Kovove Mater. 52 2014 117–123
DOI: 10.4149/km_2014_2_117

Mechanism and reliability of sheets embedded by cold press joining

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Received 19 January 2013, received in revised form 14 November 2013, accepted 15 November 2013

Abstract

Conventional mechanical joining methods, such as riveting, threaded connection and stamping connection, have obvious shortcomings in heterogeneous sheets joining. A new method of embedded cold joining was put forward, which can easily realize the connection between heterogeneous sheets. The method is suitable for connection of heterogeneous sheets with multi-layers and different thicknesses. This method can also decrease the cost greatly at the same time. Numerical simulation and experimental results indicate that a round hole sample has the maximum embedded depth and flash volume. Meanwhile, the elongation of aluminum sheet in hexagonal hole sample is the smallest. The joint strength of round hole sample increases with increment of the load pressure. Under the same load conditions, the joint strength of hexagonal hole sample is significantly higher than that of round hole and square hole sample. Additionally, the thickness decreased at different points on joint region because of the load pressure increasing. This paper shows an effective way how to realize the heterogeneous sheets connections.

Key words: heterogeneous sheets, cold press joining, mechanism, reliability

1. Introduction

Light weight is one of the effective means to achieve energy conservation purpose in aerospace and automotive industry. Therefore, a large number of new structural materials like aluminum-magnesium alloys and composites are widely used. However, it is rather difficult to connect these materials to steel sheets. Especially for the traditional joint techniques, there are many quality and technical problems. For example, laser welding [1–3] is efficient, reliable, and induces less heat-affected zone, but the cost is relatively high and it is difficult to connect multilayer sheets. Spot welding [4–6] can not be used to heterogeneous sheets connection. Riveting joining [7, 8] obviously increases the weight of the connections, although it can realize the connection between heterogeneous sheets. Sheet material, thickness and the number of layers have no influence on the threaded connections [9, 10], but the connections are easy to loose during long time performance. Press circle connection [11, 12] is a widely used technology in heterogeneous sheets joining, but the carrying capacity in thickness direction is poor and the sheets are easy to fall off.

Subsequently, shot peening joining method is proposed. In this method, shot peening load is conducted to the heterogeneous sheets lapped preliminarily until the plastic deformation of joint region occurs and realizes the connection. Because peening joining belongs to the local load forming technology, its efficiency is low and it cannot be used for sheets with different thickness and multi-layer sheets joining. Therefore, this paper presents a new method, embedded cold press deformation joining, and brings further analysis of the deformation laws by numerical simulation. Combined with the experimental means, the connection quality and defects of the connections are evaluated quantitatively.

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Fig. 1. Hole shapes.

2. Cold press joining

2.1. Principle

For embedded cold press joining, the sheets ends were cut into strips with fixed spaces. Provided a certain quantity and shape of holes at the end regions, sheets were lapped and pressed under a normal load to the joint region until the plastic deformation of each side appeared, embedded into the holes and interlocked. According to the plastic theory, the yield condition of sheets with lower yield strength was reached and plastic deformation appeared firstly. Therefore, special shaped holes were processed at the end of sheet with higher yield strength. When the normal load was applied on the joint, plastic deformation of lower strength sheets appeared firstly. Then they embedded into holes gradually and interlock connection realized.

In this method, surface grinding treatment of the sheets was not necessary, and the interlock structure of the ends provided constraint to the both sides of the joint regions. Additionally, it also had positioning function, which significantly reduced the possibility of cracking and shedding in this direction. In order to study the effects of the hole-shape on embedded capacity and joint strength, holes were processed into round, square and hexagonal shape in this paper, respectively, as shown in Fig. 1.

2.2. Research approach

All samples were preformed to 80 mm × 30 mm rectangular sheets, and the materials were pure aluminum and SS304 stainless steel with thickness of 1.15 mm. According to the above analysis, holes were prefabricated at the end of stainless steel sheet. The diameter of the round holes, the edge length of the square holes and hexagonal holes were all 5 mm. At the same time, DEFORM-3D finite element analysis software was used to analyze the connection process. Four-node tetrahedron isoparametric element was used to disperse the sheets in the simulation process. In order to improve the calculation accuracy and convergence, only half of the model was modeled, as shown in Fig. 2.

