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Optimization and Prediction of Aluminum Alloy Stamping Forming Parameters Based on Gray Correlation

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Abstract: *The selection of stamping process parameters has very important influence on the mechanical properties, production cost and production efficiency of forming parts.This paper is based on the Simufact Forming simulation platform, using the grey system theory, to design the orthogonal experimental scheme, with automotive aluminum alloy stamping parts, performed stamping forming experiments under different parameters, taking the forming part and equal effect force, equivalent plastic strain, flushing pressure and outer diameter deviation as evaluation indexes, by analyzing its integrated gray correlation degree, Multi-objective parameter optimization for aluminum alloy stamping parts, the optimal combination of process parameters and the influence order on the evaluation index are obtained, using the grey system theory to establish the GM (0, N) prediction model, realize the rapid prediction of the evaluation index of automobile aluminum alloy stamping forming parts.The results show that the influence order of process parameters on the evaluation index is: heat treatment temperature > friction coefficient > stamping speed; when the stamping speed is 5mm / s, friction coefficient is 0.1 and heat treatment temperature is 350℃, the mechanical properties of aluminum alloy stamping parts reach the optimal 50; GM (0, N) gray prediction model can predict the performance of alloy stamping parts, with simple modeling and small error.*

Keywords: *Aluminum Alloy, Gray Correlation, Stamping Forming*

1. Introduction

Aluminum alloy has low density, high specific strength and specific stiffness, many advantages of good impact resistance and corrosion resistance, and can meet a series of requirements of lightweight vehicle, making aluminum alloy material has gradually become the main material in the realization of lightweight vehicle. However, due to the problems of high production cost, poor welding performance and large rebound, it is particularly important to study the comprehensive performance of aluminum alloy stamping forming process. The optimization of the micro-processing process parameters of SNR and gray correlation studied by Jia Zhenyuan et al[1]of Dalian Institute of Technology, Multi-objective optimization of turning parameters based on Tiankou algorithm and gray correlation theory studied by Xu Xianbo et al[2] from Shanghai Jiao Tong University, Planar grinding process based on gray correlation analysis studied by Li Haolin et al[3] of University of Shanghai for Science and Technology, The milling parameter optimization method based on the gray theory studied by Xin Min et al[4]of Beijing Institute of Technology has achieved very good results with the combination of the orthogonal test design method and the gray correlation method. The method of orthogonal experiment was used for the optimization of the stamping forming process parameters of aluminum substitute steel studied by Liu Jianpeng et al[5]of Xiangtan University revealed influence of process parameters on the mechanical properties of aluminum alloy stamping workpiece , and the optimized process parameter combination is obtained. In this paper, the grey system theory is introduced into the field of process parameter optimization and prediction of automobile aluminum alloy stamping parts, selecting the stamping speed, friction coefficient and heat treatment temperature as the test factors, evaluating the equivalent effect force, punching pressure and outer diameter deviation, calculate the average correlation according to the gray correlation method, so as to determine the optimal parameters of aluminum alloy stamping forming process and the influence order of the process parameters on the comprehensive evaluation index, and establish the GM (0, N) rapid prediction model through the gray system theory to predict the performance of aluminum alloy stamping parts quickly.

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2. Simufact Forming Finite element simulation experiment

2.1 Finite-element modeling

Establish each part model of aluminum alloy stamping in proe software, and assemble the convex mold, concave mold and blank. The 2 D model is shown in Figure 1 below, export the assembled stamping model into the STP file, import the STP file of the stamping model into Simufact Forming, and its attributes are defined, as shown in Figure 2 below.

