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ORIGINAL ARTICLE

On a reshaping method of clinched joints to reduce the protrusion height

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Abstract The existence of relatively high protrusions above the sheets on most of the clinched joints could sometimes bring about an undesired result in the subsequent processing and, therefore, the application of the clinching technologies might be restricted. The current study proposed a countermeasure by imposing compression on the joints with a pair of contoured tools and then obtaining a controlled local plastic deformation of the joints, resulting in a reduction of the protrusion height. A typical two-layer clinching of 6063 aluminum alloy sheets with the thickness of 0.8 mm was employed to study the successional processes of clinching, reshaping, and separation. Geometrical parameters of the reshaping tools were optimized in terms of pull-out strength on the basis of numerical simulation and orthogonal design. It was found that diameter *d* of the truncated cone end on the reshaping die, inclination *α* of the truncated cone, and then fillets of the die and punch are of important influence on the connecting strength. Moreover, connecting strengths of the clinched joints before reshaping and after reshaped with the optimal parameters of the tools were compared experimentally. The results show that the protrusion height of the clinched joints can be reduced dramatically by the method without decreasing the connecting strength. In the example, the protrusion height of the clinched joint decreased from 1.7 to 0.68 mm, while the average pull-out strength of the joints increased from 230.8 to 331.4 N, and the shear strength increased from 559.7 to 657.5 N.

Keywords Clinching · Numerical simulation · Joint · Connecting strength · Reshaping

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1 Introduction

Compared with the traditional connecting processes such as spot welding, joining by forming technologies, especially various kinds of mechanical clinching, have the advantages of no special requirement of the sheet surface, wide variety of materials which can be joined similar or dissimilar, low energy consumption, low noise, and no gas exhaust [1]. For these reasons, the technologies have attracted more and more attentions in industrial field such as automobile and household appliances in recent years.

The essential of clinching is to create an interlock between the sheets by employing localized cold deformation of the sheet metal with the aid of relatively simple tools, while no additional elements such as rivets or bolts are used. Till date, extensive researches have been conducted on the deformation mechanism, designing of tools, failure and defect modes, connection between different materials, and so on. Varis and Lepisto [2] proposed a simple test-based procedure for establishing clinching parameters; Saberi et al. [3] investigated three different coated thin steel sheets in the clinching process and found that there are minor influences of the coating system on the punch force and joining parameters; Lee et al. [4] presented a design method for clinching tools based on the analytical model that was defined as a function of the neck thickness and the undercut; Mori et al. [5] discussed the mechanism of superiority of fatigue strength for aluminum alloy sheets joined by mechanical clinching and self-pierce riveting. As He [6] pointed out, numerical simulation had shown its validity in the researches of forming and separating process of clinch; therefore, it might be more cost-effective to analyze the optimization problem with numerical techniques like the finite element method (FEM). For example, De Paula et al. [7] simulated the forming process of clinch joining of metallic sheets, while Coppieters et al. [8] investigated the possibility of predicting the shear and pull-out strength of a

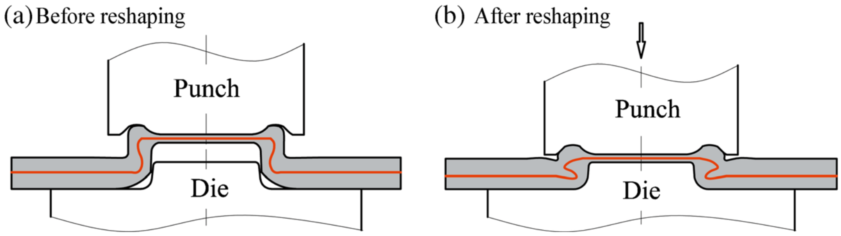


Fig. 1 Reshaping process of the clinched joint

clinched sheet metal assembly using FEM and discussed numerical difficulties associated with these simulations.

However, on the conventional clinched joints, there are relatively high protrusions above the sheets, which could have an adverse effect on the subsequent processing like assembly, etc., and therefore, the application of the technology might be restricted. A few improved clinching technologies were proposed, on which the protrusions height is lower than that on the conventional joints, for example, the dieless clinching or flat-clinch-connection reported by Neugebauer et al. [9]. Nevertheless, among these approaches, prepared holes on the sheet or additional elements like rivets are required [10], or the combined movement of blank holder and punch, together with their acting force must be precisely controlled during the operation, resulting in a complicated device and reduction of the process stability.

