Numerical investigation of tool parameter influence on the interlock forming during flat clinching process

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Abstract
Tool parameters play a vital role in the mechanical interlock formation during the flat clinching process. To understand the influence of tool parameters on the interlock formation, the finite element software DEFORM-2D was used to build the numerical model of the flat clinching process, and the numerical model was verified by the experiment. The influences of the punch radius, punch fillet radius, and blank holder radius on the interlock formation of the clinched joint were investigated using the numerical model. Then, the relationship between the punch radius and blank holder radius was studied. The results showed that the interlock gradually increases with the increase of the blank holder radius; after that, the interlock begins to decrease. To maximize the interlock, the punch radius and the blank holder radius should be increased simultaneously. It can be concluded that the blank holder radius and the punch radius should keep a linear relationship when designing the geometric dimensions of the flat clinch tools, which can promote the application of the flat clinching process in car body manufacturing.

Keywords Flat clinching · Aluminum alloy · Tool parameter · Interlock forming

1 Introduction

To increase fuel economy and reduce exhaust gas emissions, lightweight materials have been a strategy for building vehicle body structures, and suitable joining techniques are required to create such structures [1, 2]. Some mechanical joining processes, such as mechanical clinching, have been developed for joining these hard-to-weld lightweight materials. In the clinching process, two or more workpieces can interlock together only by local plastic deformation without additional elements [3]. The mechanical clinching process is used to join many materials, such as steels, aluminum alloys, magnesium alloys, titanium alloys, and carbon fiber-reinforced plastics (CFRP) [4–6]. Mechanical clinching has become a viable option for joining similar or dissimilar lightweight materials.

In the mechanical clinching process, two or more overlapping metal sheets are joined by local plastic deformation so that a clinched joint with a die-side protrusion can be obtained. Due to this protrusion, conventional clinching technology cannot be used for visible and functional surfaces [7]. To solve this problem, Chen et al. [8, 9] used a pair of flat dies to decrease the protruding height of the conventional clinched joint and enlarge the neck thickness and interlock of the joint. Chen et al. [10] divided the reshaping process into two steps and used a special rivet in the second step to produce a reshaped joint with a rivet. Lambiasi and Ko [11] investigated the effectiveness of two-step clinching for joining aluminum and CFRP. The reshaping process could improve the strength of the joints but result in damage to the CFRP sheet. The reshaping method with (or without) a rivet increases the joint strength and reduces the protrusion, but the process is complex and time-consuming for sheets need to be turned and positioned during the reshaping process [12]. Wen et al. [13] investigated the flat hole clinching process to form a joint with a flat surface. It needs a hole to be pre-punched before joining, which reduces work efficiency. All the above reshaping methods suffer from increased cycle time due to the additional step.

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To solve this problem, flat clinching technology was developed at Chemnitz University of Technology [14], flat clinching technique is a one-step method that uses a punch, blank holder, and flat anvil. A one-sided planar joint can be produced in the process. The flat clinched joint is formed by the sheet material flowing upward and radially in the control of the blank holder [12]. The geometrical of the punch and blank holder are the critical factors affecting the quality of the flat clinched joint. Many investigations have been carried out to study the effect of different geometries and structures of tools on the mechanical strength of the flat clinched joint to obtain the best joint quality. Lüder et al. [15] investigated the influence of moisture content in wood on the strength of the flat-clinched joint. Han et al. [16] used the orthogonal experimental design simulation method to optimize the geometrical parameters, results show that the punch fillet radius and the blank holder radius have a significant impact on the flat-clinched joint. However, the punch diameter was not taken into account, and the parameter interactions were assumed to be negligible in her study. Chen et al. [17] investigated the effect of punch diameter and holder force on materials deforming behavior and quality of the flat clinched joint. The results showed that an increase in punch diameter could improve the neck thickness and interlock, and a higher holder force is required for restricting the material flow. The changes in the radius of the blank holder were not taken into account in the study. Atia et al. [18] studied the joining process of AA7075 aluminum alloy in different temper conditions by flat clinching, they investigated the effect of blank holder parameters and forming force on the interlock shapes and found that the blank holder groove was effective in enhancing the interlock formation. A modest decrease in groove blank holder depth improved interlock formation, a blank holder groove diameter greater than 150% of the punch diameter and groove depth greater than 20% of sheet thickness are recommended to the flat clinch joining process. In another work, Atia et al. [19] investigated the influence of the blank holder parameters on material flow and the geometrical structure of the die-less clinched joints by a numerical method and they indicated that increasing the groove diameter or decreasing the blank holder depth enables the interlock depth to increase. Furthermore, Atia [20] jointed high-strength AA7075 aluminum sheets by hot die-less clinching with an electrical resistance heating method in which the local region was heated. Chen et al. [21] investigated the flat clinching process for joining three-layer sheets on thin-walled structures. Gerstmann and Awiszus [7] developed a flat clinch bonding technique as a combination of flat clinching and adhesive bonding. After gluing, metal sheets can be mechanically connected by flat clinching, this ensures the assembly strength and shortens the processing time. However, the relationship between the punch radius and blank holder radius in the flat clinching process was not studied in their studies.

