Research Article

Forming Parameters on Friction during Single Point Incremental Forming

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Friction in the single point incremental forming (SPIF) process is the main factor affecting the surface quality and forming performance of the workpiece. In order to study the effect of process parameters on friction in SPIF, the contact area between the forming tool and the metal sheet was taken as the analysis object according to the principle of SPIF and the characteristics of friction in the forming process. The force status was analytically expressed under the condition of considering friction, and a correlation expression between the forming force and the friction coefficient was given. On this basis, the friction coefficient values under different process parameters were calculated through experimental force measurement, and the accuracy and validity of the obtained friction coefficient were verified by finite element simulation. Finally, the influence of the forming parameters on the friction coefficient and the prediction model of the friction coefficient were analyzed using the surface response method. The research results revealed that the increase of tool diameter or spindle speed helped to reduce the friction coefficient between the contact surfaces, while the increase of layer feed, feed rate, or forming angle increased the friction coefficient to different degrees. The results obtained in this work may provide a reference in theory and technology for improving the surface quality and formability of parts.

1. Introduction

SPIF is a highly flexible computer numerical control (CNC)-controlled sheet metal forming process that can quickly form shell parts with complex shapes without special molds, which can well meet the needs of single-piece, small-batch, and rapid prototyping manufacturing. It has broad application prospects in various fields [1, 2]. In the forming process, the forming tool and the sheet are surface-to-surface contact, and the sheet metal is continuously rolled to cause local plastic deformation, which is accompanied by the occurrence of friction. Friction not only affects the forming limit but also affects the surface quality of the formed parts. Therefore, it is of great significance to study the friction in the SPIF process.

The surface quality of the formed parts is a key issue affecting their industrial application, and it is also a hot topic on the study of SPIF of sheet metal [3]. Scholars at home and abroad have studied the methods to improve the surface quality of formed parts from different aspects, but most of them have focused on the influence of forming parameters on the surface quality. Liu et al. studied the influence law of forming parameters on the inner and outer surface roughness through the method of multiobjective optimization and established a prediction model for the overall surface roughness of single point incremental forming parts [4]. Lasunon studied the influence of feed speed, layer feed, and forming angle on the surface roughness of AA5052 aluminum alloy [3]. The research results show that the layer feed, forming angle, and their interaction have a significant effect on the surface roughness of the formed parts, while the feed speed has less effect on the surface roughness. Song et al. performed SPIF by setting different preset residual wave peak heights, using original sheets with different surface roughness and different types of tool, and revealed the reasons for different contact states affecting the surface quality of formed parts [5].
In terms of SPIF, domestic and foreign scholars have also done a lot of research. Ambrogio et al. carried out thermal incremental forming of three kinds of light alloy sheets commonly used in aerospace by continuously supplying current to generate heat [6]. The experimental results show that, compared with cold forming, this method of heating the sheets locally greatly improves the formability of the sheets. Some scholars have studied and analyzed the reasons for the improvement of material formability in SPIF. Studies have suggested the strain in the thickness direction is an important factor affecting the formability [7]. In addition, many composite-forming processes have been proposed one after another in order to further improve the formability and forming quality of sheet metal [8]. Shamsari et al. used hydraulic bulging and multistage SPIF to reduce the thinning rate and increase the forming limit [9]. Al-Obaidi et al. proposed a method of electromagnetic induction heating-assisted SPIF [10]. The experimental results have shown this method can significantly reduce the forming force and effectively improve the precision of the formed parts.

At present, there are few studies related to friction in SPIF of sheet metal, and the research mainly focuses on friction reduction and lubrication. Azevedo et al. conducted friction lubrication research on AA1050 aluminum plate and DP780 steel plate, and the research preliminarily showed that choosing the appropriate lubricant can effectively improve the surface quality and precision of the formed parts and reduce the forming force [11]. Durante et al. used two types of tool heads to form AA7075 aluminum alloy sheets and studied the influence of contact conditions on the surface quality, forming force, and formability of the formed parts by changing the frictional contact state [12]. Sabater et al. studied the effect of process parameters on thermoplastic forming and found that increasing the spindle speed and tool diameter helped to reduce forming force and friction [13]. Zha et al. found that the frictional stress caused the uneven distribution of sample thickness in the experiment of making medical prosthesis with aluminum plate [14]. Researchers have improved the quality or formability of the formed parts by changing the friction lubrication state between the sheet and the tool, but there are few studies on the influence of process parameters on the contact friction.

Based on the above discussion, an analytical expression of the relationship between forming force and friction coefficient was given, which considered friction between sheet and tool. Under the condition of unchanged lubrication conditions, the experimental was carried out by using Box–Behnken design (BBD) to study the influence of process parameters on friction coefficient, so as to provide technical support for the improvement of friction mechanism and forming quality in SPIF.

