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ARTICLE

Prediction Model of Punching Springback of Windshield Beam Based on Response Surface Method

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Abstract: Considering the springback of 5182 aluminum alloy wind beam as the research object, the real stress-strain curves of 5182 aluminum alloy sheet under different rolling directions and strain rates were obtained through one-way tensile test, and introduced into the numerical simulation mode. The influence of sheet metal forming speed, die clearance, and friction coefficient on the springback of 5182 aluminum alloy windshield beams was studied and the formation mechanisms were analyzed. According to the response surface method, the prediction model of 5182 aluminum alloy windshield beam springback was established. The prediction model was verified by experiments under different conditions. The research provides a new method for the analysis of aluminum alloy sheet springback.

Key words: 5182 aluminum alloy; numerical simulation; springback prediction; response surface model

With the increase of demands for energy saving and emission reduction in the automotive industry, especially for the continuous development of the automobile market in recent years and the increasingly fierce competition for new energy vehicles, light weight has become an important direction for the further development of the automotive industry[1-4].

Generally, the methods of mass reduction include material mass reduction, process mass reduction and design mass reduction. The application of lightweight materials is the most common development direction, and 5182 aluminum alloy is one of the lightweight materials because its density is only 1/3 of the steel with good corrosion resistance and fatigue resistance, and the performance of 5182 aluminum alloy is similar to that of steel plates. Therefore, it is widely used in the production of automobile structural parts. However, 5182 aluminum alloy is a non-heat-treatable alloy, and its sheet material has a large amount of rebound after stamping[5,6], which leads to the inaccurate forming process and unqualified product size. In fact, springback has always been one of the main defects of sheet metal during stamping, mainly because it is difficult to accurately predict the springback. To solve this problem, many scholars carried out a lot of researches.

Yue[7] used a new damage model to study the effect of toughness damage on springback of 7055 aluminum alloy under different strain paths by three-point bending experiment. Liu[8] studied the influence of process parameters on springback of 7075 aluminum alloy after aging for different time with various cross-section plate widths and thicknesses. Orallo[9] studied the impact of high-speed short electric pulses on the post-forming process (closed mold), and analyzed the amount of obtained springback. Shen[10] used a combination of numerical simulation and regression orthogonal test to establish the model including initial temperature, friction factor, and blank holder force, based on the cylinder deep drawing deep-cutting ring experiment. Concave regression model of the die fillet radius, convex-concave die clearance, and springback was built. The influence of each process parameter on the springback of the workpiece was obtained, and the optimal process parameters were determined. Using Marciniak-Kuczyinski forming limit diagram, U-shaped bending springback simulation, yeld2000-2d anisotropic yield function and the deformation constitutive relationship, Choi[11] studied the formability mechanism and springback of w-tempered steel plate. The above-mentioned scholars used different processes and

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methods to study the springback characteristics of different sheets, however, few researches studied the 5182 aluminum alloy as the automotive structural parts. Predictive research can improve the production efficiency and reduce the assembly errors, which is of great significance in engineering.

This research studied the influence of process parameters on the maximum springback of the windshield beam through Autoform numerical simulation for the 5182 aluminum alloy automobile windshield beam, and established the second-order response surface model of the maximum springback and the maximum springback prediction model. The accuracy of models was testified through experiments, indicating a new method for improving the production efficiency.

1 Establishment of Numerical Simulation Model

According to the structure of windshield of the car and the actual production needs, the expansion drawing of the windshield beam parts was calculated, and the initial blank size was 398.26 mm×162.45 mm×1.5 mm (the thickness of the sheet is 1.5 mm). The numerical simulation model of automobile windshield beams was established by Autoform software, as shown in Fig.1.

The chemical composition of the selected 5182 aluminum alloy sheet in this research is shown in Table 1.

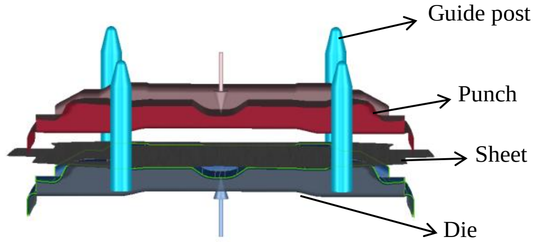

Fig.1 Finite element model of automobile windshield

Table 1 Chemical composition of 5182 aluminum alloy (wt%)

Si	Mg	Fe	Hg	Cr	Au	Al
0.2	5.0	0.35	0.5	0.1	0.15	Bal.

