Kovove Mater. 52 2014 65–70
DOI: 10.4149/km_2014_1_65

Research on reliability of punch bonding technology with steel-aluminum sheet metals

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Received 29 May 2012, received in revised form 25 September 2013, accepted 25 September 2013

Abstract

In order to reveal the influence of technological parameters in the punch bonding process with dissimilar sheet metals, using experimental methods in this article, laws of the influence of technological parameters on the connection in quality and reliability are analyzed systematically. The results show that the connection thickness decreases when punching load increases. When punching load increases to 28 kN, the maximum shearing load immediately presents decreasing trend after arriving at the peak, and the defects of the shearing tests change into the ring groove cracking from the bottom one. Along with increasing of X_1 and X_2, the thicknesses of the joint parts all tend to reduce, and connection strength reaches the maximum when X_2 is 1.0 mm. The technology experiment of punching bonding is performed and the results show that when the steel sheet is located at the punch side, it is easy to form an "S" type interlocking structure, whose ultimate shearing load value is about seven times larger than that of the aluminum sheet. The above results provide theoretical basis for the process development of punch bonding technology with dissimilar sheet metals and the die design.

Key words: dissimilar sheet metals, punch bonding, law of figuration, die design

1. Introduction

The connection of dissimilar sheet metals is one of the effective ways to achieve the lightweight structures in motorcar, mechanical manufacture and other areas [1, 2]. But the difference of materials properties brings some trouble to develop the connection technique [3, 4]. Taking the connection of steel and aluminum alloy as an example, the spot welding makes connecting multilayer sheets more difficult, because the large discrepancy of melting point between them makes it hot when it forms and destroys the surface coating with thermal deformation. The spot welding is helpless to dissimilar sheet metals connecting [5]. Although riveting can overcome some drawbacks of spot welding, the technique is more complicated and the equipments are more expensive [6, 7]. The screwed connection can be used for dissimilar sheet metal connection, but the joint is not so reliable and easily becomes loose [8]. Laser welding costs too much comparatively, furthermore, it is not applicable to the connecting of multilayer sheets.

In view of the above problems, emerge as the times require the punch bonding technology. Compared with the traditional connection technique, punch bonding can connect sheet metals with the same or different materials, of two or more layers and of the same or different thicknesses. Therefore this technique received adoption spreading rapidly. At present, reports about the design of punch bonding mould structure or shaping law are seldom. This essay systematically analyzes an influence law of technological parameters concerning quality and property by research on punch bonding process of the carbon steel and the rust-proof aluminum sheets.

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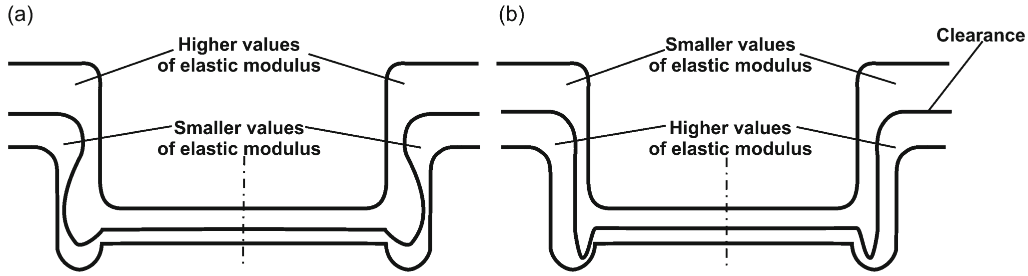


Fig. 1a, b. Analysis of punch bonding with dissimilar sheet metals.

