Effect of Forming Parameters on Profile Thinning of Flexible 3D Multi-Point Stretch Bending

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Abstract: The ABAQUS finite element simulation software is used to simulate the flexible multi-point three-dimensional stretch bending process of aluminum profiles. The effect of process parameters on the web thickness of rectangular profile in flexible multi-point three-dimensional stretch bending is studied by orthogonal experiment and range analysis. The process parameters used in the experiments include pre-stretching value, post-stretching value, the number of multi-point dies and friction coefficient. The optimal combination of process parameters is obtained by numerical simulation and experimental verification. When the aluminum profile is completed flexible multi-point stretch bending according to the best parameters, the thickness thinning of outer web and inner web is the smallest. The experimental result is closed to the numerical simulated results. The effectiveness of the numerical simulation is verified by the corresponding experimental methods.

Keywords: aluminum profile; bending-stretch; flexible manufacturing; thinning; simulation; multi-point

1. Introduction

Due to the rapid development of the automobile and high-speed rail industry in recent years, people pay more and more attention to the lightweight design of the structure [1]. In this situation, reducing the weight of cars and high-speed trains cannot only decrease energy consumption and alleviate the growing energy crisis, but also lessen waste emissions. The aluminum is widely used in aerospace, rail vehicles and automobile manufacturing because of its low density, high strength and easy recycling.

The rapid development of the manufacturing industry has made the demand for parts more diversified. Therefore, the stretch bending process of profiles has been widely used, and it has always been a hot issue in the field of material processing. Researchers from various countries have done a lot of research on this process. In the manufacturing process, the distribution of plate thickness and the maximum thinning rate have a great impact on product quality. Nguyen and Trung found that the change of thickness depends on input parameters such as process parameters, die geometry and workpiece material, and determined the relationship between thickness distribution and input parameters [2]. Hussain et al. proposed a novel method to test the thinning limit of the sheet in incremental forming, and verified the thickness distribution by using the law of cosine. Based on the law of cosine, a mathematical expression for predicting the thickness distribution along the depth of the part and the thinning limit of the thin plate is derived. The proposed method can test the thinning limit of sheet metal while reducing processing time and cost [3].

Yang et al. analyzed the principle of thickness deformation in the process of single-point incremental forming, fitted a high-precision deformation zone thickness prediction formula based on the simulation results, and proposed a method to control the thinning rate by changing the forming trajectory [4]. The local thinning below the die entry radius largely depends on the plate die friction during sliding contact. Taleff et al. found that increasing...
the sheet-die friction at the die entry radius can reduce the compressive stress generated by the sheet and reduce local thinning [5].

The traditional stretch-bending method is only limited to the two-dimensional deformation of the profile. If you want to process the three-dimensional profile, you must manually twist the profile after the two-dimensional deformation. This is time-consuming and labor-intensive, and the scrap rate is extremely high [6,7]. Therefore, it is especially important to explore new processing methods to implement three-dimensional deformation of the profile. In order to reduce the production cost and shorten the production cycle in three dimensional stretch bending, a new flexible multi-point three-dimensional (FMD) stretch bending technology has been developed [8,9]. In this method, traditional integral mold has been replaced by discrete multi-point dies, thus the mold profile is reconfigurable. This new technology inherits the advantages of multi-point forming and it can control the impact of springback. In addition, this advanced forming technology can save the cost of die manufacturing, and make it possible to shorten the development cycle [10].

Profiles is formed in horizontal plane and vertical plane respectively, therefore, the FMD stretch bending is more diversified than the conventional process according to the increased vertical bending of the profile during the process [11].

The stages of FMD stretch bending are as following. Firstly, adjust the position parameters of each flexible unit in multi-point dies to the target position in order to adjust the profile shape [12,13]. Under the action of axial tension, the profile is pre-stretched to a plastic state, which can effectively reduce the springback of the forming parts. This stage is called pre-stretching (pre). Then, the profile gradually closed to the die in horizontal plane [14,15]. This stage is named horizontal bending. Once the workpiece fully contacts with the multi-point dies, the hydraulic loads are applied to form workpiece in the vertical direction. This stage is called vertical bending. At last, profile along the tangential direction to make up stretch after the three directional bending, which can also effectively ensure the forming precision of profile parts. This stage is called post-stretching (po) [16].

