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Study on Springback Properties of Different Orthodontic Archwires in Archwire Bending Process

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Abstract

The archwire bending is one of processes the most frequently used in the orthodontic treatment. Furthermore, the springback of sheet metal, which is defined as elastic recovery of the part during unloading, should be taken into consideration so as to produce formed archwire within acceptable tolerance limits. In this paper, the springback angle of different alloy archwires (including NiTi alloy wire, Beta-Ti alloy wires, Chinese stainless steel wires, and Australian stainless steel wires) were performed by the theoretical calculation based on large deformation theory and the finite element analysis. A series of numerical simulations has been conducted for the bending test, which physically simulates the actual bending of alloy archwire with a robotic apparatus. The finite element analysis of springback is shown to be very consistent with the theoretical calculation results.

Keywords: *Orthodontic archwire, Springback properties, Simulation modeling, Large deformation theory, Archwire Bending*

1. Introduction

Alloy archwire, especially Ni-Ti alloy wire and stainless steel alloy wire attract attention for application as biomaterial in medical and dentistry areas due to their good mechanical properties, high corrosion resistance, and excellent biocompatibility [1-5]. Traditionally, archwire is bent by orthodontist by manual operation. However, this process is boring and inefficient. A robotic apparatus was introduced to free orthodontist from hard work. The archwire-bending process plays a major role in orthodontic treatment. In the bending process, after release of the load by loosening the fixture, the archwire tries to return to its original shape because of the elastic stresses. Springback is an important parameter in tooling design and obtaining the desired configuration of archwire. So study on springback in archwire-bending process of different alloy archwire is a key issue. However, there is little experimental data in the literature about springback of different alloy archwire.

Many efforts have been made to study the mechanical, physical, and chemical characterization of various materials orthodontic wires. The torque characteristics of various nickel titanium and steel wires in a pure torsion were compared [6]. The mechanical properties and clinical applications of stainless steel, cobalt-chromium, nickel-titanium, and multistranded wires were described and commented [7]. There were also some people focused on the incorporation of a hollow cross-section in the wires as a new method for changing the properties of the super-elastic Ni-Ti alloy wires. And it was found that the hollow wires delivered much lighter and more continuous orthodontic force which fit for orthodontic application [8]. Transformation temperatures and mechanical properties such as transformation stresses at different temperatures and the super-elasticity have been

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investigated in NiTiCu alloy with various copper concentrations. And the results were the addition of copper was effective to narrow the stress hysteresis and to stabilize the superelasticity characteristics [9]. It was proved that Ti-Ni-Cu alloy castings produced effective orthodontic force as well as stable low residual deflection [10]. Surface mechanical attrition treatment was found to induce the formation of a parent B2 phase from the martensite B19 [11]. Instead investigating the internal structure and principle, our research, on the other hand, focused on the springback angles in different bending angles of the selected wires. And these experimental data could be directly used in archwire bending.

2. Materials and Methods

The archwire-bending process is one of the most important components in orthodontic treatment. In this study, the bending process was simulated using finite element software Marc. In the simulation modeling, the fixture and rotary disk are defined geometrically by rigid surfaces. The archwire is represented by a deformable beam. The fixture, rotary disk and archwire of the process and the geometry parameters are shown in Figure 1.

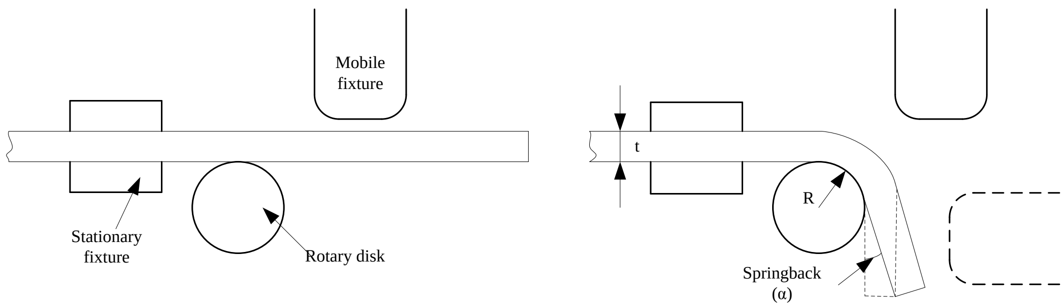

Figure 1. The Fixture, Rotary Disk and Archwire of the Process and the Geometry Parameters

