Interaction between forming and joint quality of the friction-assisted clinching

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Abstract. In order to achieve the effective joining of aluminum and magnesium alloy sheets, a friction-assisted clinching is innovatively proposed to reduce material damage during the process and improve the joint quality. 2 mm thick Al5052 aluminum sheet and 2 mm thick AZ31 magnesium alloy sheet were selected as the research objects, the interaction between different forming parameters, i.e., die depth, rotational speed and rotation time, and the joint quality, i.e., the damage, neck and interlock were explored by DEFORM-3D. The influence of sheet temperature on damage and punch load is analysed, the rotational speed and rotation time have great influence on the forming joint, the die depth mainly affects the neck and interlock. Comparing the joint qualities under different forming parameter combinations, it is found that the joint quality is the best when the bottom die depth is 2.2 mm and the bottom punch is applied at 1000 rpm for 0.5 s. The research will provide a valuable reference for the realization of joining the aluminum and magnesium sheets.

1. Introduction

In recent years, a series of policies on energy saving and emission reduction of automobiles have been issued to cope with the increasing environmental pollution and energy crisis, has resulted in the increased demand for lightweight vehicles [1, 2]. Aluminum alloy and magnesium alloy have been widely used in automotive body-in-white due to higher specific strength [3]. The difference in chemical compositions and physical properties of these two alloys are large, the welding process can’t realize an effective joining. As an advanced joining technology, clinching is developed in manufacturing of lightweight vehicle body structure.

The clinching process equipment is mainly composed of a punch, a holder, and a bottom die. The principle of clinching is that sheets are deformed locally under the pressure of the punch, and embedded in the bottom die due to the plastic flow characteristics of material, an S-shape interlock joint is finally formed. Due to it does not require any additional rivet or fastener, the clinching has an important advantage in automobile lightweight [4-6].

The deficiency of traditional clinching process is that it is impossible to realize the connection of materials with poor plasticity, the materials with poor plasticity are prone to damage and fracture under the pressure of punch. In view of this deficiency, scholars have done some research on it. In
order to improve the formability of aluminum alloy, Lambiase et al. [7] proposed a friction-assisted clinching process. Aluminum alloy AA6061 was selected as the upper sheet, and the pre-holed CFRP was selected as the lower sheet. The results showed that under reasonable process parameters, friction-assisted crimping could significantly improve the formability of AA6061, and the forming effect of the joint was better than that of the traditional clinching process. Chen et al. [8, 9] combined clinching and hot stamping process, a hot stamping clinching process forming system with resistance heating system was developed, and the joint strength was tested to verify the feasibility of the new process. Kaczyński et al. [10] proposed a clinching process that preheated the bottom sheet to enhance the joint strength, and verified through experiments that the new process could increase the shear and tensile strength of the joint.

Based on the existing research, a new friction-assisted clinching process is proposed, the die depth, rotational speed and rotation time are selected as forming parameters, and the simulation study on the process is carried out to provide a valuable reference for the realization of joining the aluminum and magnesium sheets.

2. Modelling and finite element analysis

The new friction-assisted clinching process model is shown in Figure 1. It can be seen in Figure 1(c), the traditional fixed bottom die is replaced by a movable bottom die. The movable bottom die is composed of a base and a bottom punch. A through hole is machined in the base. The base and the bottom punch is used together, the bottom punch can rotate in the through hole. In the initial stage of the process, the top punch is pressed down, and the sheets move downward under the force of the top punch. When the lower sheet contacts the bottom punch, as shown in Figure 1(b), the bottom punch starts to rotate, and the lower sheet will be heated by the rotating friction of the bottom punch, and the top punch will continue to press down and stop moving when it reaches the specified stroke position, and the joint is formed. Two rotation time of 0.5 s and 2 s are selected, Figure 1(c) represents the process diagram when the bottom punch rotates for 0.5 s, that is, when the rotation time is 0.5 s, the rotation of bottom punch will stop at the position of Figure 1(c), and the 2 s rotation time represents the bottom punch rotation will be maintained to the end of the process, as shown in Figure 1(d). Because the die depth is different, the corresponding time in Figure 2(b) is also different, which is about h/2 s.

![Figure 1](image)

**Figure 1.** Schematic of friction-assisted clinching process. (a) Positioning, (b) punching and friction starting, (c) friction acting for 0.5 s, (d) joint formed.

