Mechanics & Industry **24**, 7 (2023)

https://doi.org/10.1051/meca/2023007

Mechanics & Industry

Available online at:
www.mechanics-industry.org

Regular Article — Open Access

Simulation of dieless clinching process considering the limit of blank holder

Zhiyong Wang[1,2], Shanling Han[1,*], Zhiyong Li[1], and Yong Li[1]

[1] College of Mechanical and Electronic Engineering, Shandong University of Science and Technology, Qingdao 266590, China
[2] College of Mechatronics Engineering, Binzhou University, Binzhou 256600, China

Received: 10 August 2022 / Accepted: 22 February 2023

Abstract. The low strength and large protrusion of the traditional dieless clinched joint hindered its application. To improve the mechanical properties of the dieless clinched joint, a novel dieless clinching process considering the limitation of the blank holder was proposed. The finite element model of the dieless clinching process was established by DEFORM-2D, the influences of the blank holder spring stiffness, the blank holder limit height, and the punch diameter on the mechanical interlock of the joint were analyzed, and the influence laws of blank holder spring stiffness and blank holder limit height on material flow and mechanical interlock were obtained. Then, the influence of these three die parameters and their interaction on the joint interlock were analyzed using the response surface method. The results show that the blank holder displacement plays a key role in the formation of mechanical interlock in the dieless clinching process. Reasonable limit height and spring stiffness of the blank holder can control the flow direction of materials, so as to improve the mechanical interlock and the strength of dieless clinched joints. It provides a new idea for improving the dieless clinching process.

Keywords: Dieless clinching / DEFORM-2D / mechanical interlock / blank holder limitation / response surface method

1 Introduction

As an important means of energy conservation and emission reduction, automobile lightweight has received more and more attention, the application of lightweight materials (such as high-strength steel, aluminum alloy, magnesium alloy, etc.) promotes the development of automobile lightweight [1–3]. At the same time, due to the large differences in physical properties of heterogeneous materials, the traditional resistance spot welding technology is difficult to achieve reliable joining, which brings new challenges to the joining technology of multi-material hybrid body [4,5]. Benefiting from avoiding the problems of interface hard brittle phase and joint softening caused by thermal joining, mechanical joining technology, such as clinching and self-piercing riveting, has been widely used in automobile body manufacturing [6–8]. The clinching process can realize the mechanical joining by stamping the sheet, which will produce local plastic deformation under the action of the die [9]. Clinching process has the advantages of no heat generation, low cost and no additional weight gain, due to the disuse of joining elements such as bolts, screws and welding electrodes, weight and cost reduction purposes could be met. Unlike fusion welding, applying heat is not required, and there is no metallurgical bonding at the interface of the workpieces, thus, a considerable saving on the energy can be realized, and no surface pre-processing is required [6]. The pre-heating time of joining the sheets can reduce to less than 1 s, and the punching time is less than 3 s, but the drawback is that there is a high protrusion at the bottom of the clinched joint, which limits its application and aesthetics [10,11].

To solve this problem, many reshaping methods have been used by many researchers to reduce the bottom protrusion of the clinched joint. Chen et al. [12,13] used a pair of flat dies to decrease the protrusion height of clinched joint. In another work, Chen et al. [14] proposed a two-step reshaping process, a special rivet was used in the second step to produce a reshaped joint. Wen et al. [15] reduced the protrusion height from 1.7 to 0.68 mm by a reshaping method, a reduction of 50% in protrusion height can be achieved without affecting the joint strength. Lambiase and Ko [16] investigated the two-step clinching process for joining aluminum and CFRP, and found that the reshaping process could reduce the protrusion but lead to damage in CFRP sheet. Although reshaping methods could reduce the protrusion of traditional clinched joint, they make the

* e-mail: hanshanling@sdust.edu.cn

process complex and time-consuming. Hence, many new clinching methods that differ from the traditional clinching process have been proposed.

As an improvement of the traditional clinching process, the flat-clinching process with flat die can reduce the bottom protrusion of the joint significantly [17], it can be divided into two types, the flat-clinching process without bottom protrusion and the dieless clinching process with bottom protrusion. The main differences between the two processes are blank holder pressure, blank holder geometry and whether there is a protrusion at the bottom of the joint. It needs large pressure and complex shape of the blank holder in the flat clinching process, Chen Chao et al. [18,19] have carried out a lot of research work in this regard. Unlike this, the dieless clinching process does not need complex blank holder shape and large pressure, and the bottom protrusion of the joint is much lower than that of the traditional clinched joint [20].

Neugebauer et al. [21] proposed dieless clinching process to join magnesium alloy, which is similar to the flat clinching process. The formation of mechanical joints between sheets in the dieless clinching process depends on the coordinated movement of punch and blank holder, especially the blank holder is used to control the material flow along the axial and radial direction to form mechanical interlocking between sheets [15]. The bottom protrusion height of the joint is affected by the blank holder, the pressure and moving height of the blank holder are the key factors affecting the quality of the joint [10]. To obtain a soundly mechanical joint, many researchers have studied the influence of the geometry and parameters of the blank holder on material flow and the performance of the joint. Atia et al. [22] used blank holder with different shapes and parameters to control the material flow in the flat-clinching process, and found that mechanical interlock can be increased by limiting the material flow along the radial direction. Chen et al. [23] analyzed the influence of blank holder spring stiffness and punch radius on material flow and joint interlock during the flat clinching process, and found that increasing blank holder spring stiffness will reduce the joint interlock by affecting the material flow direction. Chen et al. [24] proposed a two-step flat clinching process (TSFC) to produce double-sided flat joints by flattening the initial dieless clinched joint. Through the second step, the protrusion height of the dieless clinched joint can be decreased from 1.23 mm to a negligible 0.04 mm. However, it need two steps, which increases the complexity of the process. In another study, The finite element method is popularized in mechanical clinching for it can get similar results to the experiment and require less time, manpower, material resources, and energy [25–27]. At the same time, orthogonal test [28], Taguchi experiment and other analysis methods were used to analyze the relationship between influencing factors and joint performance.

However, the problems of poor mechanical properties and high protrusion of the traditional dieless clinched joint still exist. Compared with other clinching processes, the strength of dieless clinched joints is lower [10]. Thus, Chen et al. [29] compare the failure mechanism of the dieless clinched joints of various aluminum alloys, protrusion heights of the AL5052 joint, AL5182 joint, and AL6061 joint are 1.08 mm, 1.17 mm, and 1.20 mm, the protrusion height is faintly affected by the sheet materials. The protrusion height of the traditional dieless clinching joint mainly depends on the blank holder, the gap between the upper and lower sheets is obvious, and the protrusion height is between 0.33 mm to 1 mm, using a compressed method, the protrusion height can be reduced from 1.62 to 0.94 mm [30].

Therefore, to improve the mechanical properties and reduce the bottom protrusion height of the joint, this paper proposed a novel dieless clinching process considering the blank holder limit. This study set out to investigate the usefulness of the blank holder limit for the dieless clinching joint, and explain the regulation mechanism of blank holder spring stiffness and blank holder limited height on material flow, finally, optimize the parameters to obtain the joint with the best mechanical properties.