In the process of FMD stretch bending, the profile is made of light high-strength aluminum alloy with large deformation resistance and poor plasticity. There are few studies on the thinning change of profile after three-dimensional deformation. Therefore, the study of profile thinning during the FMD stretch bending has certainly guiding significance for the actual production.

2. Materials and Methods

2.1. Material Properties and Behavior

Aluminum alloy materials have good mechanical properties and low density, and are widely used in railways, automobiles and other fields. In the finite element model, the material used was a 6005A aluminum alloy. In order to accurately describe the change of cross-sectional area during large deformation, it is necessary to use true strain ($\varepsilon_{\text{true}}$) and true stress ($\sigma_{\text{true}}$).

Rectangular profile with length of 3600 mm, blank section size is $40 \times 30$ mm, wall thickness is 2 mm, bending part length is 2840 mm, yield strength $\sigma_y = 260$ Mpa, elastic modulus $E = 70,000$ Mpa, Poisson’s ratio $\nu = 0.3$, density $\rho = 2710$ kg m$^{-3}$, friction coefficient $\mu = 0.1$–0.15, tensile strength $\sigma_b = 328$ MPa and assumed isotropic. Material mechanical properties follow the von Mises yield criterion and the Prandtl-Ruess flow rule. The constitutive stress-strain relationship of the material is expressed as:

$$ \sigma = \begin{cases} E\varepsilon, & \varepsilon \leq \varepsilon_{\text{el,lim}} \\ K\varepsilon^n, & \varepsilon > \varepsilon_{\text{el,lim}} \end{cases} $$  \hspace{1cm} (1)$$

where, $\varepsilon_{\text{el,lim}}$ is the elastic limit strain, $K$ is the strength coefficient, $n$ is the exponential strain-hardening parameter.
2.2. Model of FE Simulation

The numerical simulation of FMD stretch bending is performed using ABAQUS/Explicit dynamic. The geometry of the profile and the forming process of profile are symmetrical, the 1/2 model is used for analysis in order to shorten the calculation time and improve the efficiency. The model consists of profiles, clamps, multi-point dies and limit screws. The clamps are used to apply tension and bending moments. The limit screw is designed to limit the displacement of the dies during the vertical bending process. The FMD stretch bending process is a three-dimensional simulation problem, which can cause grid distortion. According to the principle of solid element selection, the solid element C3D8R can be selected for the aluminum profile. C3D8R is a hexahedral linearly reduced integral solid element with 8 nodes for large strain and deformation. In the model, C3D8R solid element is enabled with hourglass control. Multi-point dies, limit screws and clamps are modeled using the rigid element R3D4, since the rigid element is mainly used to simulate very strong components that can be either fixed or moving. Additionally, the size of the rigid body element adopts the default setting, thus the calculation time can be shorten significantly. The classical Coulomb model is chosen to represent the interface friction condition $\sigma_t = \mu \sigma_n$. Tangential friction stress is represented by $\sigma_t$. Friction coefficient is represented by $\mu$. Positive pressure on the contact surface is represented by $\sigma_n$. The assembled FMD stretch bending model is shown in Figure 1. The horizontal bending angle is 25° and the vertical bending angle is 15°. The trajectory of the clamp is shown in Figure 2.

![Finite element assembly model](image1)

**Figure 1.** Finite element assembly model.

![The trajectory of the clamp](image2)

**Figure 2.** The trajectory of the clamp. (a) Horizontal bending. (b) vertical bending.
horizontal bending.

\[
\Delta z = (L + \delta_{pre}) - \left\{ R \sin \alpha + \left[ (L + \delta_{pre}) - Ra \right] \cos \alpha \right\} 
\]

vertical bending:

\[
\Delta y = R(1 - \cos \alpha) + \left[ (L + \delta_{pre}) - Ra \right] \sin \alpha 
\]

post stretching:

\[
x = \delta_{po} \sin \beta \\
y = \delta_{po} \cos \beta \sin \alpha \\
z = \delta_{po} \cos \beta \cos \alpha 
\]

where, \( L \) is the length of the profile. \( \delta_{pre} \) is the amount of pre-stretching. \( R \) is the horizontal bending radius. \( \alpha \) is the horizontal bending angle. \( r \) is the vertical bending radius. \( \beta \) is the vertical bending angle. \( L_1 \) represents the length of the profile projected in the vertical plane. \( L_2 \) is the projection length of the contact part between the profile and the multi-point dies in the vertical plane. \( \delta_{po} \) is the amount of post-stretching.