2 mm thick Al5052 aluminum sheet and 2 mm thick AZ31 magnesium alloy sheet are selected as the research objects. The mechanical properties of Al5052 and AZ31 are shown in Table 1.

| Material | Density $\rho$ (kg.m$^{-3}$) | Elastic modulus $E$ (GPa) | Yield strength $\sigma_y$ (MPa) | Ultimate tensile strength $\sigma_b$ (MPa) | Elongation $\delta$ (%) |
|----------|-------------------------------|---------------------------|-------------------------------|---------------------------------|-------------------|
| Al5052   | 2680                          | 71                        | 195                           | 230                             | 10                |
| AZ31     | 1780                          | 45                        | 169                           | 297                             | 8                 |

The ductility of AZ31 magnesium alloy sheet is poor, if AZ31 sheet is selected as the upper sheet, the traditional friction-assisted clinching based on top punch rotating can indeed improve its ductility,
and reduce the risk of fracture damage during the process. But the frictional heat will also make the sheet soft, it is difficult to press into the lower aluminum alloy sheet to form an effective joint. In view of this, this article selects Al5052 aluminum alloy sheet as the upper sheet and AZ31 magnesium alloy as the lower sheet. During the deformation of the AZ31 magnesium alloy, the temperature of the AZ31 magnesium alloy sheet is increased by the rotation friction of the bottom punch, so as to improve its ductility and reduce the fracture damage during the process, and obtain an effective joint.

The whole model was established by UG, the size of AZ31 sheet and Al5052 sheet are both 26 mm×26 mm×2 mm, the diameter of the top punch is 7 mm, the draft angle is 1°, the diameter of the bottom punch is 10 mm, the through hole diameter of the base is 10 mm. The established three-dimensional geometric model was exported to stl format and imported into DEFORM-3D software, and the tetrahedral mesh element was selected to mesh the upper and lower sheet, top punch and bottom punch. In order to improve the accuracy of the simulation results, the middle part of the upper and lower sheet were refined, and finally the finite element model was established as shown in Figure 2.

In order to observe the damage of sheet during the process, the Normalized Cockcroft & Latham damage model was used in the DEFORM-3D software, as shown in equation (1).

\[
C = \int_0^1 \frac{\sigma^*}{\bar{\sigma}} d\bar{\varepsilon} = \frac{\sigma^*}{\bar{\sigma}} \bar{\varepsilon}_f
\]

Where \(C\) is the damage factor, \(\bar{\varepsilon}_f\) is the equivalent strain at fracture, \(\bar{\varepsilon}\) is the equivalent strain, \(\sigma^*\) is the maximum principal stress, \(\bar{\sigma}\) is the equivalent stress, \(\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T)\), \(\dot{\bar{\varepsilon}}\) is the equivalent strain rate, \(T\) is the temperature of sheet.

The die depth, the rotational speed and rotation time of the bottom punch are selected as variables to explore the influence of different parameters on the forming quality. The depth of the bottom die is determined by the stop position of the bottom punch. The pressing speed of the punch in all simulations is set to 2 mm/s, two rotation time of 0.5 s and 2 s are selected. The designed simulation parameters are shown in Table 2.

| No. | Die depth (mm) | Rotational speed (rpm) | Rotation time (sec) |
|-----|----------------|------------------------|---------------------|
| 1   | 2.2            | 0                      | 2.0                 |
| 2   | 2.2            | 1000                   | 2.0                 |
| 3   | 2.4            | 1000                   | 2.0                 |
| 4   | 2.0            | 1000                   | 0.5                 |
| 5   | 2.2            | 1000                   | 0.5                 |
| 6   | 2.4            | 1000                   | 0.5                 |
| 7   | 2.0            | 3000                   | 0.5                 |
| 8   | 2.2            | 3000                   | 0.5                 |
| 9   | 2.4            | 3000                   | 0.5                 |

The joint quality parameters are shown in Figure 3. The main factors for evaluating the quality of the clinched joints are neck thickness \(t_n\), interlock \(t_{\text{il}}\), undercut thickness \(t_o\) of the upper sheet, and undercut thickness \(t_m\) of the lower sheet. The neck thickness mainly affects the shear strength of the joint. The thicker the neck, the higher the shear strength of the joint. The interlock value mainly affects
the tensile strength of the joint. The greater the interlock value, the higher the joint tensile strength. The undercut thickness of the upper and lower sheets have an indirect effect on the neck thickness and interlock value. In theory, the lower the undercut of the sheet, the greater the neck thickness and interlock of the joint.