### 2. The Principle of SPIF and the Determination of Friction Coefficient

The SPIF of sheet metal is a gradual forming process from the edge to the center of the sheet metal. The sheet metal is controlled on the workbench of the numerically controlled machine tool, and the forming tool head is installed on the spindle of the machine tool. The forming tool extrudes the sheet metal layer by layer according to the preset track. When one layer is formed, the tool will drop and feed one layer and keep approaching the center of the formed part until the target part is formed [15, 16]. The forming principle is shown in Figure 1, where $\alpha$ is the forming angle, $r$ is the initial thickness of the sheet, $D$ is the diameter of the tool, and $Z$ is the layer feed.

Generally, the friction coefficient is used to characterize the magnitude of friction. The friction coefficient in physics is related to the physical properties of the contact surface, but not to the contact area and contact pressure. However, in the plastic forming of sheet metal, the metal is formed under the action of pressure, and there are special dynamic conditions on the contact surface. In this state, the friction is related to the contact pressure, and the calculation of the friction coefficient is relatively complicated [17].

In the process of SPIF, the deformation of sheet metal must be accompanied by the plastic flow of material. The friction generated on the contact surface between the tool and the sheet metal has a great impact on the flow of metal. Excessive friction leads to uneven flow of the metal material, material accumulation, and wrinkling on the surface of the formed part. In the SPIF process, the tool extrudes and stretches the metal sheet according to the preset trajectory, as shown in Figure 2. Studies have shown that the sheet metal in SPIF is mainly deformed by shear deformation in the circumferential direction, tensile deformation in the radial direction, and compression deformation in the thickness direction.

Lu et al. used a rolling tool head and a hemispherical rigid tool head to form a sheet with tiny holes [18]. After forming, the deformation of the transverse and longitudinal sections of the formed hole was observed using a microscope to study its forming mechanism. The experimental results show that the two tools have obvious shear deformation in the circumferential direction, only the shear deformation of the rolling tool is relatively small, and for the radial direction, both only have tensile deformation.

The area where the tool contacts the metal sheet is defined as $Sc$, and a small element is selected from the contact area $Sc$ for analysis, and any point in the contact area is subject to the principal stress and shear stress in the circumferential, radial, and thickness directions. Since there is only obvious shear effect in the circumferential direction, only the circumferential shear stress is considered, and the shear stress in the radial and thickness directions is ignored. The principal stresses in the circumferential, radial, and thickness directions are defined as $\sigma_\theta$, $\sigma_\alpha$, and $\sigma_z$, respectively, and the circumferential shear stress is defined as $\tau_{\theta\alpha}$. The main stress distribution of the microunit is shown in Figure 3.

The forming force in SPIF consists of circumferential force $F_\theta$, radial force $F_\alpha$, and axial force $F_z$. The forces in the three directions collected in the experiment are defined as force $F_z$ in the vertical direction, and the two forces in the horizontal direction are $F_\theta$ and $F_\alpha$, respectively.

The circumferential shear stress can be expressed as $\tau_{\theta\alpha} = \mu \sigma_\theta$; and $\mu$ is the friction coefficient between the tool and the sheet.
Therefore, the force $F_h$ in the horizontal direction can be expressed as

$$F_h = \sqrt{F_x^2 + F_y^2} = \sqrt{F_x^2 + F_y^2} = \sqrt{(\sigma_\alpha S_\alpha S_r \sin^2 \alpha / 2)^2}$$

$$= S_x \sigma_x \sin^2 \alpha / 2 + \mu^2.$$  

(1)

The force in the vertical direction can be expressed as

$$F_z = S_x \sigma_x \cos \alpha / 2$$  

(2)

The ratio of horizontal force to vertical force can be obtained:

$$\mu = \sqrt{\left(\frac{F_x^2 + F_y^2}{F_z^2}\right) \cdot \cos^2 \alpha / 2 - \sin^2 \alpha / 2}.$$  

(3)

The values of $F_x$, $F_y$, and $F_z$ in the forming process can be measured by using a dynamometer, and the friction coefficient value under specific process parameters in SPIF can be obtained using (3). It can be seen from equation (3) that, when the forming angle is constant, the changes of other forming parameters cause the horizontal force to increase more than the vertical force, which increases the friction coefficient between the contact surfaces. This is because, during the forming process, the tool mainly squeezes the sheet around the circumference. According to the friction theory and forming characteristics, when the friction conditions are poor, the resistance of the tool to push the material forward is relatively greater, so the horizontal force increases to a greater extent.

3. Materials and Methods

3.1. Material and Process Parameters. There are many factors that affect the friction state of the contact surface in SPIF, including the material of the sheet and the tool, the surface microscopic topography, the lubrication conditions, and the forming parameters. This paper mainly studies the influence of forming parameters on the friction coefficient under the same working conditions except the forming parameters. In order to reduce the complexity of the experiment and the number of runs, the type of material, the thickness of the sheet, and its initial roughness are not considered. A standard 1060 pure aluminum plate sheet was chosen as the workpiece, with a size of $140 \text{ mm} \times 140 \text{ mm}$ and a thickness of $1 \text{ mm}$. The basic performance parameters of the material are given in Table 1.

