N demonstrate optimal efficacy in promoting tooth movement while potentially minimizing adverse consequences [1]. NiTi archwires with superelastic properties are widely used during the treatment period because of its capacity to transmit consistent and moderate force across a broad range of deflection.

The superelastic property of NiTi archwires is derived from its reversible and diffusionless solid-to-solid phase transformation, known as the martensitic phase transformation. This martensitic phase change is distinguished by the conversion of the NiTi archwire material from the austenite (B2) phase at high temperatures to the martensite (B19') phase at low temperatures. This phase transformation involves cooperative movement between the nickel and titanium atoms, allowing the alloy to revert to its original form after the applied load is removed [2]. Several bending models have been established to enhance the understanding of the flexural characteristics of NiTi archwires. These models encompass cantilever bending [3], three-point bending [4], and bracket bending model [5]. The force plateau phenomenon is often seen and well-documented in the superelastic behavior of NiTi archwires during load loading and unloading in three-point bending

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configurations [6]. However, when paired with orthodontic brackets, sliding friction causes the force plateau of superelastic NiTi archwires to shift into a force slope throughout both the loading and unloading cycles [7,8].

Commercial orthodontic archwires can be classified into three distinct geometries: round, square, and rectangular. In the initial phase of orthodontic treatment, round wires are frequently employed due to their enhanced flexibility, lower bending force and reduced frictional resistance in comparison to square and rectangular wires. For an identical brackets system, round wires of 0.016 inch demonstrated an unloading force of 1.1 N, whereas 0.016 × 0.022-inch NiTi archwires promote an unloading force of up to 3.5 N [9]. Once the teeth have begun to straighten, the orthodontist will switch to a rectangular archwire to provide torque to the misaligned tooth. While the rectangular archwire is the greatest option since it can accommodate both force and torque components, it is not often used at the beginning of treatment because it produces a lot of force and is difficult to insert into the bracket slot. Thus, it would benefit the orthodontic field if the flexural properties of the rectangular wire could be changed to make it more flexible, allowing it to produce less force and be used as soon as possible during orthodontic therapy.

It is widely known that sliding friction plays a key role in determining the force-deflection trend of NiTi archwires in bracket configuration. The friction formed at the contact surface of archwires and bracket slots has been found to increase as a function of applied deflection [10], larger archwire size [11], smaller bracket slot size [12], and smaller inter bracket distance [13]. With these settings, the archwire pushes the bracket corners harder, increasing the amount of sliding friction. If the friction component is strong enough, it has the potential to transform the conventional constant force behavior of superelastic NiTi archwires into a force slope. This indicates that the force is no longer provided at a constant magnitude when the tooth moves, as was claimed in the first place this type of material is utilized. Frequent adjustments in force magnitude applied to the malpositioned teeth during orthodontic treatment are not advised since they will slow the tooth movement pace [1].

The process of ageing has been widely recognised as a heat treatment method that effectively enhances the mechanical and thermal performance of nickel-rich NiTi alloys [14,15]. NiTi alloys with Ni contents ranging from 49.8at% to 56at% are susceptible to the formation of secondary phases of Ni-rich precipitates such as Ti_3Ni_4 [16]. It is well known that ageing a NiTi alloy at temperatures from 300 °C to 600 °C for 10 to 60 minutes successfully affects the size and density of Ti_3Ni_4, consequently changing the thermal transformation temperature [17] and mechanical behavior [18]. The effect of ageing treatment on NiTi alloys has previously been examined primarily in terms of tensile deformation behavior. The strength of the force plateau in NiTi alloys exhibits a decreasing trend when the temperature during the ageing process is elevated from 330 °C to 500 °C [19]. The process of ageing conducted within the temperature range of 300 °C to 600 °C consistently yielded notable residual strain seen subsequent to the completion of the tensile test [20]. Overall, the ideal ageing conditions for good superelastic performance and maximal recoverability have been indicated to be between 400 °C and 450 °C for ageing durations less than 60 minutes [21].