3. Results and discussion
It is an important goal of this article to reduce the fracture damage of the material during the forming process and improve the joint quality. First, the damage of AZ31 sheet of No.1, No.5 and No.8 during the simulation of the top punch stroke to 3 mm were extracted, as shown in Figure 4. When the top punch went up to 3 mm, AZ31 sheet and the bottom punch have come to contact, frictional heat had been applied to AZ31 sheet under the rotation of the bottom punch in simulation No.5 and No.8. The damage of AZ31 sheet at this time is more representative.

The Figure 4(a), 4(b) and 4(c) represent the side view of AZ31 sheet damage of No.1, No.5 and No.8, respectively, and the Figure 4(d), 4(e) and 4(f) represent the damage on the bottom of AZ31 sheet of No.1, No.5 and No.8, respectively. It can be seen from Figure 4 that the damage is mainly concentrated in the bottom of AZ31 sheet, this is the main part where AZ31 sheet is extruded by the bottom punch. The damage decreases step by step from the bottom to the top along the vertical direction. The damage degree of No.1 AZ31 sheet without frictional heat is the most serious. Frictional heat generated by rotation will soft AZ31 sheet, the ductility of AZ31 sheet is improved, and the damage is reduced. It can be seen that the AZ31 sheet damage value of 3000 rpm is lower than that of 1000 rpm. It shows that the higher the rotational speed is, the lower the sheet damage is.

Figure 4. The side view of AZ31 sheet damage of (a) No.1, (b) No.5 and (c) No.8, the damage on the bottom of AZ31 sheet of (d) No.1, (e) No.5 and (f) No.8.

The simulation results of No.2 and No.3 are shown in Figure 5. It can be seen from Figure 5 that the neck thickness and interlock of No.2 and No.3 are basically 0, the undercut of the upper sheet is too large, and the undercut of the lower sheet is too small. The simulation results of No.2 and No.3 show that when the rotation time is 2 s, the die depth basically has no effect on the forming of the joint, and an effective joint cannot be formed during the process.
The temperature distributions of AZ31 sheet of No.2 and No.3 are shown in Figure 6. It can be seen that when the rotational speed continues to act on AZ31 sheet, the temperature of AZ31 sheet will continue to rise. The material of AZ31 tend to move around under the centrifugal force and the downward pressure of the top punch. The accumulation of the AZ31 material around the bottom die also causes much pressure to Al5052 sheet, and the S-shape interlock cannot be formed. When the undercut of AZ31 sheet is close to 0, under the action of heat generated by friction and plastic deformation, the bottom center temperature of AZ31 sheet in No.2 is as high as 529 ℃, and the bottom center temperature of AZ31 sheet in No.3 is as high as 509 ℃, which is close to the melting temperature of AZ31 magnesium alloy sheet, it will be pierced under the action of continuous pressure of the bottom punch. It is indicated that the 2 s of rotation time of the bottom punch cannot improve the joint quality. On the contrary, excess frictional heat generated by rotation make AZ31 sheet excessively softened, resulting in ineffective forming.

According to the above results, it can be seen that the main function of the bottom punch is to improve the ductility and reduce the damage by frictional heating the AZ31 magnesium alloy sheet when it is deformed. In order to reduce the adverse effects of excessive frictional heat, the rotation time of the bottom punch in the No.4-9 simulation is only 0.5 s.

The final joint of No.4-9 simulation results are shown in Figure 7, and the joint quality parameters are shown in Table 3.

By the simulation results in Figure 7 and joint quality parameters in table 3, it can be seen that in the case of the same rotational speed, as the die depth increases, the neck thickness gradually decreases and the interlock gradually increases. In the case of the same die depth, the joint quality parameters at the 1000 rpm rotational speed is better than those at 3000 rpm. In the case of 1000 rpm rotational speed, the total undercut is maintained at 1.4 mm by controlling the stop position of top punch stroke. At this time, the undercuts of the upper sheets are maintained between 1.0-1.1 mm and the undercuts of the lower sheet are maintained between 0.3-0.4 mm. There is little difference in joint quality parameters, indicating that the die depth has little effect on the undercut of the upper and lower sheets. The undercut of AZ31 sheet under 3000 rpm is thinner than that under 1000 rpm, the main reason is that the heat generated by friction and plastic deformation at 3000 rpm is too much, which
causes the temperature of AZ31 sheet to be too high, the ability of AZ31 sheet to resist material deformation becomes worse. The results are similar to the No.2 and No.3.