3.2. Experimental Setup. The experiments were conducted on a three-axis vertical NC milling center, and the final shape of the sheet was a truncated cone, which is shown in Figure 4. To deform the metal sheet, cemented carbide hemispherical forming tools were used during the process, with dimensions $\phi 14 \text{ mm}$, $\phi 10 \text{ mm}$, and $\phi 6 \text{ mm}$, respectively, as shown in Figure 5.

A fixture designed specifically for conducting SPIF was mainly composed of upper and lower platen, and the metal sheet was fixed in the fixture by bolts, and the dynamometer was placed on the bottom of the fixture and was also bolted to the machine table. The force measuring system is shown in Figure 6. The force measuring instrument used in the experiment was a KISTLER 9257B three-way-force measuring sensor. The force collected by the sensor was transmitted to the data acquisition instrument through the charge amplifier. By using Vib'SYS software, the voltage signal can be observed on the terminal computer by the channel, acquisition time, and acquisition frequency, and the data of the three directions of force in the forming process can be obtained by multiplying it by the magnification.

3.3. Experimental Scheme. The response surface method is a method used to explore the relationship between the test index and its influencing factors, and it can also explore the influence of the interaction of each factor on the test index. Since there are many forming parameters involved in SPIF, considering the factors of resources and experimental complexity, the BBD experimental design was selected, and the effect of forming parameters on the friction coefficient can be accurately and comprehensively analyzed with fewer experimental runs.
In this experiment, 5 factors—including tool diameter, layer feed, spindle speed, feed speed, and forming angle—were selected, and each factor was set to 3 levels. The design factors and levels of BBD are given in Table 2.

### Table 1: The property of 1060 aluminum.

| Material | Yield strength, MPa | Tensile strength, MPa | Density, kg/m³ | Elastic modulus, MPa | Poisson ratio |
|----------|---------------------|-----------------------|----------------|----------------------|--------------|
| 1060Al   | 138                 | 145                   | 2712           | 59000                | 0.30         |

In this experiment, 5 factors—including tool diameter, layer feed, spindle speed, feed speed, and forming angle—were selected, and each factor was set to 3 levels. The design factors and levels of BBD are given in Table 2.

### 3.4. Experimental Results

46 molded parts were obtained along with the completion of 46 sets of experiments. By measuring the forming force in each set of experiments and substituting it into (3), the change curve of the friction coefficient under the set of forming parameters can be obtained. The average friction coefficient in the stable period was taken as the friction coefficient value under each group of process parameters. This is because that a stable friction state provides a reliable measurement for each formed part. In addition, the coefficient of friction in plastic forming is generally referred to as its average coefficient of friction. The calculation results of the friction coefficient in the specific experimental scheme are given in Table 3.

The change curve of the friction coefficient of the 1# forming part during the forming process is shown in Figure 7. It can be seen from the figure that the friction coefficient remains relatively stable after forming for a period of time, but the friction coefficient at this stage still fluctuates up and down. It is mainly caused by the constant wear of the tool and tiny vibrations during the forming process.

### 4. Simulation Verification

The friction coefficients calculated under the two sets of process parameters were set in the simulation, respectively, and the forming force in the simulation was compared with the forming force measured in the experiment to verify the effectiveness of the scheme and ensure the correctness of the results.

#### 4.1. Establishment of the Finite Element (FE) Model

Abaqus CAE was used in this project for FE modeling of the SPIF process, in which the sheet was divided by S4R four-node reduced integral shell element. The division of mesh size is an important link in numerical simulation, which directly affects the convergence of simulation results. The smaller the mesh, the higher the accuracy; but the smaller the mesh density, the longer the analysis time. Through multiple analyses of the simulation results, selecting a grid size of $1 \times 1$ can obtain relatively accurate analysis results and save computing time at the same time. The forming tool and platens were considered an analytical rigid body. The 1060 aluminum sheet was chosen as the workpiece, and the specific mechanical properties are given in Table 1. In order to obtain the stress-strain properties of the sheet, the specifications of the tensile test pieces were selected according to the tensile standard, and the tensile test was carried out on the HT2402 electronic tensile testing machine. In the test, the stress-strain curves of the sheet in the rolling direction of $0^\circ$, $45^\circ$, and $90^\circ$ were obtained after data processing, as shown in Figure 8.

The classical Coulomb friction model provided in Abaqus was used to describe the friction relationship between the forming tool and the sheet. The sheet forming parameters of FE simulation are given in Table 4.

The final established finite element model is shown in Figure 9.
4.2. Simulation Results. The thickness distribution cloud diagram of the sheet after the simulation under the two sets of process parameters and corresponding friction coefficients is shown in Figure 10. When \( \mu = 0.393 \) and 0.451, the corresponding minimum thicknesses of the formed parts are 0.6584 mm and 0.6388 mm, respectively, and the corresponding maximum thinning rates are 34.2\% and 36.1\%, respectively. It can be seen that the greater the friction coefficient, the greater the thinning rate, and the more uneven the thickness distribution of the molded part.