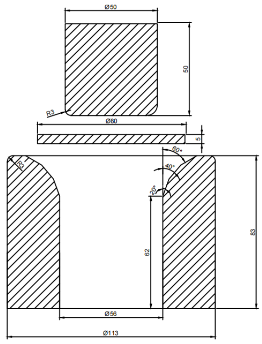

Figure 1: Two-dimensional model of aluminum alloy stamping process assembly

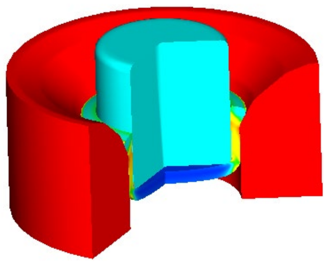

Figure 2: Simufact Forming schematic diagram of software attribute definition

2.2 Material Definition

Using ALZn5.5MgCu aluminum alloy as the stamping forming experiment object, ALZn5.5MgCu for aluminum-copper-magnesium system of typical hard aluminum alloy, its composition is reasonable, with low density, high specific strength and specific stiffness, good impact resistance and corrosion resistance, and many other advantages, good comprehensive performance, due to the current car, aircraft and other transport more and more tend to lightweight development, so widely used in aircraft structure, rivets, truck wheels, propeller components and other structural parts.The stress and strain curve is shown in Figure 3 below, and the specific material composition[6] is shown in Table 1 below. The elastic modulus of the material is 71000MPa, the Poisson's ratio is 0.33, and the density is 2810. kg/m^3 .

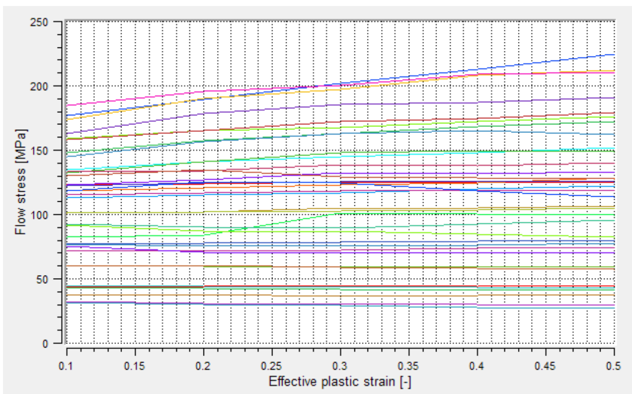

Figure 3: ALZn5.5MgCu Aluminum alloy stress and strain curve

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Table 1: ALZn5.5MgCu Material content of aluminum alloy

Chemical Composition	Al	Si	Cu	Mg	Mn
Mass Fraction/ %	margin	≤0.04	≤0.10	4.0~4.9	0.40~1.0
Chemical Composition	Ti	Cr	Fe	Zn	
Mass Fraction/ %	≤0.15	0.05~0.25	0.00~0.40	≤0.25	

2.3 Friction definition and grid differentiation

In the process of stamping, there is a large extrusion stress between the convex mold and the blank, and the concave mold and the blank, and with the stamping process, the blank material will not only become thinner, the friction form between the concave mold and the blank, the convex mold and the blank will constantly change, and there are a variety of friction forms interwoven.To obtain a better simulation result, the shear friction model was used in the simulation.In Simufact Forming, the edge length is 0.5mm, with 830 grids, as shown in Figure 4 below.

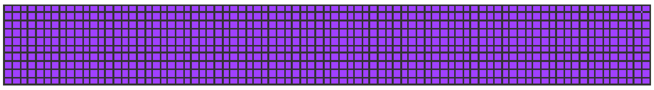

Figure 4: Schematic diagram of the grid differentiation

2.4 Simulation and experiment design

The simulation experiment scheme adopts orthogonal experiment scheme, in which the stamping speed, friction coefficient and heat treatment temperature are selected as the test factors. After the stamping is finished, the isoeffect force, equivalent plastic strain, flushing pressure and outer diameter deviation in the aluminum alloy stamping process are selected as the evaluation indexes.Design the orthogonal experiment table for $\boldsymbol{L_9(3^3)}$, as shown in Table 2 below.

