Joining thin-walled structures without protuberance by two-strokes flattening clinching process

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Abstract
Clinching technology has better performance in joining different sheet materials. However, the protuberance and mechanical behaviors of clinched joints have always been needed to be improved. In this paper, a new clinching method, named the two-strokes flattening clinching (TFC) process, was proposed to improve the mechanical behaviors of joints and flatten the protuberance. Mechanical testing including tension-shearing tests was employed under quasi-static conditions to evaluate the different mechanical behaviors between TFC and conventional clinched joints. The influences of the different forming forces on mechanical response of these joints were studied. The static strength, energy absorption, material flow, and failure modes of TFC and conventional clinched joints were investigated comparatively. The experimental results demonstrated that the tension-shear strength of TFC clinched joints was increased by 30.3% compared with conventional clinched joints at the forming force of 30 kN. Furthermore, the material flow analysis showed that the thickness and interlock of TFC clinched joints were increased by 79% and 45.9%, respectively. The energy absorption of TFC clinched joint was increased by 82%. In addition, the TFC process did not change the failure mode of clinched joints, and the failure mode of all clinched joints was neck fracture.

Keywords Clinching · Two-strokes flattening clinching process · Failure mechanism · Mechanical properties

1 Introduction
Lightweight materials such as magnesium alloys [1], aluminum alloys [2, 3], and titanium alloys [4] are widely adopted in manufacturing industries. These lightweight materials have almost replaced the use of steel in car bodies [5–8]. The connection methods of these materials have been studied by many researchers [2–4]. Clinching technology is a joining method which can join the sheet materials without any auxiliary part. It was introduced by the German patent issued in 1897 [9]. At that time, the development of the clinching technology was limited by the widespread use of steel sheets. Clinching technology was firstly widely used in the manufacturing industries in 1980s because the lightweight alloys were widely adopted in manufacturing. Clinching technology was used at Audi Company in 1985 [10]. Subsequently, more and more manufacturers used clinching technology to join body sheet materials. Recently, clinching technology was widely employed to join parts of the car body [11–13].

Clinching technologies join metal sheets by creating an interlock, which is formed by local cold deformation between the sheets. The tools for the clinching process are simple and do not need auxiliary parts, such as bolts and rivets [14]. However, the strength of traditional clinched joints is not high, which is also the main drawback hindering the application of clinching technology. Many researchers have researched the clinching process, such as deformation mechanism, tool parameters, failure mode, punch force, and so on, to refine the strengths of clinched joints. Lee et al. [3] designed tools of the clinching process for joining the Al6063 alloy sheet materials to refine the quality of clinched joints. He et al. [15, 16] investigated the clinched joint strength and energy absorption with extensible dies by numerical and experimental methods. The authors found that the strength and elongation rate of the
joints can be increased by the adhesive layer. Lambiase et al. [17, 18] studied the effects of parameters of the clinching process on the joint strength and optimized the clinching tools by numerical and artificial intelligence methods. The study proposed the undercut can be increased by reducing the diameter of the bottom die, and the thickness of the joint neck can be improved by the larger punch and die, smoother corner radius, and shallow dies. Chen et al. [19–21] studied the effects of different sheet thicknesses on the mechanical performance of the joints. The results of their works showed that joints formed with thick sheet at the top and thin sheet at the bottom have better energy absorption and static strength in the tensile-shearing test.

Furthermore, due to the special requirements of industry for the surface of clinch joints, many researchers have innovated the clinching process and clinching tools, resulting in higher strength and lower protuberance. Wen et al. [14] reduced the protuberance of the joints and increased the strength of the joints by a reshaping process, which involves compressing the clinched joints with a pair of reshaping tools. The results of their studies found that the protuberance of the joint can reduce dramatically, and the static strength of reshaped joints has better performance than clinched joints. The protuberance height can be decreased by a new reshaping process using a cambered die and flat anvil (or two flat anvils), which was proposed by Chen et al. [22, 23]. The neck thickness and the interlock of the joint can reduce dramatically, and the tensile-shearing strength of the joints was all increased by these reshaping methods.