2.3. Calculation of the Rectangular Profile Thinning

Thinning amount can be characterized by the change of the distance between the outer centerline of outer web and the inner centerline of outer web, and the distance between outer centerline and inner centerline of inner web respectively. The sectional view of the rectangular profile along the profile is as shown in Figure 3. The aluminum profile is meshed in the ABAQUS software. The original coordinates of the inner and outer adjacent points of the outer web are \((x_i, y_i, z_i), (x_{i+1}, y_{i+1}, z_{i+1})\) (\(i = 0, 1, 2, 3 \cdots n\)). The coordinates after deformation are \((x'_i, y'_i, z'_i), (x'_{i+1}, y'_{i+1}, z'_{i+1})\). Taking \(A(x_0, y_0, z_0), B(x_1, y_1, z_1)\) as an example, the coordinates after deformation are \(A(x'_0, y'_0, z'_0), B(x'_1, y'_1, z'_1)\). According to the distance between two points in space, the distance between the original \(AB\) is:

\[
d_0 = \sqrt{(x_0 - x_1)^2 + (y_0 - y_1)^2 + (z_0 - z_1)^2}
\]
Distance between $AB$ after deformation is:

$$d_1 = \sqrt{(x'_1 - x'_0)^2 + (y'_1 - y'_0)^2 + (z'_1 - z'_0)^2} \quad (12)$$

The spatial equation of the inner centerline of the outer web can be determined by the following formula:

$$\begin{cases} F(x, y, z) = 0 \\ G(x, y, z) = 0 \end{cases} \quad (13)$$

Point $B$ is on the inner centerline of outer web, and the normal plane of the point is:

$$\left| \begin{array}{ccc} F_y & F_z & (x - x'_0) \\ G_y & G_z & (y - y'_0) \\ F_x & G_x & (z - z'_0) \end{array} \right| = 0 \quad (14)$$

Its normal vector is

$$\vec{a} = \left( \begin{array}{c} F_y \\ G_y \\ F_z \\ G_z \\ F_x \\ G_x \\ F_y \\ G_y \end{array} \right) \quad (15)$$

$$\vec{AB} = (x'_1 - x'_0, y'_1 - y'_0, z'_1 - z'_0) \quad (16)$$

$$|\vec{a}| = \sqrt{F_y^2 + F_z^2 + F_x^2 + G_y^2 + G_z^2 + G_x^2} \quad (17)$$

$$|\vec{AB}| = \sqrt{(x'_1 - x'_0)^2 + (y'_1 - y'_0)^2 + (z'_1 - z'_0)^2} \quad (18)$$

$$\cos(\vec{a}, \vec{AB}) = \frac{\vec{a} \cdot \vec{AB}}{|\vec{a}| \cdot |\vec{AB}|} \quad (19)$$

$$\theta = \arctan \cos(\vec{a}, \vec{AB}) \quad (20)$$

The thickness on the inner side of the outer web is

$$d_2 = d_1 \cos(\frac{\pi}{2} - \theta) = d_1 \sin \theta \quad (21)$$

The thinning amount between the two points $A$ and $B$ of the rectangular web is $\triangle_1 = d_0 - d_2$, and the maximum value of the thinning amount of the outer web of the profile is $\triangle_{\text{max}} = \max \{ \triangle(i+1) \}$. For the same reason, maximum value thinning amount of the inner web is $\triangle_{\text{max}}' = \max \{ \triangle'(i+1) \}$.