Table 2: Orthogonal experiment results

Number	Stamping speed (mm/s)	Friction factor	Heat treatment temperature(℃)	Equivalent stress (MPa)	Equivalent plastic strain (mm)	Punching pressure (KN)	External diameter deviation(mm)
1	3	0.1	250	217.95	1.6	83.215	0.575
2	3	0.2	300	162.35	2.67	73.111	0.185
3	3	0.3	350	132.16	2.78	61.274	0.5
4	5	0.1	300	165.97	1.44	65.325	0.365
5	5	0.2	350	128.64	2.48	58.523	0.28
6	5	0.3	250	223.75	2.08	110.279	0.34
7	7	0.1	350	132.84	1.45	55.159	0.48
8	7	0.2	250	233.79	2.36	97.806	0.53
9	7	0.3	300	162.75	2.91	81.766	0.28

3. Interpretation of result

3.1 Gray correlation degree analysis and optimization

Gray association method[7] is a multivariate statistical analysis method that uses gray correlation degree to describe the strength, magnitude, and order of the relationships between factors. It is a kind of relative ranking analysis. The basic idea is to judge whether the sequence curve is closely related according to the similarity of the sequence curve geometry. The closer the curve is, the greater the correlation between the corresponding sequences, and the less vice versa.

In the process of processing, the equal effect force, equivalent plastic strain and flushing pressure of the material will have a great impact on the forming quality and processing cost of the stamping parts,

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and the outer diameter deviation of the forming parts indicates the accuracy of the product.Therefore, in order to reduce the adverse effects and improve the product accuracy, this study hopes the aluminum alloy stamping effect force, equivalent plastic strain, impact pressure and the outer diameter deviation value the smaller the better, so the small calculation formula for data processing, because of the orthogonal test results data range and units, need to standardize the original data. The following:

Look at the formula of small sex:

$$x_i(k)=\frac{\max x_i^0(k)-x_i^0(k)}{\max x_i^0(k)-\min x_i^0(k)} \tag{1}$$

$$\left(i=1,2,\ldots;\quad k=1,2,\ldots\mathrm{n}\right)$$

Where, $x_i(k)$ is the data obtained after processing; $x_i^0(k)$ is the raw data; $\max x_i^0(k)$ is the largest in the raw data; $\min x_i^0(k)$ is the minimum value in the raw data.The relation of the correlation coefficient $\xi_i(k)$ is as follows:

$$\xi_i(k)=\frac{\Delta_{\min}+\varphi\Delta_{\max}}{\Delta_{0i}(k)+\varphi\Delta_{\max}} \tag{2}$$

$$\Delta_{0i}(k)=X^0(k)-x_i(k) \tag{3}$$

Where, $\Delta_{\min}$ is the minimum deviation; $\Delta_{\max}$ is the maximum deviation; $X^0(k)$ is the reference target; $\Delta_{0i}(k)$ is the deviation between reference target $X^0(k)$ and comparison target $x_i(k)$; φ is the deviation coefficient, $\varphi\in[0,1]$.Usually circumstances ordered $X^0(k)=1$, $\varphi=0.5$ .After obtaining the gray correlation degree coefficient, the gray correlation degree γ_i is obtained according to its average value as follows:

$$\gamma_i=\frac{1}{n}\sum_{i=1}^{n}\xi_i(k) \tag{4}$$

Table 3 shows the gray correlation coefficient and gray correlation degree. According to Table 3, experiment number 7 has the highest gray correlation degree. Therefore, the processing process parameters of experiment number 7 are the optimal processing process parameters among the 9 experiments, and the stamping speed is 7 mm/s, the friction coefficient is 0.1, and the heat treatment temperature is 350°C.

Table 3: Gray correlation coefficient and gray correlation degree

Experimental number	Factor			Grey relational coefficient				Grey correlation degree
	Stamping speed(mm/s)	Friction factor	Heat treatment temperature(°C)	Equivalent stress	Equivalent plastic strain	Punching pressure	External diameter deviation	
1	3	0.1	250	0.151	0.891	0.491	0	0.505
2	3	0.2	300	0.679	0.163	0.674	1	0.647
3	3	0.3	350	0.967	0.088	0.889	0.192	0.623
4	5	0.1	300	0.645	1	0.816	0.538	0.708
5	5	0.2	350	1	0.293	0.939	0.756	0.744
6	5	0.3	250	0.095	0.565	0	0.603	0.455
7	7	0.1	350	0.960	0.993	1	0.244	0.827
8	7	0.2	250	0	0.374	0.226	0.115	0.382
9	7	0.3	300	0.675	0	0.517	0.756	0.630