To our knowledge, very few research has been carried out to identify the suitability of ageing treatment to alter the force-deflection of commercial NiTi archwire and analyse its force-deflection behavior at different inter-bracket settings. The NiTi archwire with the lowest bending force in the three-point bending test was selected for a more in-depth investigation of archwire deformation in orthodontic bracket configurations. The right selection of ageing condition may help to reduce the bending force exhibited by the rectangular NiTi archwires, allowing them to be used earlier during the early stages of orthodontic treatment.

2. MATERIAL AND METHODS

2.1 Ageing Treatment

The present investigation was carried out with Orthoform superelastic NiTi orthodontic wires of 0.016 × 0.022 inches in dimensions. For the specimens, the straight portion of the archwire was segmented into lengths of 50 mm. The heat treatment procedure was conducted utilising a GSL-1100X tube furnace under the presence of argon gas flow. In order to mitigate the impact of prior treatments, the wires were subjected to a solution annealing procedure, including exposure to a temperature of 920 °C for a duration of 15 minutes. Subsequently, the ageing procedure was conducted for a period of 45 minutes at different temperatures, spanning from 370 °C to 520 °C, with intervals of 30 °C. To reduce the possibility of further precipitation activity, the specimens were quickly quenched in cold water following the heating process.

Figure 1(a) shows the experimental setup for three-point bending used to evaluate the flexural behavior of the aged NiTi archwire. This test was carried out using a three-point bending jig built in accordance with ISO 15841: Dentristy-Wires for Use in Orthodontics. The indenter and the support point were spaced apart by 10 mm and rounded to an accuracy of 0.1 mm. A 500 N load cell was attached to an Instron 3367 universal testing machine for the three-point bending test. The experiment involved installing an indenter affixed to the machine load cell to induce deflection on the NiTi archwires. The NiTi archwires were deflected to 3.1 mm deflection at 1.0 mm/min crosshead speed before being unloaded at the same rate as they were loaded. An electric heater was utilised to maintain the experimental conditions at a temperature of 36 °C. The force-deflection curve was subsequently recorded and monitored using Bluehill v2.0 software.

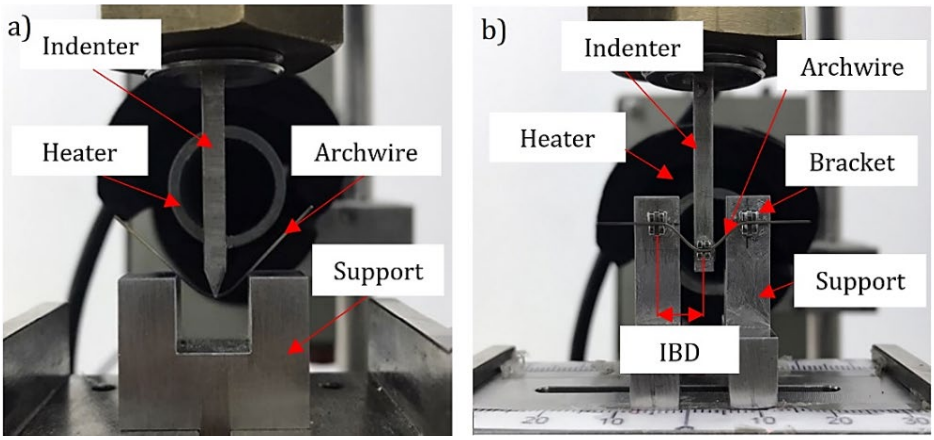

Figure 1. Bending setup used to record the force-deflection behavior of NiTi archwires; (a) three-point setup and (b) three-bracket setup

The aged NiTi archwires with the lowest unloading force during the three-point bending test were chosen for future deformation behavior evaluation in brackets arrangement. The force-deflection behavior of the aged NiTi archwires was assessed using a three-bracket setup, as depicted in Figure 1(b). This particular model has been extensively studied in numerous studies [22,23], as it depicts the scenario of a malposed canine on a maxillary arch, which is commonly encountered in orthodontic practice. Three orthodontic brackets made of stainless steel (specifically, grade 316L) were considered with each bracket had a slot height of 0.40 mm and a slot width of 3.40 mm. The canine was represented by the central bracket, which was attached to the movable indenter, while the first premolar and lateral incisor were represented by the adjacent brackets, which were attached to the fixed support. The experiment was carried out with aged archwires of similar dimensions, measuring 0.016 × 0.022 inch.