However, these reshaping methods above can only reduce the protuberance of joints to a certain extent, but cannot make it completely flat. In this paper, a new reshaping method, named the two-strokes flattening clinching (TFC) process, was proposed. The TFC method not only increases joint strength but also results in a significant reduction in protuberance of joints. Al1060 sheet materials were used for experimental tests. The influence of forming forces on the TFC process was investigated. Furthermore, the mechanical properties, including tensile-shear strength, failure modes, material flow, and energy absorption, were compared between conventional and TFC clinched joints. From the results of the test, the protuberance of joints was flattened, and the strengths and the neck thicknesses of the joints were improved. The tension-shear strength of TFC joints is increased by 30.3% compared with conventional clinched joints at the forming force of 30 kN. The failure modes of joints were all neck fracture. The results also showed that the energy absorption of the TFC joints is better than that of conventional clinched joints.

### 2 Two-strokes flattening clinching mechanism

The clinching tools that are employed in the TFC process include a punch, double flap gaskets, bottom ring, flat die, and anvil. As shown in Fig. 1, the anvil is fixed on the base. The bottom ring can move up and down along the anvil. The double flap gaskets are obtained by cutting off two halves of a ring.

The double flap gaskets are placed under the bottom ring. The clinched joint is created by compressing the sheets with a punch. The materials of the sheets expand outward to extrude the bottom ring and are tightly combined with the ring. Subsequently, we remove the double flat gaskets and compress the upper sheets with a flat die to make the clinched joint completely flat.

The conventional clinched joints are used to compare the strength of TFC clinched joints. Conventional clinched joints are created by the extensible dies, as illustrated in Fig. 2. The punch, dynamic die sectors, fixed die anvil, and blank holder make up the extensible dies. The extensible dies can promote good flow of sheet materials and facilitate demolding. The sheets are joined by an interlock. The main parameters that affect the quality of clinched joints are neck thickness ($t_n$), bottom thickness ($X$), and interlock ($t_i$), which are generally determined by the parameters of the extensible dies. Furthermore, the energy absorption, static strengths, dynamic strengths, and failure modes are all affected by these parameters.

### 3 Experimental procedure

#### 3.1 Materials

The material of Al1060 aluminum alloy was adopted in the TFC process. All sheets are cut from the rolling direction, and their dimensions are 2.5 mm thick × 80 mm long × 25 mm wide. The mechanical properties of the Al1060 sheet materials are obtained by the average value of three samples tested by the Instron 5982 universal tester. These sheet materials were tested by a uniaxial tensile test with the Instron 5982 tester at a velocity of 1 mm/min. Table 1 lists the principal test results of the Al1060 sheet materials.

#### 3.2 Forming procedure

The conventional clinching processes are conducted on the CMT-5105GJ machine. The conventional clinched joints are created by mechanical clinching with the extensible dies. As indicated in Fig. 3, the fixed anvil, punch, three movable die sectors, and blank holder are the main components of the extensible die. A ring of rubber surrounds the outside of the three movable die sectors so that the sheet materials maintain a
certain resistance when it expands outward. Compared with the common grooved dies, the extensible dies facilitate the demolding after the joint is formed, and the required forming force is smaller [28, 29]. The geometric dimension of the extensible dies is described (see Fig. 4). The diameter of the round punch is 5.4 mm. The different punch forces were configured to obtain different clinched joints in the conventional clinching. The punch speed was set to a fixed value of 4 mm/min. The control pattern of the punch was configured to “controllable force.” Different punch forces were set to 25 kN, 30 kN, and 35 kN.

The tools of the TFC process are shown in Fig. 5. In the first stroke, the flap gaskets are placed under the bottom ring, and the punch compresses the sheets at constant speed of 4 mm/min. The punch control pattern of the CMT-5105GJ machine is configured to “controllable force.” As a conventional clinching process, the different punch forces are set to 25 kN, 30 kN, and 35 kN. The joint extrudes the bottom ring and bonds tightly to it. In the following stroke, the gasket is removed and compresses the upper sheet with a flat die to move the bottom ring downward, and the protuberance of the clinched joint is gradually flattened by the fixed anvil. The geometric dimensions of the TFC tools are described in Fig. 6. The control mode of the flat die of the CMT-5105GJ machine is set to “controllable force.” The force of the flat die is configured to 16 kN, and the lowering velocity is configured to a constant 4 mm/min.

