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

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Research Article

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Abstract

Clinching technologies have 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 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 were 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.

1. Introduction

Lightweight materials such as magnesium alloys, aluminum alloys, titanium alloys, etc. are widely adopted in manufacturing industries. These lightweight materials have almost replaced the use of steel in car bodies [1–4]. The connection methods of these materials have been studied by many researchers. Clinching technologies is a joining method which can join the sheet materials without any auxiliary part. It was introduced by the German patent issued in 1897. At that time, the development of the clinching technology was limited by the widespread use of steel sheets. Clinching technologies was firstly widely used in the manufacturing industries in 1980s because the lightweight alloys were widely adopted in manufacturing. Clinching technologies was used at Audi Company in 1985 [5]. Subsequently, more and more manufacturer used clinching technology to join body sheet materials. Recently, clinching technology was widely employed to join parts of the car body [6–8].

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 [9]. 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. [10] designed tools of the clinching process for joining the Al6063 alloy sheet materials to refine the quality of clinched joints. He et al. [11, 12] investigated the clinched joint strength and energy absorption with extensible dies by numerical and experimental method. The authors found that the strength and elongation rate of the joints can be increased by the adhesive layer. Lambiase et al. [13, 14] studied the effects of parameters of clinching process on the joint strength, and optimize 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 joint neck can be improved by the larger punch and die, smoother corner radius and shallow dies.

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. [9] 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 anvil), which was proposed by Chen et al. [15, 16]. The neck thickness and the interlock of joints can be refined by this process since the materials of the protuberance flows to the around the neck. Moreover, Chen et al. [17–21] also proposed methods of reshaping joints with and without a rivet. The heave of joints was reduced, and the strength of 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 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 joint. Al1060 sheet materials were used for experimental test. The influence of forming forces on 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 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 were employed in TFC process include a punch, double flap gaskets, bottom ring, flat die and anvil. As shown in Fig. 1, the anvil 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, 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_s), which are generally determined by the parameters of the extensile 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.

Table 1 The principal mechanical properties of the Al1060 sheet materials

Mechanical properties	Yield strength (MPa)	Young's modulus (GPa)	Poisson's ratio
Al1060	117.9	54.5	0.33

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 [22, 13, 23]. 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 valued 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 TFC process are shown in Fig. 5. The punch, double flap gaskets, bottom ring and fixed anvil constitute the TFC tools. The double flap gaskets are obtained by cutting off two halves of a ring. The bottom ring can move down and up along the fixed anvil. 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 CMT-5105GJ machine is configured to ‘controllable force’. As conventional clinching process, the different punch forces are set to 25 kN, 30 kN and 35 kN. The joint extrudes 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 clinched joint is gradually flattened by the fixed anvil. The geometric dimensions of the FTC 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.

3.2 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 CMT-5105GJ tester. The velocity of 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 test 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 tension-shear 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 article.

4 Results And Discussion

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 [24, 25]. 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 parameters 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 material flow of the clinched joints is improved by TFC process. The interlock and the neck thickness are all improved by the TFC process. The bottom appearances of different clinched joints created with diverse forming force are displayed 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 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 conventional clinching process and TFC process with different forming force 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. The neck thicknessess and interlock of the TFC clinched joint are significantly increased compared to conventional clinched joints. The parameter value 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 TFC process. The protuberance height of the joint was flattened by the bottom anvil. The materials of the protuberance flow upwards 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.

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 TFC clinched joints are all greater than that of 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 shearing 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 force 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 force. 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 TFC clinched joint is highest at a forming force of 30 kN, which is 412 N greater than 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.

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 [26, 27]. 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 bear the lateral load. When the neck bearing capacity is greater than that of 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 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. 13, the process of neck fracture of conventional and TFC clinched joint is essentially the same.

As shown in Fig. 14, 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 [28]. The basic tensile-shear strength prediction model F_s is calculated by Eq. (1):

$$F_s = \tau_f \cdot A_N = \pi \cdot (2R_p t_n + t_n \cdot t_n) \cdot \tau_f \qquad (1)$$

Where τ_f is the neck shearing stress of clinched joint. A_N is cross-sectional area of the neck, 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 TFC process.

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

4.4 Energy absorption

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. More energy absorbed by clinched joint before failure, the better its impact resistance [29, 30].

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. 15). As depicted in Fig. 16, energy absorption of all TFC clinched joints is greater than that of 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.

5 Conclusion

The TFC method was introduced to improve the neck thickness and flatten the protuberance of the joint in 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 TFC process. The energy absorption, neck thickness and tensile-shear strength of TFC joints were improved than conventional clinched joint. 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-shearing 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 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 joint is 45.9% more than that of conventional clinched joint 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.

(4) The energy absorption ability of TFC clinched joints has better performance than conventional clinched joints. Energy absorption of TFC clinched joint reach highest at forming force of 30 kN under the tensile-shearing test.

Declarations

Ethical Approval

Compliance with ethical standards.

Consent to Participate

All authors agreed with the consent to participate.

Consent to Publish

All authors have read and agreed to the published version of the manuscript.

Authors Contributions

Chao Chen conceived and designed the experiments; Chao Chen performed the experiments; Yawen Ouyang and Denglin Qin analyzed the data; Chao Chen and Denglin Qin contributed reagents/materials/analysis tools; Chao Chen and Yawen Ouyang wrote the paper.

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Competing Interests

The authors declare that they have no competing interest.