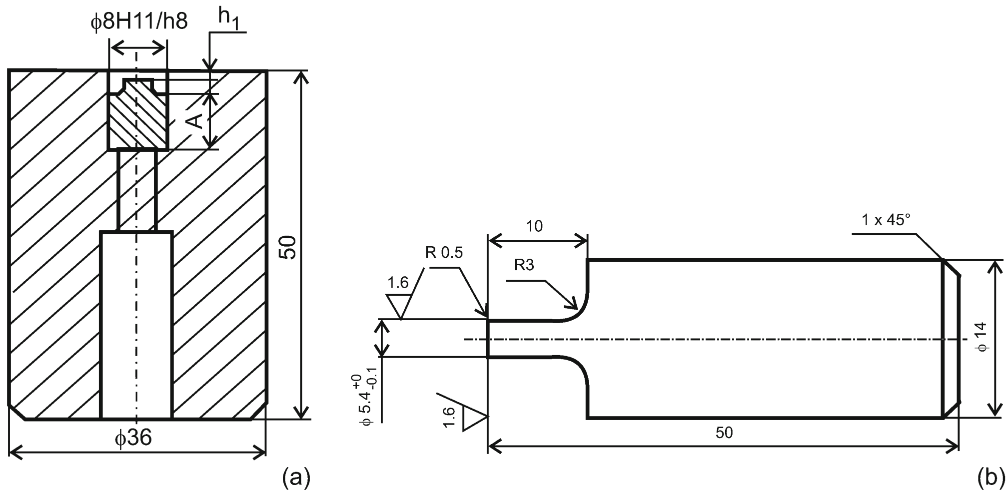


Fig. 2. Design of the combined die (units: mm): (a) female die, (b) punch.

2. Research procedure

2.1. Feasibility analysis of connection

Except the technical factors, the mechanical properties of material also play an important part in whether or not realizing the connection process and joint strength in punch bonding with dissimilar sheet metals. Based on the theory of mechanics of materials, when materials with different elastic modulus or yield strength are loaded to produce plastic deformation and then unloaded, their elastic recovery patterns are of significant difference, which directly affects the reliability of the connection because of existing remarkable differences on elastic modulus and strength of dissimilar sheet metals. Therefore, different connection effects can be obtained by exchanging their position, as shown in Fig. 1.

According to Fig. 1, the stress-strain curve of material with higher elastic modulus and higher strength should be in the top position, as shown in Fig. 1a. When loaded to plastic deformation and then unloaded, the quantity of elastic recovery of sheet on female die side is significantly larger than that on punch side, since the strength of punch side sheet is higher and the quantity of deformation is larger, and the degree of hardenability is higher than that of female die side. Furthermore, the joint is easily formed as an "S" interlocking structure, which makes a good connecting effect. When the two sheets exchange their position, as shown in Fig. 1b, i.e., the sheet with larger elastic modulus and higher strength is on the female die side, the quantity of elastic recovery of female die side sheet is smaller than that of the punch side sheet. There exists clearance between the two sheets and the interlocking structure can not be formed. Therefore, it is incapable to realize the connection.

From the above, to obtain the ideal connection of dissimilar sheet metals, the material with higher elastic modulus and higher strength should be in the top position, and the material with smaller elastic modulus and lower strength should be in the lower one, which is an ideal pattern of accordance.

2.2. Die design

According to the literature, if the thickness of the sheets is in the area from 2.0 to 3.5 mm, in order to get ideal connection, the diameter of the connection dot can be chosen to 8 mm. The female die can be in group as shown in Fig. 2a. Different h_1 can be got by adjusting the A, which can meet the combination requirements of various thicknesses of sheets. An outside diameter and height of the female die can be designed