In the current study, a countermeasure to reduce the protrusion height was presented by simply utilizing a controllable plastic deformation of the clinched joint without using any ancillary joining elements. Geometrical parameters of the reshaping tools were theoretically optimized in terms of connecting strength and then verified by the experiment. The method can be used as a helpful supplementary procedure of the conventional clinching, especially in the place where a lower height of the joint is required.

2 Principle of reshaping the clinched joint

Figure 1 illustrates the process of reshaping a conventional clinched joint. By compressing the joint in a single stroke with a pair of contoured tools on a press, shape of the joint was modified and the protrusion height was dramatically reduced, yet the two layers of the sheets still nested with each other at the joining position. Blank holder is not necessary in the operation.

Whether a clinched joint is reshaped or not, since no additional elements are used, it is clear that for given material of the sheets, the joint resistance is highly dependent on the final geometry. In order to validate such a concept and guarantee the connecting strength after the handling, it is important to assess the connecting strength after reshaping.

3 Analytical models and procedure

In the current study, a typical two-layered clinching of Al6063 sheets with the nominal thickness of 0.8 mm was used, as shown in Fig. 2. Geometric parameters of the clinching tools were chosen according to those reported in [2]. Thickness at the base of the joint that is called *X* parameters is 0.4 mm, and the interlock is about 0.15 mm. The height and diameter of the protrusion and the diameter of the joint concave are 1.7, 8, and 5.4 mm, respectively.

Numerical simulation was performed using the commercial finite element (FE) analysis software Deform-2D®. The simulation was divided into three stages, namely, clinching, reshaping, and separating. Clinching and reshaping are typical elastic–plastic deformation processes, and axisymmetric FE

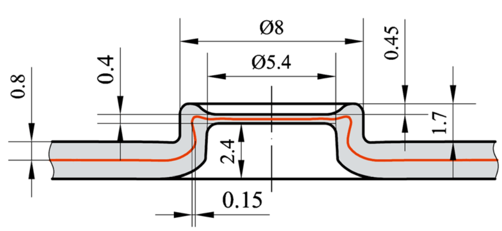


Fig. 2 Geometry of the clinched joint of Al6063 sheets

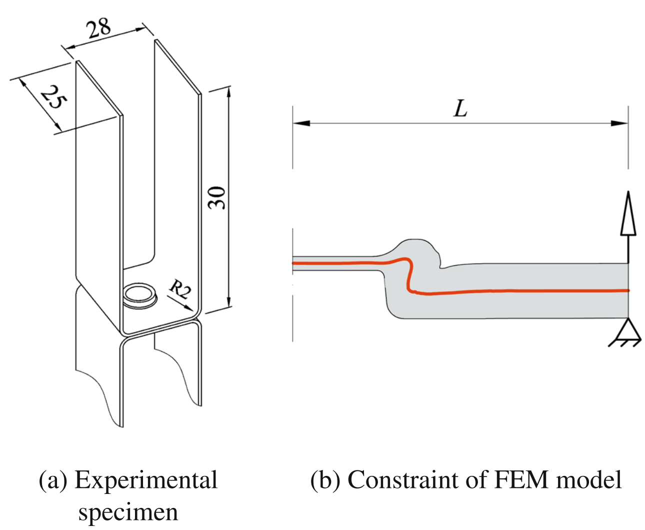


Fig. 3 H-type tension test model for pull-out strength

models were used in the study. The punch, die, and blank holder were taken as rigid. Coulomb friction model was assumed in the study, and friction coefficient between the sheets was taken as 0.3, while between the sheets and tools was taken as 0.1 because of the lubrication. Blank holder and the die are fixed, and the punch move downwards with a constant speed of 5 mm/min. Local mesh subdivision was used to balance the accuracy and calculating time. The mechanical properties of Al6063 sheet were selected as Lee et al. [4] recommended, where the elastic modulus is 70 GPa, yield stress is 218 MPa, and tensile strength is 277 MPa.

In general, the connecting strengths of a mechanical clinched joint are classified as tensile strength (also referred to as pull-out strength) and shear strength. As pointed out in [11], shear strength of this type of connections is much higher than the tensile strength, and most of the failures in practice were owing to the lack of tensile strength. Therefore, the tensile strength is a major concern in the following discussion.

H-type tension test [12] was utilized to evaluate the failure load of joints before and after reshaping. In the experiment, specimens of Al6063 sheet were cut into strips with the size of $90\times25\times0.8$ mm. The connected specimens were formed to H-type before the tension test, as shown in Fig. 3a.