Figure 11 shows the equivalent stress distribution of the formed parts under the two sets of process parameters and corresponding friction coefficients. It can be seen that, when \( \mu = 0.393 \) and 0.451, the maximum equivalent stress values are 125.2 MPa and 125.9 MPa, respectively.

| Number | Tool diameter (D), mm | Layer feed (Z), mm | Spindle speed (n), r/min | Feed speed (vf), mm/min | Forming angle (\( \alpha \)), ° |
|--------|-----------------------|-------------------|--------------------------|-------------------------|----------------------------|
| -1     | 6                     | 0.2               |                          |                          |                           |
| 0      | 10                    | 0.5               | 700                      | 550                     | 30                         |
| 1      | 14                    | 0.8               | 1000                     | 800                     | 45                         |

Table 2: Factors and levels of BBD design.

Table 3: The experimental scheme and results.

| Experiment | \( D_i \), mm | \( Z \), mm | \( n \), r/min | \( v_f \), mm/min | \( \alpha \), ° | \( \mu \) |
|------------|----------------|-------------|----------------|------------------|---------------|---------|
| 1          | 14             | 0.5         | 700            | 550              | 30            | 0.393   |
| 2          | 10             | 0.5         | 700            | 800              | 30            | 0.635   |
| 3          | 10             | 0.5         | 700            | 550              | 45            | 0.578   |
| 4          | 10             | 0.5         | 700            | 550              | 45            | 0.548   |
| 5          | 10             | 0.5         | 400            | 550              | 60            | 0.618   |
| 6          | 6              | 0.5         | 700            | 800              | 45            | 0.605   |
| 7          | 6              | 0.8         | 700            | 550              | 45            | 0.618   |
| 8          | 10             | 0.2         | 700            | 300              | 45            | 0.432   |
| 9          | 10             | 0.8         | 1000           | 550              | 45            | 0.576   |
| 10         | 10             | 0.2         | 700            | 550              | 60            | 0.616   |
| 11         | 6              | 0.5         | 700            | 300              | 45            | 0.561   |
| 12         | 10             | 0.8         | 400            | 550              | 45            | 0.617   |
| 13         | 10             | 0.5         | 700            | 550              | 45            | 0.591   |
| 14         | 10             | 0.2         | 1000           | 550              | 45            | 0.401   |
| 15         | 6              | 0.5         | 400            | 550              | 45            | 0.626   |
| 16         | 10             | 0.5         | 1000           | 300              | 45            | 0.501   |
| 17         | 10             | 0.8         | 700            | 300              | 45            | 0.583   |
| 18         | 6              | 0.5         | 700            | 550              | 60            | 0.605   |
| 19         | 6              | 0.5         | 1000           | 550              | 45            | 0.566   |
| 20         | 10             | 0.5         | 700            | 550              | 45            | 0.577   |
| 21         | 14             | 0.8         | 700            | 550              | 45            | 0.471   |
| 22         | 14             | 0.2         | 700            | 550              | 45            | 0.433   |
| 23         | 10             | 0.2         | 700            | 550              | 30            | 0.441   |
| 24         | 10             | 0.5         | 700            | 550              | 45            | 0.607   |
| 25         | 10             | 0.5         | 700            | 800              | 60            | 0.586   |
| 26         | 10             | 0.8         | 700            | 550              | 60            | 0.614   |
| 27         | 10             | 0.5         | 1000           | 550              | 30            | 0.5     |
| 28         | 6              | 0.5         | 700            | 550              | 30            | 0.537   |
| 29         | 10             | 0.2         | 400            | 550              | 45            | 0.487   |
| 30         | 14             | 0.5         | 1000           | 550              | 45            | 0.405   |
| 31         | 14             | 0.5         | 700            | 800              | 45            | 0.474   |
| 32         | 10             | 0.5         | 700            | 300              | 60            | 0.599   |
| 33         | 6              | 0.2         | 700            | 550              | 45            | 0.522   |
| 34         | 10             | 0.8         | 700            | 550              | 30            | 0.601   |
| 35         | 10             | 0.8         | 700            | 800              | 45            | 0.603   |
| 36         | 10             | 0.5         | 400            | 550              | 30            | 0.532   |
| 37         | 14             | 0.5         | 700            | 300              | 45            | 0.424   |
| 38         | 10             | 0.5         | 1000           | 800              | 45            | 0.537   |
| 39         | 10             | 0.5         | 400            | 800              | 45            | 0.601   |
| 40         | 10             | 0.5         | 700            | 300              | 30            | 0.496   |
| 41         | 10             | 0.2         | 700            | 800              | 45            | 0.607   |
| 42         | 10             | 0.5         | 1000           | 550              | 60            | 0.577   |
| 43         | 10             | 0.5         | 700            | 550              | 45            | 0.567   |
| 44         | 14             | 0.5         | 700            | 550              | 60            | 0.512   |
| 45         | 14             | 0.5         | 400            | 550              | 45            | 0.451   |
| 46         | 10             | 0.5         | 400            | 300              | 45            | 0.532   |

Figure 7: Distribution of friction coefficient for part 1#.  
Figure 8: True stress-true strain curves at different directions for the 1060 aluminum.
coefficient, the higher the equivalent stress and the minimum stress. As the friction coefficient increases, the equivalent stress and the minimum stress value both tend to increase.