The remainder of this paper is organized as follows. The working principle of the novel dieless clinching process were introduced, and the finite element numerical model was established for subsequent analysis. And then the traditional dieless clinching process and the novel dieless clinching process with blank holder limit were analyzed respectively through a lot of numerical analysis, and compared them. Based on this, the effect of blank holder limit height, blank holder spring stiffness, and the punch radius on the material flow and the mechanical interlock of the joint were analyzed, the regulation mechanism of blank holder spring stiffness and blank holder limit height on material flow, and the formation of mechanical interlock were achieved. Aiming at improving the joint mechanical properties, the response surface method were used to attain the process parameters that can maximize interlock length of the novel dieless clinched joint.

2 Material and methods

The dieless clinching process considering the blank holder limit proposed in this paper is a novel technology base on the traditional dieless clinching process, which is a mechanical joining process that causes local plastic deformation of the sheets under the action of the punch, blank holder, and flat anvil, thus forming a mechanical interlock. The key of the proposed process is to control the limited height of the blank holder, as shown in Figure 1. It can be divided into four stages: the positioning and clamping stage (see Fig. 1a), the blank holder generate a pressing force, and the punch contacts the upper sheet. In initial deformation stage (see Fig. 1b), the punch downward, and the material under the punch flows upward along the outer surface of the punch, the blank holder moves upward under the push of the sheet. The deformation of the blank holder spring gradually increases, and the downward pressure of the blank holder gradually increases. At the same time, the lower sheet produces protrusion. In the joint forming stage (see Fig. 1c), after the blank holder moves upward for a certain distance, the movement of the blank holder is limited, the resistance of the upward flow of material gradually increases, after then,

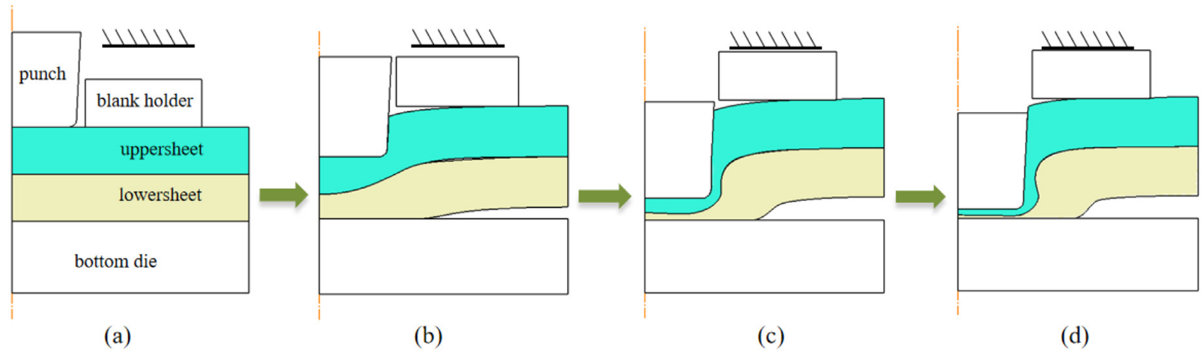

Fig. 1. Mechanism of the dieless clinching process considering the limitation of the blank holder (a) positioning and clamping (b) initial deformation (c) forming (d) withdrawal.

prompting the material under the punch to flow along the radial direction, thus forming an S-shaped mechanical interlock. In the withdrawal stage (see Fig. 1d), after the punching process is completed, the dies exit the workpiece.

In the joint forming stage, the material at the bottom of the punch flows in the radial direction under the restriction of the blank holder, which is the key to the formation of interlocking [20]. In the traditional dieless clinching process, the pressure of the blank holder is controlled by the spring. With the punch moving down, the pressure of the blank holder gradually increases, and the constraint of the blank holder on the material gradually increases, which is easy to miss the best time for the material at the bottom of the punch to flow radially. Therefore, the dieless clinching process with the blank holder limited was proposed. The limit of blank holder is to stop the blank holder from moving upward after it moves upward for a certain distance, after that the blank holder will no longer move upward, so as to quickly restrict the material from flowing upward, which can increase the material under the punch flow in the radial direction and facilitate the formation of mechanical interlocking. The limit height of the blank holder (h) is the distance that the blank holder has moved from the initial positioning position to the final stopped position, as shown in Figure 2.

To study the influence of punch and blank holder process parameters on material flow and joint interlock, DEFORM-2D was used for numerical simulation, to reduce computational resource usage, the simulations were carried out using an axis-symmetric model [31]. The finite element model of dieless clinched process with the blank holder limited was established, as shown in Figure 2. The finite element model includes punch, blank holder, upper and lower sheet, and flat anvil. The upper and lower sheet are plastic bodies, and the dies were set as rigid bodies. The punch diameter (D) was set as 5.5 mm, the thickness of the upper and lower plates is 2 mm, and the upper and lower sheets are al5052. The material property and stress-strain curve of al5052 were shown in Table 1 and Figure 3 respectively. Quadrilateral elements were used to mesh the sheets, to avoid mesh distortion, the adaptive mesh generation technology was adopted, and the interference depth of mesh is 1/2 of side length of the minimum mesh, which is about 0.03 mm. The friction law of Coulomb was chosen, the coefficient between die and sheet was set as

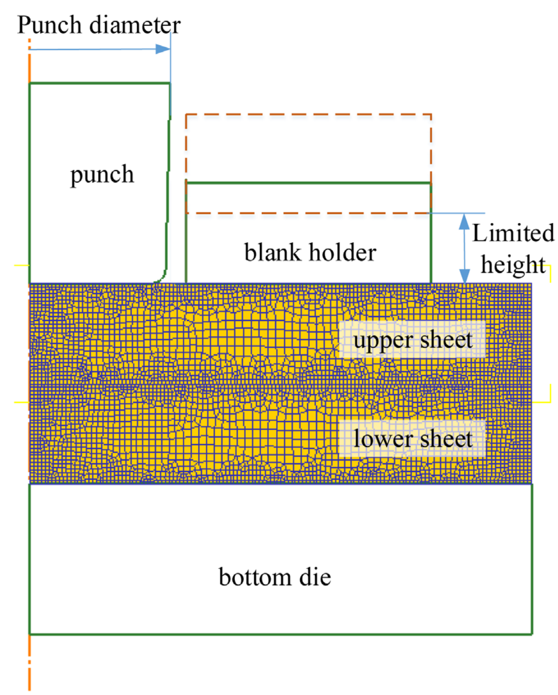

Fig. 2. Finite element model of the dieless clinching process with blank holder limitation.

0.15, the friction coefficient between sheets was set as 0.30, and the speed of punch is 0.5 m/s. The limit height of the blank holder was set in the blank holder movement control module.

After the dieless cinching process was completed, a mechanical interlock can be formed between the upper and lower sheets, and the main geometric parameters of the formed mechanical joint were shown in Figure 4. They are interlock length (T_u), protrusion height (T_p), and limited height (h) is the distance between the initial position and the final position of the blank holder during the dieless clinching process. In the following study, the limited height of the blank holder, the spring stiffness of the blank holder and the punch diameter were selected as experimental factors, and the result parameter is the interlock (T_u) of the joint.