The FE analysis model of separation was simplified with the lower sheet fixed at a distance of L from the joint center, while uniform displacements are exerted to the upper edge at the same distance, as shown in Fig. 3b. The maximum load was considered to be the tensile strength. To have a reliable simulation tool, the models

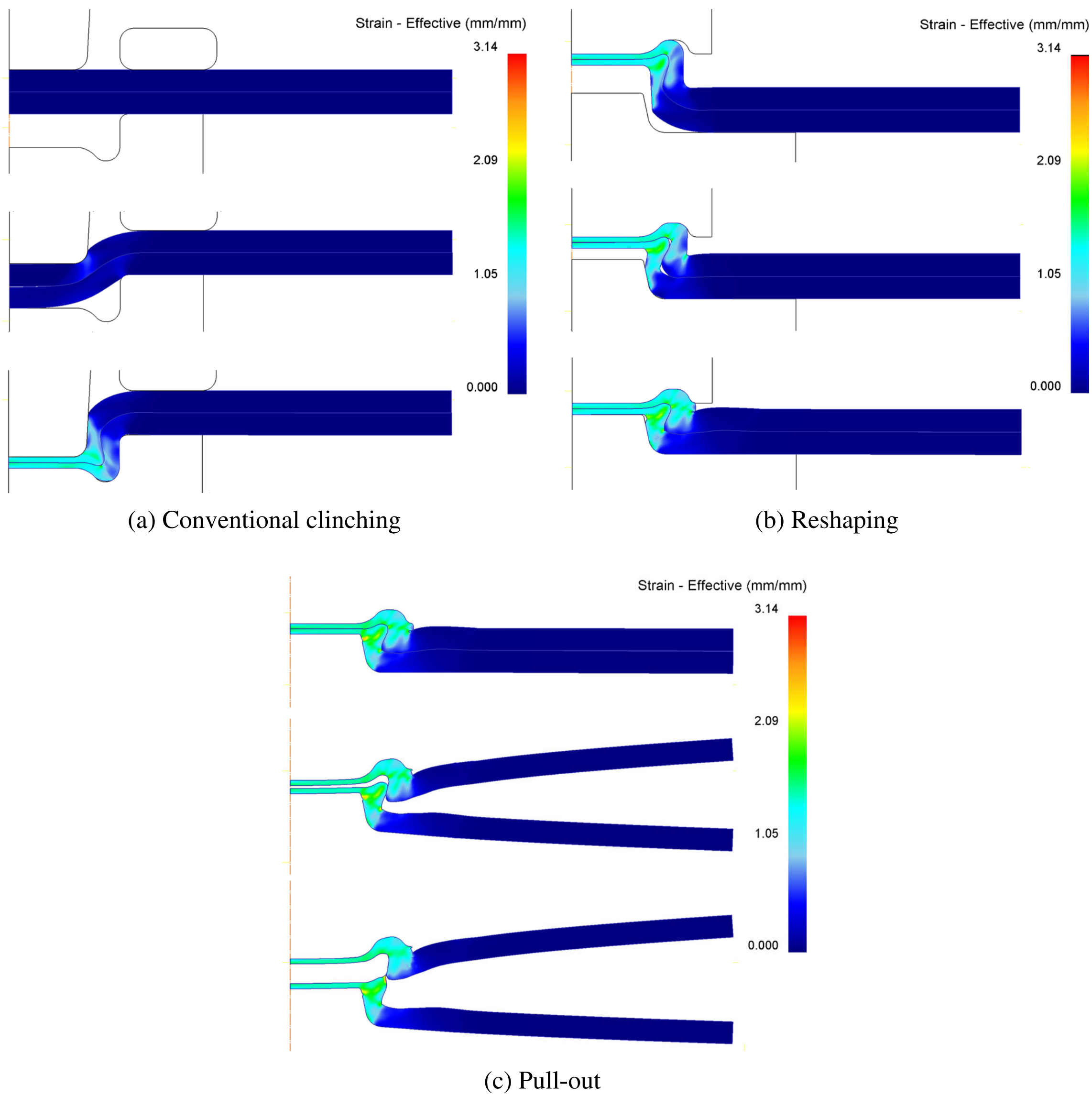


Fig. 4 Numerical results of clinching, reshaping, and pull-out process

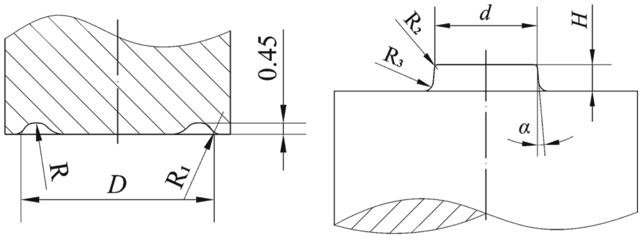


Fig. 5 Schematic illustration of the geometry of reshaping tools

were corrected with experiment. Five groups of specimens with clinched joints before reshaping were tested, and an average maximum tensile force of 230.8 N was observed. By comparing the theoretical and experimental results, the input conditions of FE analysis, especially the loading location of L was then corrected in order to obtain a similar result of the tensile force. Since the original purpose of the study is to compare the connecting strength under different conditions, it is acceptable to certain extent for such a handling of the separating load, even though there might be a slight deviation from the actual process due to factors like the bending effect, as discussed in [11].

In each time of the simulation, the threefold calculation was conducted in succession via changing the tools and the load in the software. By doing this, the deformed geometry together with the strain distribution was reserved and then inherited; therefore, the effect of plastic deformation can be taken into account.

Figure 4 shows the FEM results of clinching, reshaping, and pull-out. With the presented geometry of tools, a small fold was observed on the outside of the protrusion during the reshaping process. Anyway, after reshaping, the joint becomes more compact with the protrusion height lowered significantly. The fracture mode of the joint after reshaping is a so-called button separation mode, as classified in [4].

4 Optimization of geometric parameters of reshaping tools

4.1 Orthogonal design

