# Numerical Simulation and Parameter Optimization of Drawing Forming of 316Ti Stainless Steel Coronary Guidewire

Lin Teng[1], Zezhong Chen[1, a] and Hao Xu[2]

[1]School of Materials and Chemistry, University of Shanghai for Science and Technology, Shanghai 200093, China

[2]Shanghai General Hospital, Shanghai 200080, China

[a]1037972647@qq.com

## Abstract

**The drawing numerical simulation of 316Ti stainless steel coronary guide wire was carried out by DEFORM-3D finite element simulation software. the process parameters of different friction coefficient, drawing speed, die angle, diameter reduction and other process parameters were simulated on the drawing process of coronary guide wire. Influenced by the drawing force, damage and stress-effective. Orthogonal experiments were carried out on the key parameters, and the drawing process parameters were optimized. The results show that the friction coefficient is 0.06, the drawing speed is 2mm/s, the die angle is 12°, and the diameter reduction is 10%, which are the optimal drawing process parameters for 316Ti stainless steel coronary guide wire.**

## Keywords

**Drawing; Finite Element Simulation; Drawing Speed; Friction Coefficient; Die Angle.**

## 1. Introduction

As an important instrument of minimally invasive medical treatment, the guide wire plays the role of first entering blood vessels or other cavity of the human body, and guiding catheters and other instruments into the human body. It plays an indispensable and irreplaceable role in minimally invasive surgery and endovascular treatment[1]. The 316 stainless steel alloy commonly used in the core of coronary guide wire has good mechanical properties and biocompatibility, and is widely used in the field of medical devices[2]. Compared with 316 stainless steel, 316Ti stainless steel adds Ti element on the basis of 316 stainless steel, which not only has the advantages of 316 stainless steel, but also enhances the intergranular corrosion resistance of the material. The grade of 316Ti is 06Cr17Ni12Mo2Ti, and its melting point is 1400°C. In the actual production process, different processing parameters can produce alloys with different microstructures and mechanical properties. Drawing[3] refers to the process of reducing the cross-sectional area and extending the length of the metal material through the mold through the die through the action of the drawing force along a certain direction and track. The drawing operation is simple and feasible, and can effectively improve the surface finish of the wire, refine the grains, and improve the overall performance of the material[4]. The demand for wire materials is constantly increasing, and the importance of drawing technology is also increasing.

With the advent of the information age and the rapid development of computer technology, finite element analysis software, such as Deform, Dynaform, ANSYS, etc., has also been widely used[5]. Through the finite element simulation technology, it is possible to observe the change of the damage coefficient, stress-effective, strain-effective and temperature field of the metal during the forming process[6], predict the possible deformation and defects, and save a lot of time and cost. has great advantages.

Using DEFORM-3D[7] finite element simulation software to simulate the core drawing process of 316Ti stainless steel coronary guide wire, finite element simulation was carried out on the drawing process of 316Ti stainless steel wire, and the friction coefficient, drawing speed, die cone angle and diameter reduction rate were studied[8]. The effects of different process parameters on the drawing process were analyzed, and the changes of drawing force, fracture tendency and Stress-effective[9] were analyzed. Orthogonal experiments were carried out on it, and the optimal process parameters were obtained, which provided a basis for the design of the drawing die[10].

## 2. Finite Element Model Establishment and Simulation Parameters

### 2.1 Basic Assumptions of Finite Element Model

In order to improve the calculation efficiency of finite element analysis and eliminate the interference of secondary factors, it is necessary to simplify the corresponding model. The model assumes the following:

(1) Assuming that the model material of the wire is uniform, its volume remains constant during the drawing process.

(2) Assuming that there is no heat transfer between the wire, the mold and the outside world during the drawing process, the influence of the drawing temperature rise is ignored [11];

(3) It is assumed that the drawing die does not produce elastic deformation during the drawing process.