By observing the simulated forming force in Figure 12, it can be noticed the forming force change curve changes in a wave-like manner during the forming process. The force in the Z direction gradually reaches a stable state after a period of rising process, and the force in the X and Y directions shows a sinusoidal variation law. The comparative analysis shows that the friction has a greater influence on the fluctuation of the horizontal force, while it has a lesser effect on the fluctuation of the axial forming force, which is mainly

| Molded parts | Original thickness (t), mm | Forming angle (α), ° | Tool diameter (D), mm | Feed rate (vf), mm/min | Spindle speed (n), r/min | Layer feed (Z), mm | Friction coefficient (μ) |
|--------------|---------------------------|----------------------|----------------------|------------------------|------------------------|---------------------|------------------------|
| 1# molded part | 1                         | 30                   | 14                   | 550                    | 700                    | 0.5                 | 0.393                  |
| 45# molded part | 1                         | 45                   | 14                   | 550                    | 400                    | 0.5                 | 0.451                  |

Figure 9: Finite element model of single point incremental forming.

Figure 10: Cloud diagram of thickness distribution under two sets of process parameters and corresponding friction coefficients: (a) 1# formed part and (b) 45# formed part.

Figure 11: Cloud diagram of equivalent stress under two sets of process parameters and friction coefficient: (a) 1# formed part and (b) 45# formed part.
because the greater the friction, the greater the resistance to the tangential movement of the tool.

4.3. Result Verification. The comparison between the simulated forming force and the experimental forming force is shown in Figure 13. Since friction has a great influence on the force in the horizontal direction, in order to verify the accuracy of the obtained results, this paper extracts the results of the horizontal force obtained from the simulation and experiment, respectively. By comparing the experimental and simulation results, it can be demonstrated that an excellent agreement has been achieved, which fully proves the validity of the experimental plan and the accuracy of the experimental results.

5. Results and Discussion

5.1. Response Surface Modeling of Friction Coefficient. By measuring the forming force, the average friction coefficient of the tool and the sheet metal contact surface under different experimental conditions can be calculated. In order to deeply analyze the influence of forming parameters on the friction coefficient, the response surface method was used to fit the functional relationship between each factor and the friction coefficient. The friction coefficient model adopts a second-order model, as shown in (4).

\[
Y = \beta_0 + \beta_i x_i + \beta_{ij} x_i x_j + \beta_{ii} x_i^2 + \varepsilon, \quad (4)
\]

where \(Y\), \(n\), and \(x_i\) are the response value, the number of variables, and the factor variables, respectively; \(\beta_i\), \(\beta_{ij}\), and \(\beta_{ii}\) represent the coefficient of the primary term, the coefficient of the interaction term, and the coefficient of the quadratic term, respectively; and \(\varepsilon\) is the error term of the experiment.

The response value, that is the friction coefficient, is a combined function of its forming parameters, which can be expressed as

\[
\mu = f(D, Z, n, v_f, \alpha). \quad (5)
\]

The measured and calculated data were imported into Design-Expert 8.0 statistical analysis software in order to
establish a statistical model suitable for the friction coefficient and each forming parameter and to analyze the influence of each forming parameter on the friction coefficient.

Analysis of variance (ANOVA) can be used to analyze whether the fitted data is reliable, and its main function is to judge the influence of various factors and interaction factors on the response value. In the ANOVA table, $P$ stands for the reliability, and a smaller $P$ value indicates a higher degree of statistical significance. Generally, the $P$ value is required to be less than 0.01, and the lack-of-fit term represents the part of the regression equation that cannot be fitted. When the lack-of-fit test is not significant, it means that the fitted regression equation is better. Therefore, the analysis of variance can be used to evaluate the fitness of the established model and also to obtain the degree of influence of each factor on the response.

Table 5 provides the variance analysis results of the friction coefficient obtained by the statistical software, and the $P$ value is 0.0001, indicating that the model is extremely significant. It can also be clearly seen from this table that the tool diameter, layer feed, spindle speed, feed speed, and forming angle all have a significant impact on the friction coefficient, and the interaction between some factors also has a significant impact on the response value, such as layer feed and forming angle. The analysis of the $F$ value of each forming parameter in Table 5 reveals that the influence of each forming parameter on the friction coefficient is in descending order: tool diameter, layer feed, forming angle, feed speed, and spindle speed.