In order to make the simulated situation more approach to the actual situation, uniaxial tensile tests were carried out on 5182 aluminum alloy sheet along different rolling directions (0° represents the same drawing direction and rolling direction) and at different strain rates. The real stress-strain curves were obtained, as shown in Fig.2.

In addition, through the cupping test, the forming limit curve of 5182 aluminum alloy sheet was obtained, as shown in Fig.3. The points in the Fig.3 refer to the limit strains under different experimental conditions, and the line refers to the forming limit curve. Below the line is the safety zone, and above the line is the fracture zone. The obtained data were imported into the Autoform material library. Other relevant parameters were set as follows: elastic modulus E=7.1 GPa, Poisson's ratio ν=0.33, and density ρ=2.81 g/cm^3. Therefore, the 5182 aluminum alloy model was established.

According to the needs of the windshield beam stamping process, the process was divided into stamping step and unloading rebound step. During the simulation, the punching speed was set as 50, 100, 150, 200, and 250 mm/s, the die clearance was set as 1.05, 1.1, 1.15, 1.2, and 1.25 T (T represents a unit of sheet thickness, 1 T=1.5 mm), and the friction coefficient was set as 0.09, 0.11, 0.13, 0.15, and 0.17. Then the calculation of single-factor transformation simulation performed in turn.

2 Analysis of Simulation Results

In general, the main indicators for judging the quality of stamping products are thickness and rebound. In this research, the maximum thickness reduction of automobile windshield beam changes little with different process parameters, and the maximum thinning rate is below 8.3%. Therefore, this research mainly takes the maximum springback of windshield beam as the evaluation index of its forming quality. Through the previous research, it is found that the maximum springback position of the windshield beam is located at the flange protruding downward from both sides with different process parameters, as shown in Fig.4 (the positive and negative values represent the outward rebound and inward rebound, respectively). Therefore, the main research is the influence of process parameters on the maximum springback of the windshield beam.

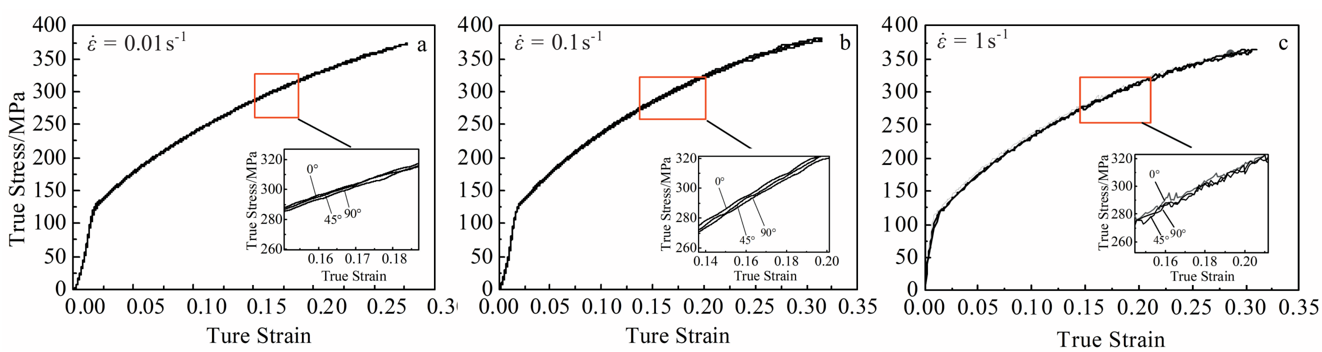

Fig.2 True stress-true strain curves of 5182 aluminum alloy along different rolling directions and at different strain rates: (a) $\dot{\varepsilon}$=0.01 s^{-1}, (b) $\dot{\varepsilon}$=0.1 s^{-1}, and (c) $\dot{\varepsilon}$=1 s^{-1}

