Multi-parameter joint optimization of self-piercing riveting on aluminum alloy plate

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Abstract. Self-piercing riveting technology can achieve more efficient connection of aluminum alloy plate parts. In this study, the 5052 plate and the 6061 plate are taken as the research objects. By establishing a finite element model and using a multi-objective optimization method, multiple parameters are jointly analyzed. The sensitivity parameter analysis was used to determine the value range of the research parameters, and the response surface analysis method was used to construct the functional relationship between the parameter variables and the system response. Finally, a multi-objective optimization model was established to obtain a reliable combination of rivet parameters and die parameters.

1. Introduction

With the continuous progress of automotive lightweight technology, aluminum alloys, magnesium alloys and other materials have become more widely used in bodywork. For the connection of lightweight alloy materials, traditional welding and other technologies have not performed satisfactorily. At present, the more commonly used connection technology is self-punching riveting technology.

Self-piercing riveting technology is a cold forming technology. With the cooperation of a punch and a die, the rivet is embedded in the connected plate to form a self-locking structure. As shown in Figure 1, the process flow of self-piercing riveting technology includes four stages: clamping stage (a), sprint stage (b), expansion stage (c) and riveting completion (d).

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

Self-piercing riveting technology was first studied by foreign scholars, and its application has become more widespread as the technology matures. Rezwanul et al. analyzed the performance of self-piercing riveted joints from the perspective of cross-sectional dimensions. This article confirms
that the quality of joints 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. M. Carandente et al\cite{3} took into account the thermal deformation caused by friction during mechanical deformation during the forming process, established riveting models at various temperatures, and compared the simulation results with the experimental results to improve the accuracy of self-piercing riveting numerical simulation.

In this study, an aluminum alloy body panel for a passenger car company was established by using finite element simulation and experimental verification methods. A 5052 and 6061 aluminum alloy plate with a thickness of 2.0 mm was used as the research object to establish a finite element model. Through the sensitivity analysis test, the influence degree of the rivet and mold parameters on the evaluation index of joint quality is obtained. The objective genetic optimization algorithm is used to optimize rivet parameters and mold parameters to improve the quality of self-piercing riveting streets.

2. Method

2.1. Finite element model

In this study, 5052 and 6061 aluminum alloy sheets with a thickness of 2.0 mm were selected as riveting objects. According to the "Mechanical Materials Room Temperature Tensile Test Method" GB / T228-2010, the mechanical test standard is used to design the metal mechanical test\cite{4}. Through the tensile test, the main material parameters obtained are shown in Table 1.

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

As a key component in the self-piercing riveting process, the rivet has a mature manufacturing process. In this study, finite element modeling is used to analyze the cross-sectional shape of rivets with different hardness. The rivet material parameters selected are shown in Table 2.

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

HyperMesh and LS-DYNA software were used to establish a self-piercing riveting finite element model\cite{5,6}. In order to simplify the simulation process, a two-dimensional axisymmetric model was established in HyperMesh. When using LY-DYNA to solve, the model was built on the right side of the Y axis. The ALE method was used to improve the accuracy of calculations to obtain more accurate experimental results. Figure 2 shows the physical diagram and two-dimensional model of the key components of riveting, and Figure 3 shows the finite element model of self-piercing riveting.

2.2. Quality evaluation index of self-piercing riveted joint

The quality of self-piercing riveted joints is affected by many factors such as rivets, dies, plates and stamping equipment. In this study, the cross-sectional dimensions of self-piercing riveted joints were selected as the main quality evaluation indicators of this study\cite{7}. As shown in Figure 2, the cross-section parameters for evaluating the forming quality of joints are mainly: undercut amount (self-locking amount) \( Z \), bottom thickness \( D \) and remaining thickness \( S \).
Rivets and dies are a collection of multiple geometric features. These features are quantified in numerical form to obtain a parametric model of rivets and dies[8]. Two diameters of \( \phi = 3.3\text{mm} \) and \( \phi = 5.3\text{mm} \) are mainly used in engineering. In this study, a rivet of \( \phi = 5.3\text{mm} \) was selected according to the thickness of the aluminum alloy, and the length \( L \) of the rivet was used as a rivet study parameter. Select the die radius \( R \), the radius of the bottom of the boss \( r \), the height of the boss \( t \), and the depth of the die \( h \) as the die research parameters to obtain the five optimized parameters of this study, as shown in Figure 5.