Table 4 shows the average grey correlation difference analysis of factors, from table 4 difference analysis results show the maximum mean gray correlation, the largest mean gray correlation of friction coefficient level 1 and heat treatment temperature level, 3, the greater, the average correlation represents the better the characteristics of the level, so the process parameter level with the maximum average correlation is the optimal process parameter, namely the optimal combination of process

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parameters using gray correlation optimization is: stamping speed 5 mm/s, friction coefficient 0.1, and the heat treatment temperature 350℃.Then according to the factors of the average gray correlation difference on aluminum alloy stamping molding performance order, from table 4, the maximum difference of heat treatment temperature, namely the heat treatment temperature is the parameters of the aluminum alloy stamping forming quality influence the biggest factors, influence degree order is: heat treatment temperature > friction coefficient > stamping speed.

Table 4: Average grey correlation degree of each factor

Factor	Mean gray correlation degree			max-min
	Level 1	Level 2	Level 3	
Stamping speed(mm/s)	0.592	0.636	0.613	0.044
Friction factor	0.680	0.591	0.569	0.111
Heat treatment temperature(℃)	0.447	0.662	0.731	0.284

3.2 Gray prediction

The raw data obtained from the orthogonal experiment is collated and the change law is found according to the gray theory, and the gray prediction model is established to quantitatively predict the experimental results. This paper adopts the multivariate discrete gray GM (0, N) model without derivatives. In order to ensure that the gray prediction model established in this paper can be accurately used in the aluminum alloy stamping forming process, and the equal effect force and flushing pressure can be selected to establish the model. The specific establishment steps are as follows.

(1) Organize the raw data sequence:

$$\begin{cases} X_1^{(0)} = [x_1^{(0)}(1), x_1^{(0)}(2), ..., x_1^{(0)}(n)] \\ X_2^{(0)} = [x_2^{(0)}(1), x_2^{(0)}(2), ..., x_2^{(0)}(n)] \\ X_3^{(0)} = [x_3^{(0)}(1), x_3^{(0)}(2), ..., x_3^{(0)}(n)] \\ \vdots \\ X_N^{(0)} = [x_N^{(0)}(1), x_N^{(0)}(2), ..., x_N^{(0)}(n)] \end{cases} \tag{5}$$

$$C^{(0)} = [c^{(0)}(1), c^{(0)}(2), ..., c^{(0)}(n)] \tag{6}$$

Where: n is the modeling dimension; $x_N^{(0)}(i)$ is the sequence of process parameters, $i = 1,2,...,n$; $c^{(0)}(i)$ is the mechanical properties of aluminum alloy forming parts, $i = 1,2,...,n$.

(2)1-AGO sequence for the raw data:

$$X_N^{(1)} = [x_N^{(1)}(1), x_N^{(1)}(2), ..., x_N^{(1)}(n)] \tag{7}$$

$$C^{(1)} = [c^{(1)}(1), c^{(1)}(2), ..., c^{(1)}(n)] \tag{8}$$

Where: $x_N^{(1)}(i) = \sum_{i=1}^{k} x_N^{(0)}(i), k = 1,2,...,n; c^{(1)}(k) = \sum_{i=1}^{k} c^{(1)}(i), k = 1,2,...,n$

(3)For the immediately adjacent mean generation sequence of $x^{(1)}$ and $c^{(1)}$:

$$z_i^{(1)} = (z_1^{(1)}(2), z_2^{(1)}(3), \cdots, z_N^{(1)}(n)) \tag{9}$$

$$z_i^{(1)}(k) = 0.5(x_i^{(1)}(k) + x_i^{(1)}(k-1)), k = 2,3,\cdots,n; i = 1,2,\cdots n \tag{10}$$

$$d_i^{(1)}(k) = 0.5(c_i^{(1)}(k) + c_i^{(1)}(k-1)), k = 2,3,\cdots,n; i = 1,2,\cdots n \tag{11}$$

