Stamping Parameters Optimization of an AA5754 A-pillar by Response Surface Methodology

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Abstract. In this paper, an A-pillar was selected as an example to investigate the effect of stamping parameters on the parts forming quality of AA5754 sheet. A finite element model was established using commercial stamping software PAMSTAMP2G. Barlat2000 yield function was used to describe yield behavior of the material. Stamping experiment was conducted to validate the reliability of the model. The studied parameters are blankholder force (100-700 KN) and drawbead’s geometrical variables, including two fillet radii R1 (8-12 mm), R2 (4-8 mm) and the height of drawbead D (2-6 mm). The central composite experiment design method has been employed to design the simulation matrix. In order to obtain stamped parts with optimal forming quality, response surface methodology was used to establish the relationship between stamping parameters and forming quality (rupture and springback). The non-domination sorting genetic algorithms II (NSGA-II) was adopted to conduct an optimal calculation of the models. A pareto optimal solution set in the solution space was obtained. A reasonable optimized scheme was selected. The optimum blankholder force is found to be 700KN with the drawbead’s geometrical parameters R1, R2 and D of 12mm, 6.6mm and 3.8mm, respectively.

1. Introduction
In recent years, the demand of automotive lightweight has become more and more urgent. The aluminum alloy has been widely used in the automotive industry because it’s low density, high specific strength and corrosion resistance. The automotive inner panels usually use 5xxx series aluminum alloy with high formability, such as AA5754, AA5182. However, stamping has numerous quality problems in aluminum alloy forming. The quality of the sheet metal forming product is determined by defects such as wrinkling, fracture, springback, etc. The defects can be improved by optimization of the sheet metal stamping process parameters. The process parameters are the boundary conditions of the sheet, such as the velocity of punch, friction coefficient, the blank holding force (BHF), the geometrical dimensions of drawbeads, etc.

Many researchers have studied the effect of process parameters on the forming quality [1-5]. However, many conclusions are only qualitative descriptions of process parameters on the forming quality of parts. And a lot of single process parameter was be researched. It’s difficult to know the interaction between process parameters. For example, when the blank holding force or the drawbead restraining force is increased, the value of springback will be reduced and the wrinkling will be eliminated, but the material will be more easily fractured. Therefore, an optimized process parameter is very important for the forming quality of the parts. Researches on optimization the process parameters are not studied much, especially for the real aluminum alloy part stamping process. Response surface method (RSM) can be used to establish the relationship between stamping parameters and forming quality. For example, Jae-Jun Lee et al. [6] were use RSM to determine BHF...
and DBRF and the objective is to minimize the wrinkle. Zhou Jie et al. [7] were establish the relationship between forming defects (such as fracture, wrinkle and serious thinning) and process parameters (such as fillet radius, position drawbead, blank size and blank holding force). After the response surface models were established, a nonlinear multi-objective optimization method should be used. Non-dominated sorting genetic algorithm-II (NSGA-II), a fast and elitist optimization technology developed by Deb et al. [9] has been widely used in multi-objective optimization problems.

In this paper, an A-pillar was selected as an example to investigate the effect of stamping parameters on the parts forming quality of AA5754 sheet. A finite element model was established using commercial stamping software PAMSTAMP2G. Stamping experiment was conducted to validate the reliability of the model. Response surface method (RSM) was used to establish the relationship between forming quality and process parameters. The data for response surface modeling were obtained by the finite element simulation. The non-domination sorting genetic algorithms II (NSGA-II) was adopted to conduct an optimal calculation of the models.

2. Numerical simulation and experimental verification

In this section, taking an internal A-pillar as example, a simulation model of stamping process was established by using PAMSTAMP2G. The objective of this simulation model is to get the data for the response surface modeling. The stamping experiment was carried out to verify the accuracy of the simulation model.

2.1. Numerical simulation

The model of the A-pillar is shown in Figure1. The model includes punch, die, blank holder and blank. The blank is elastic-plastic body and the tools are rigid body. The tools of A-pillar were designed to make the left and the right A-pillar in one mould. So the tools structure was symmetrical structure. In order to enhance the computation efficiency, only one side of the model was simulated and analyzed.