3.1. Sensitivity Analysis Theory
Sensitivity analysis is a method to study and analyze the sensitivity of the state or output changes of a system or model to changes in system parameters or surrounding conditions. Sensitivity analysis is mainly used for optimization problems. By studying the parameters those have a greater impact on
the optimization goal, the input variables can be determined more quickly and the system change trend can be predicted according to their degree of influence and range, and the optimization range can be adjusted. The functional relationship between the system response function and the study variables is:

\[ u = f(x_1, x_2, x_3, \ldots, x_n) \quad (1) \]

The value range of the constraint variable \( x_i \) is:

\[ a_i \leq x_i \leq b_i, a_2 \leq x_2 \leq b_2, \ldots, a_n \leq x_n \leq b_n. \]

Where the sensitivity of the system response \( u \) to the variable \( x_i \) is expressed as:

\[ S_{x_i}^u = \frac{\partial u}{\partial x_i} \quad (2) \]

### 3.2. Experimental design for sensitivity analysis

The physical meaning of sensitivity is the ratio of the change in the system response to the difference between the variables when the variable takes different values, which is the change in the system response caused by the unit variable. In this study, the cross-sectional dimensions of the joint after molding, including the undercut amount \( Z \), the bottom thickness \( D \), and the remaining thickness \( S \) were taken as the system response. The influence variables were selected as rivet length \( L \), die radius \( R \), boss bottom radius \( r \), and boss height \( t \), die depth \( h \).

#### Table 3. Variable parameter test level table. (mm)

| Variable name/symbol | Level1 | Level2 | Level3 |
|----------------------|--------|--------|--------|
| Rivet length/ L      | 6.00   | 6.10   | 6.20   |
| Die 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   |
| Die depth/ h         | 1.90   | 2.00   | 2.10   |

### 3.3. Analysis of influence of quality parameters of riveted joints

According to the variable parameter test level table and the orthogonal test design principle, an orthogonal test table is designed. A finite element model is established in HyperMesh based on each set of test data, and it is imported into LS-DYNA for calculation. The undercut amount \( Z \), the bottom thickness \( D \) and the remaining thickness \( S \) are measured. The test results are shown in Table 4:

#### Table 4. Sensitivity analysis test results. (mm)

| Number | \( Z \) | \( D \) | \( S \) | Number | \( Z \) | \( D \) | \( S \) |
|--------|-------|-------|-------|--------|-------|-------|-------|
| 1      | 0.595 | 1.090 | 0.364 | 13     | 0.577 | 1.260 | 0.280 |
| 2      | 0.453 | 0.971 | 0.451 | 14     | 0.566 | 1.114 | 0.519 |
| 3      | 0.482 | 1.161 | 0.479 | 15     | 0.569 | 1.128 | 0.329 |
| 4      | 0.628 | 1.230 | 0.264 | 10     | 0.648 | 1.346 | 0.306 |
| 5      | 0.604 | 1.211 | 0.374 | 11     | 0.547 | 1.092 | 0.469 |
| 6      | 0.582 | 1.100 | 0.377 | 12     | 0.529 | 1.172 | 0.364 |
| 7      | 0.561 | 0.975 | 0.617 | 16     | 0.603 | 1.038 | 0.527 |
| 8      | 0.540 | 0.977 | 0.483 | 17     | 0.561 | 1.141 | 0     |
| 9      | 0.593 | 1.154 | 0     | 18     | 0.486 | 1.023 | 0.612 |

According to the test results, the main effects of each factor on the undercut amount, bottom thickness, and remaining thickness are shown in Figure 6:
According to the test result and the main effect diagram of the evaluation index, it can be known that the length of the rivet can be appropriately reduced in the horizontal interval. The radius of the die should be taken in the low level range, and the radius of the bottom of the boss should also be taken in the low level range. The depth of the die is decreasing, avoiding taking the value to the high level interval, the boss is not adjusted. The range of values for each optimization parameter is shown in Table 5:

| Parameter parameters | L      | R      | r      | h      | t      |
|----------------------|--------|--------|--------|--------|--------|
| Value range          | 6.05–6.20 | 4.05–4.20 | 2.60–2.80 | 1.90–2.05 | 0.15–0.25 |

4. Multi-objective parameter joint optimization

4.1. Response surface test design

The joint optimization of multi-objective parameters needs to comprehensively consider the influence of each parameter. In this study, the central composite design (CCD) is used as a parameter optimization test method, and the parameters are input into the response surface equation die of the Design-expert software to establish a CCD experiment\[11\]. For 26 groups of experiments, each group of experimental data is modeled in HyperMesh and imported into LS-DYNA for calculation. The undercut amount $Z$, bottom thickness $D$, and remaining thickness $S$ are used as responses to obtain the results of the first 12 groups of tests as shown in Table 6.

| Number | Z      | D      | S      | Number | Z      | D      | S      |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 1      | 0.592  | 1.082  | 0.467  | 7      | 0.522  | 0.909  | 0.467  |
| 2      | 0.557  | 1.179  | 0.244  | 8      | 0.469  | 0.978  | 0.455  |
| 3      | 0.528  | 1.130  | 0.349  | 9      | 0.637  | 1.158  | 0.467  |
| 4      | 0.571  | 1.134  | 0.409  | 10     | 0.458  | 1.131  | 0.226  |
| 5      | 0.636  | 0.931  | 0.523  | 11     | 0.596  | 1.123  | 0.604  |
| 6      | 0.469  | 0.978  | 0.455  | 12     | 0.525  | 0.975  | 0.470  |