### 2.2 Establishment of Wire Drawing Geometric Model

Create wire and mold models in SolidWorks software. A wire model with a diameter of 0.35mm and a length of 10mm and a drawing die model of different sizes were drawn by software, and saved and exported as STL format files. Use Deform to import the wire and drawing die separately, name the wire Workpiece, name the drawing die Top Die, and adjust the wire and die to the actual drawing structure, as shown in Figure 1.

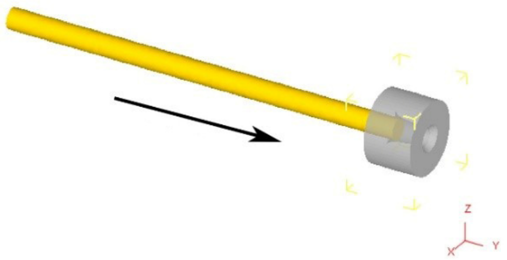

**Figure 1.** The geomotric model

The drawing die drawn by SolidWorks software is shown in Figure 2. The mold size is shown in Figure 2, the diameter of the sizing belt $d$ and the mold cone angle $2\alpha$ are set as variables.

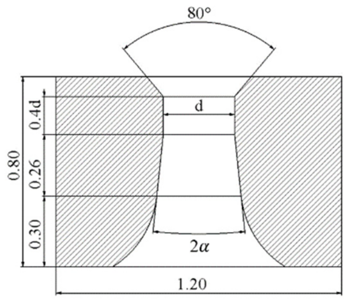

**Figure 2.** Structural dimensions of the drawing die

### 2.3 Mesh Division

Set the 316Ti stainless steel wire model as a plastic body, use relative meshing, set the number of meshes to 32000, and set the ratio of the largest and smallest mesh size to 2, as shown in Figure 3; the drawing die model is set to rigid body without meshing.

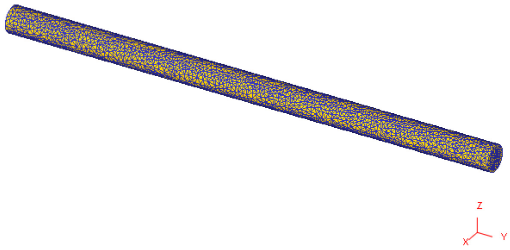

**Figure 3.** The meshing of wire model

### 2.4 Establish the Drawing Material Model

After the model is imported, a material model needs to be created. The researched drawing forming material is 316Ti, and the corresponding material selected in the Deform material library is DIN-X10CrNiMoTi1810. Import the material model into Deform, and set the wire temperature to 550°C.

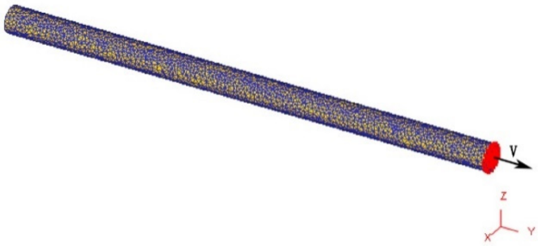

**Figure 4.** Displacement load settings

### 2.5 Simulation Parameter Setting

The process parameters affecting wire drawing are friction coefficient, drawing speed, die angle, and diameter reduction. The specific setting parameters are shown in Table 1. The initial values were set as friction coefficient 0.08, drawing speed 2mm/s, die angle 12°,diameter reduction 15%, and the simulation was studied using the single factor variable method.

**Table 1**. Key Variable Parameters

| Friction coefficient | Drawing speed | Die angle | Diameter reduction |
|---|---|---|---|
| 0.08 | 1mm/s | 6° | 10% |
| 0.09 | 1.5mm/s | 8° | 15% |
| 0.10 | 2mm/s | 10° | 20% |
| 0.11 | 2.5mm/s | 12° | 25% |
| 0.12 | 3mm/s | 14° | 30% |

## 3. Analysis of Finite Element Simulation Results

### 3.1 Simulation Results Analysis of Different Friction Coefficients

Set the friction coefficient to 0.08, 0.09, 0.1, 0.11, 0.12, respectively, and keep the other parameters as the initial values. Figure 5 shows the effect of different friction coefficients on the drawing force. As shown in the figure, when the friction coefficient changes from 0.09 to 0.12, the maximum drawing force continues to rise, and the drawing force is the smallest when the friction coefficient is 0.08.