2.1. Specimen Preparations

Four alloy archwires were evaluated in this study. There were American stainless steel alloy wires (diameter: 0.018 in.), called wire 1, Australian stainless steel alloy wires (diameter: 0.018 in.), called wire 2, Chinese nickel-titanium alloy wires (cross section: 0.018 in. × 0.025 in.), called wire 3 and beta-titanium alloy wires (cross section: 0.018 in. × 0.025 in.), called wire 4. The material is assumed to be isotropic elastic-plastic following the Von-Misses yield criterion and isotropic hardening. The detailed mechanical parameters of the four alloy wires are shown in Table 1.

Table 1. Mechanical Parameters of Wire1 to Wire 4

Wire	Friction factor	Poisson's ratio	Modulus of elasticity (Mpa)
1	0.31	0.27	17.40
2	0.30	0.28	18.32
3	0.31	0.26	12.77
4	0.31	0.26	14.68

2.2. Modeling and Simulation

In this study, a parametric finite element model which is variable geometry parameters and bending angles was developed. The simulations are carried out in two groups. In the first group simulation, the distance between the mobile fixture and stationary fixture is t=2mm.

And in the second group, the distance is changed into t=10mm. The bending angles which we wanted to get are set to 110º, 90º, 60º, 45º, 30º, 15º, 10º, 8º, 4º and 2º in all simulations.

In the process, firstly one end of the archwire is clamped by the stationary fixture, and then the mobile fixture moves to clamp the other end of the archwire. Then the mobile fixture rotates with the rotary disk. When the target angle θ_1 is achieved, the rotary disk stopped and kept still for a few seconds. After release of the load by loosening the mobile fixture, the archwire will rebound a certain angle due to its super-elastic. Then we can get the angle after springback which we name θ_2. Change the angle θ_1 to experiment according to the aforementioned process, a series of springback angles (α) will be obtained. The model when the angle θ_1 is 60º is shown in Figure 2 and the model after springback is shown in Figure 3.

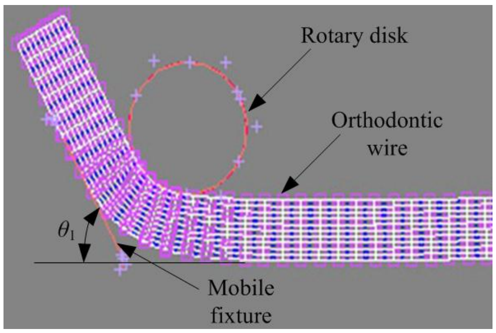

Figure 2. Mobile Fixture Clasp

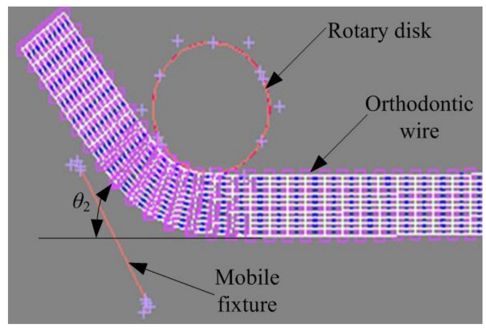

Figure 3. Mobile Fixture Release

2.3. Theoretical Calculation

In this section, the springback properties of the four selected alloy archwires will be obtained by theoretical calculation based on large deformation theory. Generally speaking, with the decrease of the relative bend radius (the ratio of the gyration radius to the height of orthodontic wires), the internal tangential stress will increase. Furthermore, the plastic deformation begins to be produced at edge layer (outer layer and internal layer) firstly and expands to the geometrical middle layer of wires gradually [12, 13]. According to the deformation extent, there are three kinds of bending type which are elastic bending, elastic-plastic bending and plastic bending. The bending type of archwire bending belongs to elastic-plastic bending. In the process of springback properties analysis, we rendered the following assumption:

1. The axial elongation of the orthodontic wires was ignored in the process of bending.
2. Section which perpendicular to the axis of bending is plane before bending. It will remain plane after bending. And the cross section is still vertical with the axis.
3. We assume that the orthodontic wires are only plane bending in the process of bending. Not containing twist.