3. Results and Discussion
3.1. Orthogonal Experiment and Range Analysis for Best Parameters of Aluminum Profiles in the Process of Three-Dimensional Pulling

In order to find the proper process parameters that minimize the degree of profile thinning in the FMD stretch bending process, the orthogonal experiment was used to predict the pre-stretching amount, post-stretching amount, the number of multi-point dies, and the friction coefficient by the finite element simulation software. The comprehensive discussion and analysis of the values of these parameters is essential. Additionally, the range method is used to discuss the primary and secondary levels of effect and find the best combination of processing parameters. The experimental factors and levels of this orthogonal experiment are shown in Table 1, and the orthogonal experiments are shown in Table 2. The number of flexible units of the multi-point dies is represented by $N$. The friction coefficient is represented by $\mu_s$. 
Table 1. Experimental factors and levels.

| Level | δ_{pre} (%) | δ_{p0} (%) | N   | μ_s |
|-------|-------------|-------------|-----|-----|
| 1     | 0.8         | 0.8         | 7   | 0.1 |
| 2     | 1           | 1           | 10  | 0.12|
| 3     | 1.2         | 1.2         | 12  | 0.15|

Table 2. Orthogonal table and simulation experiment profile thinning results.

| Group | N   | δ_{pre} (%) | δ_{p0} (%) | μ_s | Horizontal Bending | Vertical Bending | Post-Stretching |
|-------|-----|-------------|-------------|-----|--------------------|-----------------|-----------------|
|       |     |             |             |     | △_{max} | △'_{max} | △_{max} | △'_{max} | △_{max} | △'_{max} |
| 1     | 7   | 0.8         | 0.8         | 0.1 | 0.043    | 0.04    | 0.095   | 0.093   | 0.142   | 0.136   |
| 2     | 7   | 1           | 1           | 0.12| 0.041    | 0.028   | 0.099   | 0.095   | 0.142   | 0.133   |
| 3     | 7   | 1.2         | 1.2         | 0.15| 0.038    | 0.034   | 0.065   | 0.062   | 0.153   | 0.133   |
| 4     | 10  | 1           | 1.2         | 0.1 | 0.031    | 0.029   | 0.051   | 0.047   | 0.082   | 0.072   |
| 5     | 10  | 1.2         | 0.8         | 0.12| 0.031    | 0.027   | 0.064   | 0.0478  | 0.127   | 0.098   |
| 6     | 10  | 0.8         | 1           | 0.15| 0.029    | 0.0242  | 0.055   | 0.035   | 0.121   | 0.097   |
| 7     | 12  | 1.2         | 1           | 0.1 | 0.027    | 0.027   | 0.077   | 0.073   | 0.120   | 0.097   |
| 8     | 12  | 0.8         | 1.2         | 0.12| 0.028    | 0.027   | 0.076   | 0.073   | 0.119   | 0.093   |
| 9     | 12  | 1           | 0.8         | 0.15| 0.025    | 0.022   | 0.067   | 0.065   | 0.111   | 0.086   |

The profile thinning degree under horizontal bending stage, the vertical bending stage, and post-stretching stage are calculated respectively. The effect of each processing parameter on profile thinning during the three-dimensional bending process is studied by the range method. The range method can be used to measure the effect level of each processing parameter on the profile thinning during the stretch bending process, and the effect level is greater with expanded range.

The specific method is as follows (the following is an example of the calculation of the factor pre-stretching amount δ_{pre}):

1. Calculate the comprehensive average of each level of each factor. For example, first, the sum of the data corresponding to the ith level of δ_{pre} is recorded as K_{iδ_{pre}} (i = 1, 2, 3), and the arithmetic mean value is calculated as k_{iδ_{pre}}.

2. Calculate the range R of the composite mean of each factor and distinguish the primary and secondary factors. Calculate as follows:

\[ R_{δ_{pre}} = \max\{k_{iδ_{pre}}\} - \min\{k_{iδ_{pre}}\} \quad (23) \]

\[ r_{δ_{pre}} = R_{δ_{pre}} / 3 \quad (24) \]

For example: thinning of the outer web during horizontal bending are: K_{1δ_{pre}} = 0.1, K_{2δ_{pre}} = 0.033, K_{3δ_{pre}} = 0.097, K_{4δ_{pre}} = 0.032, K_{5δ_{pre}} = 0.096, K_{6δ_{pre}} = 0.032, R = 0.001. The range analysis method can be used to see the effect degree of different processing stages of the rectangular section processing parameters. The greater difference has determined the greater effect of the processing parameters, and vice versa. The data obtained by the range analysis method is shown in Table 3.