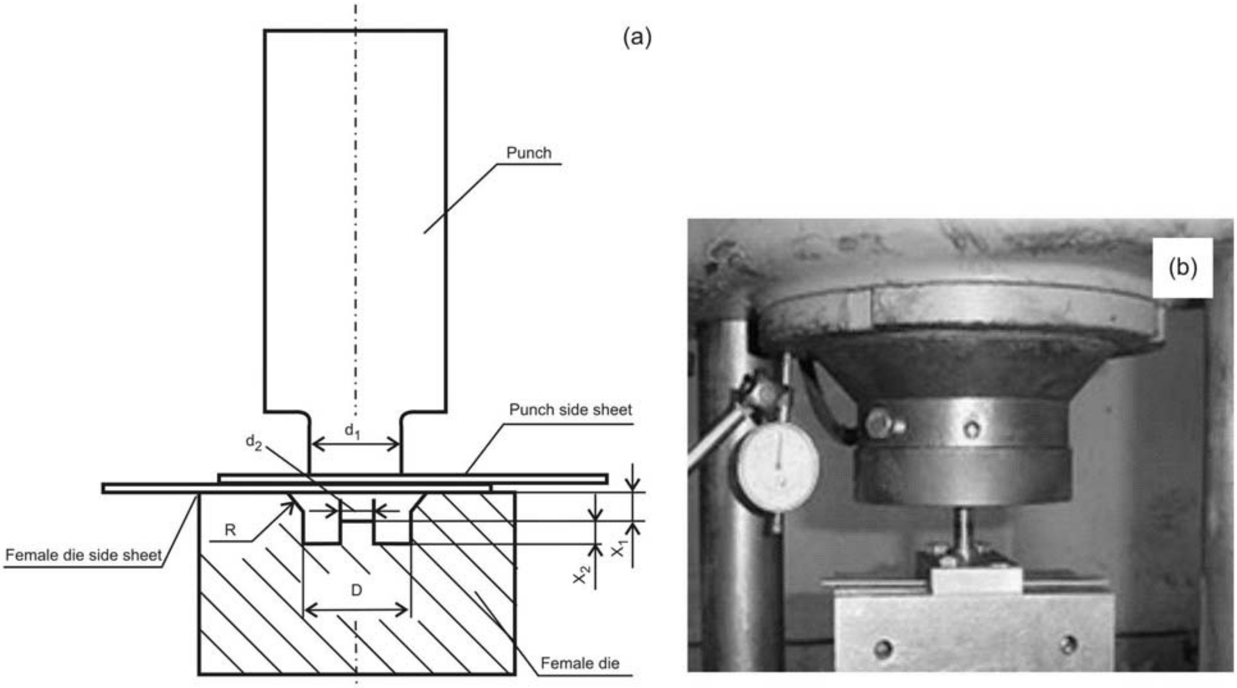


Fig. 3. Experimental equipment: (a) parameter setup, (b) photo of experimental equipment.

Table 1. Mechanical properties of materials

Material	Elastic modulus (GPa)	σ_s (MPa)	σ_b (MPa)	Elongation, δ (%)
Rust-proof aluminum	71	–	130	23
Carbon steel	238	210.84	419.01	56

according to the built-up moulds of the female die.

After determining diameter of female die, the unilateral space difference as well as the lateral interference (the thickness of composition board and the unilateral space of moulds) can be defined by the diameter of punch, lateral interference plays a role in whether there is enough material to produce plastic flow, and then mutually embedded in bonding process. Lateral interference is usually from 0.5 to 1 mm.

For convenience, the thickness of composition board in the experiment is 2.8 mm, so the diameter of punch is 5.4 mm, which can guarantee the quantity of lateral interference. The design of two punches with different diameters, the effect of lateral interference on the connection strength and size of the punch are shown in Fig. 2b.

2.3. Research procedure

The punch bonding experiments were carried out by universal testing machine with capacity of 60 kN, the accuracy of control was 0.5 kN. Figure 3 shows the key technological parameters and the experimental equipment. The displacement of punch was measured by dial indicator, the range of dial indicator is 6 mm and the precision is 0.01 mm.

Among them, the diameter of boss (d_2) is 4 mm, the thicknesses of punch side sheet (δ_1) and the female die side sheet (δ_2) are 1.4 mm, and the boss height (X_1), the distance from bottom of boss to upper surface of female die (X_2) are all important technological parameters in punch bonding process. For dissimilar sheet metals, the influence of technical parameters on the quality and properties of punch bonding was thoroughly analyzed by changing parameters. Rust-proof aluminum and carbon steel sheets are chosen to perform the punch bonding, and the mechanical properties of materials are shown in Table 1.

There are many factors affecting the quality and reliability of punch bonding with dissimilar sheet metals, and among them, X_1 and X_2 are important technical parameters of punch bonding structure, which determine the quality of connection by changing the parameters to be analyzed and then fixing other parameters. The influence of parameters X_1 and X_2 on the quality and reliability of punch bonding process was examined.