The bending test was initiated by placing the aged NiTi specimen into the slots of the three brackets. The NiTi specimen underwent bending deformation, resulting in a deflection of 4.0 mm. This was achieved by vertically displacing the indenter at a constant rate of 1.0 mm per minute. Subsequently, the specimen was allowed to return to its initial straight configuration by retracting the indenter at the same speed. The bending test took into account five possible inter-bracket distances: 7.0 mm, 7.5 mm, 8.0 mm, 8.5 mm, and 9.0 mm.

These inter-bracket distances replicate the spacing between placed brackets during orthodontic treatment, which can range from 7.0 mm to 9.0 mm [24] depending on one's tooth structure. This inter-bracket distance range was considered in this study to see how changes in bending setting affect the force-deflection behavior of aged NiTi archwires. Similar to the three-point bending case, a heater set to 36 °C was also employed to simulate the oral temperature. The Bluehill v2.0 software was employed to monitor and record the magnitudes of forces and deflections yielded by the NiTi archwires during the course of the experiment.

3. RESULTS AND DISCUSSION

Figure 2 depicts the force-deflection results for aged NiTi archwires obtained from the three-point bending test performed at 36 °C. In general, the NiTi archwires that had undergone ageing exhibited deformation characterized by superelastic behavior, resulting in the generation of a force plateau throughout both the loading and unloading phases. The loading curve demonstrated a linear rise in force until it reached a deflection of 0.8 mm. The observed linear curve can be attributed to the elastic deformation of the austenite structure that is inherent in the wire. Upon subjecting the archwires to additional bending of 3.1 mm, a noticeable force plateau was seen, suggesting the change of the NiTi archwire from an austenite to a martensite structure. Upon the removal of the bending load, the archwire undergoes a restoration to its initial straight form, which is accompanied by the emergence of a second force plateau. This occurrence is a result of the reverse transformation of the martensite structure back to austenite.

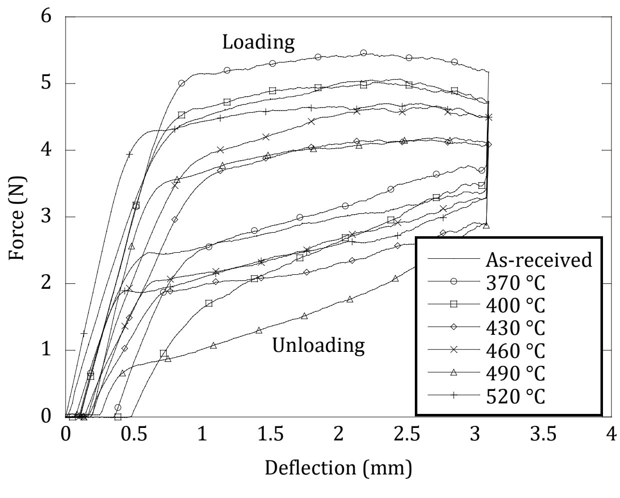

Figure 2. Force-deflection curve from three-point bending of NiTi archwires after aged at different temperatures.

Ageing treatment certainly affected the force-deflection trend of the as-received superelastic NiTi archwires, as shown in Figure 2. During the loading cycle, the specimen aged at the lowest temperature of 370 °C exerted the greatest force. At the end of the unloading cycle, the residual deflection of 0.4 mm revealed that this specimen exhibited incomplete wire curvature recovery. At 1.5 mm deflection, the as-received specimen registered 4.7 N and 2.0 N of force throughout the loading and unloading cycles, respectively.

Meanwhile, specimens aged at high temperatures ranging from 460 °C to 520 °C displayed loading and unloading forces that were significantly lower than these values. For the record, the specimen aged at 490 °C exhibited the lowest unloading force of 1.3 N at 1.5 mm deflection. In comparison to the as-received specimen, the unloading force is reduced by 35 %, from 2.0 N to 1.3 N. Because the purpose of this work is to minimise the bending force of the rectangular NiTi archwire to the smallest possible magnitude, this temperature was chosen as the appropriate temperature for further bending deformation evaluation. The observed decrease in the amount of the unloading force implies that the bending stiffness of the NiTi archwire aged at 490 °C has decreased.