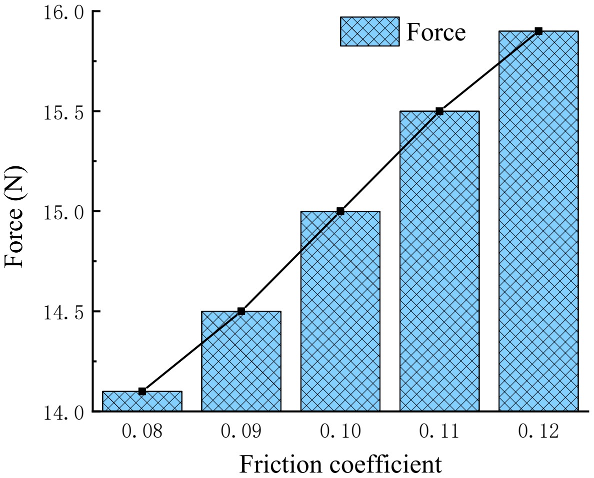

**Figure 5.** Effect of different friction coefficients on drawing force

The maximum Stress-effective and fracture tendency at different friction coefficients are shown in Figure 6. The maximum Stress-effective and damage value both increase under the drawing simulation with friction coefficient 0.11 to 0.12. When the maximum Stress-effective is larger, the maximum damage value also increases correspondingly, and the change law of the two is relatively consistent [12]. If the Stress-effective and damage value are too large, the wire is prone to defects and leads to fracture. As shown in Figure 5, it is more appropriate to choose 0.08 for the friction coefficient.

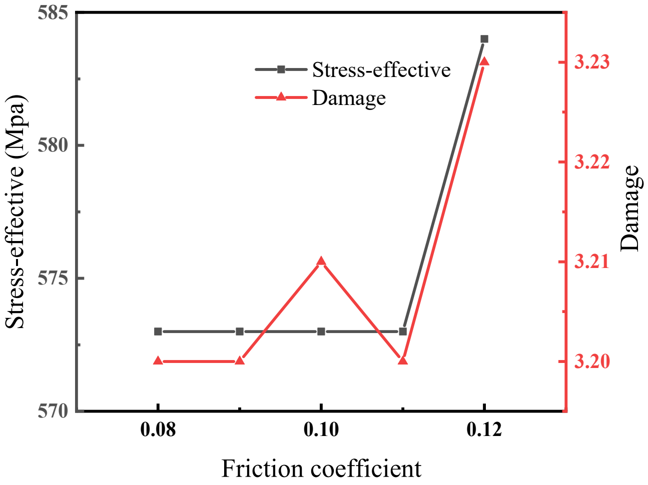

**Figure 6.** Stress-effective and damage at different friction coefficients

### 3.2 Simulation Results Analysis of Different Drawing Speeds

Set the drawing speed to 1mm/s, 1.5mm/s, 2mm/s, 2.5mm/s, 3mm/s respectively. The rest of the parameters remain unchanged from the initial values. The increase of the drawing speed will lead to the continuous increase of the deformation resistance of the wire and the increase of the degree of work hardening. Figure 7 shows the line chart of the maximum drawing force variation corresponding to different drawing speeds. With the increase of drawing speed, the maximum drawing force first decreased and then increased. From 14.6N at a pulling speed of 1mm/s, it decreases to 14N at 2.5mm/s, and then rises rapidly.

The maximum Stress-effective and fracture tendency at different drawing speeds are shown in Figure 8. The maximum value of the Stress-effective first decreases and then increases, and the value of the Stress-effective is the lowest at 2mm/s. However, the damage value fluctuates greatly, and it is the smallest at 2.5mm/s. As shown in Figure 7, it is more appropriate to keep the drawing speed at about 2mm/s.