It can be seen from the calculation data of Table 3 that the effect degree of each process parameter is different for different processing processes. And the effect on outer web thinning is: \( r_{δ_{pre}} = 0.028, r_{δ_{p0}} = 0.013, r_N = 0.066, r_{μ_s} = 0.034 \). Effect on inner web thinning: \( r_{δ_{pre}} = 0.026, r_{δ_{p0}} = 0.022, r_N = 0.094, r_{μ_s} = 0.028 \). According to the data analysis, for the thinning of outer and inner webs, the order of the processing parameters is: \( N > μ_s > δ_{pre} > δ_{p0} \). The number of multi-point dies has the greatest effect on the thinning, and the effect of post-stretching on thinning is minimal.
Table 3. Range analysis data.

| Index | $\delta_{pre}$ | $\delta_{p0}$ | N   | $\mu_s$ | $\triangle_{max}$ | $\delta_{pre}$ | $\delta_{p0}$ | N   | $\mu_s$ |
|-------|----------------|----------------|-----|---------|-------------------|----------------|----------------|-----|---------|
| Horizontal bending | $k_1$ | 0.033 | 0.033 | 0.041 | 0.033 | $k_1$ | 0.030 | 0.030 | 0.034 | 0.031 |
|         | $k_2$ | 0.032 | 0.032 | 0.030 | 0.033 | Horizontal bending | $k_2$ | 0.026 | 0.026 | 0.027 | 0.027 |
|         | $k_3$ | 0.032 | 0.032 | 0.027 | 0.031 | $k_3$ | 0.032 | 0.030 | 0.025 | 0.027 |
|         | $R$   | 0.001 | 0.001 | 0.014 | 0.002 | $R$   | 0.006 | 0.004 | 0.009 | 0.004 |
| Vertical bending | $k_1$ | 0.075 | 0.075 | 0.086 | 0.074 | $k_1$ | 0.067 | 0.069 | 0.083 | 0.071 |
|         | $k_2$ | 0.072 | 0.076 | 0.056 | 0.080 | Vertical bending | $k_2$ | 0.069 | 0.068 | 0.043 | 0.072 |
|         | $k_3$ | 0.069 | 0.068 | 0.073 | 0.062 | $k_3$ | 0.061 | 0.061 | 0.070 | 0.054 |
|         | $R$   | 0.006 | 0.008 | 0.03  | 0.018 | $R$   | 0.008 | 0.008 | 0.04  | 0.018 |
| Post-stretching | $k_1$ | 0.127 | 0.0422 | 0.146 | 0.115 | $k_1$ | 0.109 | 0.109 | 0.134 | 0.102 |
|         | $k_2$ | 0.112 | 0.0426 | 0.11  | 0.129 | Post-stretching | $k_2$ | 0.097 | 0.109 | 0.089 | 0.108 |
|         | $k_3$ | 0.133 | 0.0393 | 0.117 | 0.128 | $k_3$ | 0.109 | 0.099 | 0.092 | 0.105 |
|         | $R$   | 0.021 | 0.004 | 0.036 | 0.014 | $R$   | 0.012 | 0.01  | 0.045 | 0.006 |

3.2. The Effect of Various Process Parameters on Thinning

In order to explore the effects of various process parameters on profile thinning respectively, numerical simulation of the parameters is shown in Table 4. And the number of multi-point dies effect on rectangular profiles thinning is shown in Figure 4.

As can be seen from Figure 4a, with the increase of the number of multi-point dies, the thinning degree of the outer web of the rectangular profile decreases sharply. At the end of the horizontal bending, vertical bending and post-stretching process, the same law is observed. This is because the more the number of dies, the closer the die surface is to the overall die, and the better the forming effect of the profile. Similarly, the thinning degree of the inner web of the rectangular profile decreases with the increase of the number of dies. However, from the comparison of Figure 4a,b, it can be concluded that the thinning amount of the inner web is less than that of the outer web. This is due to the fact that the outer surface of the profile is stretched and the inner surface is compressed during the stretch-bending forming process.