After reshaping, characteristic parameters of the joint such as thickness at the joint base, neck of the joint, and interlock are no longer valid in the prediction of the connecting strength. As stated earlier, the mechanical strength of the joint is entirely determined by its final shape, and, consequently, by the geometry of the forming tools. In order to evaluate the effects of all geometrical parameters, involving in both the punch and the die, on the forming quality, and to identify the influential geometrical parameters, a specially designed analysis procedure is needed. Oudjene et al. [12] presented a response surface methodology with moving least-square approximation for shape optimization of the clinching tools. Taguchi method is a powerful and so far the most commonly used technique for the design of experiment. Thus, in the following sections, FE simulations and orthogonal design were used to identify the optimal combination of key geometric parameters of the reshaping tools in terms of tensile strength based on the joint shown in Fig. 2.

Table 1 Geometric parameters and levels

Levels	A d (mm)	B α (deg)	C R_1 (mm)	D R_2 (mm)	E R_3 (mm)
1	4.5	0	0.1	0.1	0.2
2	4.8	4	0.3	0.2	0.4
3	5.1	8	0.5	0.3	0.6
4	5.4	12	0.7	0.4	0.8

Table 2 Results of orthogonal design

No.	A	B	C	D	E	Pull-out strength F (N)
1	1	1	1	1	1	315
2	1	2	2	2	2	324
3	1	3	3	3	3	336
4	1	4	4	4	4	319
5	2	1	2	3	4	330
6	2	2	1	4	3	326
7	2	3	4	1	2	319
8	2	4	3	2	1	313
9	3	1	3	4	2	310
10	3	2	4	3	1	315
11	3	3	1	2	4	347
12	3	4	2	1	3	335
13	4	1	4	2	3	305
14	4	2	3	1	4	317
15	4	3	2	4	1	319
16	4	4	1	3	2	302

Table 3 Extreme difference analysis

	A	B	C	D	E
K_1	323.50	315.00	322.50	321.50	315.50
K_2	322.00	320.50	327.00	322.25	313.75
K_3	326.75	330.25	319.00	320.75	325.50
K_4	310.75	317.25	314.50	318.50	328.25
R	16.00	15.25	12.50	3.75	14.50
Rank	1	2	4	5	3

K_i: average connecting strength value in i-th level of each factor, i: levels of each factor (i=1, 2, 3, 4), R: range fluctuations index of each factors' maximum connecting strength, *Rank*: influence rank of all factors

