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Simulation and Analysis of Orthodontic Archwire Bending Robot

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Abstract

A 3D mathematical model of orthodontic archwire with rectangular curve is established. Simplified 3D solid model of orthodontic archwire bending robot, which is consistent of bending die, support structure and archwire are established by Creo software, then the simplified model of bending die is put into ANSYS Workbench. Material parameters the contact condition and boundary conditions are set reasonably for the model. Based on the finite element analysis method, the calculation and analysis of the nonlinear contact problem of archwire and bending die, besides the stress distribution of curve bending and bending die is got. This provides the reference for optimal design of bending planning and bending die.

Keywords*: Orthodontic archwire bending robot, bending die, stress distribution, ANSYS Workbench*

1. Introduction

In orthodontic treatment, fixed orthodontic appliance is a highly efficient way to get a wide range of therapeutic successes [1]. Orthodontic archwire bending is an important part of clinical orthodontic. Orthodontic archwire bending robot is used to realize the bending of archwire, not only can get rid of manually bending, but also can be achieved customized. Bending die is the most important component of the archwire bending robot. Bending die spacing, shape and radius directly affect the radius of curvature of the archwire bending and the kinds of orthodontic bending. Stiffness of bending die has an effect on forming precision of orthodontic curve. In the bending process, bending die elastic deformation will be produced owing to the interaction between the archwire and bending die. Therefore, it is particularly important to research stress and strain of bending die in the condition of bending. Therefore, there are many scholars conducting research and analysis of orthodontic archwire. Jingang Jiang *et al.* has analyzed transient dynamic analysis of the simplification simulation model of orthodontic archwire bending, and studied the springback characters of the alloy archwires in different bending angle by finite element software Marc [2-6]. Geramy *et al.* established different maxillary arch model by finite element method, and optimize unilateral molar rotation[7]. Naceur *et al.* studied the influence of the bending force of the super elastic NiTi orthodontic archwire under different temperatures, and compare the experimental data[8]. Rodrigues and Ferreira *et al.* analyzed the force system, moment-force ratios (M/F) and von mises stresses in an orthodontic delta spring using a 3D finite element model [9, 10]. ANSYS Workbench which has a technology platform of engineering simulation is launched by ANSYS, Inc. It provides a powerful method of interaction with ANSYS solver series. It not only can interface with most CAD software, share and exchange of data, but also has abilities of analysis such as nonlinear dynamics and buckling.

In this paper, the main research objects are to analyze the mathematical model of orthodontic archwire and the strain distribution of bending die. The bending die, square

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archwire, and blocking archwire structure are simplified. 3D model is built by CREO software, then the geometric data is imported into ANSYS Workbench through the software interface program automatically. The stress, strain and other parameters of the distribution of parts can be able to get accurately by using ANSYS Workbench transient dynamic finite element model. It can verify that the bending die conforms to actual requirements and provide the force data of the actual bending curve for the orthodontic robot.

2. Mathematical Model of the Orthodontic Archwire

In orthodontics, researchers have proposed some common forms for standard arch shape, such as the power function model and the beta equation models.

The power function model is adopted to represent the target archwire curve[11]. It is relatively mature and suitable for the arch character of the majority of people, so the power function model can be used to express the mathematical model of orthodontic archwire. The basic archwire curve mathematical model can be represented by the following formula:

$$y = \alpha x^{\beta} \quad x \geq 0$$

Where α and β are the parameters of the patient's dental arch, and which can be calculated as the following expression:

$$\begin{cases} \beta = \sigma(S/W - \mu L/W)^{\tau} \\ \alpha = L/W^{\beta} \end{cases}$$

Where S, W and L are arc length, width and height of the half mandibular or dental arch, and σ, μ and τ are constants, *i.e.*, σ=10.889, μ=0.88, τ=3. Therefore, as long as the oral arch parameters of S, W and L are given, the archwire standard model can be calculated, as shown in Figure 1.