![Figure 1. Finite element model of A-pillar deep drawing](image)

The blank material was AA5754 aluminum alloy sheets. The geometry of blank is 1345×640mm and the blank thickness is 2.0mm. The results of tensile tests were shown in Table 1. According to the results of uniaxial tensile tests and biaxial tensile tests, Barlat2000 yield function was used to describe yield behavior of the material and the material constants as see in Table 2. The forming limit diagram (FLD) was determined by experiments, as seen in Figure2. The friction coefficient between the blank and the tools was set to 0.12. The blank holder force was set to 400KN. For springback with contact, it is convenient to use an advanced implicit solver which enables the involvement of contact. A gravity option must be used in this kind of simulation. In springback with contact simulation, no blank locking was set because the blank position was clearly determined by the punch.

| Material | m | $\beta_1$ | $\beta_2$ | $\beta_3$ | $\beta_4$ | $\beta_5$ | $\beta_6$ | $\beta_7$ | $\beta_8$ |
|----------|---|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| AA5754   | 4 | 0.965     | 0.925     | 0.755     | 0.960     | 0.966     | 0.755     | 0.954     | 1.206     |

Table 1. Material properties obtained from the tensile tests of AA5754

Table 2. Yield function and the material constants of AA5754
2.2. Simulation results and experimental verification
Because all the factors that affect the stress distribution will affect the springback values. So it is most appropriate to use the springback values to verify the correctness of the simulation model. The A-pillar part is shown in Figure 3. A 3D scanning device was used to obtain the point cloud data of the part. The geomagic Qualify software was used to compare the experimental data with the simulation results, as shown in Figure 4. The deviation values between the experimental and calculated springback are within ±0.5 mm.

3. Response surface model and multi-objective optimization

3.1. Design variables and forming quality indices
The studied considered parameters are blankholder force (100-700 KN) and drawbead’s geometrical parameterdata, including two fillet radii \( R_1 \) (8-12 mm), \( R_2 \) (4-8 mm) and the height of drawbead \( D \) (2-6 mm). The considered forming quality indices are rupture distance and springback. Rupture distance is the vertical distance between the strain points of the dangerous elements and the forming limit curve (FLC). A negative value corresponds to a point below the curve and a positive one to a point above. If the value of the rupture distance is negative, rupture does not occur; if it is positive, a fracture may occur. [8] The springback is the average value of the seven key points on the part.

3.2. Response surface model establishment
The simulation experiments were designed by the central composite design method (CCD). Response surface model is a useful method to construct the function between the test variables and the test indices. Based on the simulation results, the equations for predicting rupture distance and springback are expressed as follow. Through the analysis of variance (ANOVA), linear model is suitable to describe rupture distance. And a second order regression model is selected to analytically formulate the response surface for springback. The variable \( x_1, x_2, x_3, x_4 \) are two fillet radii \( R_1, R_2 \), the height of drawbead \( D \) and BHF respectively. The objective \( y_1 \) is the rupture distance and objective \( y_2 \) is the average springback value.
\[ y_1 = 9.334 \times 10^{-3} - 1.748 \times 10^{-3} x_1 - 4.221 \times 10^{-3} x_2 \\
+ 4.248 \times 10^{-3} x_3 + 3.089 \times 10^{-3} x_4 \] (1)

\[ y_2 = -2.033 + 8.484 \times 10^{-1} x_1 - 1.449 \times 10^{-1} x_2 - 3.404 \times 10^{-3} x_3 + 8.300 \times 10^{-1} x_4 \\
- 1.748 \times 10^{-3} x_5 x_6 - 3.879 \times 10^{-5} x_1 x_3 + 2.09 \times 10^{-2} x_2 x_5 + 2.3616 \times 10^{-3} x_2 x_4 \] (2)

According to the mathematical model, the influence of process parameters on the fracture and springback can be analysed. For example, \( R_3 \) had a greater impact on rupture than \( R_1 \), \( D \) and \( \text{BHF} \) had a similar effect on rupture. The effect of drawbead and \( \text{BHF} \) on the rupture is linear. The effect of \( \text{BHF} \) on springback is greater than drawbead, and \( R_1 \) had a greater impact on springback than \( R_2 \) and \( D \).