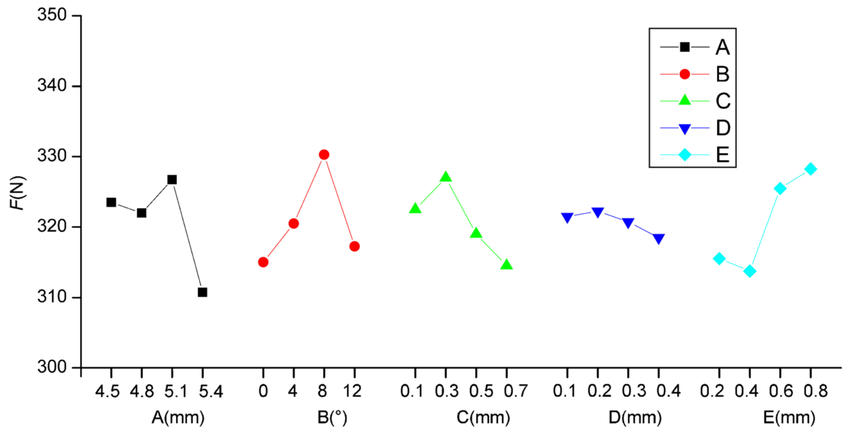


Fig. 6 Effect of parameter levels on the pull-out strength

Figure 5 shows the geometry of working part of the reshaping tools. The punch is a cylinder with a circular groove on the undersurface. The depth of the groove should fit the vault of the clinched joint, which is 0.45 mm in the study. Fillet R and dimension D of the groove are dependent on the original shape of the joint. Transitional fillet R_1 is small, but it has certain effect on the outward flow of the materials. Diameter of the cylinder has no direct influence on the deformation.

The die is a cylinder with a truncated cone on the top surface. The truncated cone can be used for workpiece positioning before the compression. Diameter d of the truncated cone end should be less than or equal to the diameter of the joint concave, which is 5.4 mm as shown in Fig. 2. The height H of the truncated cone determines the amount of protrusion compressing. In the study, rate of the height reduction is set to 60 %, namely, the protrusion height will be reduced from 1.7 to 0.68 mm. With the reference of simulation, H was set to 1.6 mm. Other geometric parameters of the truncated cone that might affect the connecting strength include the inclination angle α and fillet radii R_2 and R_3.

Based on a comprehensive view of the FEM analysis and relative references [4, 12], it can be determined that the key geometric parameters of the reshaping tools in orthogonal design include diameter d (A) and inclination α (B) of the truncated cone, fillet radius R_1 (C) of the punch, fillet radii R_2 (D) and R_3 (E) of the die, and then an orthogonal array table can be expressed as L_{16} (4^5) with five four-level factors was established, as presented in Table 1. On the basis of the table, 16 times of calculations that relate to reshaping of the joints, together with the pull-out processes were conducted. The results are summarized in Table 2.

Extreme difference analysis was introduced to find out how much the factors affect the connecting strength. Table 3 is the result of analysis and Fig. 6 shows the effect curves of the factors. Apparently, the larger the range value is, the greater the factor influences the connecting strength. It was observed that the diameter d of the truncated cone end on the reshaping die is the most important factor that influences the pull-out strength.

Since extreme difference analysis cannot distinguish data fluctuation caused by the deviation of experiment condition or experimental error, analysis of variance (ANOVA) was performed as presented in Table 4. It can be found that factor D has slight effect ($P>0.05$) on strength, while factors A, B, C, and E have significant effects ($P<0.05$).

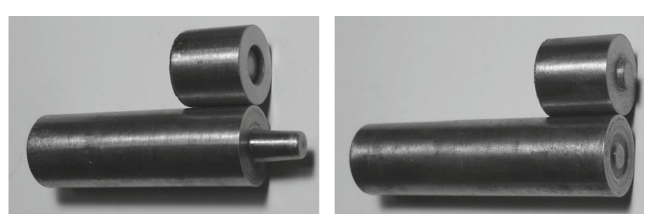
The results of extreme difference analysis and ANOVA indicate that the order of the importance of factors was diameter d of the truncated cone end on the reshaping die, inclination α of the truncated cone, fillet R_3 of the die, fillet R_1 of the punch, and fillet R_2 of the die. Thus, the best combination of

Table 4 Analysis of variance

Factors	Sum of squares	DOF	Mean square	F value	Significance P
A	580.5	3	193.50	18.43	0.020
B	542.5	3	180.83	17.22	0.021
C	337.0	3	112.33	10.7	0.041
D	31.5	3	10.50	1	0.500
E	621.5	3	207.17	19.73	0.018

$F_{0.05}$=9.28, $F_{0.01}$=29.46. P>0.05: No significant effect factor ($F<F_{0.05}$); P<0.05: Significant effect factor ($F_{0.01}>F>F_{0.05}$)