The results of the model prediction can be made more accurate by removing insignificant items, so $P$ values greater than 0.05 in the ANOVA table, such as $AC$, $AD$, $CD$, $CE$, $D2$, and $E2$, are deleted. Then according to (5), the model of friction coefficient calculated by Design-Expert 8.0 mathematical statistics software is shown in the following equation.

$$
\mu = -0.5365 + 0.0431D + 1.0805Z + 3.1416 \times 10^{-3} n \\
0.0101a - 0.0121DZ + 2.1667 \times 10^{-4} Da + 1.2500 \times 10^{-3} Zn \\
-5.1667 \times 10^{-2} Zv - 9.0000 \times 10^{-2} Zt - 1.0133 \times 10^{-2} v_f a \\
-3.3346 \times 10^{-3} D^2 - 0.2030Z^2 - 2.9189 \times 10^{-7} n^2.
$$

(6)

5.2. Model Diagnosis. According to the RSM model, the friction coefficient of the 1060 aluminum plate under different forming parameters was predicted, and the normal cumulative distribution diagram of the residual error of the RSM model was used to judge the rationality of the model. Figure 14 shows the residual normal cumulative distribution diagram of the second-order model. It can be seen that the distribution of these points is close to a straight line, and there is no abnormal variable value, so it can be determined that these data conform to the normal distribution, and the RSM model is relatively accurate.

5.3. Response Surface Method Analysis of Process Parameters on the Distribution Law of Friction Coefficient

5.3.1. Univariate Analysis. Figure 15 is a main effect plot, which mainly represents the response of one factor to the friction coefficient, and the confidence interval is shown in blue, indicating the 95% confidence level. The black line represents the influence of each forming parameter on the friction coefficient, the straight line represents the linear relationship between the parameters and the friction coefficient, and the curve represents the nonlinear relationship. It can be seen from Figure 15 that increasing the diameter $D$ of the forming tool or increasing the rotational speed $n$ of the spindle can help reduce the friction coefficient. The main reason is that the increase of these two parameters greatly improves the tangential velocity of the circumferential movement of the tool, and then the friction coefficient decreases, especially the tool diameter $D$, which has the most significant effect on the friction coefficient. However, as the layer feed $Z$, the feed speed $v_f$, or the forming angle $a$ is raised, the friction coefficient value between the sheet and the tool will also increase to varying degrees, which is because that the increase of these parameters greatly enhance the contact force, especially the horizontal tangential force.

The relationship between the tool diameter $D$ and the friction coefficient $\mu$ is shown in Figure 15(a). From the visual observation of results in Figure 15(a), it can be seen that the friction coefficient value gradually decreases with the increase of the tool diameter. When tool diameter increases, the axial force increases due to the increase of the contact area, and the bending force decreases, so that the force required to extrude the material is small, which is mainly manifested in the decrease of the tangential force, so the friction coefficient decreases.

As shown in Figure 15(b), with the increase of the layer feed, the friction coefficient value increases, which is because that the increase of the layer feed enhances the amount of material pushed forward by the tool, resulting in a large circumferential force; at the same time, the adhesion shear phenomenon is more obvious, so the friction coefficient increases.

The influence trend of the spindle speed on the friction coefficient is similar to that of the tool diameter on the friction coefficient, but with a weaker influence, as illustrated in Figure 15(c). When $n$ is less than 1000 r/min, the measured temperature of the contact area is lower than 100 degrees, and the frictional heat effect is not enough to cause the material to recrystallize but accelerate the flow rate of the material. At the same time, the higher spindle speed generates a certain degree of microvibration, which reduces the adhesive friction between the tool head and the sheet.

As shown in Figure 15(d) of the relationship between the feed speed and the friction coefficient $\mu$, an increase in feed speed leads to the friction coefficient increases. The main reason is that the increase of the extrusion speed causes more heat to be generated in the deformation zone, and a large amount of heat is too late to diffuse and thus more prone to adhesion.

As illustrated in Figure 15(e), the values of friction coefficient increase to a certain extent as the forming angle increases. The reason is similar to the effect of the layer feed on the friction coefficient, that is, more materials participating in the deformation during the forming process increase the resistance of the tool to extrude the material.
forward, so the friction force increases and the friction coefficient increases accordingly.

5.3.2. Interaction Factor Analysis. The influence of interaction on the response refers to the influence of a factor on the response when one factor changes relative to another factor, as shown in Figure 16. The interaction diagram provides some intuitive metrics, such as the distance between the two lines in each area, the relative angle between the two lines, and the shape of the curve.

The distance between the two lines is its main influence index. The parallel line indicates that the response trend of the interaction between the two factors remains unchanged; the angle between the two lines indicates the degree of change in the response trend of the other factor when one factor changes; the shape of the curve represents the relationship between the forming parameters and the response.
and the degree of influence of each parameter on the response.