### 3.3 Static strength tests

The quality of the conventional and TFC clinched joints were estimated by the tensile-shearing test. The tensile-shearing test was performed by the CMT-5105GJ tester. The velocity of the tensile-shearing test was configured to 3 mm/min. The final tensile-shear strength of the joints was obtained by testing five clinched joints.

The conventional and TFC clinched joints were divided into five groups for tensile-shearing tests according to different forming forces. The tensile-shearing tests of conventional clinched joints were performed to get the preliminary joint strengths. The strength of TFC clinched joints was obtained to compare the initial strength under different forming forces.
The specimen employed in the tension-shearing test is presented in Fig. 7. Furthermore, energy absorption of a joint is an important basis for assessing joint safety. It is necessary to determine the energy absorptions of the joints, which can be assessed by determining the areas of the force-displacement curve in the tensile-shearing test. Furthermore, the energy absorptions of TFC and conventional clinched joints were compared in this paper.

### 4 Results

#### 4.1 Material flow and neck thickness

The flow of the sheet materials is affected by the clinching process parameters and the size of the clinching tools, which is an intuitive manifestation of sheets forming [30, 31]. By studying the material flow of the sheets, it is possible to visualize the process of deformation of the sheets and to make the appropriate parameter corrections.

The transverse section shapes of each diverse clinched joint under various forming forces are compared in Fig. 8. To investigate differences in material flow between TFC clinched joints and conventional clinched joints at each forming force, the transverse section shapes of conventional and TFC clinched joints are compared in the same sub-diagram. The right side of each sub-diagram is the conventional clinched joint (CJ) section, and the left side is the TFC clinched joint section. The bottom appearances of different clinched joints created with diverse forming forces are displayed in Fig. 9.

The material flow of the sheet materials in the clinching process determines the geometric parameters of clinched joints. The interlock ($t_s$) and the neck thickness ($t_n$) are the significant parameters for evaluating quality of the clinched joints. The neck thicknesses and the interlocks of joints created by the conventional clinching process and TFC process with different forming forces are compared in Fig. 10. Different parameters (interlock and neck thickness) are represented by different colored lines. The same parameters of different processes are represented by straight lines and double dotted lines.
Fig. 6 The geometric dimensions of the TFC tools

![Image of TFC tools dimensions]

Fig. 7 The specimens used in the tensile-shearing test

![Image of tensile-shearing test specimens]

Fig. 8 The transverse section shapes of different clinched joints: (a) $F = 25$ kN, (b) $F = 30$ kN, (c) $F = 35$ kN

![Image of transverse section shapes]

Fig. 9 Bottom appearances of joints formed by the (a) TFC process and (b) conventional clinching process

![Image of bottom appearances of joints]
4.2 Tensile-shearing test

Five sets of tensile-shearing tests were performed to obtain the average joint strength of each type of the joint. The average tensile-shear strengths of the conventional and TFC clinched joints under different forming forces are displayed in Fig. 11. The tensile-shear strengths of the TFC clinched joints are all greater than those of the conventional clinched joints under different forming forces. The tensile-shearing strengths of TFC joints are highest when the forming force is 30 kN. The tensile-shear strengths of conventional clinched joints remain essentially constant under different forming forces. The TFC process can improve the tensile-shear strengths of the joint, and the improvement effect is the best at the forming force of 30 kN.

The force-displacement graphs of different joints under diverse forming forces are displayed in Fig. 12. The tensile-shearing load curves of clinched joints with various forming forces are marked by short dotted lines of different colors. The straight lines of different colors represent the tensile-shearing load curve of the TFC clinched joints with various forming forces. All the TFC clinched joints have greater strength than conventional clinched joints. The strengths of the conventional clinched joints are hardly affected by forming force. The tensile-shear strength of the TFC clinched joint is highest at a forming force of 30 kN, which is 412 N greater than the conventional clinched joint. The static strength of the conventional joint can be improved by the TFC process. This is because the ductility of Al1060 sheet materials is relatively good. The material of the protuberance flows to the neck while the protuberance of the joint is pressed back, which increases the thickness of the joint and improves its strength.

Impact resistance is one of the important factors for assessing structural stability. Impact resistance is especially important in automobiles that are subjected to frequent shocks. Energy absorption is an important factor in assessing impact resistance. The more energy absorbed by the clinched joint before failure, the better its impact resistance [32, 33].