Table 3 provides the adjusted R-squared value, predicted R-squared value and adequate precision of the RSM. As show in this table, the difference between the adjusted R-squared and predicted R-squared values is within 0.1 for the two objectives. The adequate precisions are greater than 4. These results indicate that the models are significant and provide good predictions of the outcomes.

**Table 3. Accuracy of the response surface methodology**

| Response function \( y_i \) | Adjusted R-squared value | Predicted R-squared value | Adequate precision |
|------------------------------|--------------------------|----------------------------|--------------------|
| Rupture distance \( y_1 \)   | 0.9026                   | 0.8585                     | 31.651             |
| Springback \( y_2 \)         | 0.9462                   | 0.8700                     | 19.654             |

3.3. **Multi-objective optimization**

The aim of multi-optimization is to obtain the best combination of process parameters so that the stamping part without any defects. The object function and constraint equations of the optimization process can be formulated as Equation (3):

\[
F = \min [y_1, y_2] \\
\text{s.t.} \\
8 \leq x_1 \leq 12, 4 \leq x_2 \leq 8 \\
2 \leq x_3 \leq 6, 100 \leq x_4 \leq 700
\] (3)

The non-dominated sorting genetic algorithm (NSGA) proposed by Srinivas and Deb is a popular algorithm for multi-objective optimization. NSGA-II, a modified version developed by Deb et al. [9], features an enhanced sorting algorithm. In this paper, NSGA-II is applied to optimize the Equation (3). The following parameters are set within the NSGA-II program: population size=100, crossover probability=90\%, mutation probability=10\% and termination generation=200. After 200 iterations by the RSM, some Pareto-optimal solutions for the two objectives are obtained. Figure 5 shows the Pareto frontier for rupture distance and springback. As seen in Figure 5, the rupture distance and springback present inverse relationship. It is evident that springback and rupture are contradictory. In other words, a higher drawbead or a bigger \( \text{BHF} \) increases the rupture risk but decrease the springback. For the results from the Pareto front, springback and rupture distance cannot be optimized simultaneously because of the conflicting relationship between them. Improve the forming quality of part is refers to the part without defects such as wrinkling and rupture occurred, at the same time makes the springback is minimal. So the ideal solutions are near the rupture distance equal to zero, as seen in Figure 4. The corresponding process parameters combinations are shown in Table 4.
Figure 5. Pareto frontier for rupture distance and springback

Table 4. The optimal process parameters combinations and forming quality indices

| No. | R₁/mm | R₂/mm | D/mm | BHF/KN | Rupture distance | Springback/mm |
|-----|--------|--------|------|--------|-----------------|---------------|
| 1   | 12     | 6.766  | 3.944| 700    | 0               | 0.713         |
| 2   | 12     | 6.730  | 3.931| 700    | 0               | 0.705         |

As seen in Table 4, the optimal process parameters combination can be summarized as follow: R₁=12mm, R₂=6.6mm, D=3.8mm and BHF=700KN. Under such process parameters, the rupture distance is about zero and the average springback is about 0.7mm. To demonstrate the optimization, the stamping simulation was carried out using the optimal process parameters. As shown in Figure 6, the part can be drawn successfully without any rupture and the material is close to necking. At the same time, the average springback value of the seven key points on the part is 0.705mm, as shown in Figure 7. According to the current result, the validity and rationality of the multi-objective optimization can be demonstrated.
4. Conclusion

In this paper, the response surface methodology, NSGA-II and FEM were used to optimize the stamping parameters of an AA5754 A-pillar, the results shows that:

(1) The finite-element model can predict the forming quality of the parts. The Barlat2000 yield function is an appropriate option in the finite element simulation of sheet metal forming process of aluminum alloy.

(2) The proposed multi-objective optimization approach was an effective method to optimize the quality of stamping parts of aluminum alloy. By analysing the response surface models, it is found that: R₂ had a greater impact on rupture than R₁; D and BHF had a similar effect on rupture; The effect of drawbead and BHF on the rupture is linear; The effect of BHF on springback is greater than drawbead, and R₁ had a greater impact on springback than R₂ and D.

(3) The optimal process parameters of the A-pillar are: R₁=12mm, R₂=6.6mm, D=3.8mm and BHF=700KN. Under such process parameters, the rupture distance is about zero and the average springback is about 0.7mm.

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