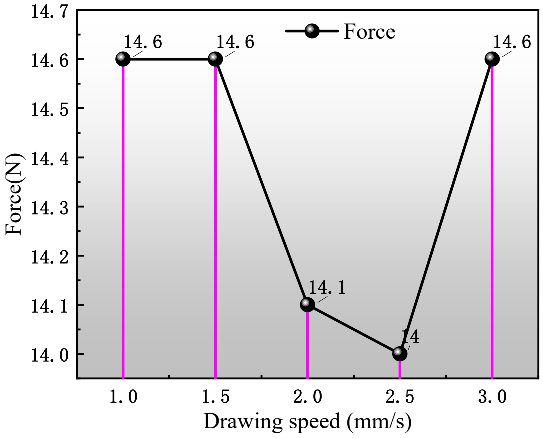

**Figure 7.** The influence of different drawing speeds on the drawing force

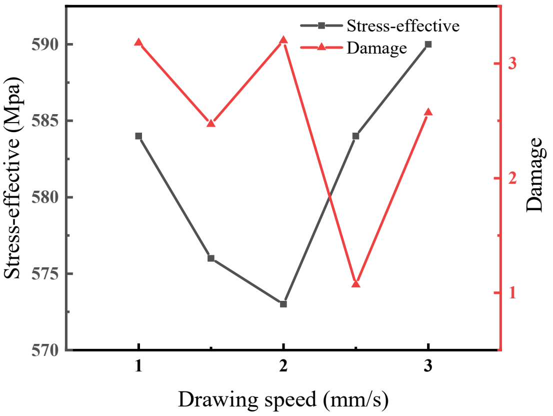

**Figure 8.** Stress-effective and damage at different drawing speeds

### 3.3 Simulation Results Analysis of Different Die Angles

Set the simulation parameters of the mold cone angle to 6°, 8°, 10°, 12°, and 14°, respectively, and keep the rest of the parameters at their initial values. Figure 9 is the effect of different die cone angles on the pulling force. As the cone angle of the die increases, the drawing force first decreases and then increases, and the drawing force is the smallest at 10°, and the value of the drawing force is 10.4N.

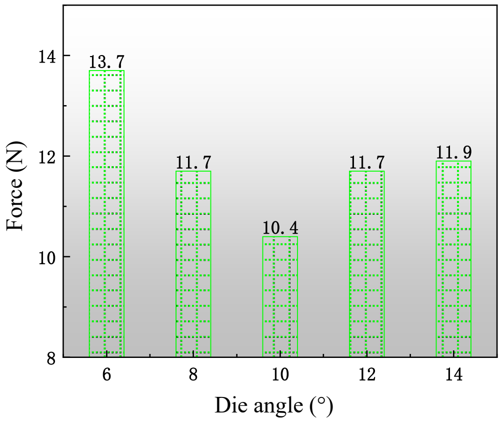

**Figure 9.** Effect of different die angles on drawing force

The maximum Stress-effective and fracture tendency under different die angles are shown in Figure 10. With the increase of the die angle, the Stress-effective value of 316Ti stainless steel increases slightly at first, then decreases sharply, and then increases. Increased die angles result in more severe deformation at the edge of the wire. When the die angle is 12°, the Stress-effective of the mold is the smallest, which is 573Mpa, and the damage is also the smallest. Combined with Figure 9, select 10° or 12° as the best die angle.

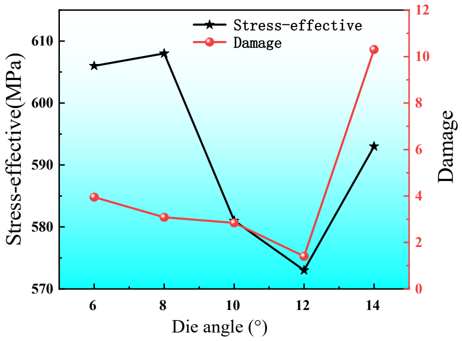

**Figure 10.** Stress-effective and damage at different die angles

### 3.4 Simulation Results Analysis of Different Diameter Reductions

The simulation parameters of the diameter reduction were set to 10%, 15%, 20%, 15%, and 30%, respectively, and the rest of the parameters remained unchanged from the initial values. Figure 11 is the effect of different diameter reductions on the drawing force. With the increase of the diameter reduction, the drawing force gradually increased to 25%, and then decreased to 30%, and the drawing force was minimum when the diameter reduction was 10%.