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

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Figures

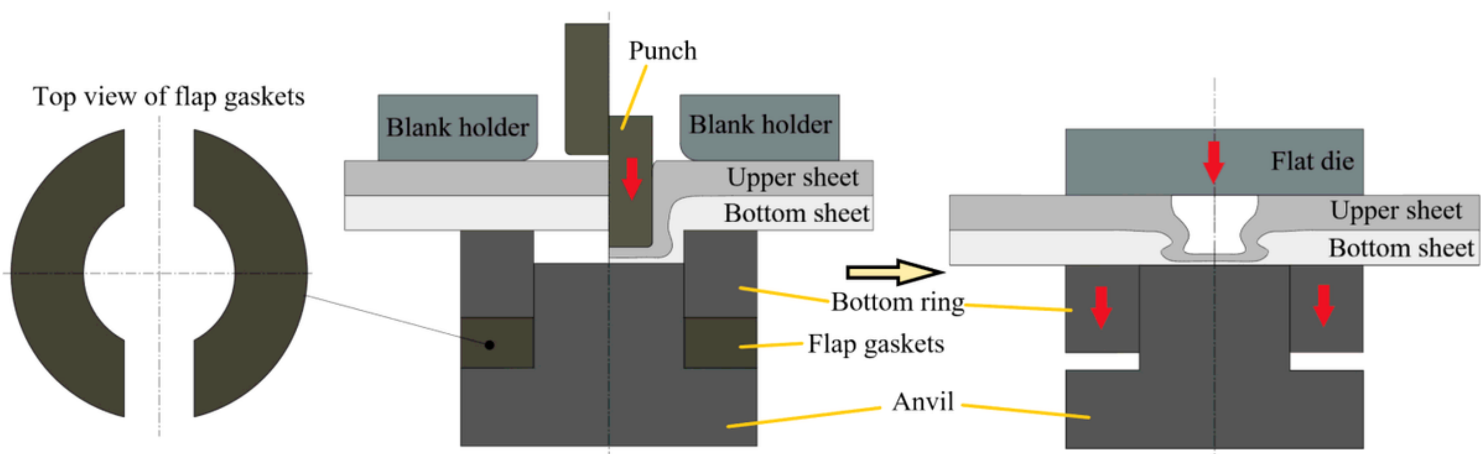

Figure 1

The schematic of the TFC process

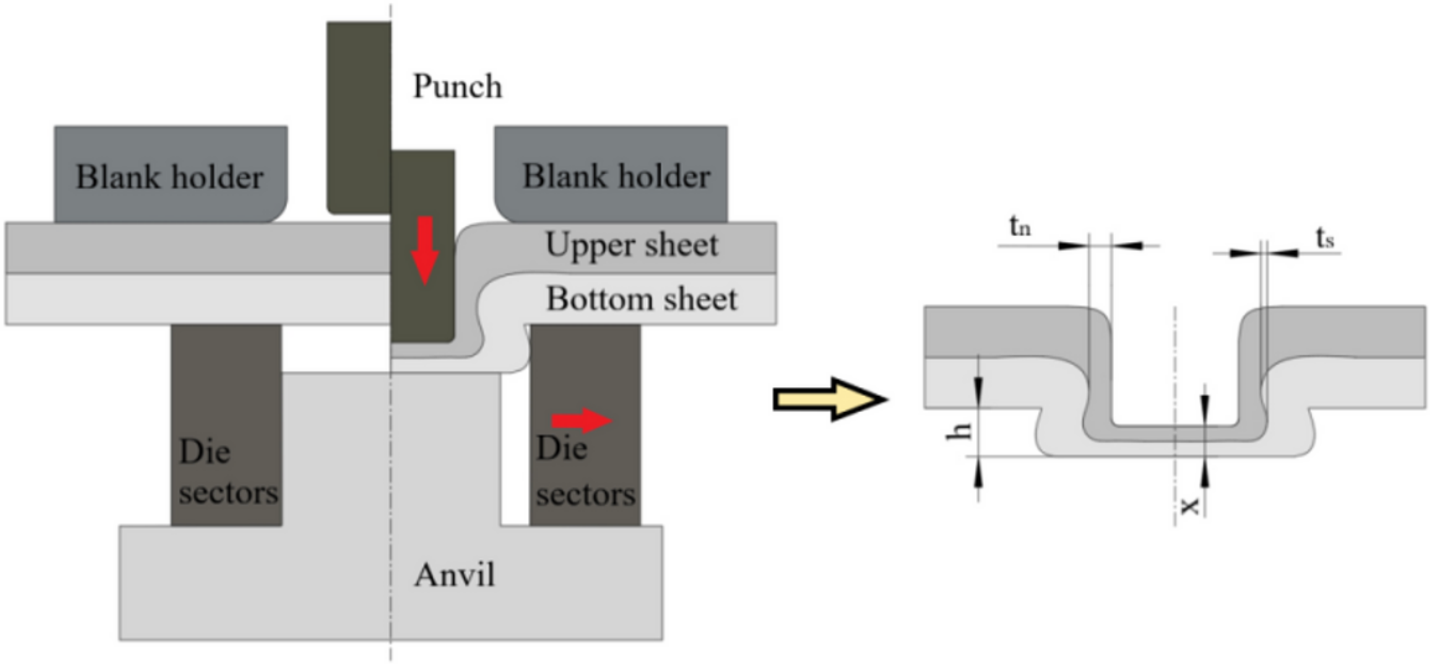

Figure 2

Mechanism of conventional clinching process

Figure 3