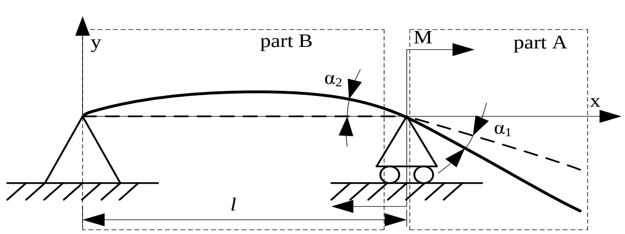

Figure 4. The Theoretical Calculation Model of Archwire Bending

The theoretical calculation model of archwire bending is shown in Figure 4. In order to realistically simulate the process of archwire bending using robotic apparatus, the distance between mobile fixture and stationary fixture t must be considered. So the springback model is divided into two parts (part A and part B). Next we will analyze both of these parts' effect in the overall springback respectively.

2.3.1 The effect of part A on springback angle

The schematic diagram of springback is showed in Figure 5. The width of the archwire is B. So, we can describe the externally applied torque M as (1) in the process of bending.

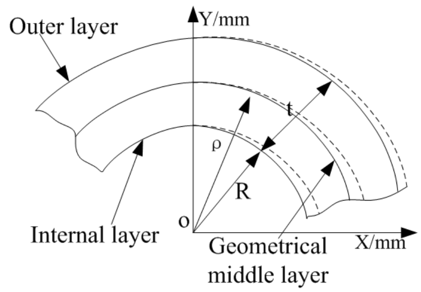

Figure 5. Schematic Diagram of Springback

$$M = 2\int_0^{\frac{t}{2}} B\sigma y dy \tag{1}$$

Where σ is the tangential stress which is given as (2):

$$\begin{cases} \sigma = E\dfrac{y}{\rho} (|y| < \delta = \dfrac{\sigma_s \rho}{E}) \\ \sigma = \sigma_s (|y| \geq \delta = \dfrac{\sigma_s \rho}{E}) \end{cases} \tag{2}$$

Where σ_s is the allowable tangential stress, which is determined by the mechanical performance of material. So the externally applied torque M can be finally described as (3):

$$M = 2\int_0^{\delta} \frac{BE}{\rho} y^2 dy + 2\int_{\delta}^{\frac{t}{2}} B\sigma_s y dy = \frac{2}{3}\frac{BE}{\rho}\delta^2 + B\sigma_s[(\frac{t}{2})^2 - \delta^2] = B(\frac{\sigma_s t^2}{4} - \frac{1}{3}\frac{\sigma_s{}^3 \rho^2}{E^2}) \tag{3}$$

We assume the radius of curvature of the curving orthodontic wires is ρ. The radius of curvature after the tongs is unstuck of the orthodontic wires is ρ_0. And then we can get the rebound dependent variable ε:

$$\varepsilon = -(\frac{1}{\rho} - \frac{1}{\rho_0})y \tag{4}$$

The relationship between the rebound stress and rebound dependent variable fit Hooke's law. The relationship can be described as (5):

$$\sigma = E\varepsilon = -Ey(\frac{1}{\rho} - \frac{1}{\rho_0})y \tag{5}$$

The springback bending torque is:

$$M_r = 2\int_0^{\frac{t}{2}} B\sigma y dy = -2\int_0^{\frac{t}{2}} BE(\frac{1}{\rho} - \frac{1}{\rho_0})y^2 dy = -\frac{BEt^3}{12}(\frac{1}{\rho} - \frac{1}{\rho_0}) \tag{6}$$