The effect of friction coefficient on thinning is shown in Figure 5. It can be seen from Figure 5a,b that after the horizontal bending, the friction coefficient has little effect on the thinning of the outer and inner webs of the profile, which can be ignored. The amount of thinning of the outer web and inner web of the profile increases with the increase of the friction coefficient during the vertical bending forming and the post-stretching forming process, respectively. This is because the greater the friction coefficient, the greater the friction force in the forming process, which hinders the forming process. Therefore, it is necessary to increase the stretching amount to meet the forming effect of the profile, resulting in more serious profile thinning.

Post-stretching is the last process of FMD stretch-bending forming. Therefore, in the horizontal bending forming and vertical bending forming process, the amount of post-stretching will not affect the thickness changes of the outer web and the inner web. Figure 6 shows the effect of post-stretching amount on the thickness change of rectangular profile after post-stretching forming. It can be seen from Figure 6a,b that when the amount of post-stretching increases from 0.8% to 1.2% of the profile length, the thickness reduction of the outer web increases from 0.122 mm to 0.152 mm, and the thickness reduction of the inner web increases from 0.098 mm to 0.12 mm. Therefore, the greater the amount of post-stretching, the more serious the thinning of the profile.
The effect of the number of multi-point dies on thinning is shown in Figure 4a. With the increase of the number of multi-point dies, the thinning of the outer web of the rectangular profile decreases sharply. At the end of the horizontal bending, vertical bending and post-stretching forming, it can be seen from Figure 6a, b that when the amount of stretching amount on the thickness change of rectangular profile is 10, 1, 0.8, 0.15. This is because the greater the friction coefficient, the greater the amount of the inner web is less than that of dies. However, from the comparison of Figure 5, it can be concluded that the thinning degree of the outer web of the rectangular profile decreases with the increase of the number of multi-point dies. Therefore, in the overall die, and the better the forming effect of the profile. Similarly, the thinning degree of the inner web of the rectangular profile decreases with the increase of the number of dies. However, from the comparison of Figure 5, it can be concluded that the thinning degree of the inner web of the rectangular profile decreases with the increase of the number of dies.

Table 4. Numerical simulation processing parameters settings.

| Group | Parameter | (N) | \(\delta_{pre}(\%)\) | \(\delta_{po}(\%)\) | \(\mu_s\) |
|-------|-----------|-----|----------------------|----------------------|-----------|
| 1     | \(\delta_{pre}\) | 10  | 1                    | 0.8                  | 0.15      |
|       | \(\delta_{po}\) | 7   | 1                    | 0.8                  | 0.15      |
|       | \(\mu_s\) | 12  | 1                    | 0.8                  | 0.15      |
| 2     | \(\delta_{pre}\) | 10  | 1                    | 0.8                  | 0.15      |
|       | \(\delta_{po}\) | 10  | 0.8                  | 0.8                  | 0.15      |
|       | \(\mu_s\) | 10  | 1.2                  | 0.8                  | 0.15      |
| 3     | \(\delta_{pre}\) | 10  | 1                    | 0.8                  | 0.15      |
|       | \(\delta_{po}\) | 10  | 1                    | 1.2                  | 0.15      |
|       | \(\mu_s\) | 10  | 1                    | 1                    | 0.15      |
| 4     | \(\delta_{pre}\) | 10  | 1                    | 0.8                  | 0.12      |
|       | \(\delta_{po}\) | 10  | 1                    | 0.8                  | 0.15      |
|       | \(\mu_s\) | 10  | 1                    | 0.8                  | 0.1       |

Figure 4. The effect of the number of multi-point dies on thinning. (a) Outer web. (b) Inner web.

Figure 5. Effect of friction coefficient on thinning. (a) Outer web. (b) Inner web.
post-stretching increases from 0.8% to 1.2% of the profile length, the thickness reduction of the outer web increases from 0.122 mm to 0.152 mm, and the thickness reduction of the inner web increases from 0.098 mm to 0.12 mm. Therefore, in order to obtain more accurate conclusions, it is necessary to narrow the experimental interval.