Table 1. Material property of al5052 [29].

Material	Elastic modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Poisson's ratio	Elongation
al5052-H32	62.1	158.7	228.6	0.33	16.5%

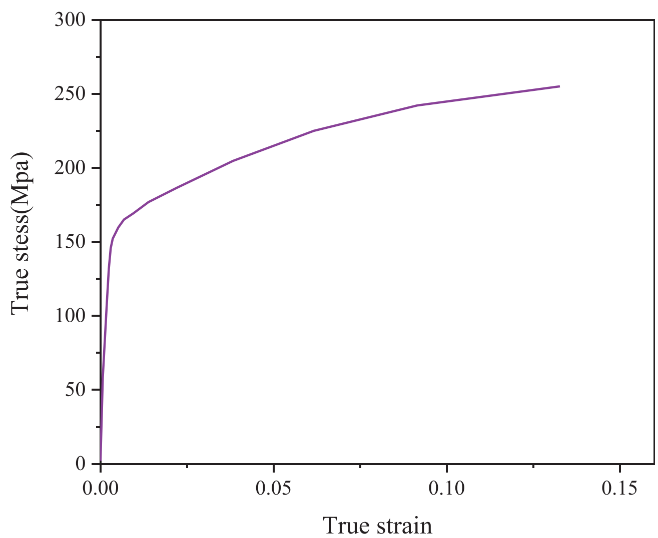

Fig. 3. True stress-strain curve of al5052.

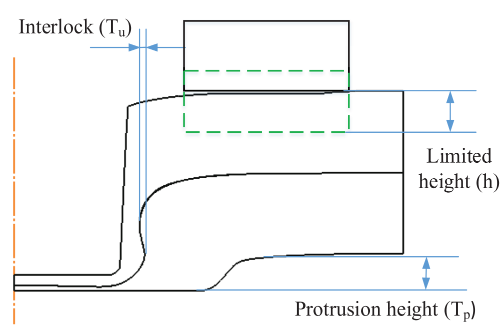

Fig. 4. Geometric parameters of the dieless clinched joint.

3 Results

3.1 Without limit of the blank holder

By the finite element simulation analysis, the geometric parameters of the joint and the displacement of the blank holder free of limitations under the action of springs with different stiffness were obtained. The results were shown in Table 2.

It can be seen from Table 2 that when there is no blank holder limit, with the increase of the spring stiffness (k) of the blank holder, the neck thickness of the joint gradually increases, in contrast, the displacement of the blank holder and the bottom protrusion of the joint gradually decreases.

Figure 5 shows the influence of spring stiffness (k) on interlock length and displacement of blank holder with the blank holder free of limit. It can be seen that with blank holder spring stiffness increases from 500 to 2000 N/mm, the interlock length increases from 0.022 to 0.077 mm, after that, it remains basically stable, and then decreases rapidly when spring stiffness (k) exceeds 6000 N/mm. When the blank holder spring stiffness is less than 2000 or larger than 6000, it is not conducive to the formation of joint. Besides, the interlock formed at medium blank holder spring stiffness is also no more than 0.077 mm. Therefore, no matter how much the stiffness of the blank holder spring is, the interlock length of the joint formed by the dieless clinching process without blank holder limit is still small.

3.2 With the blank holder limited

To study the influence of blank holder spring stiffness and blank holder limited height on interlock, the blank holder spring stiffness was selected as 500, 1000, and 2000 N/mm, and the blank holder limited height was set between 0.7 and 1.4 mm. The finite element simulation analyses were carried out, and the influence results of blank holder limited height on interlock at different blank holder spring stiffness were obtained, as shown in Figure 6.

Figure 6 shows the relationship between the limited height of the blank holder and the interlock length at different blank holder spring stiffness. Compared with the blank holder free of limit, the interlock formed by the dieless clinching process with the blank holder limited has been significantly improved. When the spring stiffness of the blank holder is fixed, the interlock length increases first and then decreases with the increase of the limited height of the blank holder. The smaller the spring stiffness of the blank holder, the greater the limited height of the blank holder is required to obtain the maximum interlock length. At the same time, the smaller the spring stiffness of blank holder is, the greater the maximum interlock can be obtained. While, the greater the spring stiffness of blank holder, the smaller the maximum interlock length of joint formed.

Under the action of the dies, the plastic flow of the upper and lower sheets material forms an S-shaped mechanical interlocking geometry, as shown in Figure 7. After that, the Geometry of the lower sheet at different blank holder limited heights were shown in Figure 8, as the blank holder limited height increases from 0.7 to 1.4 mm, the protrusion height increases continuously, meanwhile, the material around the upper part of the joint flow along the radial direction decreases gradually. Moreover, the protrusion height of the joint increases with the limited height of the blank holder, showing a linear relationship (see Fig. 9).

Furthermore, the S-shaped interlocking shape can be divided into two parts, the upper half and the lower half. Figure 10 shows the geometry of the mechanical interlock formed by different blank holder limited heights when the spring stiffness at 500 N/mm. As mentioned above, the S-shaped interlocking shape is largely affected by the

Table 2. Geometric parameters of the joint without blank holder limit.

Stiffness (N/mm)	Neck thickness (mm)	Bottom protrusion (mm)	Limit height of blank holder (mm)	Mechanical interlock value (mm)
500	0.407	1.507	1.525	0.050
1000	0.430	1.120	1.170	0.058
2000	0.482	0.866	0.927	0.077
3000	0.526	0.746	0.811	0.073
4000	0.507	0.640	0.760	0.071
6000	0.530	0.518	0.693	0.071
8000	0.560	0.415	0.520	0.022

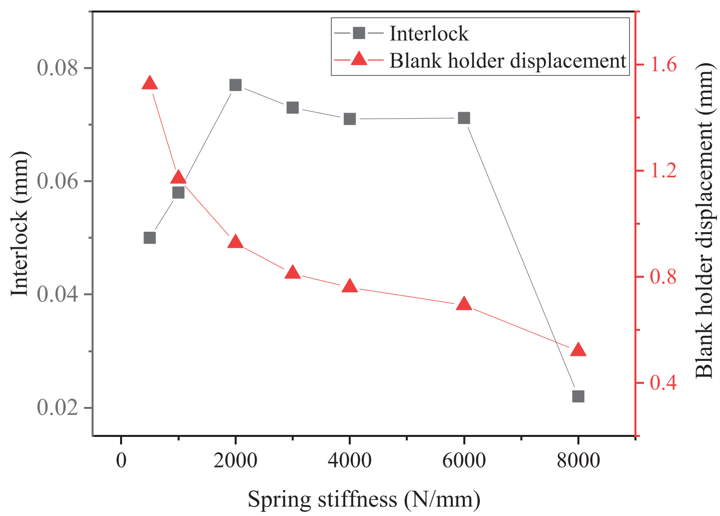

Fig. 5. The influence of spring stiffness on interlock length and displacement of blank holder with the blank holder free of limit.