DOF Degree of freedom



(a) Clinching tools (b) Reshaping tools

Fig. 7 Experimental tools

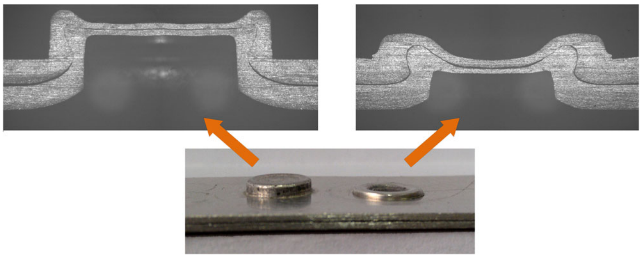


Fig. 8 Comparison of the joints before/after reshaping

the tool parameters is $A_3B_3C_2D_2E_4$, namely, d=5.1 mm, α=8°, R_1=0.3 mm, R_2=0.2 mm, and R_3=0.8 mm.

4.2 Experimental verification

Figure 7 shows the clinching and reshaping tools in the experiment. The optimized combination of the geometrical parameters of the reshaping tools was used. The experiment was carried out on a CMT6305 universal testing machine. During the reshaping process, the machine stops as soon as it reaches a reduction of 60 % of the original joint height. Forming speed of clinching and reshaping is set to be 5 mm/min, which is the same as the upward speed in separating test. To guarantee the reproducibility, each test was repeated five times and the maximum tensile load detected by the machine was considered to be the joint strength.

Figure 8 shows the appearance and cross sections of the joints before and after reshaping. It can be found that the deformation of the joints in both clinching and reshaping processes agrees with the simulation very well.

The experimental pull-out strengths of the joints before and after reshaping are summarized in Table 5. After reshaping, the average pull-out strength of the joints increased from 230.8 to 331.4 N.

The geometrical parameters of reshaping tools were optimized based on the pull-out strength. In order to clarify the influence of reshaping process on shear strength, comparative test of shear strength in accordance with that reported in [8] was also conducted. The results of five groups of the test are presented in Table 6. The lowest, largest, and average shear strength before reshaping are 533.6, 583.2, and 559.7 N, respectively; while the lowest, largest, and average shear strength after reshaping are 623.1, 677.9, and 657.5 N, respectively. Thus, the reshaped joints can bear a larger load of separation.

Table 5 Experimental results of pull-out strength before/after reshaping

	Strength F (N)					
	Test 1	Test 2	Test 3	Test 4	Test 5	Average
Before reshaping	244.2	220.1	228.1	220.3	241.2	230.8
After reshaping	342.1	356.3	295.9	325.5	337.4	331.4

Table 6 Experimental results of shear strength before/after reshaping

	Strength F (N)					
	Test 1	Test 2	Test 3	Test 4	Test 5	Average
Before reshaping	576.2	533.6	583.2	562.3	543.2	559.7
After reshaping	623.1	663.2	670.9	677.9	652.4	657.5

5 Conclusions

Aiming at the drawback of high protrusion on the conventional clinching joint, a reshaping method for reducing the joint height was put forward in the study. It can be utilized as a modification of the joint where interference could happen in the subsequent processing. Clinching of Al6063 sheets with thickness of 0.8 mm was utilized to study the connecting strengths of the joints before/after the modification; meanwhile orthogonal design was used to optimize the geometric parameters of the reshaping tools. The main conclusions can be made as follows:

1. Experimental and theoretical results prove that the reshaping method is feasible to reduce the protrusion height of the clinched joint. Instead of decreasing the connecting strength, the strengths of the joints in terms of pull-out and shear strength after reshaping were even enhanced in the experiment. To be specific, protrusion height of the clinched joint of Al6063 sheets reduced from 1.7 to 0.68 mm, and the average pull-out strength of five joints increased from 230.8 to 331.4 N, the average shear strength increased from 559.7 to 657.5 N.
2. Geometry of the reshaping tools has great influence on the connecting strength of the reshaped joints. It was found that diameter d of the truncated cone on the reshaping die, inclination α of the truncated cone, fillet R_3 of the die, fillet R_1 of the punch, and fillet R_2 of the die are the important factors that affect the connecting strength.
3. FEM simulations are a valuable tool for analyzing the clinching, reshaping, and separating processes of the joints. Theoretical results of the processes, including the elastic–plastic deformation and separating load etc., can be obtained with a desired accuracy, provided that the input conditions were properly defined.

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