Figures 3(a)-3(e) demonstrate how the force-deflection profiles of aged NiTi archwires vary when bent at different inter-bracket spacing ranging from 7.0 mm to 9.0 mm. The aged NiTi clearly demonstrated a different bending behavior in the bracket system when compared to the three-point bending system. The influence of high sliding friction generated at the contact surface between archwire and bracket corners has been recognized to be responsible for the alteration of force behavior from a plateau to a gradient [25].

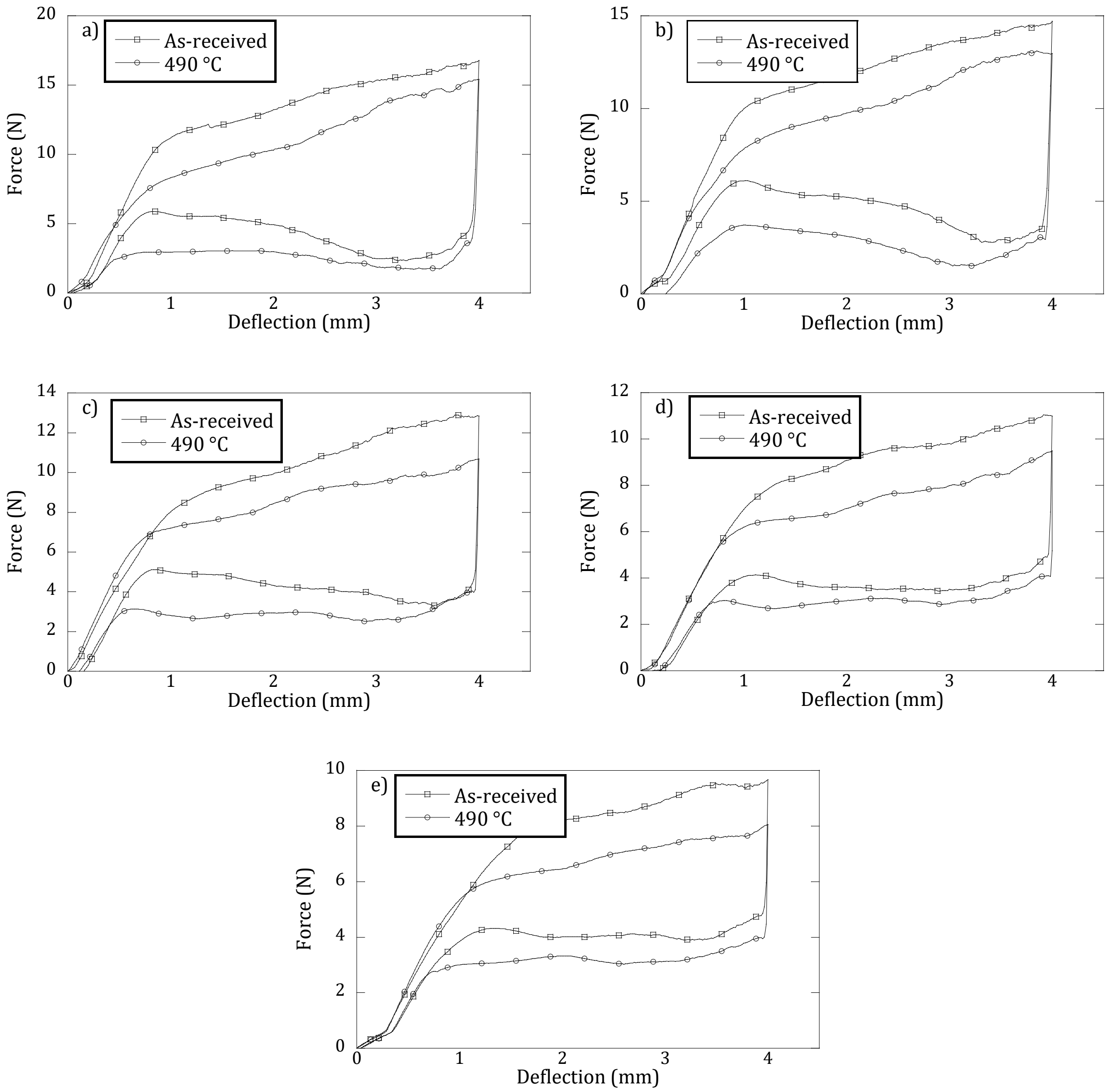

Figure 3. Force-deflection curve of selected aged NiTi archwires upon bending in different inter-bracket distance configurations; (a) 7.0 mm, (b) 7.5 mm, (c) 8.0 mm, (d) 8.5 mm and (e) 9.0 mm.