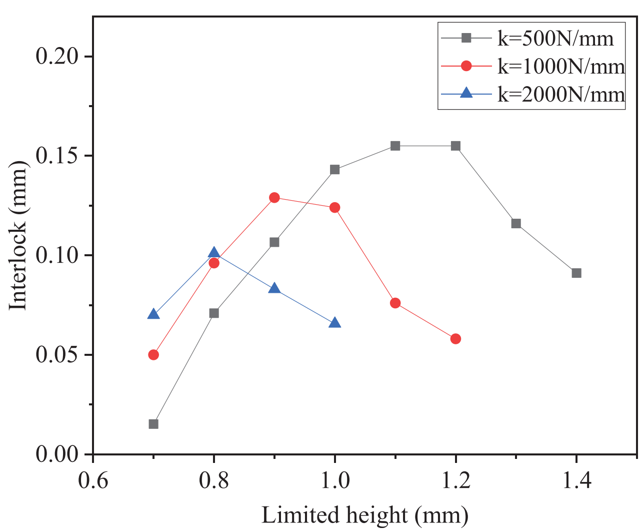

Fig. 6. The influence of blank holder limited height on interlock length.

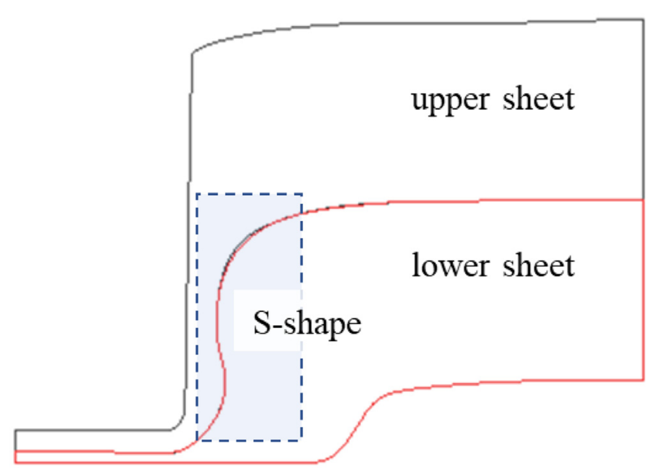

Fig. 7. The S-shape of the joint.

limited height of the blank holder. As shown in Figure 10, the minimum abscissa of the upper half of the S-shaped part decreases with the increase of the limited height of the blank holder, and the smaller the limited height of the blank holder, the greater the material flow of the upper half along the radial direction. It can also be seen from the figure that the lower part is mainly formed by the upper sheet material flows along the radial direction. With the increase of the limited height of the blank holder, the maximum

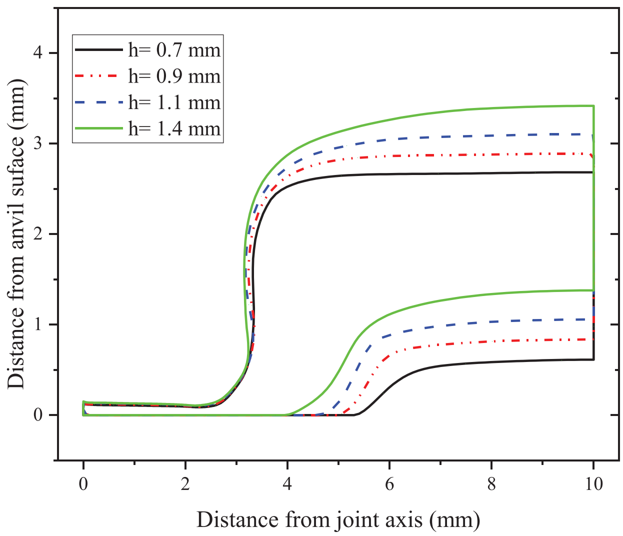

Fig. 8. Geometry of lower sheet at different blank holder limit heights.

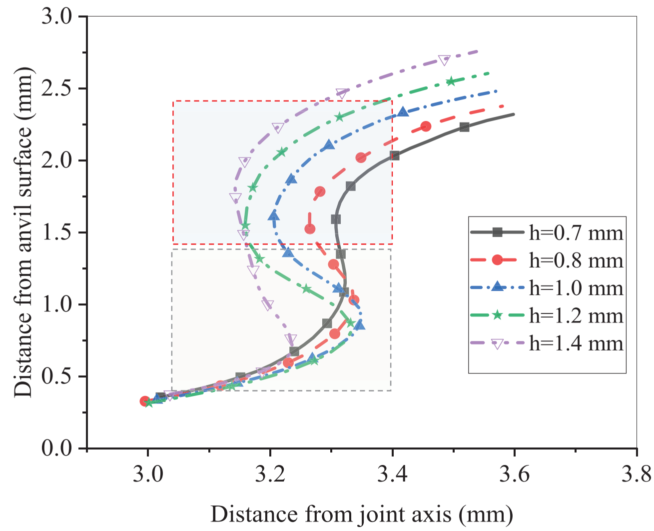

Fig. 10. Geometry of mechanical interlock at different blank holder limit heights.

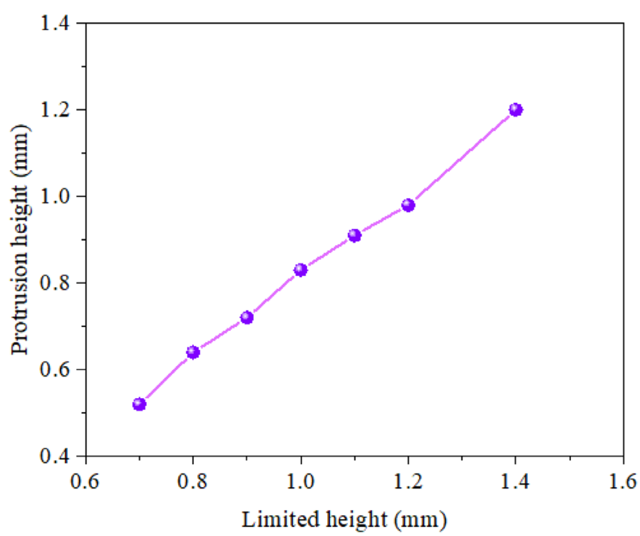

Fig. 9. Protrusion height of the joint at different blank holder limit heights.