2.4. Forming load calculation

To realize the reliable connection, the fixed bonding load is necessary. Based on the formula of the punching load, the punching load is approximated by the theoretical calculation formula [9]:

$$P = kLt\tau, \quad (1)$$

where P is the punch force, L represents the edge length of the spot joint in punch bonding, t is the thickness of sheet, τ is the shear strength of material, which is usually 0.8 σ_b, and the consistency k is usually chosen of 1.3.

The minimum needed load of punch bonding process with the carbon steel sheet and the rust-proof aluminum sheet is calculated by Eq. (1): $P_{\min} = kLt\tau = 1.3 \times \pi \times 8 \times$ E0.8 $\times 1.4 \times (130 + 419.01) = 20.08$ kN. In the punch bonding process, the deformation of materials will result in work hardening, then strength of materials is rising sharply. The actual needed load should be higher than that calculated by Eq. (1), which is significantly influenced by the properties of material, so the actual load of connection should be in the area range from 25 kN to 30 kN.

2.5. Shearing load test

To compare and evaluate the quality and liability of punch bonding process with dissimilar sheet metals, the connection parts are located at INSTRON universal material testing machine to perform the tensile test, and the velocity is 2 mm min^{-1}.

3. Results and discussion

3.1. Influence of punching load on the connection thickness

Figure 4 shows the contrast influence of punching load on the connection thickness and maximum shearing load.

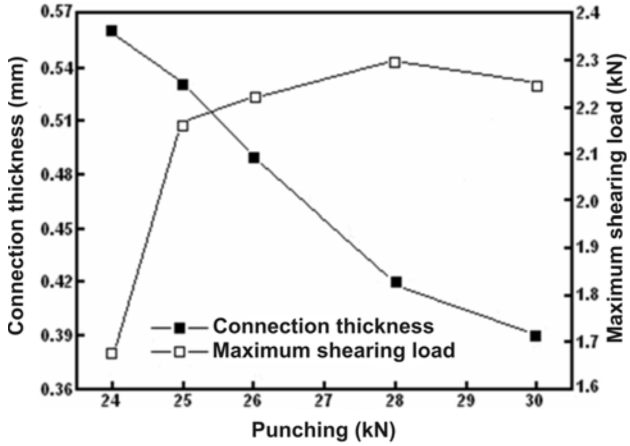
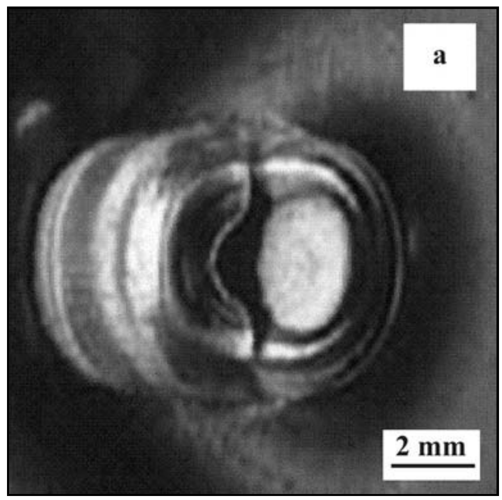


Fig. 4. The change of the connection thickness with different technological parameters.

It can be seen from Fig. 4 that when the punching load increases from 24 kN to 30 kN, the thickness of joints presents a quasi-linear decreasing trend, from 0.56 mm to 0.39 mm, which becomes thinner by 30.4 %. The reason is that with increasing of punching load, the flowing capability of sheet material below the punch increases significantly, and the sheet material beneath the punch flows to the direction of ring groove constantly, and then the joint becomes thinner constantly as well.



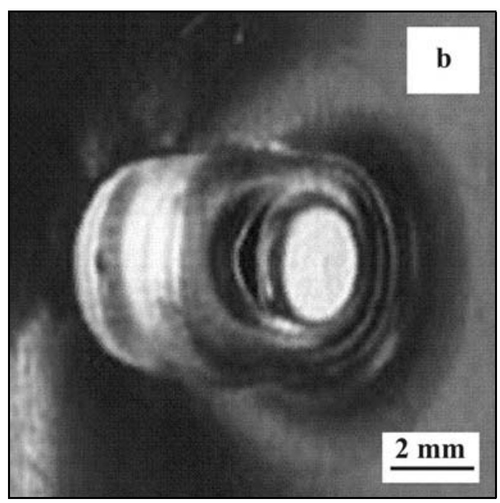


Fig. 5. Failure mode: (a) bottom cracking, (b) ring groove cracking.