Looking at each area in Figure 16, it is found that the distance between the two lines is longer in all areas in the first row, which proves that the influence of the change in the diameter of the tool on the response plays a major role in the forming parameters; while the distance between the two straight lines in the third row is shorter, it can be seen that the influence of the \( n \) on the response is relatively small. The graphs within the box marks in Figure 16 show the effect of
the $v_f$ on the friction coefficient for different values of the $Z$. When the $Z$ is at a low level, the friction coefficient increases significantly with the increase of the $Z$; but when $Z$ is at a high level, with the increase of the $v_f$, the increasing trend of the friction coefficient is relatively weakened.

5.3.3. Response Surface Analysis of Process Parameters to Friction. The experimental design of the response surface method is to find the law between the experimental index and each factor, and the response surface refers to the functional relationship between the response variable and a set of input variables, so the response surface graph is a 3D space surface plot composed of each experimental factor and the response value. The response surface graph in this thesis is the response surface graph of friction coefficient of different factors obtained by keeping the other two factors at 0 level.

The response surface graph of the tool diameter $D$ and the layer feed $Z$, the spindle speed $n$, the feed speed $v_f$, and the forming angle $a$ to the friction coefficient is shown in Figure 17. Figure 17(a) shows the variation trend of the friction coefficient due to different sizes of tools, which has been analyzed in the Section 4.3.2. When the diameter of the tool is larger, the friction coefficient is smaller, and the friction coefficient decreases with the increase of the spindle speed. When a smaller tool is used, the influence of the increase of the spindle speed on the friction coefficient decreases significantly, and the degree of change is shown in Figure 17(b). However, under the condition of the same tool diameter, the effect of feed speed and spindle speed on friction is opposite, as shown in Figure 17(c). Figure 17(d) strongly demonstrates that the effect of forming angle on the friction coefficient is more prominent when the tool diameter is larger.

The response surface graph of the layer feed $Z$ and the spindle speed $n$, the forming angle $a$, and the feed speed $v_f$ to the friction coefficient is shown Figure 18. When the layer feed is small, increasing the spindle speed, reducing the feed rate, or reducing the forming angle will help reduce the friction coefficient. When the layer feed is large, the influence of these three parameters on the friction coefficient is weak, but the effect of the layer feed on the friction coefficient is more significant, especially at lower feed speed, the coefficient of friction increases significantly with increasing layer feed.

The response surface graph of the spindle speed $n$, the feed speed $v_f$, and the forming angle $a$ to the friction coefficient is shown in Figure 19. The friction coefficient decreases with the increase of the spindle speed. When the spindle speed is combined with the feed speed, the feed speed decreases, and the friction coefficient also decreases, but the friction coefficient decreases faster at the low spindle speed than at high spindle speed.

The response surface graph of the feed rate $v_f$ and the forming angle $a$ to the friction coefficient is shown in Figure 20. It can be seen from the figure that reducing the feeding speed reduces the friction coefficient, especially at a smaller forming angle. This is because the smaller the forming angle, the less material is pushed forward during the forming process. When the feed speed is reduced, the heat
Figure 17: RS for $D$ interacting with $Z$, $n$, $vf$, and $\alpha$, respectively. (a) $\mu = f (D, Z)$. (b) $\mu = f (D, n)$. (c) $\mu = f (D, vf)$. (d) $\mu = f (D, \alpha)$.

Figure 18: RS for $Z$ interacting with $n$, $\alpha$, and $vf$, respectively. (a) $\mu = f (Z, n)$. (b) $\mu = f (Z, \alpha)$. (c) $\mu = f (Z, vf)$.
generated by friction per unit time is less and can be rapidly diffused, the friction condition is obviously improved, and the friction coefficient is greatly reduced.

6. Conclusions

(1) In this paper, by analyzing the characteristics of SPIF, a calculation method for the friction coefficient in the forming process was proposed. Through the microunit stress analysis considering friction, the relationship between the forming force and the friction coefficient was obtained from the perspective of stress and force.

(2) The Box–Behnken design in the response surface method (RSM) was used to carry out the experimental design. Through the measurement and calculation of the forming force in the experiment, the friction coefficient values under different process parameters were obtained, and by finite element simulation, the accuracy of the results was verified.

(3) The cloud diagram obtained by analyzing the finite element simulation shows that the greater the friction coefficient, the greater the thinning rate, and the more uneven the thickness distribution of the sheet after forming. When \( \mu = 0.393 \) and \( \mu = 0.451 \), the corresponding minimum thicknesses of the formed parts are 0.6584 mm and 0.6388 mm, respectively, and the corresponding maximum thinning rates are 34.2% and 36.1%, respectively. The larger the friction coefficient, the larger the equivalent stress, and the overall trend is increasing. When \( \mu = 0.393 \) and \( \mu = 0.451 \), the maximum equivalent stress values are 125.2 MPa and 125.9 MPa, respectively. At the same time, the minimum stress value also increases.