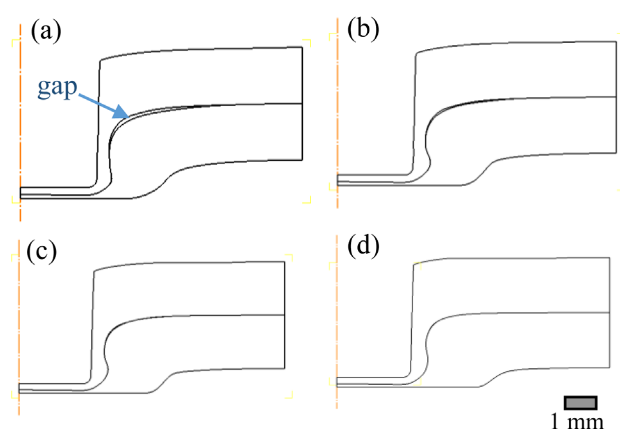

Fig. 11. Geometric morphology of the joint at different blank holder limit heights (a) 1.4 mm, (b) 1.2 mm, (c) 1 mm, (d) 0.8 mm.

abscissa of the lower half first increases and then decreases. When the limited height is too high, the material under the punch mainly flows along the axial direction, while the material flow along the radial direction is less, which cause the maximum abscissa of the lower half to be small. However, the mechanical interlock of the joint is formed by the upper half and lower half parts, which requires a reasonably limited height of the blank holder to regulate the flow of the material, so as to obtain the maximum mechanical interlock length.

Figure 11 shows the geometric morphology of the joint obtained at different blank holder limit heights at the blank holder spring stiffness 500 N/mm. When the limited height of the blank holder is 1.4 mm, it is observed that the interlock length is small, the bottom protrusion is high, and there is a clear gap between the two sheets [30]. This is due to material mainly flow in the axial direction without restriction. When the limited height of the blank holder reduced to 1.0 mm and 1.2 mm, the protrusion at the bottom of the joint decreases and the mechanical interlock length increases. This is attributed to the restriction of blank holder, which increased material flow in the radial direction arising from restricted material flow in the axial direction. Further reduce the limit height of blank holder to 0.8 mm, and the interlock length and bottom protrusion of the joint are reduced. This is because the small bottom protrusion leads to large resistance for the material flow in the radial direction, which increased the material in the upper half of the S-shape flow in the radial direction, this can also be seen intuitively in Figure 10.

Figure 12 shows the material flow velocity at different blank holder limited heights. When the limit height of the blank holder is 1.4 mm, most of the material at the joint flows upward along the axial direction because there is almost no constraint in the axial direction. In the joint forming stage, it is not conducive to the material flow along the radial direction, which is detrimental to the formation

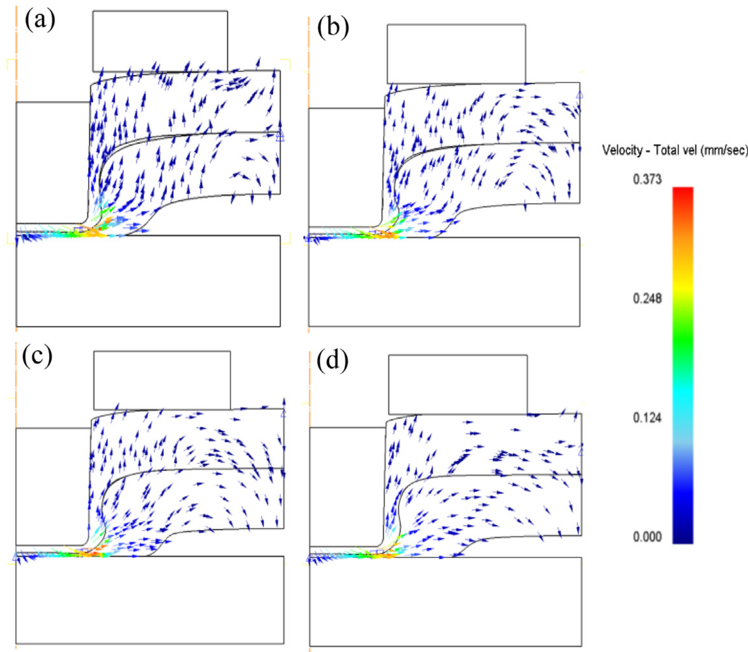

Fig. 12. Material flow velocity field at different blank holder limit heights (a) 1.4 mm, (b) 1.2 mm, (c) 1.0 mm, (d) 0.8 mm.

Table 3. Test factors and levels.

Factors	Low lever (–1)	Medium lever (0)	High lever (+1)
A: spring stiffness (N/mm)	500	1000	1500
B: Punch diameter (mm)	5.0	5.5	6.0
C: blank holder limit height (mm)	0.8	1.0	1.2

of mechanical interlock. High protrusions are generated at the bottom, and note that there is a gap between the two sheets.

At the limit height 1.0 and 1.2 mm, due to the early limit of the blank holder, the axial constraint is generated, which restricts the upward flow of material, so that the material under the punch flows along the radial direction, which promotes the formation of mechanical interlocking.

When the limited height was reduced to 0.8 mm, the blank holder prematurely restricts the material flow in the axial direction, and the bottom protrusion is low, which also cause a large resistance of material flow along the radial direction. Therefore, the upper sheet material under the punch squeezes the lower sheet material to flow in the radial direction, resulting in the reduction of the upper half of the S-shaped interlock shape and the reduction of the interlock length.

From the above results, we can infer that the limited height of blank holder directly affects the interlock length of the joint by controlling the material flow direction in the dieless clinching process considering the limit of the blank holder. In this process, the upward flow of material was restrained after the blank holder was limited, and then the material under the punch flow in the radial direction. If the limited height of the blank holder is too high, the material will be restrained too late in the axial direction, and most of the material flow upward in the axial direction. At the same time, a higher protrusion will be formed at the bottom, and less material will flow in the radial direction, which is difficult to form a good interlock. On the contrary, if the limited height of the blank holder is too small, the material flow is limited too early in the axial direction, this leads to the fact that the bottom protrusion is too small, which hinder the upper sheet material around the punch flow along the radial direction, and makes it difficult to form a mechanical interlock.

4 Response surface analysis

Response surface method is a kind of statistical and mathematical prediction, which is used to establish the model between input and result and predict the result. When all independent variable parameters in the experiment process are measurable and controllable, the second-order polynomial function can be used in the response surface method [32], as shown in the equation (1).

$$y = \beta_0 + \sum_{i=1}^{k}\beta_i x_i + \sum_{i=1}^{k}\beta_{ii} x_i^2 + \sum_{i}\sum_{j}\beta_{ij} x_i x_j + \varepsilon, \qquad (1)$$

Table 4. Response surface experimental layout and results.

FE run no.	Spring stiffness (N/mm)	Punch diameter (mm)	Limit height (mm)	Interlock length (mm)
1	1500	5.5	1.0	0.070
2	1000	6.0	0.8	0.045
3	1000	5.0	0.8	0.086
4	1000	5.5	1.0	0.124
5	1500	5.5	0.8	0.100
6	500	5.5	0.8	0.071
7	1000	5.5	1.0	0.125
8	1000	5.5	1.0	0.123
9	1500	6.0	1.0	0.110
10	1000	6.0	1.2	0.060
11	1000	5.5	1.0	0.126
12	1500	5.0	0.8	0.062
13	500	5.5	1.2	0.155
14	1000	5.0	0.8	0.062
15	500	5.0	1.0	0.140
16	1000	5.5	1.0	0.125
17	500	6.0	1.0	0.120

Table 5. ANOVA for the response surface quadratic model.