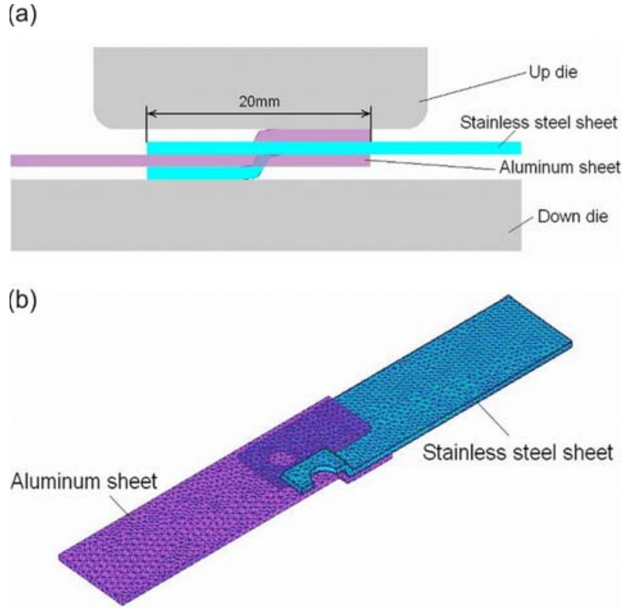

Fig. 2. (a) Finite element model, (b) mesh generation.

The process was performed at room temperature. The friction boundary conditions between the dies and billet were imposed by Coulomb friction model, and the friction factor was 0.12. The load pressures were 200 kN, 250 kN and 290 kN, and the deformation speed was 0.5 mm s^{-1}. The universal testing equipment was used in this study.

3. Deformation laws of cold press joining

3.1. Mechanical analysis

Take the round-hole sample as an example, the distributions of equivalent stress of stainless steel and aluminum sheet in the joint process are shown in Fig. 3.

It can be seen from Fig. 3a that the convex root of stainless steel sheet has the maximum equivalent stress during the initial forming process. Accordingly, the zone deformed firstly when yield condition was reached, and then the convex teeth of stainless steel sheet moved downward as upper die descended. Convex teeth of stainless steel sheet leveled with the two sides gradually, and the root of convex teeth had the maximum equivalent stress. The equivalent stress of regions increased gradually and then plastic deformation appeared successively. In terminal process, the convex teeth was almost on the same plane with two sides after downward deformation, and the end region

