Performance and Parameter Optimization of Self-piercing Riveted Joint for Aluminum Alloy Plate

Jiabin Zhong1, Yihuai Zhang1 and Baijun Shi1,*
1South China University of Technology, Guangzhou, China
*Corresponding author e-mail: bjshi@scut.edu.cn

Abstract. Self-piercing riveting is a connection technology to achieve efficient connection of aluminum alloy plates, and the quality of the connection mainly depends on the rivet and mold parameters. This paper establishes a self-piercing riveting simulation analysis model based on the ALE method, and verifies the accuracy of the model by comparing the simulation and experimental results. Five parameters such as rivet length and mould radius are selected, and the undercut amount, bottom thickness, remaining thickness, and tensile shear capacity are used as evaluation indexes to research the main factors that affect the joint forming quality, and an effective optimization scheme is proposed.

1. Introduction

As a lightweight technology, self-piercing riveting includes two forms of rivet connection and non-rivet connection. The self-piercing riveting technology in this paper refers to the semi-hollow self-piercing riveting technology. The key components usually selected when analyzing the self-piercing riveting process are punches, blank holders, rivets, plates and molds. The process flow of self-piercing riveting technology can be summarized into four phases: clamping phase, sprint phase, expansion phase and riveting completion, as shown in Figure 1.

Figure 1. Schematic diagram of self-piercing riveting process.

G. Casalino[1] used 6060-T4 aluminum alloy sheet as the research object to analyze the problems in the modeling process. The final experimental results were compared with the simulation data, which proved that the use of finite element technology to simulate self-piercing riveting was feasible. Rezwanul[2] analyzed the performance of self-piercing riveted joints from the perspective of cross-sectional dimensions, indicating that the quality of the joint is related to multiple factors, such as the height of the head of the rivet, the thickness of the bottom, and the effective length of the bottom rivet. J Domitner[3] established a two-dimensional axisymmetric model, simulated three riveting models of...
different sizes, and studied the effect of friction on forming. Han\textsuperscript{[4]} analyzed the influence of the nine parameters of the mold on the undercut amount and remaining thickness by designing an orthogonal test, and performed a range analysis on the simulation results to find out the key factors affecting the molding quality. A feasible mold optimization method was proposed.

This article conducts research based on aluminum alloy body panels used by a passenger car company. A method based on finite element simulation and supplemented by experimental verification was used to establish a numerical model to simulate the self-piercing riveting process and the tensile and shearing experiments of the joint after molding.

2. Basic theory

2.1. Self-piercing riveting process parameters and quality evaluation indicators

The core components of the self-piercing riveting mechanism include six parts: punch, rivet, die, upper plate, lower plate and blank holder. In order to comprehensively evaluate the quality of joints, the cross-sectional dimensions of self-piercing riveted joints were used as the main quality evaluation indicators in this study. The parameters are: undercut amount (self-locking amount) $Z$, bottom thickness $D$, and remaining thickness $S$, as shown in Figure 2.

![Figure 2. Quality evaluation index of riveted joint.](image)

2.2. Research Theory and Method

In the simulation of self-piercing riveting, a two-dimensional model is usually used, that is, a finite element model is established in a two-dimensional plane to analyze the stress-strain relationship in the riveting process. LS-DYNA was selected as the solver in this study to improve the accuracy of the calculation of the deformation process. LS-DYNA has three calculation methods including Lagrange, Euler and ALE (Arbitrary Lagrangian-Eulerian). ALE description\textsuperscript{[5]} combines the advantages of both Lagrangian and Euler descriptions. The ALE coordinate system can effectively describe the trend in the process of material deformation and reduce mesh distortion.

For the theory and method of multi-objective parameter optimization, this paper uses the response surface analysis (RSM) method to explore the relationship between multiple input variables and the output value of the chemical manufacturing process. The response surface analysis method\textsuperscript{[6]} is to process the data points in the design space to obtain the relationship between the target parameters and variables, and use the obtained response surface equations to predict the response values of the relevant data in the space, that is, to find the experimental factors through the experimental design. Form the best combination of the two to get the best target value.