With increasing punching load, the maximum shearing load presents an increasing trend, and then decreasing, when the punching load increases to 28 kN, the maximum shearing load reaches the peak. While the pressure is further rising, the maximum shearing load is reduced immediately. The reason is that

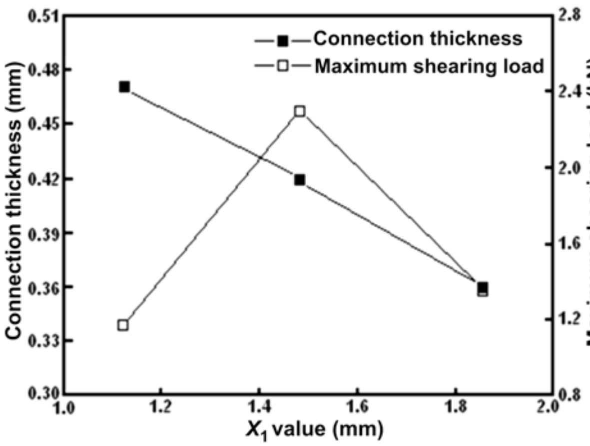


Fig. 6. Connection thickness changes with different parameters of X_1.

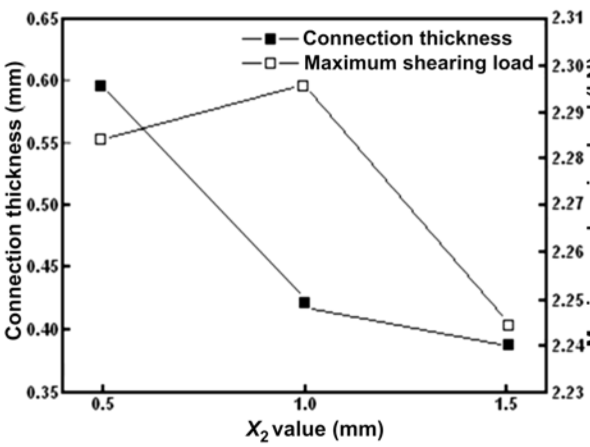


Fig. 7. Connection thickness changes with different parameters of X_2.

the thickness of the bonding zone (especially around the ring groove) becomes overly thinner with increasing the punching load, which reduces the connection strength.

Figure 5 shows the results of the tensile tests, which are carried out with the bonding sheets. As shown in Fig. 5a, while the punching load is 28 kN, the bottom of the joint cracks, but when the punching load increases to 28 kN, the ring groove of the joint cracks, as shown in Fig. 5b, and the value of thickness in the area is minimum.

3.2. Influence of X_1 value on connection thickness

While the punching load is 28 kN, X_2 is 1 mm, fixing other parameters, and parameter of X_1 is 1.12, 1.48, or 1.86 mm, respectively, the influences of different values of X_1 on the connection thickness and the maximum shearing load are compared, as shown in Fig. 6.

It can be seen from Fig. 6, when X_1 increases, the connection thickness decreases. But the connection thickness has the tendency to increase and then decrease. It is difficult to form a perfect interlocking structure, since when X_1 is small, the deformation amount of the punch side sheet is limited, therefore, the maximum shearing load is low, and even, it causes defects either of being disengaged easily or the connection is hardly being realized. However, it is easy to form a good interlocking structure with increasing of X_1, when the maximum shearing load reaches the peak. When X_1 is oversized, the connection strength decreases with the thickness of the joint excessively decreasing in value.