The result in 3.2 is based on the analysis of thinning degree between the outer and inner webs. The smaller value has exhibited the better forming effect of profile. Therefore, it is determined that the number of multi-point dies is $N = 12$ and the friction coefficient is 0.1. This combination can be represented by $N3f1$. When the pre-stretching amount is 0.8% and the post-stretching amount is 1%, the effect of thinning is not obviously. The conclusions which are obtained by orthogonal test and range analysis are not necessarily in full compliance with the actual situation of numerical simulation. Therefore, in order to obtain more accurate conclusions, it is necessary to narrow the experimental interval. In order to verify the optimal combination, it is necessary to compare the $k_i$ between pre-stretching amount and the post-stretching amount. The $k_i$ value of the pre-stretch and post stretching (the smaller $k_i$ value represents the lower effect degree of the level), the two process parameters of the pre-stretching amount and the post-stretching amount are respectively numerically simulated and verified by experiments. A total of four combina-

### Figure 6. Effect of the post-stretching on thinning. (a) Outer web. (b) Inner web.

The effect of the pre-stretching on thinning is as shown in Figure 7. The thinning degree of the outer web and the inner web increases with the increasing of the pre-stretching amount. When the pre-stretching amount is 0.8% after completion of post-stretching, the outer web is thinned by 0.12 mm and the inner web is thinned by 0.094 mm.

### Figure 7. Effect of pre-stretching on thinning. (a) Outer web. (b) Inner web.

In general, in the FMD stretch-bending process, the thickness of the profile after horizontal bending is much smaller than that after vertical bending. The thinning of the profile after the post-stretching forming is the largest. And no matter which forming stage the profile is in, the thinning degree of the outer web is always greater than that of the inner web.

### 3.3. Process Parameter Optimization and Experimental Verification

3.3. Process Parameter Optimization and Experimental Verification

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tion experiments, the combination of pre-stretching amount and post-stretching amount is shown in Table 5. The numerical simulation results of four groups of experiments with pre-stretching amount and post-stretching amount are shown in Table 6. The results show that the outer and inner webs of experiment $\delta_{3N3\mu_1}$ have the lowest thinning degree. The number of multi-point dies 12, the friction coefficient 0.1, and the pre-stretching amount 1%, post-stretching 1% are the best combination of process parameters.

Table 5. Optimal combination design of process parameters of pre-stretching amount and post-stretching amount.

| Forming Process   | $\delta_{pre}$ | $\delta_{po}$ | Combination       |
|-------------------|----------------|---------------|-------------------|
| Horizontal bending $\Delta_{max}$ | $k_3 < k_2 < k_1$ | $k_3 = k_1 < k_2$ | $\delta_{pre} \delta_{po} / \delta_{pre} \delta_{po} 3$ |
| Vertical bending  $\Delta_{max}$  | $k_3 < k_2 < k_1$ | $k_3 < k_1 < k_2$ | $\delta_{pre} \delta_{po} 3$ |
| Post – stretching $\Delta_{max}$  | $k_2 < k_1 < k_3$ | $k_2 < k_1 < k_3$ | $\delta_{pre} \delta_{po} 2$ |
| Horizontal bending $\Delta_{max}'$ | $k_2 < k_1 < k_3$ | $k_2 < k_1 < k_3$ | $\delta_{pre} \delta_{po} 2$ |
| Vertical bending  $\Delta_{max}'$  | $k_3 < k_1 < k_2$ | $k_3 < k_2 < k_1$ | $\delta_{pre} \delta_{po} 3$ |
| Post – stretching $\Delta_{max}'$  | $k_2 < k_1 = k_3$ | $k_3 < k_1 = k_2$ | $\delta_{pre} \delta_{po} 3$ |

Table 6. Numerical simulation results of four combinations.