(4)Build an indirect data matrix:

$$B=\begin{bmatrix} z_1^{(1)}(2) & z_2^{(1)}(2) & \dots & z_N^{(1)}(2) & 1 \\ z_1^{(1)}(3) & z_1^{(1)}(3) & \dots & z_1^{(1)}(3) & 1 \\ \vdots & \vdots & \ddots & \vdots & 1 \\ z_1^{(1)}(n) & z_1^{(1)}(n) & \dots & z_1^{(1)}(n) & 1 \end{bmatrix} \tag{12}$$

$$Y=\begin{bmatrix} d^{(1)}(2) \\ d^{(1)}(3) \\ \vdots \\ d^{(1)}(n) \end{bmatrix} \tag{13}$$

(5)The indirect matrix *B* and *Y* are calculated to obtain the corresponding parameter sequence matrix:

$$\hat{b} = (B^T B)^{-1} B^T Y \tag{14}$$

$$\hat{b} = [b_1, b_2, \cdots, b_N, a]^T \tag{15}$$

Where: $\hat{b}$ is the parameter column matrix; b_1 is the linear coefficient of parameter $x_1^{(1)}(n)$; b_2 is the linear coefficient of parameter $x_2^{(1)}(n)$; b_N is the linear coefficient of parameter $x_N^{(1)}(n)$; a is the linear constant.

(6)Reduce the 1-AGO sequence according to step (3), and make subtraction reduction to obtain the predicted value, that is:

$$\hat{c}^{(0)}(i+1) = \hat{c}^{(1)}(i+1) - \hat{c}^{(1)}(i), \quad i = 1,2,...,n \tag{16}$$

Where: $\hat{c}^{(0)}(i)$ is the predicted value; $\hat{c}^{(1)}(i)$ is the cumulative value of the predicted value. The GM (0, N) model of the mechanical properties of the experimental data obtained in Table 1 and Table 2.

The GM (0, N) model of equal effect force is:

$$\hat{b} = [299.125, 446.38, 595.445, 742.75, 918.94, 1097.24, 1280.555, 1478.825]^T \tag{17}$$

$$\hat{c}^{(1)}(i) = 15.5572 x_1^{(1)}(i) + 353.8072 x_2^{(1)} + 0.0409 x_3^{(1)} + 148.0238 \tag{18}$$

The GM (0, N) model of the impact pressure is:

$$\hat{b} = [119.7705, 186.963, 250.2625, 312.1865, 396.5875, 479.3065, 555.789, 645.575]^T \tag{19}$$

$$\hat{c}^{(1)}(i) = 6.9983 x_1^{(1)}(i) + 175.7105 x_2^{(1)} + 0.0073 x_3^{(1)} + 49.3109 \tag{20}$$

The gray prediction value of the mechanical properties of aluminum alloy stamping parts is obtained in $\hat{c}^{(0)}(i)$, and the results are shown in Figure 5,6 and Table 5.

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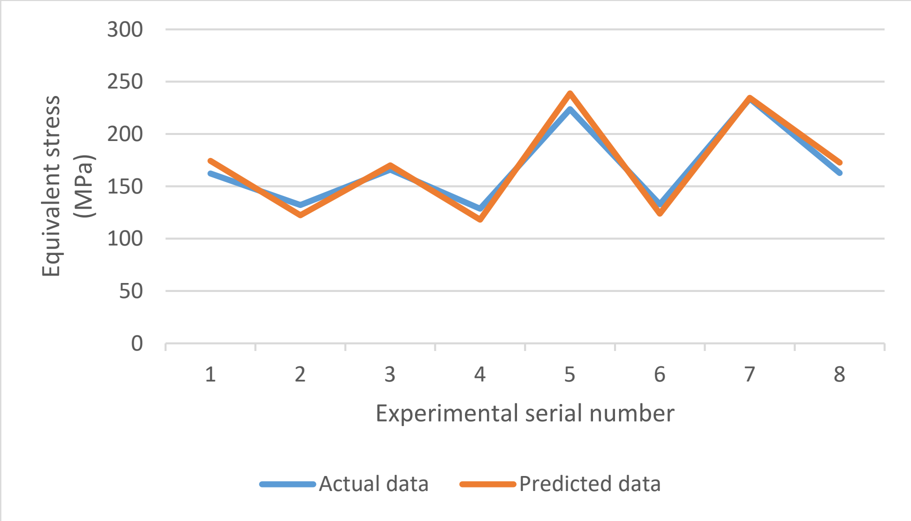