Because the springback deformation is caused by the unloading of the bending torque, there is the relationship:

$$-M_r = M \tag{7}$$

$$\begin{cases} \frac{BEt^3}{12}(\frac{1}{\rho}-\frac{1}{\rho_0}) = B(\frac{\sigma_s t^2}{4}-\frac{1}{3}\frac{{\sigma_s}^3\rho^2}{E^2}) \\ (\frac{1}{\rho}-\frac{1}{\rho_0}) = 3\frac{\sigma_s}{Et}-4\frac{{\sigma_s}^3\rho^2}{E^3t^3} \end{cases} \quad (8)$$

Through simplifying the (8) we can get ρ_0, the radius of curvature after the tongs is unstuck of the orthodontic wires.

$$\rho_0 = \frac{\rho}{1-3\frac{\sigma_s\rho}{Et}+4(\frac{\sigma_s\rho}{Et})^3} \quad (9)$$

Here, we assume that there are the approximate relationships (10) and (11):

$$\rho_0 \approx R_0 \quad (10)$$

$$\rho \approx R \quad (11)$$

So, there is the relationship between R_0 and R which is shown in (12):

$$R_0 = \frac{R}{1-3\frac{\sigma_s R}{Et}+4(\frac{\sigma_s R}{Et})^3} \quad (12)$$

Where R_0 is the radius of the orthodontic wires after springback, R is the radius of the end effector. So, the relationship between the bending angles θ and the angles θ_0 after springback can be described as (13):

$$\theta_0 = \frac{\rho}{\rho_0}\theta \approx \frac{R}{R_0}\theta = K\theta \quad (13)$$

Where K is the coefficient of resilience. Its value can be given by (14):

$$K = 1-3\frac{\sigma_s R}{Et}+4(\frac{\sigma_s R}{Et})^3 \quad (14)$$

The springback angle in part A can be described as follows:

$$\alpha_1 = |3\frac{\sigma_s R}{Et}-4(\frac{\sigma_s R}{Et})^3|\theta \quad (15)$$

2.3.2 The effect of part B on springback angle

The model of the effect of part B on springback angle is shown in Fig. 6. It is a simply supported beam.

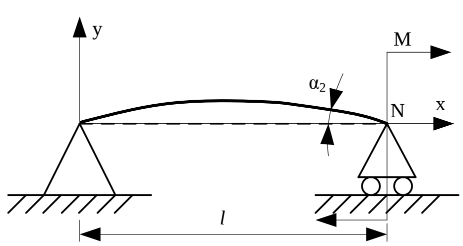

Figure 6. The Model of the Effect of Part B on Springback Angle

We assume that there is only elastic deformation in bending of part B. So we can get the deflection curve equation of the archwire as follows:

$$v = -\frac{Mx}{6EIl}(l^2-x^2) \quad (16)$$

Where E, I are the modulus of elasticity and moment of inertia respectively. Then the rotating angle equation can be described as follows:

$$\frac{dv}{dx} = -\frac{Ml}{6EI} + \frac{Mlx^2}{2EIl} \tag{17}$$

So the rotating angle at point N which equal to the springback angle of archwire in part B can be described as follows:

$$\alpha_2 = \frac{Ml}{3EI} \tag{18}$$

So the springback angle in archwire bending is as follows:

$$\alpha = \left| 3\frac{\sigma_s R}{Et} - 4\left(\frac{\sigma_s R}{Et}\right)^3 \right| \theta + \frac{Ml}{3EI} \tag{19}$$

3. Results and Discussion

The springback angles of alloy archwires against bending angles could be obtained using forenamed equation (19). After many calculations and simulations, the theoretical calculation results of springback angles and simulation results of springback angles were showed in Figure 7-10 respectively. Furthermore, we can get the conclusions as follows:

1. As the bending angles increase the springback angles of the four alloy archwires increase.

2. The simulation results of springback angles is much more consistent with the theoretical calculation results when t=2mm.

3. From large to small, the order of springback angles (α) in the same bending angles ($\theta 1$) is wire 1, wire 2, wire 4 and wire 3.