The extensible dies of the conventional clinching process

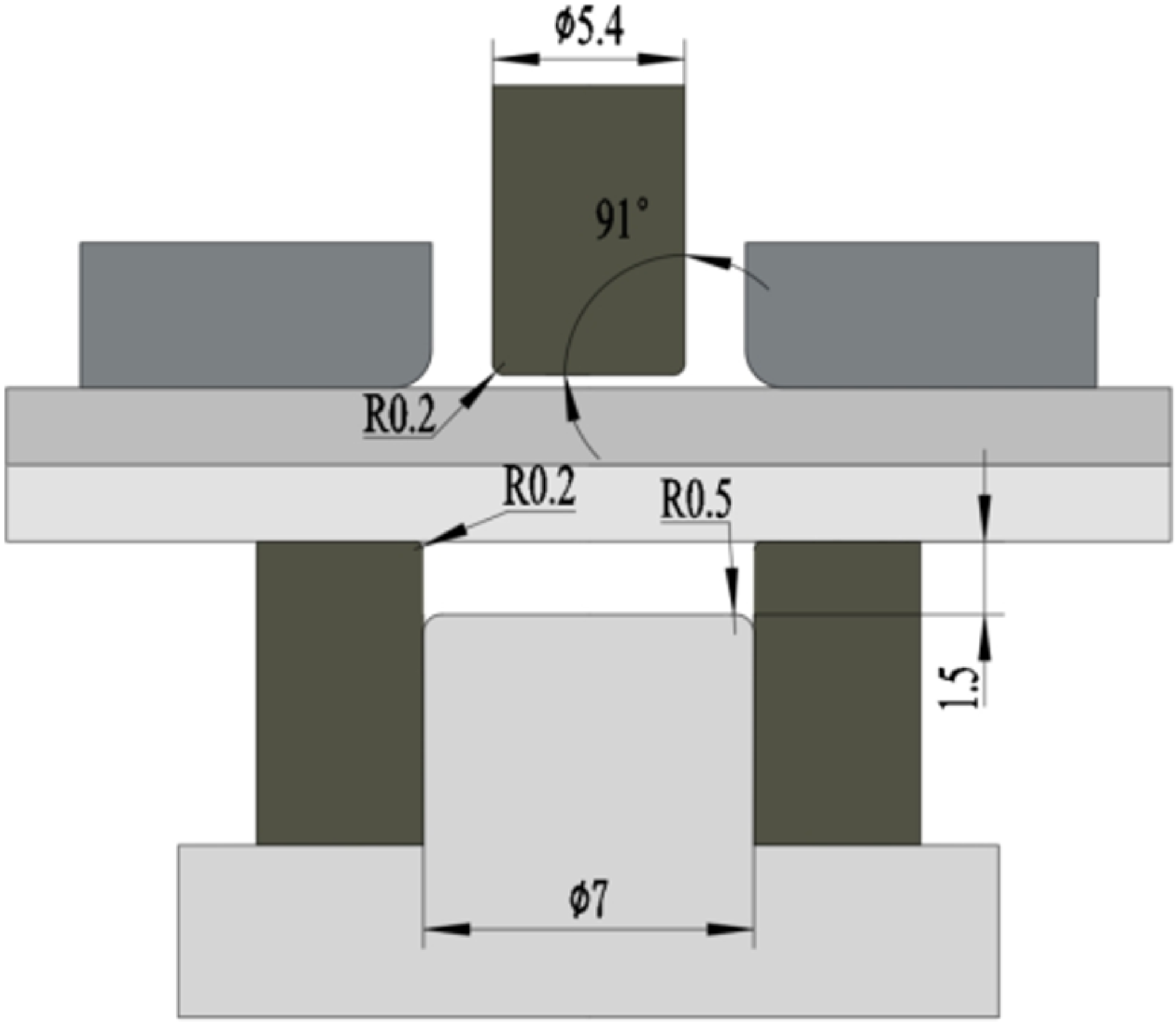

Figure 4

The main geometric dimensions of the extensible dies

Figure 5

The tools of TFC process

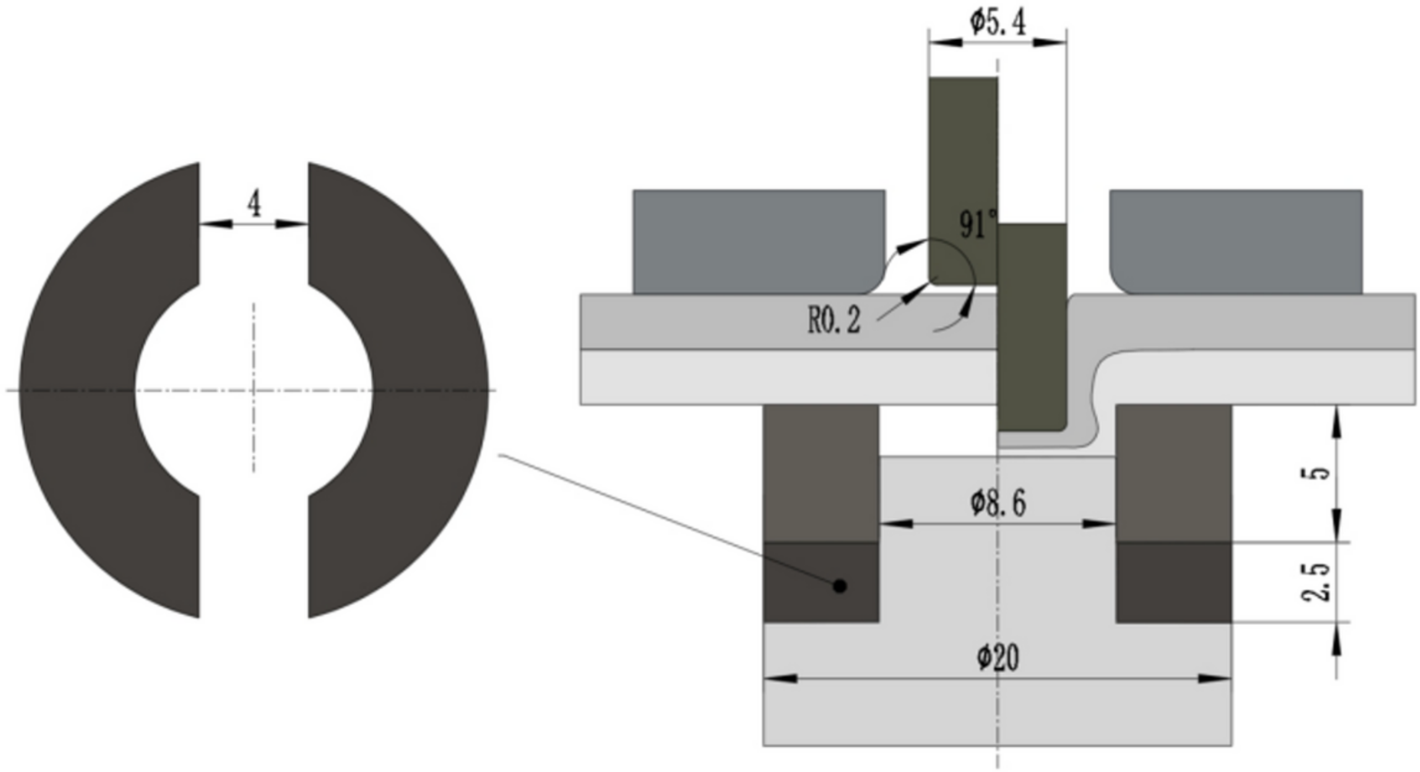

Figure 6

The geometric dimensions of the FTC tools