The energy absorption of different clinched joints under different forming forces was studied to assess the energy absorption capacity of clinched joints. Energy absorption of joints can be determined by measuring the area between horizontal coordinates and tensile-shearing load displacement curve (see Fig. 13). As depicted in Fig. 14, energy absorption of all TFC clinched joints is greater than that of the conventional clinched joints. When the forming force is 30 kN, the energy absorption of TFC clinched joints reaches the maximum, which is an increase of 82% compared to conventional clinched joints. The energy absorption is improved by the TFC process.
4.3 Failure mode

There are two main categories of clinched joint failure modes, one is button separation mode and the other is neck fracture mode [34, 35]. The interlock and the neck thickness of the joint are the decisive factors that determine the failure modes. The tensile-shearing test is to assess the ability of clinched joints to bear the lateral static load. Both the interlock and the neck thickness bear the lateral load. When the neck bearing capacity is greater than that of the interlock, the button separation failure mode occurs, and conversely, the neck fracture failure mode occurs.

In the tensile-shearing test, the main failure modes of all clinched joints are the neck fracture mode. The load is applied primarily to the neck of the upper sheet in the test, which makes the neck of joints bear most of the shear force. After the strength of the neck exceeds the yield strength of the upper sheet materials, a crack appears in the joint neck, and the crack gradually expands, making the neck completely fracture. As illustrated in Fig. 15, the process of neck fracture of conventional and TFC clinched joints is essentially the same.

As shown in Fig. 16, the neck fractures tend to occur in the area of minimal neck thickness. The neck is subjected to the opposite shearing force applied by the upper sheet and the lower sheet. The shearing stress and shearing forces are positively correlated because the area of the neck is constant and the shearing force is increasing [36]. The basic tensile-shear strength prediction model $F_s$ is calculated by Eq. (1):

$$ F_s = \tau_f \cdot A_N = \pi \cdot \left( 2R_p t_n + t_n \cdot t_n \right) \cdot \tau_f \quad (1) $$

where $\tau_f$ is the neck shearing stress of the clinched joint, $A_N$ is the cross-sectional area of the neck, and $R_p$ and $t_n$ are the radius of the punch and neck thickness. The model indicates that the tensile-shear strength of the joint is dictated by the sheet materials and neck thickness. The static strengths of the joints can be improved by increased neck thickness with the TFC process.

The TFC process does not change the failure modes of clinched joints. The failure modes of conventional and TFC clinched joints are both neck fracture. The TFC process can improve the strength of joints by increasing neck thickness.

5 Discussion

5.1 Analysis of the variation of joint parameters

The important parameters of the joint are affected by the material flow. Under different process parameters, the material flow of the sheets is different. As illustrated in Fig. 8, there are significant differences in material flow between the conventional clenching process and the TFC process. A higher protrusion is formed as the sheet material flows into the cavity of the bottom die in the conventional clenching process. The materials of protrusion flow into the neck to increase the neck thickness and interlock in the TFC process. Both the interlock and the neck thickness are increased since the TFC process improves the material flows of the sheets. Furthermore, as shown in Fig. 9, the protuberance of the joint created by the TFC process is almost flat, and the height of the protuberance is only 0.34 mm, which is more than 5 times lower than the height of the conventional clinched joint.

The parameters of different joints are shown in Fig. 10. The neck thickness and interlock of the TFC clinched joint are significantly increased compared to conventional clinched joints. The parameter values of the neck thicknesses and the
interlocks of TFC clinched joints reach the maximum at the forming force at 30 kN. The neck thickness of conventional clinched joints increases slowly with the increment of the forming force. The interlock value of the conventional clinched joints reaches the maximum when the forming force is 30 kN. The interlock and the neck thickness are improved since the better materials flow in the TFC process. The protuberance height of the joint was flattened by the bottom anvil. The materials of the protuberance flow upward and squeeze toward the center, thereby increasing the size of the interlock and the neck thickness of the joint. The materials flow to the center, which greatly increases the neck thickness and greatly reduces the height of the protuberance.