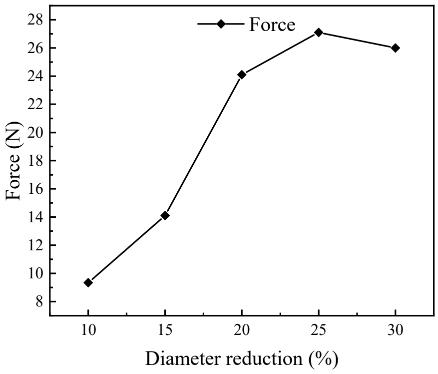

**Figure 11.** Effect of different diameter reduction on drawing force

The maximum Stress-effective and fracture tendency at different diameter reductions are shown in Figure 12. The maximum Stress-effective first decreases and then increases with the diameter reduction, and the fracture tendency increases with the increase of the diameter reduction. When the diameter reduction is 30%, the broken wire occurs. In order to maintain high productivity and safety factor, the diameter reduction range is more suitable below 20%.

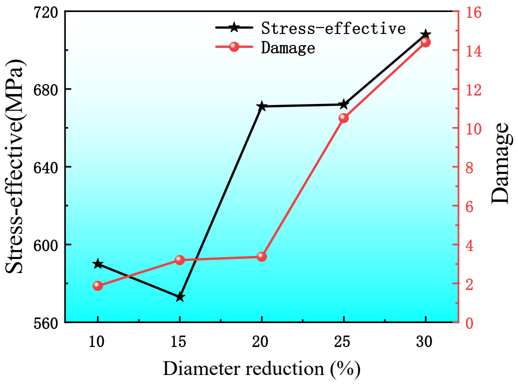

**Figure 12.** Stress-effective and damage at different diameter reduction

# 4. Orthogonal Experimental Design

## 4.1 Levels of Selected Factors

In order to further optimize the drawing process parameters, by referring to the results of single factor analysis, the main factors affecting wire drawing were selected for orthogonal test design: A friction coefficient, B drawing speed, C die angle, D diameter reduction, each factor is set with 3 levels, as shown in Table 2, and the $L_9(3^4)$ orthogonal table is used for simulation analysis, and the results are shown in Table 3.

**Table 2.** Orthogonal experiment factor level table

| Level | A | B/(mm/s) | C/(°) | D(%) |
|---|---|---|---|---|
| 1 | 0.06 | 1 | 8 | 10 |
| 2 | 0.08 | 2 | 10 | 15 |
| 3 | 0.10 | 3 | 12 | 20 |

**Table 3.** Orthogonal experiment simulation scheme and results

| Number | A | B/(mm/s) | C/(°) | D(%) | Drawing force/N |
|---|---|---|---|---|---|
| 1 | 0.06 | 1 | 8 | 10 | 13.2 |
| 2 | 0.06 | 2 | 10 | 15 | 21.8 |
| 3 | 0.06 | 3 | 12 | 20 | 24.9 |
| 4 | 0.08 | 1 | 10 | 20 | 26.6 |
| 5 | 0.08 | 2 | 12 | 10 | 9.94 |
| 6 | 0.08 | 3 | 8 | 15 | 25.1 |
| 7 | 0.10 | 1 | 12 | 15 | 22.1 |
| 8 | 0.10 | 2 | 8 | 20 | 28.1 |
| 9 | 0.10 | 3 | 10 | 10 | 10.7 |