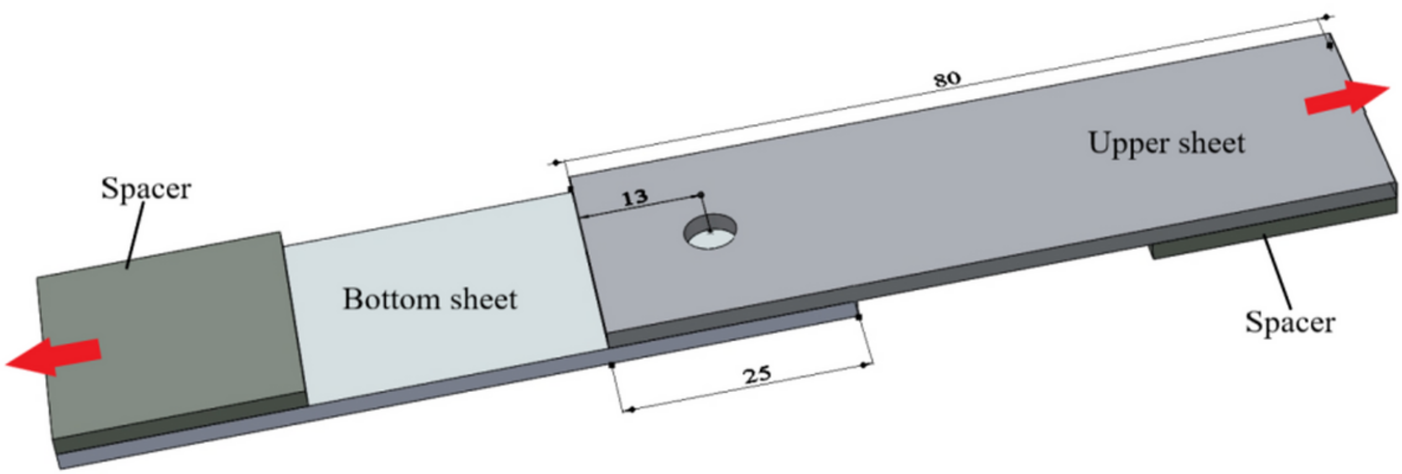

Figure 7

The specimens used in the tensile-shearing test

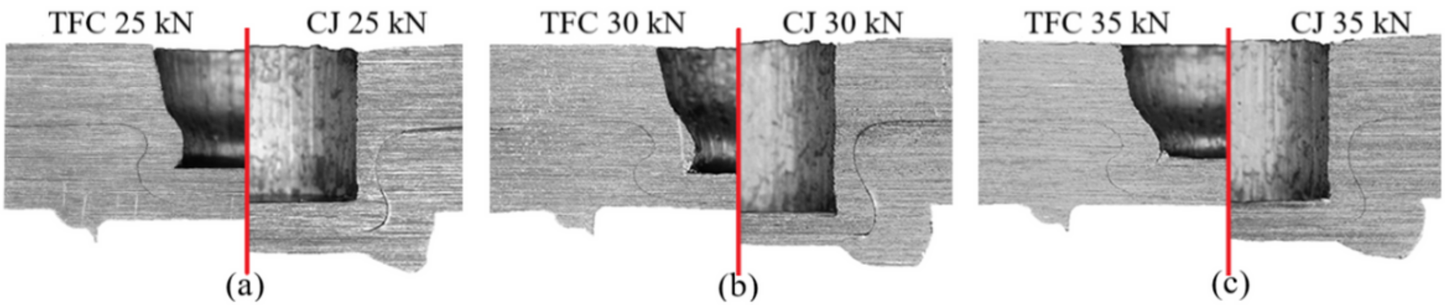

Figure 8

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

Figure 9

Bottom appearances of joints formed by (a) TFC process, (b) Conventional clinching process