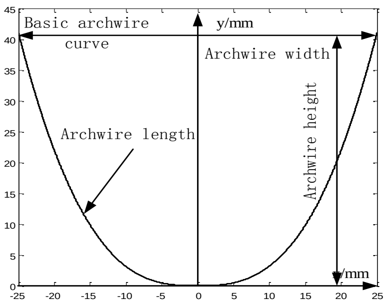

Figure 1. Mathematical Model of Achwire Curve

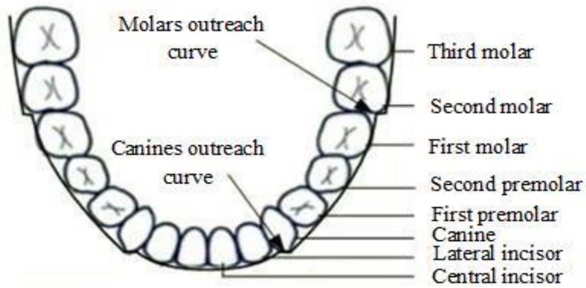

Figure 2. Target Archwire Curve on Dental Model

Healthy adults generally have about 32 teeth distributed symmetrically. Each half side of teeth in top or bottom row has two incisors, one canine, two pairs of premolars and three molars, as shown in Figure 2. Therefore we only need to analyse the right half of contour shape of teeth in the bottom row. Canines and second molars are protrude outwardly, so there is an outreach bend in the junction between canines and lateral incisor, and the junction between the second molar and first molar also has an outreach bend. The shape of the archwire with canines outreach curve and molars outreach curve is adapted to the target archwire.

Finite points derivation algorithm is used to control the nodes for searching among the limited key points[12, 13]. It has the advantages of better search efficiency and little time-consuming of algorithm. So the number of orthodontic archwire control nodes and the

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location are planned by finite points derivation algorithm. Then these nodes are connected by Matlab software, as shown in Figure 3. Because the target archwire has a rectangular curve, the piecewise function is used to establish a mathematical model owing to not continue in both rectangular curve and outreach curve.