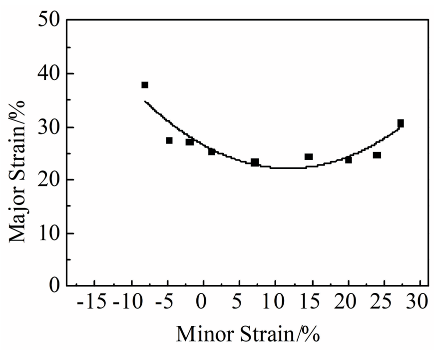

Fig.3 Forming limit curve of 5182 aluminum alloy

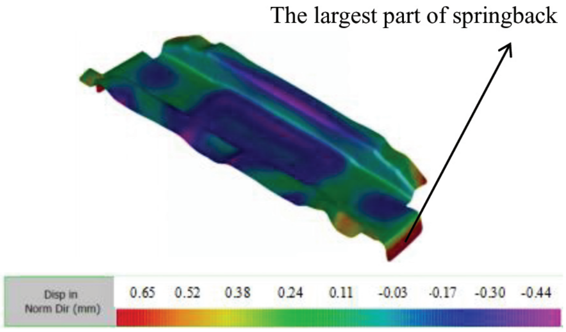

Fig.4 Cloud image of windshield beam springback distribution

2.1 Influence of forming speed on maximum springback

The gap between the male and female molds was set as 1.1 T, and the friction coefficient was set as 0.15. Under the condition of unchanged gap and friction coefficient, the forming speed varies in turn. The results of the numerical simulation are shown in Fig.5.

It can be seen that as the forming speed increases, the amount of maximum rebound shows a gradual decrease trend. When the forming speed increases from 50 mm/s to 250 mm/s, the maximum springback reduces from 1.325 mm to 1.152 mm, decreasing by 13.1%. This is because the increase of forming speed increases the deformation resistance of the sheet material at the deformation path, and the load required for the deformation of windshield beam also becomes larger, which in turn causes more bent parts to enter the plastic deformation stage, reducing the windshield beam.

2.2 Effect of friction coefficient on maximum rebound

During the stamping process, the change of friction coefficient affects the flow performance of sheet metal. The stamping speed was set as 150 mm/s, and the punch die clearance was set as 1.1 T. Under the condition of unchanged stamping speed and punch die clearance, the friction coefficient changes in turn (0.09, 0.1, 0.13, 0.15 and 0.17). The statistical results of the maximum rebound of windshield are shown in Fig.6.

It can be seen from Fig.6 that the maximum springback of the windshield decreases with the increase of friction coefficient. When the friction coefficient increases from 0.09 to 0.17, the maximum springback decreases from 1.383 mm to 1.195 mm, reducing by 13.6%. The reason is that the friction exists between the punch/die and the sheet metal. The rise of friction coefficient increases the friction force on both sides of the sheet, resulting in the increase of plastic deformation area of the sheet metal at the bending point, which in return is conducive to reducing the friction force. The increase of friction between die and sheet metal also leads to the increase of material flow difficulty during deformation. However, the friction coefficient in this research does not show the positive effect on the zero springback when the surface is dealt within the selected range of parameters.

2.3 Influence of die gap on maximum springback

The die clearance can change the contact state between the mold and the sheet, thereby affecting the fluidity and internal stress of the sheet. The stamping speed was set as 150 mm/s, and the friction coefficient was set as 0.15. Under the condition of unchanged stamping speed and friction coefficient, the clearance between the male and female dies varies (1.05, 1.1, 1.15, 1.2, and 1.25 T). The results are shown in Fig.7.

It can be seen from Fig.7 that with the increase of die clearance, the maximum springback of wind shield beam gradually increases. The reason is that the larger die gap reduces the fit degree and the contact area between the sheet and the die. The stress of the bending part of the sheet metal under the same load conditions reduces, and the plastic area reduces, leading