5.2 Analysis of the mechanical performance of joints

The tensile-shearing test results of different joints show that the strength of the TFC joints is greater than that of conventional joints. The material of protrusion flows into the neck area to increase the interlock and neck thickness of the joint in the TFC process. However, the material of sheets flows to the cavity of the die and forms a protrusion in the conventional clinching process. The TFC joint has better mechanical performance than conventional joint since it has larger interlock and neck thickness.

The value of energy absorption is determined by the force-displacement curves of joint. TFC joints have greater strength and displacement before failure compared to conventional compression joints, which is the reason for the greater energy absorption of TFC joints than conventional clinched joints. As illustrated in Fig. 14, the energy absorption of TFC joint decreases when the forming force is 35 kN, which may cause the sheet material to crack and fracture prematurely due to excessive forming force.

5.3 Analysis of failure mechanism

The fractures of the TFC joint and the conventional joint were studied by a TESCAN MIRA3 LMU SEM to analyze failure mechanisms. The SEM results of the TFC clinched joint are shown in Fig. 17. There are more U-shaped cavities in the same direction at all three areas, which indicate that the joint underwent plastic deformation before fracture. In area 1, the U-shaped cavities are dense with a small number of micropore and the particles of second phase. Furthermore, the ductile fracture of area 1 resulted from microporous

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Fig. 15 The failure mode of the clinched joints: (a) conventional clinched joint, (b) TFC clinched joint

Fig. 16 The tensile-shear strength prediction mode: (a) sectional view of the TFC joint, (b) sectional view of fracture of the upper sheet
polymerization shear. The U-shaped cavities in area 2 and area 3 become deeper and larger, which means that more energy needs to be absorbed before their fracture occurs. The TFC joint is first cracked in area 1, then diffuses through in area 2 and totally fracture in area 3.

The SEM results of the conventional clinched joint are shown in Fig. 18. All three areas are dimple fractures. The size and density of the U-shaped cavity in the three areas are essentially the same, but the depth of the dimples in area 3 is deeper than that in area 1 and area 2, which means that area 3 needs to absorb more energy before fracture. Furthermore, the fracture path of the conventional joints is the same as that of TFC joints. Crack appears in area 1, then spreads through area 2, and fractures in area 3.

The SEM results at the neck of the TFC and conventional joints are shown in Fig. 19. There is a tendency for upward flow at the neck materials of the TFC joint. There are many vertical, deep streaks on the surface of the neck of the TFC joint, which are caused by the reverse stroke during the TFC process. The material flow is downward at the neck of the conventional joint. The microcosmic profile in the neck of the conventional joint has fewer vertical, deep streaks.

6 Conclusion

The TFC method was introduced to improve the neck thickness and flatten the protuberance of the joint in the present work. The Al1060 sheet materials were adopted in the clinching process. A punch, double flap gaskets, bottom ring, anvil, and flat die were employed in the TFC process. The energy absorption, neck thickness, and tensile-shear strength of TFC joints were improved than conventional clinched joints. The main findings of this study are as follows:

1. The tensile-shear strength of the joints can be improved by the TFC process. The average tension-shear strength of the joints is improved from 1129 to 1471 N at the forming force of 30 kN.
2. The protuberances of the joints are flattened by the TFC process. A part of materials of the protuberance flows to the neck, increasing the interlock and the neck thickness of the joint. The neck thickness of the TFC clinched joints is 79% more than that of the conventional clinched joints when the forming force is 30 kN. Furthermore, the interlock of TFC clinched joints is 45.9% more than that of conventional clinched joints at the forming force of 30 kN.
3. The failure mode of all clinched joints is neck fracture in the tensile-shearing tests. The TFC process does not change the failure modes of clinched joints. The fracture path of the conventional joints is the same as that of the TFC joints.
4. The energy absorption ability of TFC clinched joints has better performance than conventional clinched joints. Energy absorption of TFC clinched joints reaches highest at forming force of 30 kN under the tensile-shearing test.
Availability of data and materials  The raw/processed data required to reproduce these findings cannot be shared at this time due to technical or time limitations.

Authors’ contribution  Chao Chen, Hao Peng, and Haijun Li analyzed the data; Chao Chen, Xiaolei Gao, and Haijun Li contributed reagents/materials/analysis tools; and Chao Chen and Hao Peng wrote the paper.

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Declarations

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