Import the results into Design-Expert, the significance and fitting accuracy of the response model of the undercut amount $Z$, remaining thickness $D$ and bottom thickness $S$ in the die are analyzed. The validity analysis of the response surface equation is performed. In order to express the response
surface equation succinctly, the variables \( a, b, c, d \) and \( e \) are used to represent the rivet and die parameters \( L, R, r, h, \) and \( t \), respectively. Response surface equations for the parameters of rivets and die:

\[
Z = +85.72 - 62.16a + 27.13b + 7.21c + 48.16d - 87.92e \\
- 4.27ab - 2.56ad + 7.23ae - 2.23bc - 6.16bd + 5.29be \\
- 4.34cd + 4.68ce + 4.6de + 6.81a^2 + 1.93b^2 + 1.86c^2 + 1.05d^2 \\
(3)
\]

\[
D = +1971.65 - 339.77a - 36.36b - 11.08c - 870.56d - 9135e \\
- 12.43ac + 147.62ad + 1504.08ae + 27.11bc - 10.88cd - 14.87ce \\
+ 4711.27de + 6.99a^2 - 4.54b^2 - 9.42e^2 - 771.89ade \\
(4)
\]

\[
S = -61.57 + 34.304a - 7.47b - 22.2c - 2.96d + 53.13e \\
- 1.67ac - 2.374ad - 5.91ae + 6.65bc + 6.74cd - 8.02de \\
- 1.94a^2 - 1.29b^2 - 1.48c^2 \\
(5)
\]

4.2. Multi-Objective Genetic Algorithm Optimization

When using genetic algorithm optimization, randomly select points in the data space and perform a global search in the data space. In this study, the undercut amount \( Z \), bottom thickness \( D \), and remaining thickness \( S \) are used as responses to ensure that no parameters are lost during optimization. Therefore, optimization is performed in the form of a maximum value. It is optimized in Isight software; the Pareto solution set is obtained through calculating, the predicted values of rivet and die parameters are obtained, as shown in Table 7[12].

| 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, simulations were performed to obtain the stress cloud diagram and measurement diagram of the riveted joint as shown in Figure 7. The rivets are fully embedded in the lower plate without upset. Undercut amount \( Z = 0.517 \) mm, error is 1.4%, bottom thickness \( D = 1.059 \) mm, error is 1.8%, remaining thickness \( S = 0.464 \) mm, error is 3.3%. The error between the simulation value and the predicted value is small. Within the tolerance range, the result of the target optimization is relatively reasonable. The multi-objective optimization scheme is feasible and can provide a certain reference for subsequent research.

Figure 7. Stress cloud diagram and measurement diagram of riveted joint.
5. Conclusion
Through multi-objective optimization of rivet and die parameters, the response surface equations of the parameters were obtained using CCD tests, and the target values of each parameter were obtained by using genetic optimization algorithms, and the error was controlled within 5%. Compared with the performance of the joint before optimization, the undercut amount $Z$ increased by 10%, the bottom thickness $D$ increased by 8.6%, and the remaining thickness $S$ increased by 3.1%. It can be seen that this research has played a certain role in the optimization of self-piercing riveted joints, and further improvement in the quality of body connection has practical guidance significance.

References
[1] Huang Z, Jiang N, Wang J 2009 FORGING&STAMPING TECHNOLOGY 34 68-71
[2] R H 2018 Archives of Civil and Mechanical Engineering 1 83-93
[3] Carandente M, Dashwood R J, Masters I G, Han L 2016 Journal of Materials Processing Technology 236 148-161
[4] GB/T228-2002, Room temperature tensile test method for metallic materials. Beijing, 2002.
[5] Bai Y, Du M, Li L 2011 New Technologies And Processes 45-47
[6] Wang Y, Jin L, Hong Q 2002 HyperMesh & HyperStudy application skills and advanced examples (Beijing: China Standard Press)
[7] Zhang X, He X, Gu F, Ball A 2019 Journal of Materials Processing Technology 268 192-200
[8] Huang X, Chen W 1995 Computer Aided Engineering 17-21
[9] Liu S.2017 (South China University of Technology)
[10] Fang K, Ma C 2001 Orthogonal And Uniform Experimental Design (Beijing: Science Press) pp1-82
[11] Xu X, He M 2010 Experiment design and Design-Expert, SPSS application (Beijing: Science Press) pp103-150
[12] Lai Y, Jiang X 2012 Detailed Isight Parameter Optimization Theory and Examples (Beijing: Beijing University of Aeronautics and Astronautics Press) pp177-190