3.3. Influence of X_2 value on connection thickness

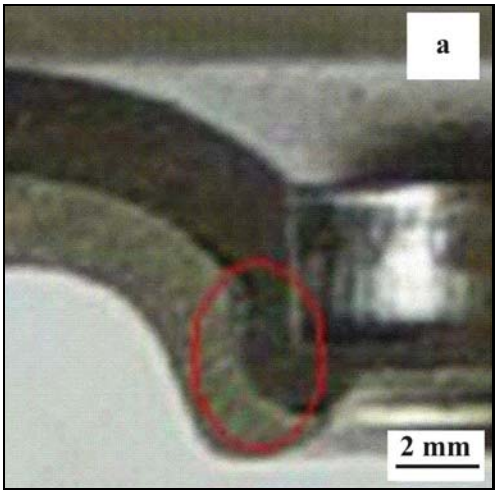
The parameter X_2 that represents the boss height is also one of important parameters, which affects the properties of the connection. While the punching load is 28 kN, X_1 is 1.48 mm, fixing other parameters, and parameter of X_2 is 0.5, 1.0, or 1.5 mm, respectively, the influences of different X_1 on the connection thickness and the maximum shearing load are compared, as shown in Fig. 7.

It can be seen from Fig. 7, with an increase of X_2, the values of the connection thickness decrease significantly. But the oversized X_2 is liable to cause the effusion of a lot of metal along the radial, which makes it difficult to fulfill the female die. When X_2 is too small, the size of the "S" type interlocking structure is also too small, which affects maximum shearing load. Therefore, with other parameters fixed, when X_2 is 10 mm, the connection strength is maximal.

3.4. Connection appearance analysis

In the process of punch bonding, the deposition of the sheet properties has great influence on the connection strength. To verify the results further, when the punching load is 27 kN, fixing other parameters and X_1 is 1.48 mm, X_2 is 1 mm, the tests on exchanging the position of the steel sheet and the aluminum sheet are performed, as shown in Fig. 8.

It can be seen from Fig. 8, when the steel sheet is located at the punch side, two sheets are connected before the formation of mosaic structure, forming an "S" type interlocking structure, which ensures the connection quality. But when the aluminum sheet is located at the punch side, the aluminum sheet can not embed in the steel side wall without forming interlocking structure, so the connection strength is lower. According to the comparison of different shearing load, with other parameters fixed, when the steel sheet is located



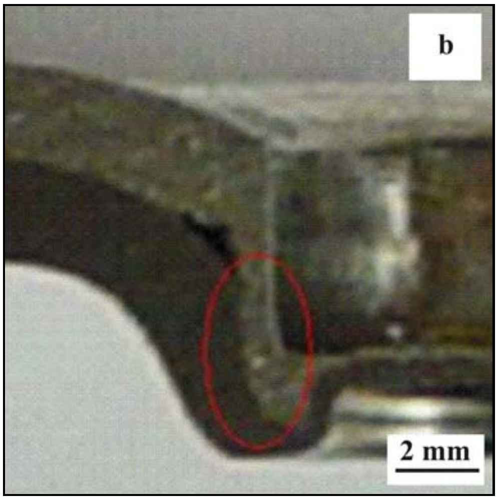


Fig. 8. Section appearances of joints: (a) steel sheet located at the punch side, (b) aluminum sheet located at the punch side.

at the punch side, the ultimate value of shearing load is 2.145 kN, which is about seven times higher than that when the aluminum sheet is located at the punch side.

4. Conclusions

1. With the increase of punching load, the connection thickness has the tendency to decrease. When the punching load increases to 28 kN, the maximum shearing load will decrease after reaching the peak; it can be seen from the shearing test, the defects turn into the ring groove cracking from the bottom one.

2. With the increase of X_1, the connection thickness has the tendency to decrease. But the maximum shearing load presents increasing trend and then decreasing. With other parameters fixed, when X_2 is 1.0 mm, the connection strength is maximal.

3. It can be seen from the comparison of the experimental results, when the steel sheet is located at the punch side, it is easy to form an "S" type interlocking structure, whose ultimate shearing load is about seven times higher than that when the aluminum sheet is located at the punch side.

Acknowledgements

This paper was financially supported by the Program for New Century Excellent Talents in Heilongjiang Provincial University (1253-NCET-008) and the Foundation of Heilongjiang Educational Committee (12520140). The authors would like to take this opportunity to express their sincere appreciation.

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