## 4.2 Range Analysis

**Table 4.** Analysis of extreme difference results of orthogonal test(MPa)

| Parameter | A | B | C | D |
|---|---|---|---|---|
| $K_1$ | 59.90 | 61.90 | 66.40 | 33.84 |
| $K_2$ | 61.64 | 59.84 | 59.10 | 69.00 |
| $K_3$ | 60.90 | 60.70 | 56.94 | 79.60 |
| $k_1$ | 19.97 | 20.63 | 22.13 | 11.28 |
| $k_2$ | 20.55 | 19.95 | 19.70 | 23.00 |
| $k_3$ | 20.30 | 20.23 | 18.98 | 26.53 |
| R | 0.580 | 0.686 | 3.153 | 15.253 |
| Optimization | $A_1B_2C_3D_1$ | | | |

Range analysis is one of the orthogonal test methods, and the size of the range R reflects the significance of the factor's influence on the result. Table 4 conducts range analysis on the simulation results of the orthogonal test. Ki and ki respectively represent the sum and average of the analysis index results corresponding to the i (i = 1, 2, 3) level of a certain factor. It can be seen from Table 4 that the order of the range of each factor is: $R_D>R_C>R_B>R_A$, indicating that the diameter reduction rate has the greatest influence on the Stress-effective, followed by the die cone angle, the third is the drawing speed, and the last is the friction factor. It can be obtained from Table 4 that the optimal process scheme is $A_1B_2C_3D_1$, that is, the optimal drawing parameters are: friction coefficient 0.06, drawing speed 2mm/s, die angle 12°, and diameter reduction rate 10%.

### 4.3 Simulation Analysis of Optimization Scheme

Using the optimal drawing process parameters, the 316Ti stainless steel alloy wire drawing simulation analysis was carried out again, and the maximum wire drawing force obtained was 9.27N. Compared with the simulation results of other orthogonal tests, the obtained drawing force is smaller, which proves the validity of the orthogonal test and has important guiding significance for the drawing of 316Ti stainless steel wire.

## 5. Model Validation

In order to ensure that the finite element simulation has a guiding effect on the actual drawing process of 316Ti stainless steel wire, it is necessary to carry out theoretical calculation and experimental verification of the numerical simulation results.

Use Ziber's formula [13] to approximate the drawing force during the wire drawing process for theoretical verification:

$$\boldsymbol{P = K_z F_1 \ln \frac{F_0}{F_1}(1 + f\tan\,\alpha + f\cot\,\alpha)} \tag{1}$$

In the formula: *P* represents the drawing force; *Kz* represents the average tensile strength; *f* represents the friction factor; *α* represents the half-die angle of the die; $F_0$ and $F_1$ represent the cross-sectional area of the blank before and after drawing, respectively.

When the friction coefficient is 0.06, the drawing speed is 2mm/s, the die angle is 12°, and the diameter reduction rate is 10%, the drawing force obtained by calculation is 9.06N. At the same time, a 316Ti stainless steel wire drawing test was carried out to verify the numerical simulation results. The wire rod was pulled through the die at a constant speed by a tensile gauge, and the test results showed that the steady-state pulling force was 9.7N. The simulation result is 9.27N, and the relative error with the test result is 4.4%. The relative error between the test result and the calculation result is 6.6%. The reliability of the established finite element model is proved, and it provides an effective reference for the design of the actual drawing die and wire drawing.

## 6. Conclusion

The drawing process of 316Ti stainless steel wire was simulated by DEFORM-3D, and the influence of different parameters on the drawing process was analyzed. The result is as follows:

(1) The main parameters of 316Ti stainless steel wire drawing simulation was analyzed by single factor, and the optimal range of process parameters suitable for wire drawing was determined.

(2) Based on the single factor analysis, the influence of different simulation parameters on the drawing force was studied through the orthogonal test method, and the results were analyzed by range, and the optimal drawing process parameters for 316Ti stainless steel wire were obtained: friction coefficient 0.06, The drawing speed is 2mm/s, the die angle is 12°, and the diameter reduction rate is 10%.

(3) Theoretical verification and experimental verification are carried out on the optimal drawing process parameters. The relative error between the experimental results and the simulation results is 4.4%, and the relative error between the calculation results is 6.6%. The reliability of the established

finite element model is proved, and it provides an effective reference for the design of the actual drawing die and wire drawing.

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