Source	Sum of square	Degree of freedom	Mean square	F value	P value
Model	0.017	9	1.88×10^{-3}	19.53	0.0004
A- spring stiffness	4.91×10^{-3}	1	4.91×10^{-3}	50.98	0.0002
B- Punch diameter	7.91×10^{-4}	1	7.91×10^{-4}	8.22	0.0241
C- blank holder limit height	8.34×10^{-4}	1	8.34×10^{-4}	8.66	0.0216
AB	2.23×10^{-3}	1	2.23×10^{-3}	23.15	0.0019
AC	4.66×10^{-3}	1	4.66×10^{-3}	48.39	0.0002
BC	1.17×10^{-3}	1	1.17×10^{-3}	12.14	0.0102
A^2	2.28×10^{-5}	1	2.28×10^{-5}	0.24	0.6416
B^2	2.19×10^{-5}	1	2.19×10^{-5}	25.09	0.0021
C^2	5.47×10^{-3}	1	5.47×10^{-3}	62.54	0.0001
Lack of fit	3.81×10^{-4}	2	1.91×10^{-4}	3.25	0.1246

where β_0 is a constant value (mean value) and β_i, β_{ii} and β_{ij} are respectively linear, second order and interaction coefficients, and e is random error.

To analyze the influence of various parameters and parameter interaction on the mechanical interlock of the joint, the Box–Behnken design (BBD) method was used to carry out the test design [33], the blank holder spring stiffness A, the punch diameter B, and the blank holder limit height C were selected as the influencing factors, and the interlock length Y of the joint as the target value. Table 3 shows the test factors and levels. Then, each dictated set of the response surface methodology's (RSM's) Box–Behnken matrix was calculated by the FE model, and the test scheme and results were shown in Table 4.

The regression model fitting of the experimental data in Table 4 was performed, and the significance of the model was tested by ANOVA, and the significance level was set to 0.05, with model critical value $P < 0.05$, the factor is significant. All univariates and significant interaction factors were preserved, and an adjusted regression model was obtained, as shown in equation (2),

$$Y = -3.1 - 1.9 \times 10^{-4}A + 0.95B + 1.42C + 1.39 \times 10^{-4}A * B - 6.62 \times 10^{-4}A * C + 0.37B * C - 9.94 \times 10^{-9}A^2 - 0.13B^2 - 1.46C^2. \quad (2)$$

From Table 5, it can be seen that the critical value of the failure load model $P = 0.0001 < 0.05$, it indicates that the resulting regression model is significant, and the three factors selected in the response surface model have a correlation with the influence of the interlock quantity, that is, there is a clear regression relationship between the joint interlock length and the spring stiffness of the blank holder, the limit height and the punch diameter. In addition, the smaller the P-value is, the more significant

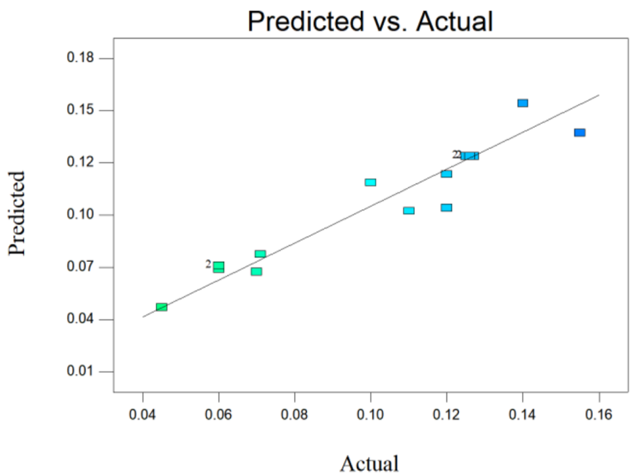

Fig. 13. Comparison between the tested and the predicted results (mm).

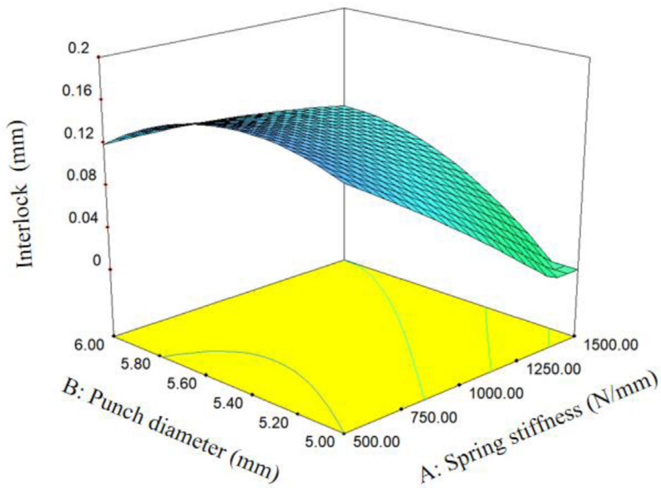

Fig. 14. Effects of spring stiffness and punch diameter on the interlock.

the influence of this factor on the response value is, and the significant influence of the single factor on the failure load is as follows: the spring stiffness of the blank holder is the most significant, the limit height of the blank holder is second, and the effect of the punch diameter is the smallest.

Figure 13 shows the comparison between the test results and the prediction results. The simulated value are distributed on both sides of the prediction line, results indicate that the established second-order response regression model, for interlock length, and blank holder spring stiffness, blank holder limited height, punch diameter, and their interaction, has relatively accurate prediction performance.

Figure 14 shows the influence of the spring stiffness of the blank holder and the punch diameter on the interlock at the limited height of the blank holder of 1.0 mm. The steeper the response curve is, the more significant the influence of factors on the amount of interlocking is. The smoother the curve is, the smaller the influence of factors on the amount of interlocking is. It can be inferred a large interlock length can be obtained only with a small blank holder spring stiffness.

Figure 15 shows the influence of the blank holder spring stiffness and the limit height on the interlock length at the punch diameter of 5.5 mm. A smaller blank holder spring stiffness can be matched with a medium blank holder limit height to obtain a higher joint interlocking amount. The larger the blank holder spring stiffness is, the smaller the limit height of the blank holder is required.

Figure 16 shows the influence of the punch diameter and the limit height on the interlock length at the spring stiffness 650 N/mm. The optimal interlock length can be obtained only with a medium limit height of blank holder and a medium punch radius.

The process conditions for obtaining the maximum interlock length predicted by the response surface optimization method are: the spring stiffness of blank holder is 590 N/mm, the limit height of blank holder is 1.0 mm, the punch radius is 5.25 mm, and the interlock length of 0.16 mm can be obtained. Based on these process parameters, the finite element simulation was also carried out. A comparison between the simulation and prediction results was carried out, as can be found in Table 6, the error between the predicted value and the simulated value of the interlocking length is 6.3%, and the prediction results are consistent with the simulation results.

5 Discussion

5.1 Effect of the blank holder limited

In this study, we proposed a novel dieless clinching process considering the limitation of the blank holder to improve the mechanical property of the traditional dieless clinched joint, we unveiled the influence law of blank holder parameters (spring stiffness and limited height) on mechanical interlock forming and material flow during the dieless clinching process, through a comparison of the traditional dieless clinching and the novel dieless clinching process with blank holder limited, we identified that the limitation of the blank holder can improve the interlock of the dieless clinched joint.