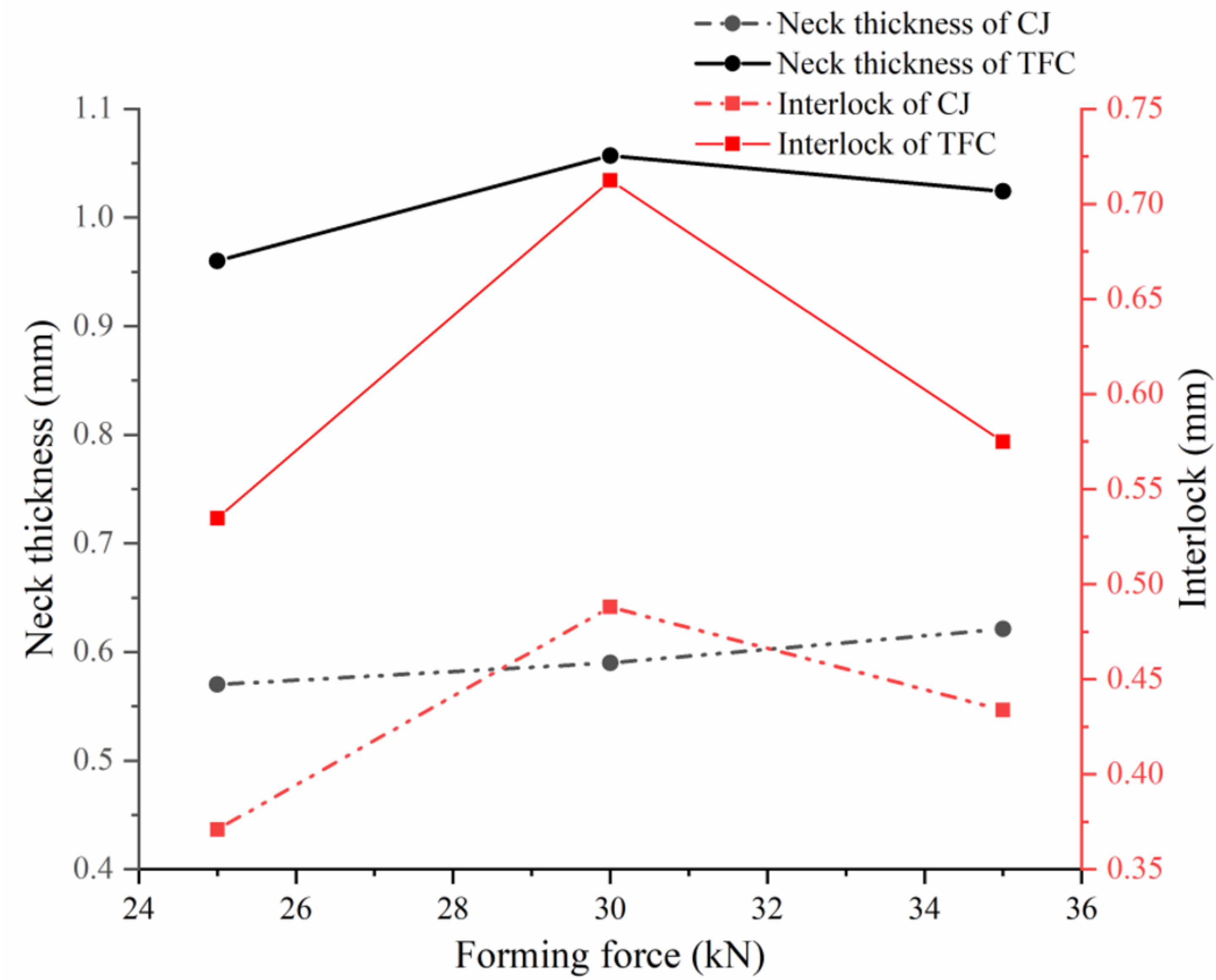

Figure 10

The neck thickness and the interlock of the clinched joint

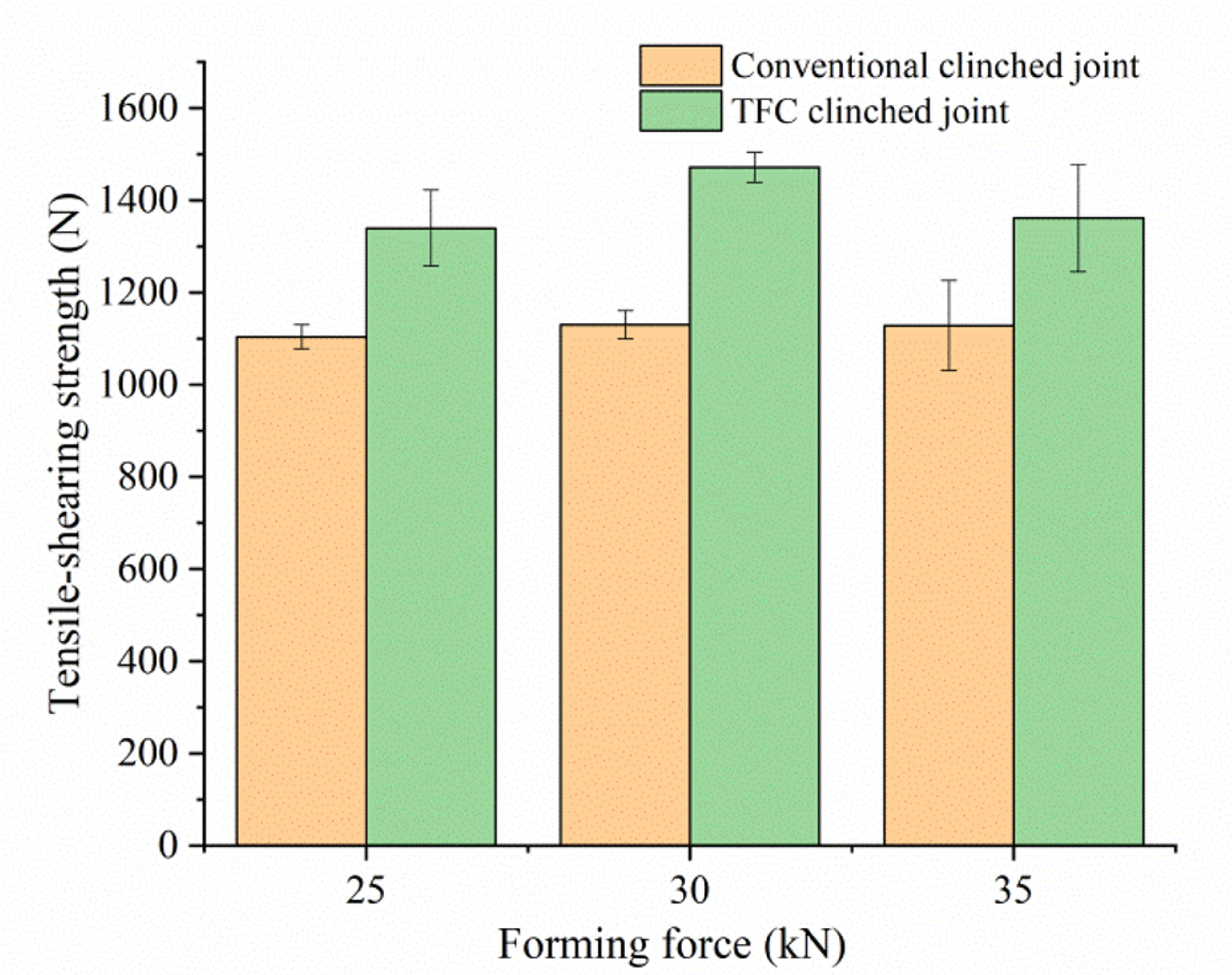

Figure 11