3. Self-piercing riveting and joint performance analysis

In this paper, 5052 aluminum alloy and 6061 aluminum alloy are used as research objects. Self-punching riveting finite element models are established using HyperMesh and LS-DYNA software. The simulation and experimental results are compared to verify the validity of the model. Tensile experiments were performed on two aluminum alloys to obtain the key parameters of the materials, as shown in Table 1.
Table 1 5052 and 6061 aluminum alloy material parameters

| Material | Density/ (g·cm$^{-3}$) | Elastic Modulus/MPa | Poisson's ratio | Yield Strength/MPa | Elongation |
|----------|--------------------------|---------------------|-----------------|---------------------|------------|
| 6061     | 2.7                      | 68000               | 0.31            | 270                 | 0.18       |
| 5052     | 2.7                      | 69000               | 0.33            | 175                 | 0.16       |

A two-dimensional axisymmetric model was established in HyperMesh to simulate the self-piercing riveting process. 5052 and 6061 aluminum alloy sheets with a thickness of 2.0mm, rivet diameter Dr = 5.30mm, rivet length = 6.00mm, mold radius = 4.15mm, radius of the bottom of the boss = 2.70mm, mold depth = 1.90mm, height of the boss = 0.10 mm, as shown in Figure 3.

![Figure 3. Physical drawing of riveted part and two-dimensional axisymmetric model.](image)

In the riveting process, the punch, die and blank holder have almost no deformation. They are divided by a 0.2mm grid. Rivets and upper and lower plates are the key areas. A mesh with a size of 0.1mm is used. Set the punch, blank holder and die as a rigid body with the keyword * MAT_RIGID. During the deformation process, the plate and rivet are deformed into elastoplastic deformation [7,8], so the plastic follow-up hardening material model (* MAT_PLASTIC_KINEMATIC) is used. The selected rivet material parameters are shown in Table 2. Two-dimensional automatic single-sided contact (* CONTACE_2D_AUTOMATIC_SINGLE_SURFACE) is used to simulate the entire contact process to improve modeling efficiency.

Table 2 Rivet material parameters

| Density/ (g·cm$^{-3}$) | Elastic Modulus/MPa | Poisson's ratio | Yield Strength/MPa |
|------------------------|---------------------|-----------------|--------------------|
| Rivet                  | 7.8                 | 188500          | 0.3                | 1818               |

The experimentally obtained cross section is compared with the finite element model. The contour of the model obtained by the finite element simulation is shown in Figure 4. The simulation and experimental contours are similar. The errors between simulation and experiment are: the undercut amount is about 3.3%, the bottom thickness is about 5.0%, and the remaining thickness is about 4.3%, which are all within 10% of the engineering tolerance. Therefore, the self-piercing riveting finite element model established in this paper is considered accurate. Can be used for subsequent parameter research on rivets and molds.
4. Research on Parameter and Die Parameterization of Self-piercing Riveting

The research parameters selected in this paper are: rivet length $L$, die radius $R$, boss bottom radius $r$, boss height $t$, die depth $h$, as shown in Figure 5.

Sensitivity analysis is a method to study and analyze the sensitivity of the state or output change of a system (or model) to changes in system parameters or surrounding conditions. There are many optimization goals in this paper. It is necessary to consider the scale and time of the experiment, reduce the amount of calculation while satisfying the calculation accuracy, and choose the orthogonal experiment design as the method to optimize the boundary.