The present study aims to elaborate on the influence of punch radius, punch fillet radius, and blank holder radius on the mechanical interlock forming of the flat clinching joint and the interrelationships among these tool parameters. The finite element model was built using the DEFORM-2D software, and Al5052 was chosen as the material for the two sheets. This model is then used to simulate the flat clinching process and assess the effect of the tool parameters on the mechanical interlock.

2 Materials and methods

2.1 Materials

The sheet used in this finite element simulation is made of Al5052-O aluminum alloy. The mechanical properties of Al5052-O sheet are shown in Table 1. The constitutive behavior of the Al5052-O aluminum alloy is described by the true stress–strain curve, as shown in Eq. (1) [22]:

\[
\sigma = 377.23 e^{0.25}
\]

where \(\sigma\) is the true stress and \(\varepsilon\) is the true strain. The Voce hardening model was implemented to fit the stress–strain curve for describing the material behavior of Al5052. Plastic material models were used to assume the upper sheet and lower sheet, while the punch, blank holder, and flat anvil were considered rigid bodies.

2.2 Mechanism of flat clinching

Flat clinching is a one-step joining process through local plastic deformation, in which a punch, blank holder, and flat anvil are used, as shown in Fig. 1. In the flat clinching process, the two sheets are placed upon a flat anvil, and the blank holder moves down to press the sheets down. Afterward, the punch moves downward to stamp the sheets. With the restriction of the blank holder, the material would flow upward rather than flow radially; the

| Table 1 Mechanical properties of Al5052-O sheet [22] |
|-----------------------------------------------|
| Properties                                   | Value   |
| Density (kg/m³)                              | 2700    |
| Yield strength (MPa)                         | 116.64  |
| Tensile strength (MPa)                       | 209.37  |
| Elasticity modulus (GPa)                     | 72      |
| Poisson’s ratio                              | 0.3     |
upper sheet material flows into the gap between the punch and blank holder, meanwhile, the lower sheet material also flows upward. Finally, the material below the punch flows radially, and a mechanical interlock is formed between the two sheets.

The main geometric parameters that affect the mechanical properties of the flat clinched joint are shown in Fig. 2, including the interlock length ($t_s$), neck thickness ($t_n$), and bottom thickness ($X$). The clinched joint produced by a flat die had higher shear strength and smaller tensile strength due to the small interlocking [23]. Gerstmann [24] found that the flat clinched joint had higher shear strength and lower tensile strength due to the higher neck thickness and lower interlocking compared with the conventional clinched joint. It is proposed that the parameters influence interlocking could be optimized for producing a sturdy flat clinched joint. Therefore, the mechanical interlock is often used to assess the property of the flat clinched joint in the following discussion.

2.3 Model

Experiments have often been used to adjust tool geometry and process parameters in the clinching process, which take a lot of time and are quite expensive. To overcome this problem, the finite element method is frequently used to investigate the joining process, mechanical properties, and failure mechanisms of the clinched joints [25]. Tenorio et al. [26] studied the effect of tool geometries and process parameters on the strength of clinched joints using the finite element method.