### Table 3. Joint quality parameters of No.4-9.

| No. | Neck (mm) | Interlock (mm) | Undercut of upper sheet (mm) | Undercut of lower sheet (mm) | Total undercut (mm) |
|-----|-----------|----------------|-----------------------------|-----------------------------|---------------------|
| 4   | 0.45      | 0              | 1.08                        | 0.32                        | 1.40                |
| 5   | 0.36      | 0.21           | 1.01                        | 0.39                        | 1.40                |
| 6   | 0.20      | 0.21           | 1.07                        | 0.33                        | 1.40                |
| 7   | 0.37      | 0              | 1.31                        | 0.09                        | 1.40                |
| 8   | 0.31      | 0.09           | 1.23                        | 0.17                        | 1.40                |
| 9   | 0.24      | 0.18           | 1.20                        | 0.20                        | 1.40                |

The simulation results of No.2, No.5, No.6, No.8, and No.9 are selected to extract the change of punch load with stroke as shown in Figure 8.

![Figure 8. Load-stroke curves.](image)

It can be seen from Figure 8 that the punch load curve is basically the same before AZ31 sheet contact to the bottom punch. The punch load begins to change after AZ31 sheet touches the bottom punch. The punch load of the No.2 changes smoothly with the stroke. Even when AZ31 sheet contact to the bottom punch, the punch load only slightly increases and then starts to drop. This is because after AZ31 sheet contact to the bottom punch, frictional heat is generated by rotation of the bottom punch. The rigidity of AZ31 sheet decreases with the increase of temperature. When AZ31 sheet is pierced, the punch load drops sharply. When the rotational speed of the bottom punch is the same and the punch descends to the same stroke, the punch load under the die depth of 2.2 mm is higher than that of 2.4 mm. The bottom die space of 2.2 mm is smaller than 2.4 mm, as the bottom die being filled with the material, the punch load will become larger and larger in the process, the punch load of No.4 and No.7 will be significantly higher than that of No.5 and No.8. When the die depth is same, the movement trend of the punch load is basically the same, indicating that the rotation time is shorter, and it will not have much impact on its forming quality, but it will have a certain effect on the load
peak. The load peak value of 3000 rpm rotational speed is about 2000-3000N lower than that of 1000 rpm rotational speed, which is because the resistance of the higher temperature sheet is lower than that of the lower temperature sheet. The sudden load drop in the last stage of the curve in the Figure 8 is due to the moment when AZ31 sheet is pierced. By analyzing the load-stroke curve and comparing the forming quality of the joint, it can be concluded that a higher punch load is beneficial to the increase of the interlock, the interlock is increased, and the joint quality is improved.

4. Conclusion

An innovative friction-assisted clinching process for is proposed, which can increase the temperature of the lower sheet through friction, improve its ductility and reduce the damage in the clinching process. The continuous frictional heat generated by rotation of the bottom punch to the lower sheet will make the temperature of the AZ31 magnesium alloy sheet close to the melting temperature in the later stage of forming. Although the pressure of the top punch in the forming process is effectively reduced, the quality of the joint is poor and an effective joint cannot be formed.

When the lower sheet is in contact with the bottom punch, the damage of AZ31 sheet begun to increase. At this time, the damage degree of the bottom punch with the rotational speed of 1000 rpm is more serious than that of 3000 rpm, but the difference is small, and from the final joint quality, the rotational speed with 1000 rpm is a more suitable choice.

The die depth will affect the punch load and has a greater impact on the forming quality. As the die depth increases, the neck thickness will gradually decrease.

For the friction-assisted clinching of 2 mm thick Al5052 and 2 mm thick AZ31 dissimilar sheets, the joint quality is the best when the bottom die depth is 2.2 mm and the bottom punch is applied at 1000 rpm for 0.5 s.

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