The tensile-shear strengths of joint with different forming force

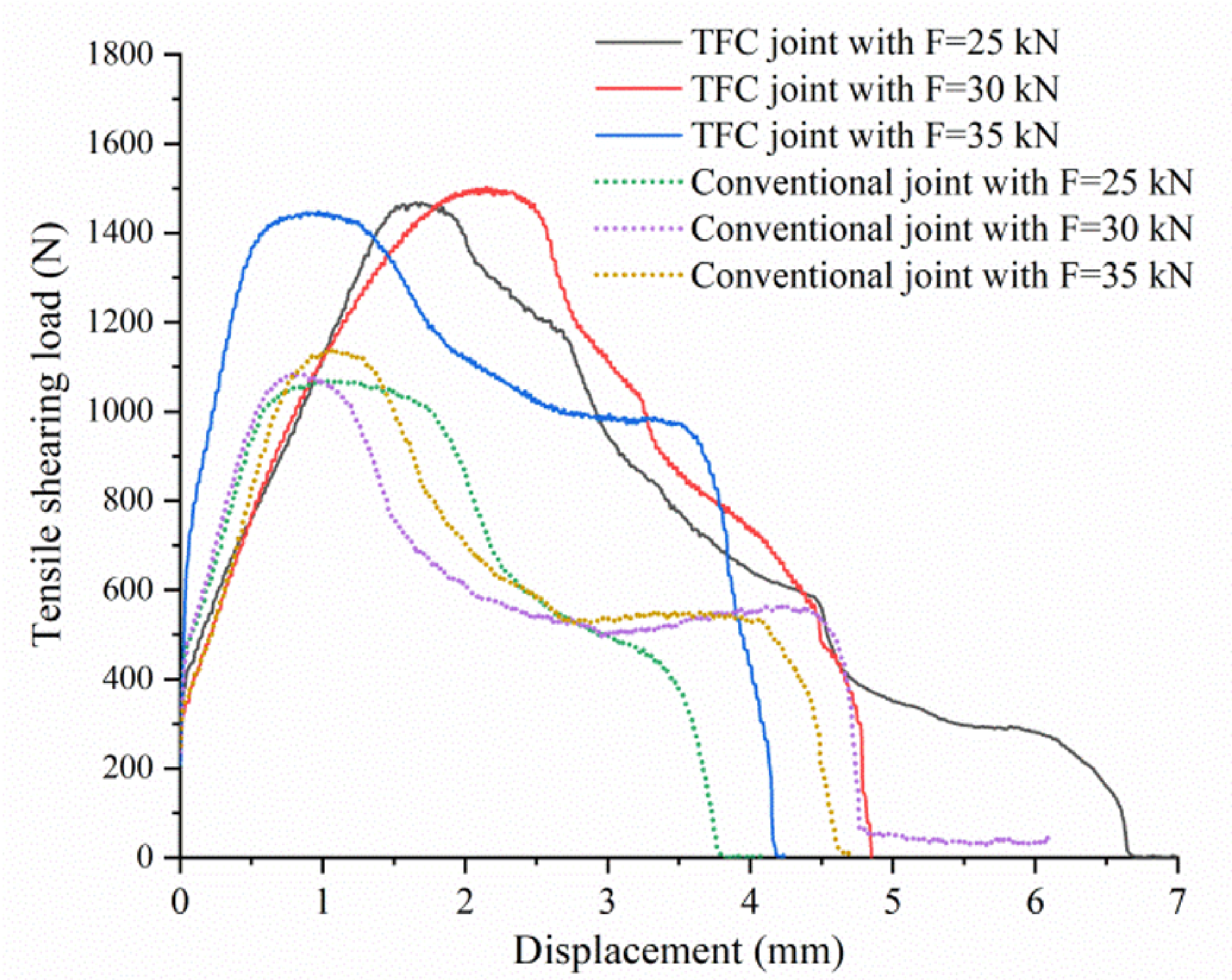

Figure 12

The tensile shearing load-displacement curves of different joints with different forming force