The formation of mechanical interlock mainly depends on the configuration of the tools [27], to study the influence of the tools geometrical parameters on the property of the flat clinched joint, as shown in Fig. 3, different punch radius ($r_p$) of 2.55, 2.75, 2.95, and 3.20 mm are adopted in the finite element simulation, and punch fillet radius ($r_0$) is set to 0.1, 0.2, and 0.3 mm, and blank holder radius ($r_h$) is set to 3.80, 4.20, 4.50, 4.80, 5.00, 5.50 mm, etc. The height of the blank holder groove ($r_c$) is set to 2 mm.

The purpose of this simulation is to investigate the effect of punch and blank holder geometrical parameters on the flat clinched joint. To reduce computational resource usage, the simulations of flat clinching were carried out using an axisymmetric model. The simulations were carried out using the finite element software DEFORM-2D. Quadrilateral elements were used to mesh the sheets, involving 2854 elements with 3148 nodes in the numerical model. To prevent the mesh distortion, the automatic remeshing method was used in the finite element simulation. Automatic remeshing was performed every ten steps in the finite element simulation. The Coulomb friction law was chosen to model the friction conditions at the contact surfaces. The friction coefficients between the sheets and tools were set as 0.15 [28], and the friction coefficient between the upper sheet and the lower sheet was set as 0.3. The flat anvil is fixed, the thickness of the upper sheet and lower sheet is 2 mm, the bottom thickness ($X$) was always fixed at 20% of the total thickness of two sheets, and the punch moves downwards with a speed of 0.5 mm/s, and the time...
increment is 0.1 s. The preload force of the blank holder is 90 kN, and the spring stiffness is 8 kN/mm.

### 2.4 Experiment

Joining dies manufactured by molded steel are shown in Fig. 4. The punch is installed on the upper die, the blank holder is installed on the sliding die, and the anvil is installed on the lower die. The springs are sleeved on the slide column between the upper die and the sliding die. Thus, with the movement of the punch, a holder preload force can be generated on the blank holder. The flat clinching experiment was carried out on an HYDLIC press machine (HYDLIC Company, Dongguan City, China).

![Experimental setup](image)

During the joining process, the velocity of the punch is 0.5 mm/s, and the total stroke of the punch is 3.6 mm.

### 3 Results and discussion

#### 3.1 FE model validation

Before using the numerical model to carry out the finite element simulation, model validation was carried out to verify the accuracy of the numerical model. Thus, experimental data were used to compare with the numerical results in terms of the neck thickness and interlocking length. The cross-sections of the flat clinched joint obtained from experiments and the numerical model are shown in Fig. 5. The numerical results agreed well with the experimental data in respect of the neck thickness and interlocking length of the flat clinched joint. The interlock from the simulation is 0.068 mm, and the interlock from the experiment is about 0.063 mm. The simulation results are 7.9% higher than the experimental results. The cross-section of the numerical model is similar to that of the experiment, which proves that the numerical model can be used to predict the outcome of a flat-clinching process with accuracy.

#### 3.2 Material flow

Material flow during the flat clinching process is shown in Fig. 6. The flat clinching process can be divided into four stages. Within stage 1, with the downward movement of the punch, the sheet material under the punch flow in the same direction, while the material around the punch region flows in the radial direction, as shown in Fig. 6a.

In stage 2, with the further punch movement, it becomes increasingly difficult for the upper sheet material to flow in the radial direction due to the limitation of the blank holder, then the upper sheet material flow in the axial direction to the gap between the punch and blank holder, the lower sheet flow in both the radial and axial direction.

![Material flow](image)
shows in Fig. 6b. Stage 3, the upper sheet material flow in the axial direction gradually becomes difficult, while the upper sheet material outside the punch fillet region exerts higher pressure on the interface between it and the lower sheet material than the upper sheet material flow in the radial direction increases significantly, and the lower sheet material flow in the axial direction increases significantly shows in Fig. 6c. Stage 4, with punch, moves downwards, the upper sheet material around the punch fillet flows in the radial direction continuously, and the lower sheet material flows in the axial direction, which results in the formation of the mechanical interlocking shown in Fig. 6d.