(4) The effect of process parameters on the friction coefficient was studied, and the results show that increasing the tool diameter or increasing the spindle speed both help to reduce the friction coefficient. If other forming parameters remain unchanged, the tool diameter is changed from 6 mm to 14 mm, and the friction coefficient is reduced from 0.58 to 0.52; while increasing the layer feed, feed speed, or forming angle, the coefficient of friction between the forming tool and the sheet increases to varying degrees. For example, when the layer feed is changed from 0.2 mm to 0.8 mm, the friction coefficient increases from 0.51 to 0.6.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] J. R. Duflou, A. M. Habraken, and J. Cao, “Single point incremental forming: state-of-the-art and prospects,” *International Journal of Material Forming*, vol. 11, pp. 743–773, 2017.

[2] E. H. Uheida, G. A. Oosthuizen, and D. M. Dimitrov, “Effects of the relative tool rotation direction on formability during the incremental forming of titanium sheets,” *International Journal of Advanced Manufacturing Technology*, vol. 96, 2018.

[3] O. U. Lasunon, “Surface roughness in incremental sheet metal forming of AA5052,” *Advanced Materials Research*, vol. 753-755, pp. 203–206, 2013.
[4] Z. B. Liu, S. Liu, Y. L. Li, and P. A. Meehan, "Modeling and optimization of surface roughness in incremental sheet forming using a multi-objective function," *Materials and Manufacturing Processes*, vol. 29, no. 7, pp. 808–818, 2014.

[5] X. C. Song, B. Lu, and J. Chen, "Influencing factor Analysis on the surface quality of incremental forming parts," *Journal of Mechanical Engineering*, vol. 49, no. 08, pp. 84–90, 2013.

[6] G. Ambrogio, L. Filice, and F. Gagliardi, "Formability of lightweight alloys by hot incremental sheet forming," *Materials & Design*, vol. 34, pp. 501–508, 2012.

[7] J. M. Allwood and D. R. Shouler, "Generalised forming limit diagrams showing increased forming limits with non-planar stress states," *International Journal of Plasticity*, vol. 25, no. 7, pp. 1207–1230, 2009.

[8] T. Mcanulty, J. Jeswiet, and M. Doolan, "Formability in single point incremental forming: a comparative analysis of the state of the art," *CIRP Journal of Manufacturing Science and Technology*, vol. 16, pp. 43–54, 2017.

[9] M. Shamsari, M. J. Mirnia, and M. Elyasi, "Formability improvement in single point incremental forming of truncated cone using a two-stage hybrid deformation strategy," *International Journal of Advanced Manufacturing Technology*, vol. 94, pp. 1–12, 2017.

[10] A. Al-Obaidi, V. Kräusel, and D. Landgrebe, "Hot single-point incremental forming assisted by induction heating," *International Journal of Advanced Manufacturing Technology*, vol. 82, no. 5-8, pp. 1163–1171, 2016.

[11] N. G. Azevedo, J. S. Farias, R. P. Bastos, P. Teixeira, J. P. Davim, and R. J. Alves de Sousa, "Lubrication aspects during single point incremental forming for steel and aluminum materials," *International Journal of Precision Engineering and Manufacturing*, vol. 16, no. 3, pp. 589–595, 2015.

[12] M. Durante, A. Formisano, and A. Langella, "Observations on the influence of tool-sheet contact conditions on an incremental forming process," *Journal of Materials Engineering and Performance*, vol. 20, no. 6, pp. 941–946, 2011.

[13] M. Sabater, M. García-Romeu, M. Vives-Mestres, I. Ferrer, and I. Bagudanch, "Process parameter effects on biocompatible thermoplastic sheets produced by incremental forming," *Materials*, vol. 11, no. 8, p. 1377, 2018.

[14] G. C. Zha, X. F. Shi, W. Zhao, L. Gao, and M. L. Wu, "Experimental research of incremental sheet forming based on fastened pre-tensioning," *International Journal of Advanced Manufacturing Technology*, vol. 82, no. 1-4, pp. 711–717, 2016.

[15] P. Sieczkarek, S. Wernicke, S. Gies et al., "Wear behavior of tribologically optimized tool surfaces for incremental forming processes," *Tribology International*, vol. 104, pp. 64–72, 2016.

[16] D. M. Neto, J. M. P. Martins, M. C. Oliveira, L. F. Menezes, and J. L. Alves, "Evaluation of strain and stress states in the single point incremental forming process," *International Journal of Advanced Manufacturing Technology*, vol. 85, no. 1-4, pp. 521–534, 2016.

[17] J. S. Wu, Y. H. Jiang, and W. R. Wang, "High temperature friction in hot stamping of 7075 aluminum alloy sheet," *Journal of Engineering Science*, vol. 42, no. 12, p. 8, 2020.

[18] B. Lu, Y. Fang, D. K. Xu et al., "Mechanism investigation of friction-related effects in single point incremental forming using a developed oblique roller-ball tool," *International Journal of Machine Tools and Manufacture*, vol. 85, no. 7, pp. 14–29, 2014.