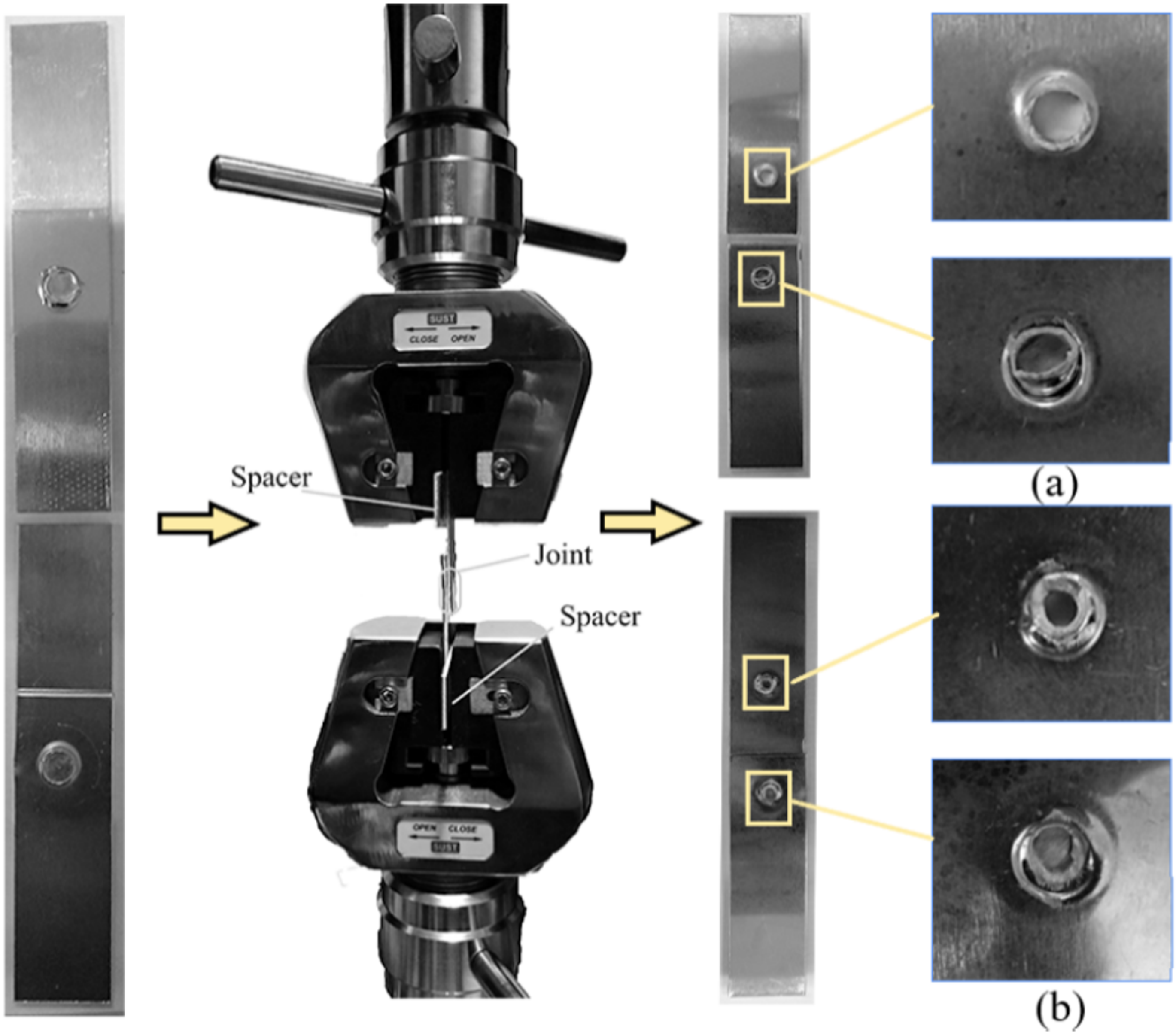

Figure 13

The failure mode of clinched joint (a) conventional clinched joint (b) TFC clinched joint