### 3.3 Influence of blank holder radius on the joint

The blank holder groove is a key factor in controlling the material flow to form the mechanical interlock between the two sheets [18]. Different blank holder radii were selected to study their effect on the interlock of the flat clinched joint at a 2.95 mm punch radius and 0.1 mm punch fillet radius. The final flat clinched joint shapes are shown in Fig. 7.

In these four joint shapes, the interlocks (or S-shapes) were formed at different blank holder radii. Notice that the lower part of the S-shapes is almost the same, but the upper part of the S-shapes is quite different due to the difference in the blank holder radius. As shown, the interlock formed at 4.20 mm and 5.50 mm blank holder radius is smaller than that formed at 4.50 mm and 5.00 mm blank holder radius.

Blank holder radius mainly affects the forming of the upper part of the S-shape by controlling the material flow. Figure 7 indicates that the material of the lower sheet flows in the radial direction is increased at the blank holder radius of 4.20 mm and 5.50 mm. It can be concluded that too large or too small of the blank holder radius is not conducive to the increase of interlock length. Therefore, a moderate blank holder radius is required for a punch diameter; it should not be too large or too small.
For explanation, the material flow at a punch stroke of 3.0 mm was chosen, the sheet material flow velocity at different blank holder radii was analyzed, as shown in Fig. 8. It indicates that the material at the upward protrusion of the lower sheet mainly flows in the axis direction for the blank holder radius of 4.50 mm and 5.00 mm, while the material flow increased in the radial direction at the blank holder radius of 4.20 mm and 5.50 mm, which result in the smaller upper parts of the S-shape, as can be seen in Fig. 7. Therefore, the increase of the lower sheet material at the upward protrusion flow in the axis direction can give rise to the improvement of the interlock.

### 3.4 Influence of punch radius and punch fillet radius on the joint

The interlock shapes formed at different punch radii are shown in Fig. 9, while the blank holder radius ($r_b = 5.00$ mm) and punch fillet radius ($r_0 = 0.1$ mm) are constants. It indicated that with the increase of punch radius, more materials under the punch will be pushed around the punch, which leads to an increase in the interlocks. Meanwhile, the whole S-shape moves along the radial and axis directions.

However, when the blank holder radius is reduced to 4.50 mm, the increase in punch radius has no obvious effect on the improvement of the interlock, as shown in Fig. 10. Furthermore, when the blank holder radius decreased to 4.20 mm, the interlock decreased with the increase of the punch radius. It can be inferred that the influence of the punch radius on the interlock is also affected by the blank holder radius. Only when the blank holder radius is appropriate, the increased punch radius can improve the mechanical interlock.

![Fig. 8 Material flow velocity in the clinched region at 3.0 mm punch stroke with different blank holder radii; a 4.2 mm, b 4.5 mm, c 5.0 mm, and d 5.5 mm](image)

![Fig. 9 A comparison of interlock shapes from different punch radii](image)
The final shapes of the flat clinched joints at different punch fillet radii at 2.95 mm punch radius and 5.00 mm blank holder radius are shown in Fig. 11a. The smaller the punch fillet radius, the lower the protrusion height, which indicates that the smaller punch fillet radius decreases the material flow in the axial direction. By contrast, a smaller punch fillet radius can give a rise to an increase of the material flow in the radius direction, which can give an increase to the lower part of the S-shape, as shown in Fig. 11b. The smaller the punch fillet radius is, the greater the interlock is, it can be seen in Fig. 12. The results show that with the punch fillet radius decreased from 0.3 to 0.2 mm and from 0.2 to 0.1 mm, the interlock volume increased by 33.8% and 56.4%, respectively. Therefore, it can be inferred that a small punch fillet radius has an important effect on the increase of joint interlock by promoting the material flow in the radial direction from the axial direction.