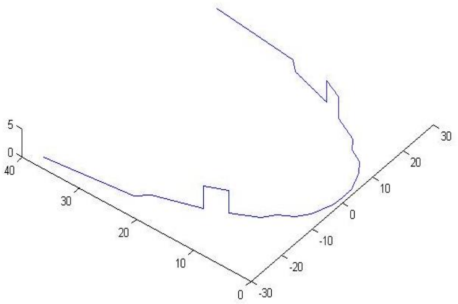


Figure 3. Target Archwire Curve

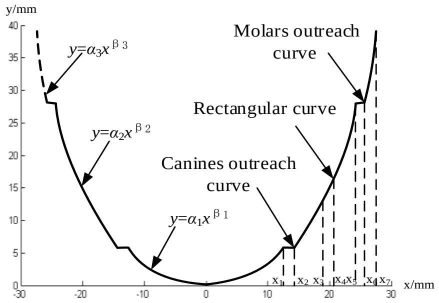


Figure 4. Target Archwire Curve on x-y Plane

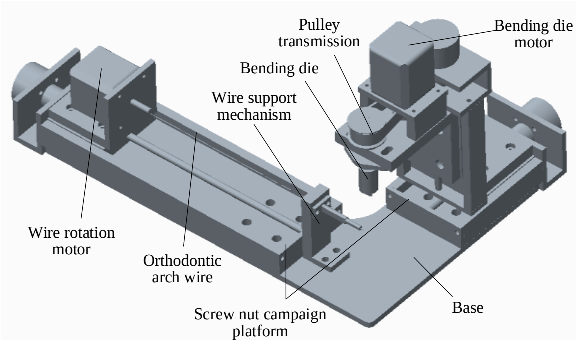
$$\begin{cases} y=\alpha_1\cdot x^{\beta_1} \quad x\in[0,x_1] \quad z=0 \\ y=\alpha_2\cdot x^{\beta_2} \quad x\in[x_3',x_4'] \quad z=n \quad n\in \mathrm{N}^* \\ y=\alpha_2\cdot x^{\beta_2} \quad x\in[x_2,x_3] \cup [x_4,x_5] \quad z=0 \\ y=\alpha_3\cdot x^{\beta_3} \quad x\in[x_6,x_7] \quad z=0 \\ x=x_3 \; y=y_3 \; z\in[0,n] \quad n\in \mathrm{N}^* \\ x=x_4 \; y=y_4 \; z\in[0,n] \quad n\in \mathrm{N}^* \\ y=y_1+\dfrac{(y_2-y_1)(x-x_1)}{(x_2-x_1)} \quad x\in[x_1,x_2] \quad z=0 \\ y=y_5+\dfrac{(y_6-y_5)(x-x_5)}{(x_6-x_5)} \quad x\in[x_5,x_6] \quad z=0 \end{cases}$$

Where x_1 and x_2 are respectively the starting and end points corresponding to the horizontal of the canine outreach curve, x_3, x_4 and x_3', x_4' are respectively the endpoint of rectangular curve from near to far from the origin in x-y plane and the endpoint of the rectangular curve from near to far from the origin that not in x-y plane, x_5, x_6 are respectively starting and end points of the molars outreach curve, x_7 is the farthest point from the origin of the target archwire curve.

As shown in Figure 3, the target archwire with rectangular curve consists of a curve that parallel to the plane of x-y and the two segment curves that perpendicular to the plane of x-y, all the remaining archwire curves are in x-y plane. Establishing method of target archwire mathematical model in x-y plane projection is shown in Figure 4, the starting point of both canines and molars outreach curve away from the each end point are very short, so the two outreach curves are connected by a straight line. The origin and the canine outreach curve starting point, the end point of molars outreach curve and archwire end point at the far right are respectively connected by two standard archwire curve model. Supposed the rectangular curve from the coordinates of the origin point in the plane y=0 near to far are pointing a, b respectively, and from the coordinate of the origin point in the plane y=5 near to far are pointing a', b' respectively. The end point of the canines outreach curve and a point, a' and b' point, b' point and the starting point of molar outreach bend are connected with a standard curve of the archwire model that through these four points. And two rectangular curve segment that perpendicular to the x-y plane, a and a' point, b and b' point are connected by straight lines. As the archwire curve is symmetrical, we can get the mathematical model of the target archwire curve's right part.

3. 3D Model of Archwire Bending Robot

3D drawing of the archwire bending robot is shown in Figure 5, it includes the base, motion platform, transmission, motor, support structure and bending die. The diameter of bending die is 0.8mm, which can bend most of the orthodontic wire. We only analyze the bending die, the support structure and archwire in order to facilitate analysis and reduce the amount of calculation. A three-dimensional model is established by Creo software, as shown in Figure 6. The model is imported in ANSYS Workbench by ANSYS Workbench software seamless connection with CAD.