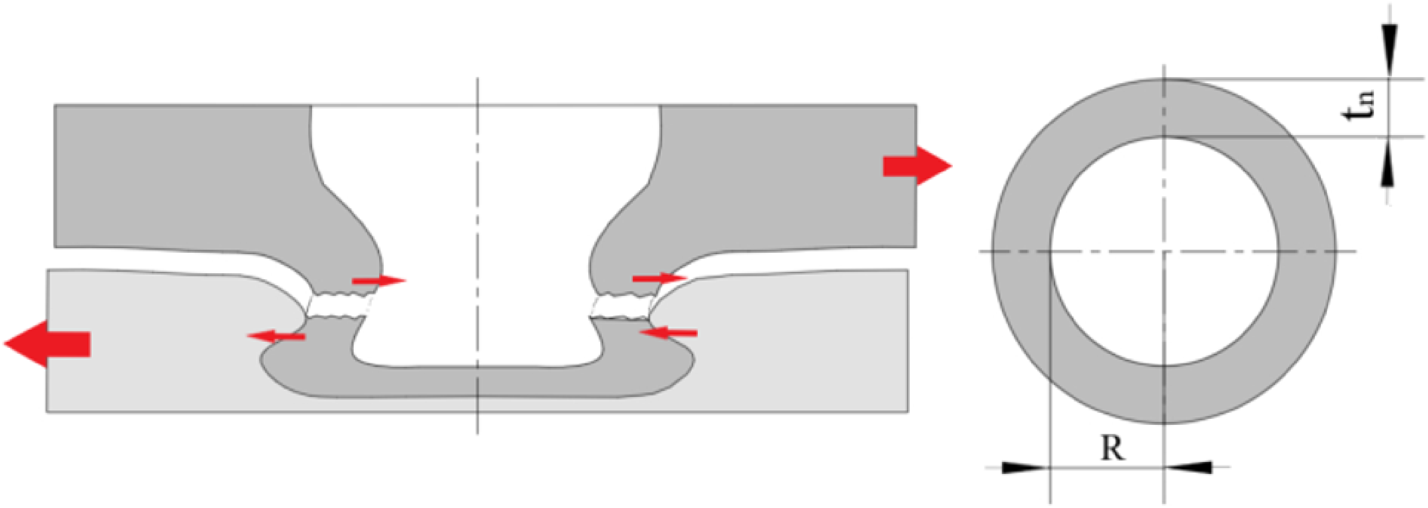

Figure 14

The tensile-shear strength prediction mode

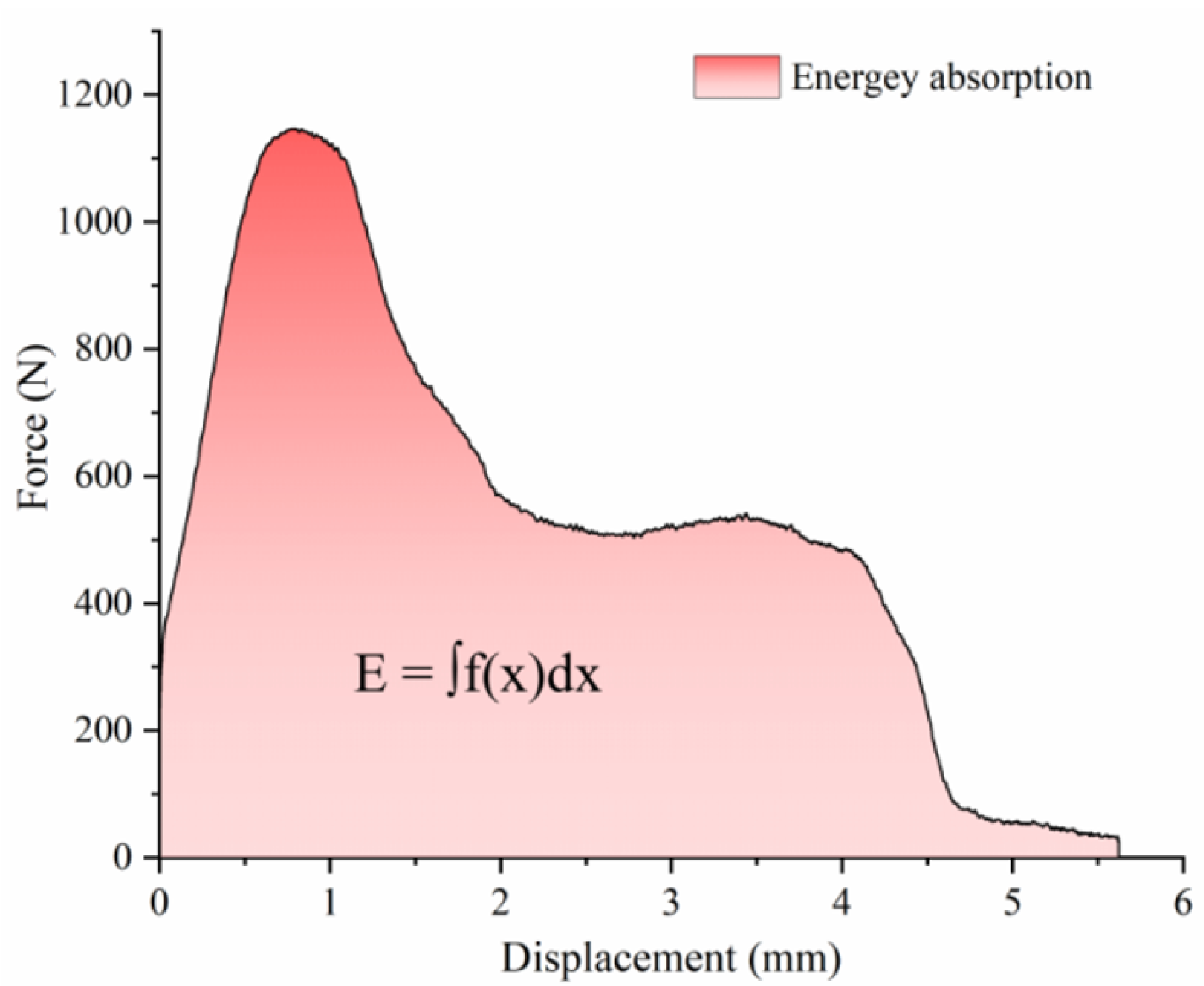

Figure 15

The energy absorption of tensile shearing test

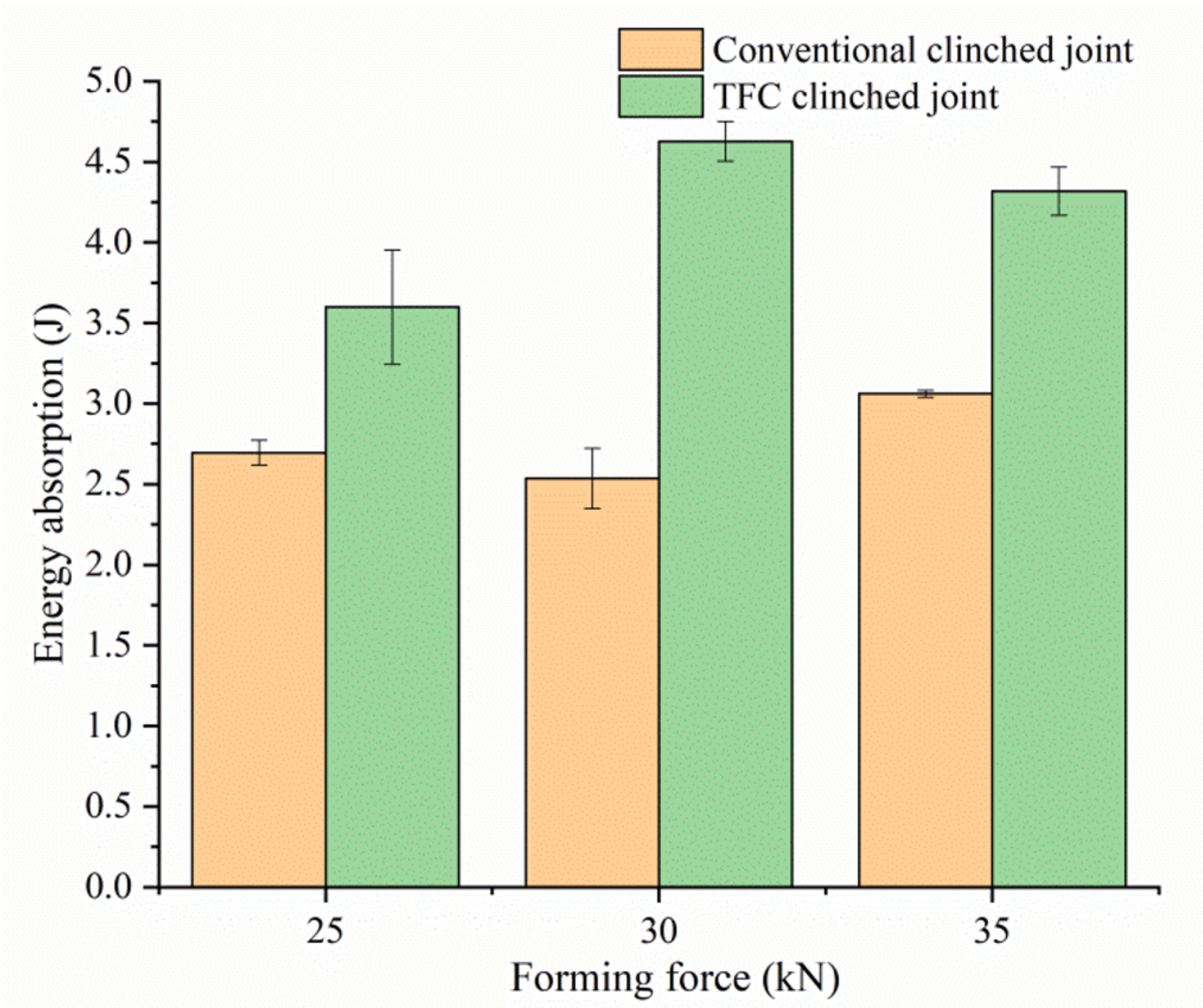

Figure 16

The energy absorption of different joints under different forming forces