The bending curve for as-received archwires begins with the production of a linear force curve up to 0.9 mm deflection, then the force steadily increases as the deflection progresses from 0.9 to 4.0 mm. The unloading cycle begins with a sharp force reduction at 3.5 mm, followed by a progressive increase in force as the deflection recovers from 3.5 mm to 1.0 mm, generating a force slope. The force steadily increased because the component of friction preventing archwire sliding weakens as wire deflection decreases [26]. In orthodontics, the loading force is the amount of force required to bend the archwire while inserting it inside the bracket slot. Meanwhile, the unloading force signifies the amount of force exerted by the archwires on the malposed tooth, which is the focus of this study.

Overall, the ageing treatment successfully adjusted the force-deflection of as-received NiTi archwires by reducing the loading and unloading force. According to Figure 3(a), the unloading force measured at 3.5 mm deflection has decreased from 2.6 N for the as-received archwires to 1.6 N for the aged archwires, representing a 38 % reduction in force. Furthermore, the as-received archwires showed unloading force in the form of steeper slope; the unloading force increased from 2.6 N to 5.7 N as the wire deflection recovered from 3.5 mm to 1.0 mm. Meanwhile, the unloading force rises from 1.6 N to 2.8 N over the same deflection for the aged archwires, resulting in a smaller force change. The lower magnitude of the unloading force indicates that the NiTi archwires, which have undergone ageing, exhibit more flexibility upon bending, resulting in a smaller force change as the archwire curvature recovers. The slope is visibly diminished as the inter-bracket lengths increase from 7.0 mm in Figure 3a to 8.5 mm (Figure 3(d)) and 9.0 mm (Figure 3(e)). This observation indicates that the influence of sliding friction on the force-deflection behavior of NiTi archwires lessens as the distance between the brackets rises. Perumalla et al. [27] suggest that an increased inter-bracket distance has the potential to decrease the rate of force deflection, hence facilitating more efficient tooth movement.

Figure 4 displays the variations in maximum loading force demonstrated by the NiTi archwires in their as-received state and after undergoing ageing, across varied inter-bracket distance settings. The maximum load was extracted from Figure 3 at a deflection of 4.0 mm. The observation reveals that as the distance between the brackets increases, the magnitude of the loading force gradually decreases. The maximum loading force of the as-received archwires decreases by approximately 43 %, specifically from 16.7 N to 9.6 N, as the distance between the brackets increases from 7.0 mm to 9.0 mm.

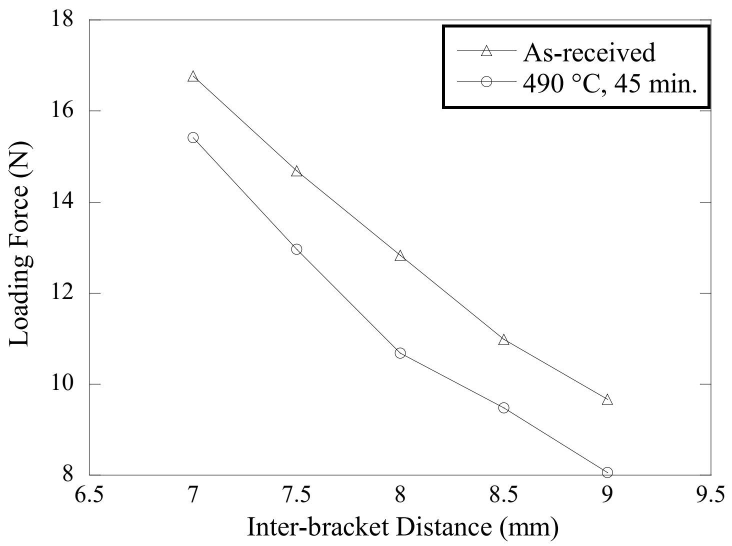

Figure 4. Loading force variation of the NiTi archwires over different inter-bracket distance configurations.