The mechanical interlock length formed by the traditional dieless clinching is less than 0.1 mm, as can be seen in Figure 5, which is close to the research result from Atia [22]. After then, we control the blank holder limited height to regulate the material flow along the axial and radial direction, benefiting from this, the interlock of the joint can be increased to 0.15 mm, as shown in Figure 6, these findings imply that the blank holder limited height and spring stiffness synergistically affect material flow.

Besides, Response Surface Methodology is used to predict the optimal joint, with the limitation of the blank holder, a dieless clinched joint with interlock of 0.16 mm and protrusion height of 1.0 mm can be achieved. From [30], Chen et al investigated the novel dieless clinching process free of blank holder by experimental methods, mechanical interlock value can be reached to 0.18 mm.

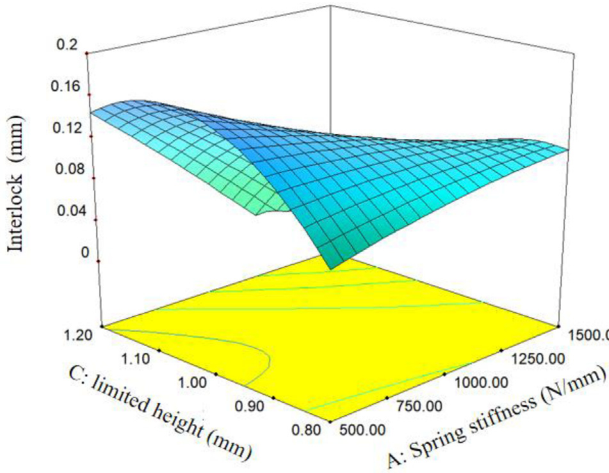

Fig. 15. Effects of spring stiffness and limited height on the interlock.

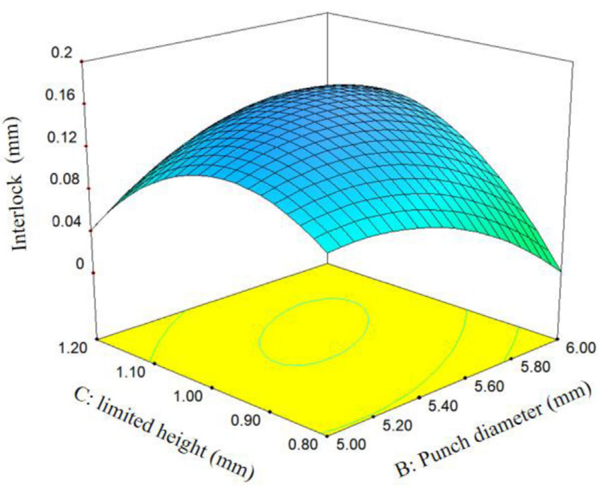

Fig. 16. Effects of limited height and punch diameter on the interlock.

Comparing these two results, it is seen that our result is consistent with the research result from Chen. While, the interlock length of the joint from Atia[34] is no more than 0.1 mm, which further confirms the effectiveness of the proposed process.

5.2 Regulation mechanism of blank holder on material flow

To understand the influence rules of the process parameters on the formation of the mechanical interlock, we must make clear the regulation mechanism of blank holder parameters on material flow during the process. Following the results (shown in Figs. 6, 8, 10 and 12), it can be inferred that big spring stiffness or low limited height of blank holder can lead to low protrusion at the bottom of the joint, which will prevent the upper sheet material around the punch from flowing longitudinally, it is not conducive to the formation of mechanical interlocking. On the contrary, small spring stiffness or high limited height of the blank holder leads to a high protrusion at the bottom of the joint, making it easier for the material to flow upward in the axial direction, but it decreased material flow in the radial direction at the later stage of the process. However, the upper sheet material flow along the radial direction at the later stage of the joining process is the basis of the mechanical interlock forming of the joint.

Table 6. Comparison between the simulated and predicted results.

	Predicted	Simulated	Error (%)
Interlock length (mm)	0.16	0.17	6.3%
Protrusion (mm)	1.02	1.00	2.0%

Furthermore, our study confirms that the limited height of the blank holder and pressure are important factors affecting the quality of the dieless clinched joint [22], the limited height of blank holder directly affects the interlock length of the joint by controlling the material flow direction in the dieless clinching process considering the limit of the blank holder. The formation of mechanical interlock is due to a large material flow in the axial and radial directions [10], noted that the restriction in material flow in the axial direction is more vital to interlock formation at the later stage of the process.

Therefore, it is necessary to comprehensively consider the influence of blank holder spring stiffness and limited height on the joint interlock. Obviously, the key to improving the interlock length of the dieless clinched joint is to find the coincidence point between the bottom protrusion height and the limit height of the blank holder and to realize the coordinated control of the plastic flow of upper and lower sheet materials along the radial and axial directions.

6 Conclusions

In the present work, a novel dieless clinching process considering the limit of the blank holder was proposed, the finite element model of the dieless clinching process was established by DEFORM-2D, the influence of the spring stiffness of the blank holder, the limited height of the blank holder and the punch diameter on the mechanical interlock of the joint was analyzed using the response surface method. From the simulation results and analysis results, the main conclusions can be drawn as follows:

- The limited height of blank holder plays a key role in the regulation of material flow. With the limit of blank holder, it can timely limit the material flow in the axial direction, and increase the material flow in the radial direction, so as to promote the formation of mechanical interlock.
- It is necessary to comprehensively consider the influence of blank holder spring stiffness and limited height on the joint interlock, the key to improving the interlock length of the dieless clinched joint is find the coincidence point between the spring stiffness and the limited height of the

blank holder, and then realize the coordinated control of the upper and lower sheets material flow in the axial and radial direction.
– The process parameters for obtaining the maximum interlock length predicted by the response surface optimization method are: the blank holder spring stiffness is 590 N/mm, the limit height of blank holder is 1.0 mm, the punch radius is 5.25 mm, and a soundly joint with the interlock length of 0.16 mm can be obtained.

It is suggested to consider the dieless clinching with blank holder limited for dissimilar materials (such as steel-aluminum, magnesium-metal sheets, etc.), different sheet thicknesses and carry out joint strength test in the following research, the additional investigation of the heat-assisted dieless clinching process are also suggested. Moreover, it will be possible to apply the introduced method in more complex and versatile process chains. This study provides a new path to improve the dieless clinched joint, future iterations of the novel dieless clinching process with blank holder limitation will exert greater potential.

Declaration of conflicting interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments. The authors acknowledge funding by the Nature Science Foundation of Shandong Province of China (Grant No. ZR2018MEE024 and ZR2022ME118) and Shandong Province Higher Educational Science and Technology Program (Grant No. J17KA018).