4. There is some singular data in Figure 6 and Figure 7 (the singular data were the springback angles which decrease along with the increasing of the bending angles).

5. In the process of bending archwire, the distance between the mobile fixture and stationary fixture should be as small as possible in order to prevent the appearance of singular data.

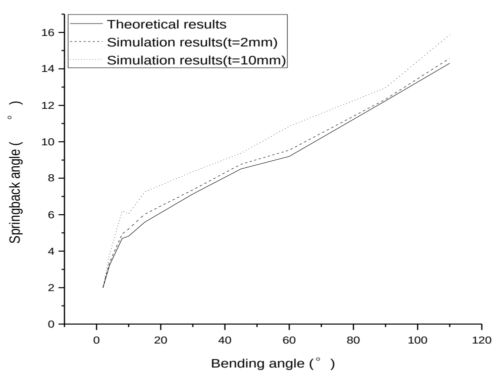

Figure 7. Springback Properties of Wire 1

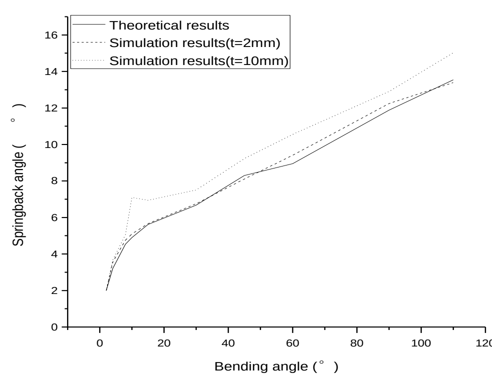

Figure 8. Springback Properties of Wire 2

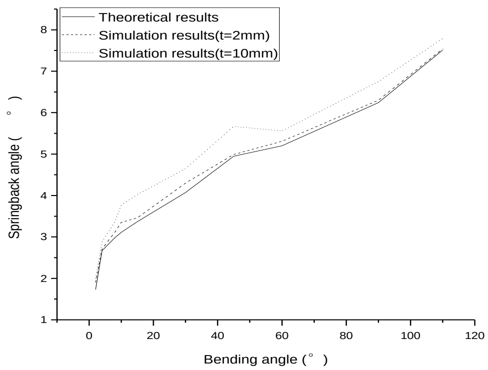

Figure 9. Springback Properties of Wire 3

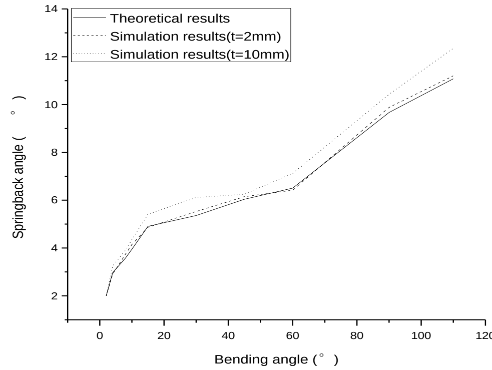

Figure 10. Springback Properties of wire 4

From the theoretical calculation we can see that it is not an easy job to calculate the every single springback angle in each bending angle, especially when the kinds of wires are large. So software which can be used to automatically calculate the springback angle should be developed and the only thing we need to do is inputting the corresponding parameters. While this work which we think is very significant will be carried out in future work.

Conclusions

(1) The springback angle of different alloy archwires (including NiTi alloy wire, Beta-Ti alloy wires, Chinese stainless steel wires, and Australian stainless steel wires) were performed by the theoretical calculation based on large deformation theory and the finite element analysis.

(2) A series of numerical simulations has been conducted for the bending test. The finite element analysis of springback is shown to be very consistent with the theoretical calculation results.

(2) As the bending angles increase the springback angles of the four alloy archwires increase. The simulation results of springback angles is much more consistent with the theoretical calculation results when t=2mm. From large to small, the order of springback angles (α) in the same bending angles (θ_1) is wire 1, wire 2, wire 4 and wire 3.