In contrast, the maximum loading force of the aged NiTi archwires demonstrates a 48 % reduction in force, decreasing from 15.4 N to 8.0 N. The observed trend of force reduction indicates that the act of bending a rectangular wire within a bracket configuration becomes more challenging when the space between the brackets is narrower, in contrast to situations when the bracket spacing is broader. It is noteworthy to emphasize that the force range demonstrated by the as-received and aged archwires aligns with previous research that examined the bending of rectangular superelastic NiTi archwires within a bracket system [28]. The majority of the research asserts that the significant loading force observed during large deflections can be attributed to the impact of friction resulting from the curvature of the wire form at the corners of the bracket [29,30].

Figure 5 illustrates the unloading force exerted by aged NiTi archwires throughout the process of wire recovery in three-bracket bending. The magnitude of the unloading force was measured when the deflection reached 2.5 millimeters. The unloading force exhibited by the as-received wires was found to be higher than that of the aged archwires for each inter-bracket distance. The inverse relationship between inter-bracket distance and unloading force is observed when comparing it to the loading cycle. The magnitude of the force exhibited a consistent rise, ranging from 2.6 N to 4.0 N, in conjunction with the progressive expansion of the inter-bracket distances from 7.0 mm to 9.0 mm. The same pattern was seen with aged wires, albeit at a lower force magnitude, where the unloading force ranged from 1.7 N to 3.4 N. The relationship between unloading force and inter-bracket spacing suggests that NiTi archwires produce greater unloading force when subjected to less friction, such as in cases with wider bracket configurations.

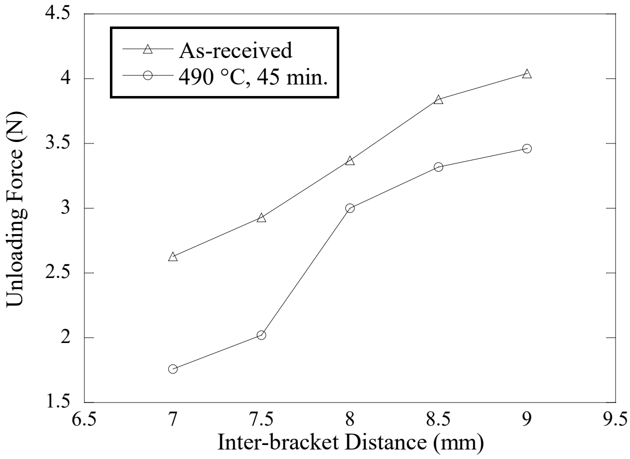

Figure 5. Unloading force variation of the NiTi archwires over different inter-bracket distance configurations.

In addition, although the ageing treatment has demonstrated effectiveness in reducing the unloading force to a certain degree, it still falls short in attaining the ideal force necessary for inducing tooth movement. The lowest unloading force seen in Figure 5 was 1.7 N, which was solely observed in the case of a bracket spacing of 7.0 mm and the values progressively rose to 3.4 N in the case of a bracket spacing of 9.0 mm. It is advisable to refrain from subjecting the dentition to excessive force (more than 2.0 N), since this can lead to many adverse effects on both comfort and biological integrity. These effects may include the loss of anchoring, root resorption (the deterioration of tooth structure), and hyalinization (the formation of dead tissues) [31].

4. CONCLUSION

The current study investigates the flexural behavior of aged superelastic NiTi archwires when bent in orthodontic bracket system of different bracket spacing. When small inter bracket intervals of 7.0 mm and 7.5 mm were utilized, the 490 °C aged NiTi archwire demonstrated unloading force in the form of a slope over the deflection course. When the inter-bracket distance was extended to 8.5 mm and 9.0 mm, the force slope decreased significantly and approached an almost constant force trend. As the inter bracket spacing increased from 7.0 mm to 9.0 mm, the unloading force of 490 °C aged NiTi archwire surged from 1.7 N to 3.4 N.

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