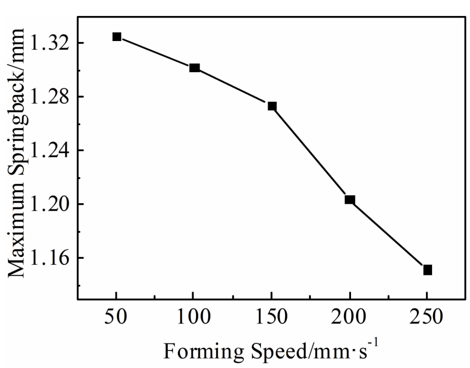

Fig.5 Effect of forming speed on maximum springback

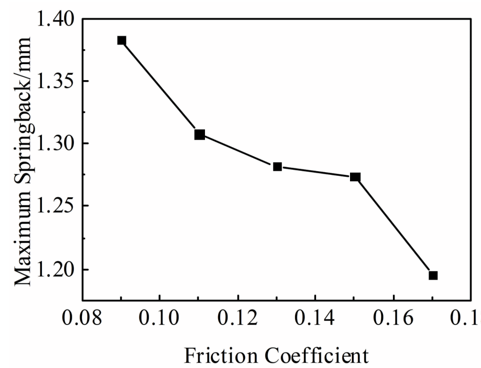

Fig.6 Effect of friction coefficient on maximum springback

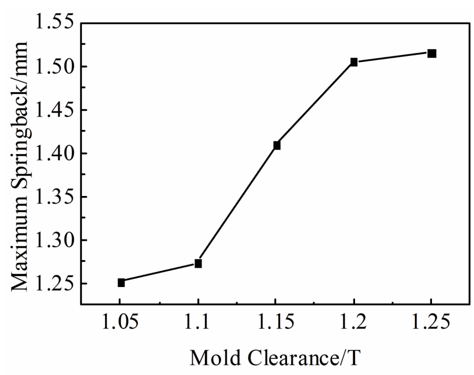

Fig.7 Influence of mold clearance on maximum springback

to the increase of maximum springback.

3 Establishment of Response Surface Model

In this research, the central composite design module in Design-Expect was used to establish the second-order response surface model. Three factors and five levels are selected for the central composite test design. The stamping speed (A), friction coefficient (B), and die clearance (C) are used in the process. Since the establishment of this model is based on the data obtained by numerical simulation, during the establishment process, the central point experiment was carried out one time without considering the experimental error. The axial distance a=2, and the experimental process parameters and levels are shown in Table 2.

According to the experiment, the maximum rebound of aluminum alloy after stamping is shown in Table 3.

Considering the effect of interaction on the maximum springback, the formula of the second-order response surface model is shown in Eq.(1):

$$Y = \beta_0 + \sum_{i=1}^{k}\beta_i x_i + \sum_{i=1}^{k}\beta_{ii} x_i^2 + \sum_{1 \leqslant i \leqslant j}^{k}\beta_{ij} x_i x_j + \varepsilon \tag{1}$$

where Y is the predicted target response value; k is the number of design variables (process parameter level value); β_0, β_i, β_{ii}, and β_{ij} represent the offset term, linear offset coefficient, second-order offset coefficient and linear interaction effect coefficient, respectively; ε is the approximate error value of the objective function; x_i and x_j are the variable values of different process parameters[12].

According to the data in Table 3, the second-order response surface model for the maximum springback of the windshield beam is obtained, as shown in Eq.(2).

Table 2 Experimental process parameters and levels

Factor	Horizontal range				
	$-a$	−1	0	1	a
Forming speed /mm·s^{-1}	50	100	150	200	250
Friction coefficient	0.09	0.11	0.13	0.15	0.17
Die clearance/T	1.05	1.1	1.15	1.2	1.25

Table 3 Experiment and simulation results

Experiment No.	A	B	C	Maximum rebound/ mm
1	−1	−1	−1	1.263
2	1	−1	−1	1.367
3	−1	1	−1	1.366
4	1	1	−1	1.358
5	−1	−1	1	1.293
6	1	−1	1	1.180
7	−1	1	1	1.191
8	1	1	1	1.317
9	$-a$	0	0	1.233
10	a	0	0	1.338
11	0	$-a$	0	1.356
12	0	a	0	1.300
13	0	0	$-a$	1.283
14	0	0	a	1.379
15	0	0	0	1.284

$$\begin{aligned} Y_{\text{Springback}} = &\ 0.296 - 7.776 \times 10^{-3} A - 7.579B + 2.03C - \\ &7.23 \times 10^{-3} AB + 4.4 \times 10^{-3} AC + 4.167BC + \\ &2.444 \times 10^{-6} A^2 - 0.922B^2 - 0.78C^2 \end{aligned} \tag{2}$$

Fig.8 is the error diagram of the prediction model and the simulated rebound. It can be seen that the difference between the numerical simulated and predicted rebound value of the second-order response surface model is small, and the data fitting effect is well. The determination coefficients R^2 (square of correlation coefficient) and R^2_{adj} (square of adjusted correlation coefficient) were used in the second-order response surface model as the evaluation indexes, with R^2=0.9896 and R^2_{adj} =0.9710. The R^2 and R^2_{adj} of the model are close to 1, indicating that the model fits well and the prediction is accurate.