Figure 5: Comparison diagram of the equal-effect force results

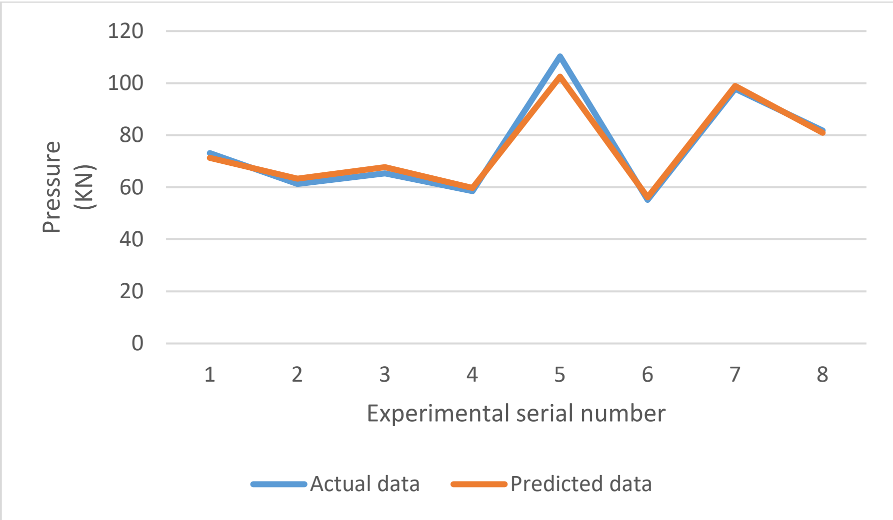

Figure 6: Comparison diagram of the impact pressure results

Table 5: GM (0, N) model prediction results

Experimental serial number	Equivalent stress (MPa)			Punching pressure (KN)		
	Actual data	Predicted data	Fractional error/%	Actual data	Predicted data	Fractional error/%
2	162.35	174.405488	7.43	73.111	71.3007	2.48
3	132.16	122.426572	7.36	61.274	63.28935	3.28
4	165.97	170.139116	2.51	65.325	67.72625	3.67
5	128.64	118.1602	8.15	58.523	59.7149	2.04
6	223.75	238.85566	6.75	110.279	102.50335	7.05
7	132.84	123.893828	6.73	55.159	56.14045	1.78
8	233.79	234.589288	0.34	97.806	98.9289	1.15
9	162.75	172.610372	6.05	81.766	80.91755	1.03
average data	167.78125	169.3850655	0.96	75.405375	75.06518125	0.45

4. Conclusion

(1) In the ALZn5.5MgCu aluminum alloy stamping forming process, heat treatment temperature is the largest process parameter with the greatest impact on the mechanical properties of aluminum alloy stamping forming parts, and the influence of three process parameters on the performance of aluminum

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alloy stamping forming parts is successively: heat treatment temperature > friction coefficient > stamping speed.

(2) In the ALZn5.5MgCu aluminum alloy stamping and forming process,when the stamping speed is 5 mm/s, the friction coefficient is 0.1, and the heat treatment temperature is 350℃,the comprehensive forming quality of aluminum alloy stamping parts reaches the best quality.

(3) For aluminum alloy stamping forming process, using the gray system theory can quickly establish the mechanical properties of GM (0, N) prediction model, modeling required data specimen less, fast and simple, for the alloy stamping forming Milky Way performance accurate, fast prediction, small error, the relative error is less than 10%, prediction value has great reference value, has great guiding significance to the actual production.

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