| Table 3 Variable parameter test level table |
|-------------------------------------------|
| Variable name/symbol | Level1 | Level2 | Level3 |
|----------------------|--------|--------|--------|
| Rivet length/ $L$    | 6.00   | 6.10   | 6.20   |
| Mold radius/ $R$     | 4.00   | 4.15   | 4.30   |
| Radius of boss bottom/ $r$ | 2.60   | 2.75   | 2.90   |
| Boss height/ $t$     | 0.15   | 0.20   | 0.25   |
| Mold depth/ $h$      | 1.90   | 2.00   | 2.10   |

The test results were analyzed from the range and main effect diagrams, and recorded as the average of the corresponding levels of each impact factor. The main effect diagram of joint undercut amount, bottom thickness and remaining thickness is shown below.
According to the above sensitivity analysis, it can be known that the rivet length can make the undercut amount and the bottom thickness reach the maximum value within the horizontal value range, and the horizontal interval of the value can be appropriately reduced. Although the mold radius has a large impact on the undercut amount, the influence of the two parameters is not large, and the remaining thickness will decrease as it increases, so it needs to be taken to a low level. The influence of the radius of the bottom of the boss on the three parameters has a large difference. Considering its influence on the remaining thickness, Influence, reduce its value interval to a low level; the mold depth is sensitive to the remaining thickness, showing a decreasing trend, so avoid the value of the high level interval; the boss is not adjusted. Table 4 shows the adjustment range of each parameter.

### Table 4. Range of optimized parameters for riveted joints

| Optimize parameters | L     | R     | r     | h     | t     |
|---------------------|-------|-------|-------|-------|-------|
| Ranges              | 6.05~6.20 | 4.05~4.20 | 2.60~2.80 | 1.90~2.05 | 0.15~0.25 |
Import the results into Design-Expert software, and analyze the significance and fitting accuracy of the response model of self-locking value, remaining thickness and bottom thickness in the Analysis module. In order to conveniently express the response surface equation, the variables a, b, c, d, and e are used to represent the rivet and die parameters. The response surface equations of the undercut amount Z, the bottom thickness D, and the remaining thickness S with respect to the rivet and die parameters are shown in equations (1), (2), and (3).

\[
Z = +85.72 - 62.16a + 27.13b + 7.21c + 48.16d - 87.92e \\
- 4.27ab - 2.56ad + 7.23ae - 2.23bc - 6.16bd + 5.29be \\
- 4.34cd + 4.68ce + 4.6de + 6.81a^2 + 1.93b^2 + 1.86c^2 + 1.05d^2
\]  

(1)

\[
D = +1971.65 - 339.77a - 36.36b - 11.08c - 870.56d - 9135e \\
- 12.43ac + 147.62ad + 1504.08ae + 27.11bc - 10.88cd - 14.87ce \\
+ 4711.27de + 6.99a^2 - 4.54b^2 - 9.42e^2 - 771.89ade
\]  

(2)

\[
S = -61.57 + 34.304a - 7.47b - 22.2c - 2.96d + 53.13e \\
- 1.67ac - 2.374ad - 5.91ae + 6.65bc + 6.74cd - 8.02de \\
- 1.94a^2 - 1.29b^2 - 1.48e^2
\]  

(3)

This article takes the undercut amount Z, the bottom thickness D, and the remaining thickness S as the response of the system. In order to ensure no loss occurs in each parameter during optimization, the optimization is performed in the form of obtaining the maximum value. The standard form of the multi-objective optimization model is transformed into the form of solving the maximum value. The expression of the optimization objective is:

\[
\begin{align*}
\max f_1 &= \frac{Z}{Z_0} \\
\max f_2 &= \frac{D}{D_0} \\
\max f_3 &= \frac{S}{S_0}
\end{align*}
\]

Among them, \(Z_0, D_0, \) and \(S_0\) respectively represent the values of undercut amount, bottom thickness and remaining thickness before optimization. Table 5 shows the parameter combinations of rivets and molds after multi-objective optimization and the predicted values of the undercut \(Z\), bottom thickness \(D\), and remaining thickness \(S\) of the riveted joint under this combination.