The response surface drawn by the response surface model is shown in Fig.9. The surface color represents the size of the parameter value, where red means higher springback and blue means lower springback. According to the slope of the curved

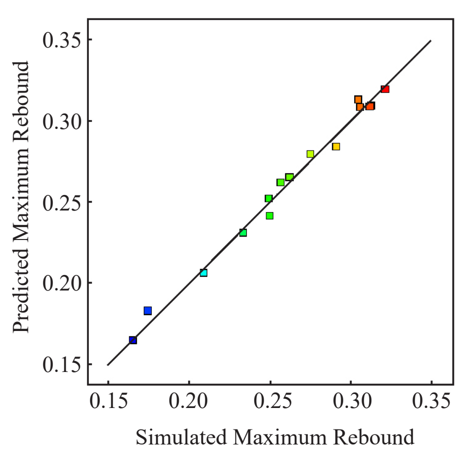

Fig.8 Predicted and simulated maximum rebound

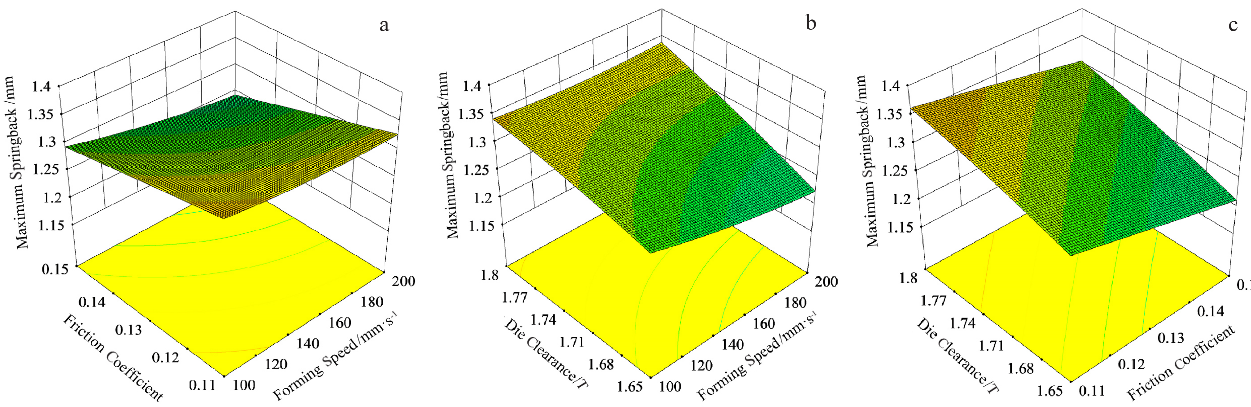

Fig.9 Response surface with interaction under different process parameters

surface in Fig. 9a, the friction coefficient has a greater effect on the rebound than the forming speed does. Similarly, as shown in Fig. 9b and 9c, the influence of die clearance on springback is greater than that of forming speed and friction coefficient on springback. The die clearance shows the largest influence on the springback, followed by the friction coefficient, and the forming speed has the smallest influence on the springback.

4 Experimental Verification

In order to verify the accuracy of Eq.(2), a hydraulic press with an engineering pressure of 500 t and a set of stamping molds for windshield beams (Fig.11) were used for the experimental verification. The selected plate of 5182 aluminum alloy was 1.5 mm in thickness .Three different lubricants were used to achieve variable friction coefficients in the stamping state: the friction coefficient of No.1, No.3, and No.4 lithium grease is 0.13, 0.17, and 0.15, respectively[13].