References

[1] S. Rosenthal, F. Maaß, M. Kamaliev, M. Hahn, S. Gies, A.E. Tekkaya, Lightweight in automotive components by forming technology, Auto. Innov. **3**, 195–209 (2020)
[2] G. Meschut, O. Hahn, V. Janzen, T. Olfermann, Innovative joining technologies for multi-material structures, Weld. World. **58**, 65–75 (2014)
[3] A. Barimani-Varandi, A.J. Aghchai, Electrically-assisted mechanical clinching of AA6061-T6 aluminum to galvanized DP590 steel: effect of geometrical features on material flow and mechanical strength, Mech. Ind. **21**, 529 (2020)
[4] U. Dilthey, L. Stein, Multimaterial car body design: Challenge for welding and joining, Sci. Technol. Weld. Joint **11**, 135–142 (2006)
[5] D. Krassmann, E. Moritzer, Development of a new joining technology for hybrid joints of sheet metal and continuous fiber-reinforced thermoplastics, Weld. World. **66**, 45–60 (2022)
[6] M. Salamati, M. Soltanpour, A. Fazli, A. Zajkani, Processing and tooling considerations in joining by forming technologies; part A—mechanical joining, Int. J. Adv. Manuf. Technol. **101**, 261–315 (2019)
[7] F. Lambiase, D.-C. Ko, Feasibility of mechanical clinching for joining aluminum AA6082-T6 and carbon fiber reinforced polymer sheets, Mater. Des. **107**, 341–352 (2016)
[8] G. Buffa, L. Fratini, U. La Commare, D. Römisch, S. Wiesenmayer, S. Wituschek, M. Merklein, Joining by forming technologies: current solutions and future trends, Int. J. Mater. Form. **15**, 27–16 (2022)
[9] X. He, Clinching for sheet materials, Sci. Technol. Adv. Mater. **18**, 381–405 (2017)
[10] H. Peng, C. Chen, H. Zhang, X. Ran, Recent development of improved clinching process, Int. J. Adv. Manuf. Technol. **110**, 3169–3199 (2020)
[11] X. Zhang, C. Chen, H. Peng, Recent development of clinching tools and machines, Int. J. Adv. Manuf. Technol. **121**, 2867–2899 (2022)
[12] C. Chen, S. Zhao, M. Cui, X. Han, S. Fan, T. Ishida, An experimental study on the compressing process for joining Al6061 sheets, Thin-Walled Struct. **108**, 56–63 (2016)
[13] C. Chen, S. Zhao, X. Han, M. Cui, X. Zhao, T. Ishida, Experimental investigation of the mechanical reshaping process for joining aluminum alloy sheets with different thicknesses, J. Manuf. Process. **26**, 105–112 (2017)
[14] C. Chen, S. Zhao, M. Cui, X. Han, S. Fan, Mechanical properties of the two-steps clinched joint with a clinch-rivet, J. Mater. Process. Technol. **237**, 361–370 (2016)
[15] T. Wen, H. Wang, C. Yang, L.T. Liu, On a reshaping method of clinched joints to reduce the protrusion height, Int. J. Adv. Manuf. Technol. **71**, 1709–1715 (2014)
[16] F. Lambiase, D.-C. Ko, Two-steps clinching of aluminum and Carbon Fiber Reinforced Polymer sheets, Compos. Struct. **164**, 180–188 (2017)
[17] T. Gerstmann, B. Awiszus, Recent developments in flat-clinching, Comput. Mater. Sci. **81**, 39–44 (2014)
[18] C. Chen, H. Zhang, D. Qin, H. Li, Joining different aluminum alloy sheets by flat clinching process, Int. J. Adv. Manuf. Technol. **116**, 1071–1079 (2021)
[19] C. Chen, H. Zhang, Y. Xu, J. Wu, Investigation of the flat-clinching process for joining three-layer sheets on thin-walled structures, Thin-Walled Struct. **157**, 107034–107010 (2020)
[20] R. Neugebauer, M. Todtermuschke, R. Mauermann, F. Riedel, Overview on the state of development and the application potential of dieless mechanical joining processes, Arch. Civ. Mech. Eng. **8**, 51–60 (2008)
[21] R. Neugebauer, R. Mauermann, S. Dietrich, C. Kraus, A new technology for the joining by forming of magnesium alloys, Prod. Eng. **1**, 65–70 (2007)
[22] M.K.S. Atia, M.K. Jain, Finite element analysis of material flow in die-less clinching process and joint strength assessment, Thin-Walled Struct. **127**, 500–515 (2018)
[23] C. Chen, S. Zhao, X. Han, Y. Wang, X. Zhao, Investigation of flat clinching process combined with material forming technology for aluminum alloy, Materials **10**, 1433–1415 (2017)
[24] D. Qin, C. Chen, H. Li, X. Ren, Investigation of the novel two-step flat clinching process to achieve double-sided flat surfaces on engineering structures, J. Braz. Soc. Mech. Sci. Eng. **44**, 1–16 (2022)
[25] Y. Zhang, H. Xu, R. Peng, Y. Lu, L. Zhu, The state of the art of finite element analysis in mechanical clinching, Int. J. Precis. Eng. Manuf. **9**, 1191–1214 (2022)
[26] D. Qin, C. Chen, Y. Ouyang, J. Wu, H. Zhang, Finite element methods used in clinching process, Int. J. Adv. Manuf. Technol. **116**, 2737–2776 (2021)
[27] A. Barimani Varandi, The non-isothermal hot deep drawing of AA5083 aluminum alloy, Mech. Ind. **21**, 112 (2020)
[28] X. Han, S. Zhao, C. Chen, C. Liu, F. Xu, Optimization of geometrical design of clinching tools in flat-clinching, Proc. Inst. Mech. Eng. Part C: J. Mech. Eng. Sci. **231**, 4012–4021 (2017)

[29] D. Qin, C. Chen, Research on the mechanical property and failure mechanism of the dieless clinched joints of various aluminum alloys, Eng. Fail. Anal. **137**, 106384 (2022)

[30] D. Qin, C. Chen, H. Zhang, X. Ren, J. Wu, Experimental investigation of the novel dieless clinching process free of blank holder, Arch. Civ. Mech. Eng. **22**, 28–40 (2022)

[31] S. Han, Z. Wang, Z. Wang, Z. Li, Y. Li, Heat-assisted hole-clinching process for joining magnesium alloy and ultra-high-strength steel, Int. J. Adv. Manuf. Technol. **115**, 551–561 (2021)

[32] Y. Javid, Multi-response optimization in laser cladding process of WC powder on Inconel 718, CIRP: J. Manuf. Sci. Technol. **31**, 406–417 (2020)

[33] W. Shu, B. Qiu, J. Yang, D. Huang, Z. Gao, Loading path optimization of shaft clinching forming assembly using finite element simulation and response surface methodology, Proc. Inst. Mech. Eng. Part C: J. Mech. Eng. Sci. **234**, 734–745 (2019)

[34] M.K. Sabra Atia, M.K. Jain, A parametric study of FE modeling of die-less clinching of AA7075 aluminum sheets, Thin-Walled Struct. **132**, 717–728 (2018)

Cite this article as: Z. Wang, S. Han, Z. Li, Y. Li, Simulation of dieless clinching process considering the limit of blank holder, Mechanics & Industry **24**, 7 (2023)