| Experiments          | Thinning of Outer Web (mm) | Thinning of Inner Web (mm) |
|----------------------|-----------------------------|----------------------------|
| $\delta_{pre} \delta_{po} 2N3\mu_1$ | 0.094                      | 0.086                      |
| $\delta_{pre} \delta_{po} 3N3\mu_1$ | 0.127                      | 0.097                      |
| $\delta_{pre} \delta_{po} 3N3\mu_1$ | 0.124                      | 0.092                      |
| $\delta_{pre} \delta_{po} 2N3\mu_1$ | 0.122                      | 0.089                      |

4. The FMD Stretch Bending Experiments

In the experiments, the FMD stretch bending machine is shown in Figure 8a. Figure 8b shows the experimental parts of rectangular profile. The material used in the experiment is 6005A aluminum alloy. The processing parameters of the FMD stretch bending machine are set according to $\delta_{pre} \delta_{po} 2N3\mu_1$, $\delta_{pre} \delta_{po} 3N3\mu_1$, $\delta_{pre} \delta_{po} 2N3\mu_1$, and $\delta_{pre} \delta_{po} 2N3\mu_1$ respectively.

![Figure 8](image-url)
As shown in Figure 9a,b, the thickness of the formed rectangular profile is measured with a thickness gauge. Due to the large length of the profile, the thickness gauge cannot measure each position of the profile. Therefore, as shown in Figure 9c, we divide the profile, cut the profile with a wire cutting machine, measure the thickness of the outer and inner webs of the middle section of each part of the profile, and get the thickness change of the profile after each process.

![Figure 9](image)

**Figure 9.** Thickness measurement experiment: (a) the thickness gauge, (b) the method of operation, (c) Display of divided areas and measuring points.

Taking experiment N3μs1δpre2δpo2 as an example, the thickness of profiles after horizontal bending, vertical bending and post-stretching forming are measured respectively, and the maximum thinning value is calculated. As shown in Tables 7 and 8, it is necessary to measure three times and take the average value of the measurement results. The remaining three groups of experiments also need to be measured in sequence.

**Table 7.** The thickness measurement results of the outer web of experiment N3μs1δpre2δpo2.

| δmax        | First  | Second | Third  | Average Value |
|-------------|--------|--------|--------|---------------|
| Horizontal  | 0.025  | 0.024  | 0.024  | 0.024         |
| Vertical    | 0.054  | 0.056  | 0.055  | 0.055         |
| Post-stretching | 0.102 | 0.099  | 0.101  | 0.101         |

**Table 8.** The thickness measurement results of the inner web of experiment N3μs1δpre2δpo2.

| δmax′       | First  | Second | Third  | Average Value |
|-------------|--------|--------|--------|---------------|
| Horizontal  | 0.019  | 0.021  | 0.021  | 0.020         |
| Vertical    | 0.051  | 0.052  | 0.049  | 0.051         |
| Post-stretching | 0.088 | 0.086  | 0.087  | 0.087         |

The experimental measurement results are shown in Figure 10. In each process stage, the thinning degree of the profile processed according to the N3μs1δpre2δpo2 parameter is smallest. Outer web is thinned by 0.101 mm. The inner web is thinned by 0.087 mm, and the results are close to the finite element simulation results in Table 6. Therefore, the finite element model can predict the thinning degree of the profile.
The degree of thinning of the outer web and inner web of the rectangular profile decreases significantly with the increase of the number of dies, and gradually increases with the increase of the friction coefficient and the pre-stretching amount. The amount of post-stretching only affects the final forming result. As the amount of post-stretching increases, the thickness of the outer web and the inner web also shows an increasing trend. And the degree of thinning of the outer web of the profile is greater than that of the inner web.

2. Using orthogonal test and range analysis, it is determined that the number of multipoint dies has the greatest effect on the thinning of the profile during FMD stretch bending, and the amount of post-stretching is the smallest. The combination of process parameters that minimizes the degree of thinning of the profile during the bending process is \( N = 12, \mu_s = 0.1, \delta_{pre} = 1\%, \) and \( \delta_{po} = 1\% \).

3. Based on the abstraction and reasonable simplification of the forming process principle, the finite element simulation software ABAQUS is used to simulate the FMD stretch bending process. The simulation results are basically consistent with the experimental results, and the trend is also consistent.

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