**Table 5.** Predicted parameters and cross-sectional dimensions of the riveted model after optimization

| Parametric variables | L  | R  | r  | h  | t  | Z   | D   | S   |
|----------------------|----|----|----|----|----|-----|-----|-----|
| Target value         | 6.10 | 4.11 | 2.75 | 2.01 | 0.21 | 0.51 | 1.04 | 0.48 |

Based on the predicted values, a riveting model is established and the simulation results are shown in Figure 9. The rivets are fully embedded in the lower plate and there is no thick pier.

**Figure 9.** Stress cloud diagram and measurement diagram of riveted joint
According to the analysis of the cross-section dimensions of the joint obtained from the physical modeling analysis of the rivet and the mold, it is known that the undercut amount before optimization is $Z = 0.470\text{mm}$, the bottom thickness is $D = 0.975\text{mm}$, and the remaining thickness is $S = 0.450\text{mm}$. After optimization, the undercut of the joint is increased by about 10%, the bottom thickness is increased by about 8.6%, and the remaining thickness is increased by about 3.1%. There is no parameter loss, but all have been improved, which indicates that the optimized rivet and die combination can be improved. The overall performance of the joint after forming. The maximum tensile shear strength of the joint after optimization is 4.84kN. It can be seen that the tensile shear capacity of the joint after optimization is improved by about 4.9% compared with that before optimization, indicating that the rivets and molds obtained after optimization can improve the tensile shear of the self-piercing riveted joint. 

5. Conclusion

The quality of self-piercing riveted joints is closely related to the rivet and mold parameters. The main influencing parameters studied in this article are rivet length, mold radius, radius of the bottom of the boss, die depth and height of the boss. The quality evaluation standard is the cross-sectional size after forming: Cut amount, bottom thickness and remaining thickness. Through the sensitivity analysis, the optimization range of the parameters is determined; the response surface model and the multi-objective optimization model are constructed to optimize the rivet parameters and mold parameters. After optimization, the undercut amount is increased by 10%, the bottom thickness is increased by 8.6%, and the remaining thickness is increased by 3.1%. The tensile and shear capacity is increased by 4.9%, and the optimization scheme proposed in the study is effective, which is of great significance for subsequent research.

References

[1] Casalino G, Rotondo A, Ludovico A. On the numerical modelling of the multiphysics self piercing riveting process based on the finite element technique[J]. Advances in Engineering Software, 2008, 39(9): 787-795.
[2] Haque R. Quality of self-piercing riveting (SPR) joints from cross-sectional perspective: A review[J]. Archives of Civil and Mechanical Engineering, 2018, 18(1): 83-93.
[3] Hönsch F, Domittner J, Sommitsch C, et al. Numerical simulation and experimental validation of self-piercing riveting (SPR) of 6xxx aluminium alloys for automotive applications[J]. Journal of Physics: Conference Series, 2018, 1063: 12081.
[4] Han S, Li Z, Gao Y, et al. Numerical study on die design parameters of self-pierce riveting process based on orthogonal test[J]. Journal of Shanghai Jiao tong University (Science), 2014, 19(3): 308-312.
[5] Hirt C.W, Amsden A. A, Cook J.L. An Arbitrary Lagrangian-Eulerian Computing Method for All Flow Speeds[J]. Journal of Computational Physics,1974,14(3):227-253.
[6] Shi S, Zhou J, Chen Y. Experiment Design—Learning Guidance and Exercises [M]. Beijing: China Statistics Press, 2005: 140-290.
[7] Hoang N.H, Porcaro R, Langseth M, et al. Self-piercing riveting connections using aluminium rivets[J]. International Journal of Solids and Structures, 2010, 47(3-4): 427-439.
[8] Zhang K. Research on Self-piercing Riveting Technology of Ultra High Strength Steel and Aluminum Alloy [D]. Changchun: Jilin University, 2017.