According to different stamping speeds and different friction coefficients, the experiment parameters for 5182 aluminum alloy windshield stamping are designed, as shown in Table 4. Every setting group was tested three times. The die clearance was 1.6 mm. The stamped parts obtained in the experiment are shown in Fig.10.

Table 4 Stamping experiment parameters

Experiment No.	Forming speed/ $mm \cdot s^{-1}$	Friction coefficient	Mold gap /mm
1	50	0.13	1.5
2	50	0.15	1.5
3	50	0.17	1.5
4	100	0.13	1.5
5	100	0.15	1.5
6	100	0.17	1.5
7	200	0.13	1.5
8	200	0.15	1.5
9	200	0.17	1.5

Fig.10 Stamped parts of windshield beam

According to the sequence of test parameters in Table 4, the stamping parts were sequentially scanned and tested using C-TRACK Blu-ray handheld scanner equipment, and then the scan results were imported into Geomagic Control. Based on the original designed stamping products, the predicted, simulated and measured values of the springback of the automobile windshield beam under different conditions are compared, as

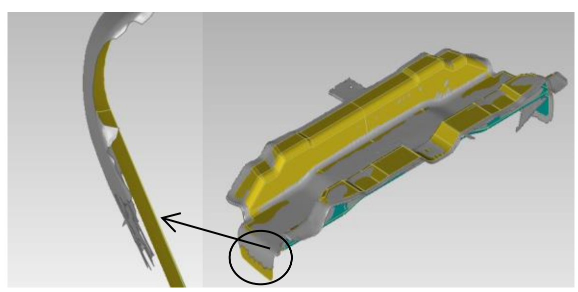

Fig.11 Comparison of springback of test stamping parts and reference parts

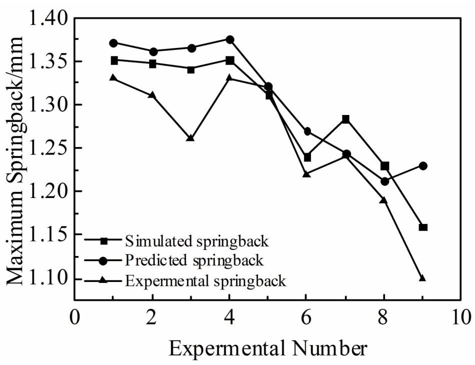

Fig.12 Comparison of experimental, simulated, and predicted maximum springback

shown in Fig. 11. The yellow area is the reference plane, the gray area is the scanned windshield beam forming part, and the partially enlarged view on the left is the maximum springback portion of the windshield beam.

Fig.12 shows the comparison curves of experimental, simulated and predicted values of the maximum springback. It can be seen that the maximum error between the experimental and the simulated values is 5.5%, and the maximum error between the experimental and predicted values is 11.8%. The results show that the error between the simulated, predicted and actual values is within a reasonable range, and the springback predicted by the model is in good agreement with the actual value. The response surface model can accurately reflect the springback and process parameters of aluminum alloy parts during forming.

5 Conclusions

1) A stamping numerical simulation model of 5182 aluminum alloy automobile windshield was successfully established. The die clearance shows the largest influence on the springback, followed by the friction coefficient, and the forming speed has the smallest influence on the springback.

2) Based on the numerical simulation results, a second-order response surface prediction model for the maximum springback of the windshield beam was successfully established. Through the stamping experiment, the maximum error between the experimental and the simulated springback is 5.5%, and the maximum error between the experimental and the predicted springback is 11.8%. The error is within a reasonable range, and the second-order response surface prediction model of maximum springback has a certain guiding significance for actual production.

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基于响应面法的挡风梁冲压回弹预测模型

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摘　要：以5182铝合金挡风梁成形后的回弹为研究对象，通过单向拉伸试验，获取了5182铝合金板料在不同轧制方向及应变速率条件下的真实应力-应变曲线，并将其引入数值模拟模型，研究了板料成形速度、模具间隙、摩擦系数对5182铝合金挡风梁成形回弹的影响规律并分析了其形成原因。然后根据响应曲面法建立了5182铝合金挡风梁回弹预测模型，进而通过不同条件下的实验对比，对该预测模型进行了验证。研究结果为铝合金板料回弹的分析提供了新的思路。

关键词：5182铝合金；数值模拟；回弹预测；响应面模型

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