Acknowledgements

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References

[1]. T. Yoneyama, H. Doi, H. Hamanaka, Y. Okamoto, M. Mogi and F. Miura, "Super-elasticity and thermal behavior of Ni-Ti alloy orthodontic arch wires", Dental Materials Journal, vol. 11, no. 1, **(1992),** pp. 1-10.

[2]. G. Laino, R. De Santis, A. Gloria, T. Russo, D. S. Quintanilla, A. Laino, R. Martina, L. Nicolais and L. Ambrosio, "Calorimetric and thermomechanical properties of Titanium-Based orthodontic wires: DSC-DMA relationship to predict the elastic modulus", Journal of Biomaterials Applications, vol. 26, no. 7, **(2012),** pp. 829-844.

[3]. M. Iijima, M. Ohta, W. A. Brantley, A. Naganishi, T. Murakami, T. Muguruma and I. Mizoguchi, "Transformation behavior of nickel-titanium orthodontic wires under tensile load", Dental Materials Journal,

vol. 30, no. 3, **(2011),** pp. 398-403.
[4]. T. Yoneyama, O. Takahashi, E. Kobayashi, T. Hanawa and H. Doi, “Bending properties of Co-Ni-Cr-Mo alloy wire for orthodontic application”, Materials Transactions, vol. 46, no. 7, **(2005),** pp. 1551-1554.
[5]. T. H. Lee, C. C. Wang, T. K. Huang, L. K. Chen, M. Y. Chou and H. H. Huang, “Corrosion resistance of titanium-containing dental orthodontic wires in fluoride-containing artificial saliva”, Journal of Alloys and Compounds, vol. 488, no. 1, **(2009),** pp. 482-489.
[6]. S. Partowi, L. Keilig, S. Reimann, A. Jager and C. Bourauel, “Experimental analysis of torque characteristics of orthodontic wires”, Journal of Orofacial Orthopedics-fortschritte Der Kieferorthopadie, vol. 71, no. 5, **(2010),** pp. 362-372.
[7]. S. Kapila and R. Sachdeva, “Mechanical properties and clinical applications of orthodontic wires”, American Journal of Orthodontics and Dentofacial Orthopedics, vol. 96, no. 2, **(1989),** pp. 100-109.
[8]. Y. Shima, K. Otsubo, T. Yoneyama and K. Soma, “Anisotropic orthodontic force from the hollow super-elastic Ti-Ni alloy wire by transforming the wire cross-section”, Journal of Materials Science Materials in medicine, vol. 13, no. 2, **(2002),** pp. 197-202.
[9]. F. J. Gil, E. Solano, J. Pena, E. Engel, A. Mendoza and J. A. Planell, “Microstructural, mechanical and citotoxicity evaluation of different NiTi and NiTiCu shape memory alloys”, Journal of Materials Science. Materials in medicine, vol. 15, no. 11, **(2004),** pp. 1181-1185.
[10]. M. Yamamoto, T. Kuroda, T. Yoneyama and H. Doi, “Bending property and phase transformation of Ti-Ni-Cu alloy dental castings for orthodontic application”, Journal of Materials Science. Materials in medicine, vol. 13, no. 9, **(2002),** pp. 855-859.
[11]. Y. D. Zhang and J. X. Jiang, “Bending Property Analysis and Experimental Study of Orthodontic Wires”, Chinese Mechanical Engineering, vol. 22, no. 15, **(2011),** pp. 1827-1831.
[12]. J. Li, J. Zhao, H. L., Sun and R. Ma, “Improvement of springback prediction of wide sheet metal air bending process”, Journal of Central South university of technology, vol. 15, **(2011),** pp. 310-315.
[13]. E. Petoumeno, M. Kislyuk, H. Hoederath, L. Keilig, C. Bourauel and A. Jager, “Corrosion Susceptibility and Nickel Release of Nickel Titanium Wires during Clinical Application”, Journal of Central South university of technology, vol. 15, (Suppl.2), **(2008),** pp. 310-315.