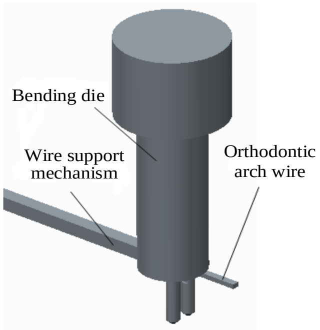


Figure 5. Archwire Bending Robot **Figure 6. The Model of Bending Die**

4. The Finite Element Analysis of Archwire Bending

4.1 Material Settings and Meshing

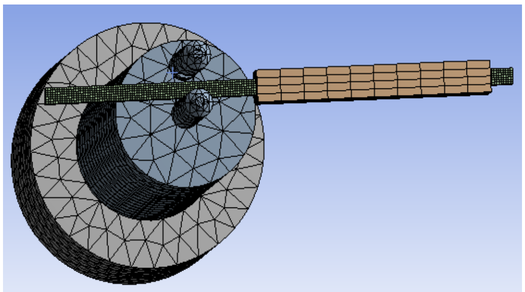


Figure 7. Mesh Generation of Bending Die

Stainless steel archwire is suitable for the use when a large torque is required. The sectional dimension is 0.018 inches×0.025 inches. Material elastic modulus E=177GPa, yield limit: σ_s=250MPa, poisson's ratio: μ=0.3, the density: ρ=7850kg/m^3. After turning the creo model into the finite element model, ANSYS Workbench automatic meshing module is used to mesh generation. In terms of grid directly affects the accuracy of the results of calculation, and the analysis for solving process requires a high quality of archwire mesh, so according to the size of the entity model and in the guarantee the size of the grid while improving the computation efficiency, the archwire mesh size is set to 0.1mm, and the rest of the model is set to 1 mm. The grid division produced a total of 17119 units and 52599 nodes, as shown in Figure 7.

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4.2 Contact and Boundary Conditions Setting in Transient Structural

In the definition of bending die and archwire contact, augmented lagrange method is used. This method adds additional control to reduce the permeability function automatically. However, due to the use of direct solvers, it might need to consume more computational cost. Contact surface was defined by asymmetric behavior manual. The contact bodies choose four profiles of arch wires and the target bodies choose four profiles inside of support structure in the connection of archwire and support structure. Meanwhile, the contact bodies choose two profiles of arch wires and the target bodies choose the two small cylindrical surfaces on bending die in the connection of archwire and bending die.

Bending die and the bottom connector select CONTACT-BODY-TO-BODY-REVOLUTE contact. According to the working condition of bending die and archwire, the bottom surface at the bending die bottom connection part, the end face of archwire block that far away from of the bending die, and the end face of square archwire that far away from bending die, each of them adds a fixed support constraint. The contact surface between bending die and the bottom connector is added a joint-load constraint. The rotation of bending die is set 110°. Finally, load step and time is added, and this analysis adds 14s of all three load step. Wherein the first step runs 9s, the bending die rotation has complete bending action. When the second step runs 1s, the bending die stop in the 110° position, and when the third step runs 4s, bending die rotated back to initial position.

4.3 Analysis of the Results

The result of the archwire stress is shown in Figure 8, it is shown that stress does not change during 0 to 1.5 seconds, indicating that the archwire bending die and the square archwire has clearance without contact at starting position. Square archwire stress increase gradually from 1.5 to 9 seconds, indicating that the wire has changed gradually from the elastic deformation to the plastic deformation in the process of the stress reaches to a maximum. Stress does not change in 9 seconds to 10 seconds, it has been maintained for one second at a maximum stress state when the bending mold is rotated to 110°. The stress reduces rapidly and in a steady state when bending die turn back to the initial position in 10 seconds to 14 seconds, indicating that square archwire has produced plastic deformation.

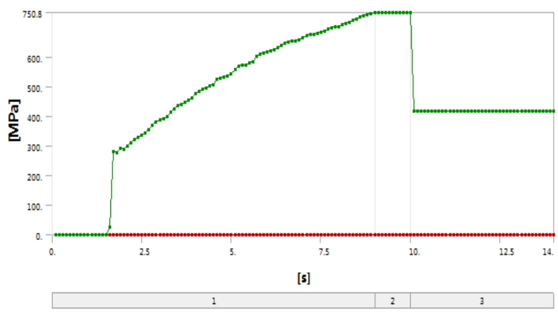

Figure 8. The Tensile Stress Change Curve

Figure 9 is the stress distribution of the archwire comparison chart, the left is the stress distribution diagram in 9.33 seconds when bending die at 110°and archwire stress comes to the biggest. The maximum value is 750.8 MPa. The right is bending die stress distribution diagram when the archwire turn back to the initial position. The stress is 417.1MPa, which is the residual stress of square archwire after bending, and square archwire has produced significant plastic deformation. Comparing the two figures, we can see that the archwire will produce rebound after bending, and bending die rotated 110°.