Point tracking technology in the DEFORM-2D post-processing module can be used to trace the material flow. To investigate the material flow passing through a fixed point, point P1 (shown in Fig. 11a) was chosen and set to fixed, then the material flow velocities at point P1 at different punch fillet radii were obtained by point tracking, as shown in Fig. 13. The results indicate that a smaller punch fillet radius reduces the material flow in the axis direction during the flat clinching process, which is why the smaller the punch fillet radius, the lower the protrusion height.

To investigate the flow velocity of the material at a point, point P2 (see Fig. 14) was chosen and set to move with the material, and then the flow of material point P2 can be traced. Material point P2 flow upwards along the surface of the punch during the flat clinching process. In this way, the flow velocity of point P2 at different punch fillet radii can be achieved by point tracking, as shown in Fig. 15. The smaller the punch fillet radius, the lower the flow velocity of the moving point P2 after 1.5 mm punch stroke. Meanwhile, the smaller the punch fillet radius is, the more violent the flow velocity curve is. It can be inferred that a decrease in punch fillet radius impeded the material flow.

3.5 The effect of punch radius, punch fillet radius, and blank holder radius on the interlock

Figure 16 shows the effect of the punch fillet radius and blank holder radius on the interlock at different punch radii.
Figure 16a–d shows the effect of the blank holder radius on the interlock at different punch fillet radii and 3.20 mm punch radius. It is noted that with the decrease of punch fillet radius, the interlock increases, which also can be seen in all of the other images in Fig. 11. It can be inferred that a small punch fillet radius can facilitate the formation of mechanical interlocks, regardless of the punch radius and blank holder radius.

With the increase of the blank holder radius, the interlock length also gradually increases, but after the interlock length reaches its maximum, it begins to decrease, as seen in Fig. 16.

The effect of blank holder radius and punch radius on the interlock of the flat clinched joint at 0.1 mm punch fillet radius was selected, as shown in Fig. 17. This trend is also true for punch fillet radii of 0.2 mm and 0.3 mm. To maximize the interlock, the punch radius and the blank holder radius should be increased simultaneously; meanwhile, there is a certain correlation between these two parameters, as shown in Fig. 18. It can be seen that the correlation between these two parameters is approximately linear, so a linear fitting was carried out, and the following formula was achieved.

\[ r_p = 1.215 \times r_h + 1.127 \]  

(2)

It can be inferred that the blank holder radius and the punch radius should keep in this linear relationship when designing the geometric dimensions of the tool.

4 Conclusion

In the present work, the flat clinching process was investigated using the finite element method. The effect of tool parameters such as punch radius, punch fillet radius, and blank holder radius on the material flow and the interlock of the flat clinched joint were investigated, and then the
The main conclusions of the present work can be drawn as follows:

1. The formation of the mechanical interlock requires the collaborative flow of upper sheet material and lower sheet material. The interlock can be improved by facilitating the upper sheet material flow in the radial direction and the lower sheet material flow in the axial direction.

2. With the increase of the blank holder radius, the interlock length also gradually increases, but after the interlock length reaches its maximum, the interlock length begins to decrease.

3. The smaller the punch fillet radius is, the more it impedes the upper sheet material flows around the punch. A small punch fillet radius has an important effect on the increase of joint interlock by promoting
the material flow in the radial direction from the axial direction.

4. The influence of the punch radius on the interlock is also affected by the blank holder radius; only when the blank holder radius is appropriate, the interlock can be improved by increasing the punch radius. To maximize the interlock, a moderate blank holder radius is required for a punch diameter, and the correlation between these two parameters is approximately linear.

**Fig. 17** Effect of blank holder radius on the interlock at different punch radii and 0.1 mm punch fillet radius

**Fig. 18** Relationship between punch radius and blank holder radius for the best interlock

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**Data Availability** All data generated or analyzed during this study are included in the present article.

**Declarations**

**Ethical approval** This research did not involve human participants or animals; thus, ethics approval is not necessary.

**Consent to participate** Not applicable.

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**Competing interests** The authors declare no competing interests.
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