Meanwhile, the square archwire only bended about 90°, indicating that it is not synchronized about the rotation angle of bending die and the rotation of square archwire.

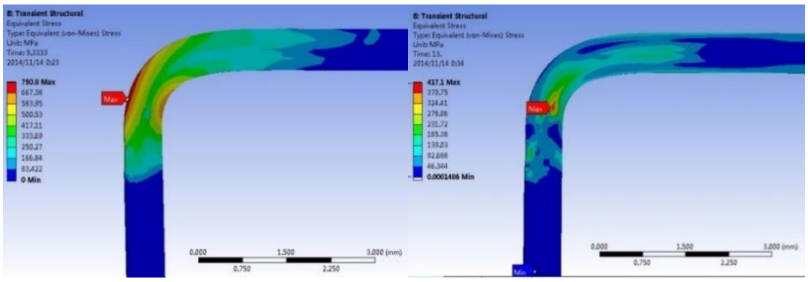

Figure 9. Stress Distribution of Archwire

Figures 10 and 11 is stress and strain distribution diagram of the bending die when the maximum force, and you can see the bending die stress distribution directly. As shown in the figure, the stress is 108.56MPa, and the bending modulus doesn't come to the elastic limit.

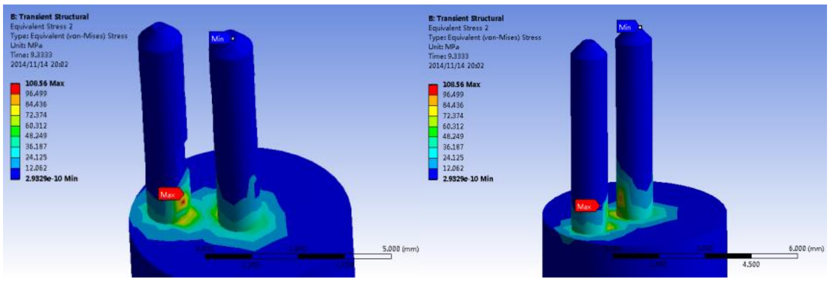

Figure 10. Stress Distribution of Bending Die

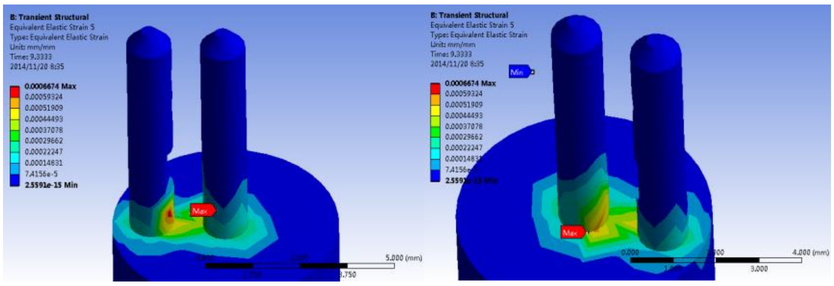

Figure 11. Strain Distribution of Bending Die

5. Conclusions

In this study, based on the finite points derivation algorithm, a 3D mathematical model with rectangular curve is proposed, and simulation analysis has carried on. It can calculate the force distribution of the square archwire and bending die and provide theoretical data for the design of other bending die and the bending of archwire. At the same time, according to this method of analysis, you can see visually the relationship of the angle between the bending die and the bending square archwire. And it's not only can play a supporting role for trajectory planning programs of archwire bending, but also can effectively avoid bending angle incorrectly or the phenomenon that archwire does not reach predetermined angle owing to rebound. Most of all, it provides the foundation for bending curve simulation.

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Acknowledgements

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