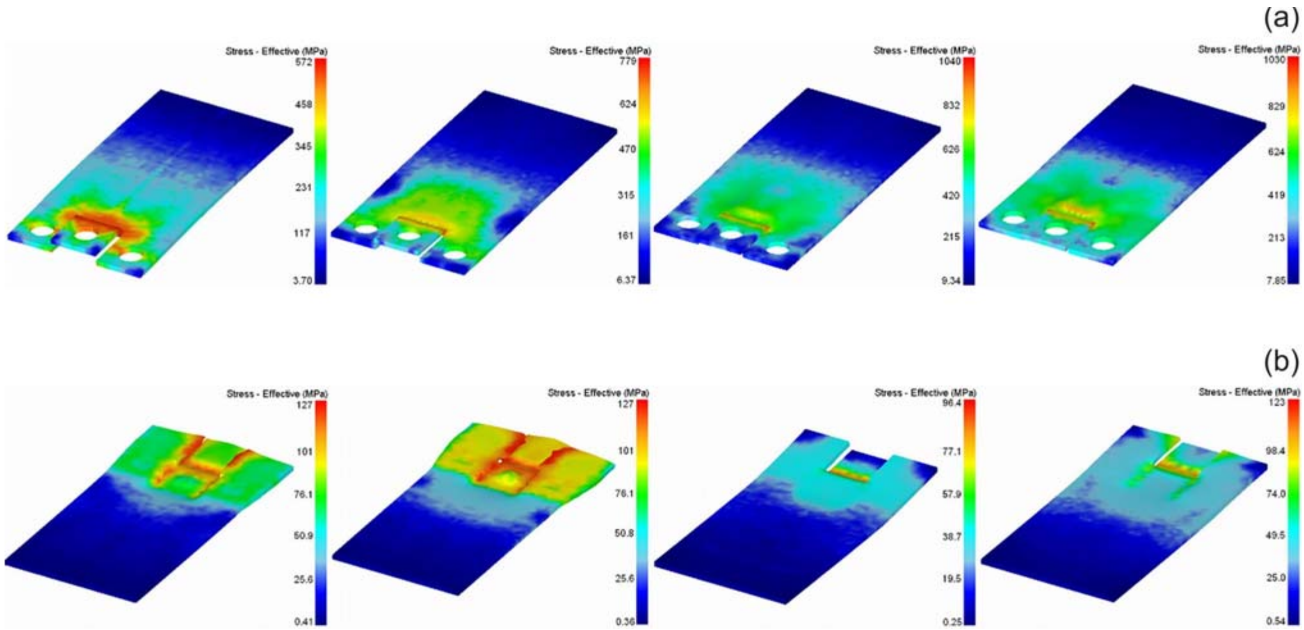

Fig. 3. Distribution of equivalent stress in the joint process: (a) stainless steel sheet, (b) aluminum sheet.

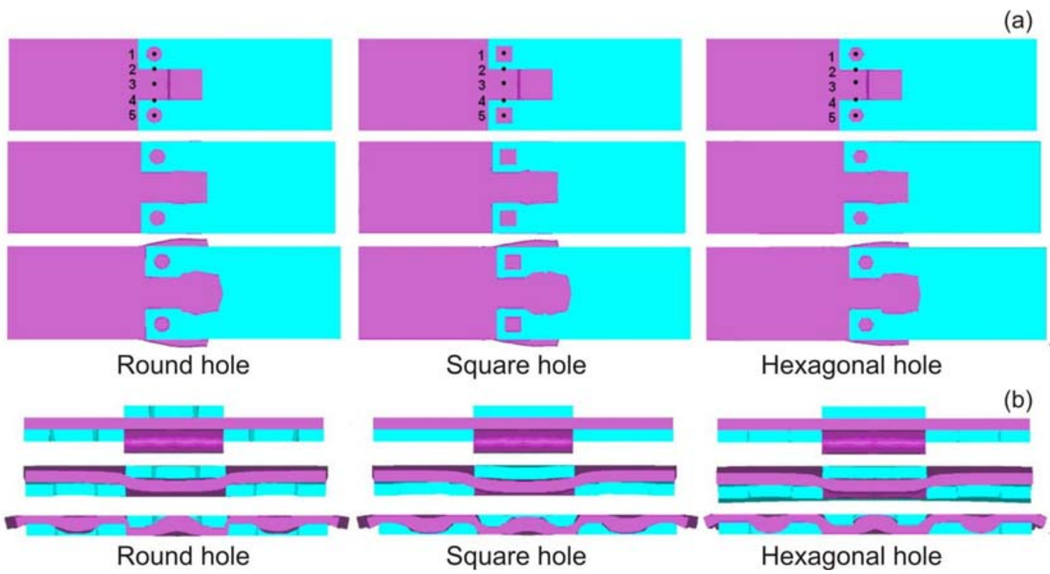

Fig. 4. Comparison of the embedded behavior in the connection process: (a) top view, (b) cross-section view.

of stainless steel sheet had a large equivalent stress.

Obvious changes appeared near the joint regions of aluminum sheet during deformation process. It can be seen from Fig. 3b that convex root of stainless steel sheet had the maximum equivalent stress during initial forming process, and the equivalent stress of joint region was significantly higher than at the other side of sheet. Obvious deformation induces the load increasing by the aluminum convex shape. The area which had larger equivalent stress also lied in connecting area. Meanwhile, both sides of aluminum sheet had a tendency to create deformation flowed outward separately. Equivalent stress of joint region increased sharply when the upper die was pressed, the convex root and the center of sheets had the maximum equivalent stress. At this moment, plastic deformation of the end area of aluminum sheet occurred when it reached yield conditions. At the end of process, the end area of aluminum sheet remained in completely plastic state. Due to the normal pressure, the sheet had a tendency to create deformation flow in the width direction.

3.2. Analysis of embedded jointing behavior

By embedded forming joining, the connection region of sheet presented a tendency to create deformation flow along horizontal direction. Moreover, aluminum sheet deformed and embedded into the hole of stainless steel sheet. The connection processes were compared with the same conditions as shown in Fig. 4.

It can be seen from Fig. 4 that the stainless steel convex moved downwards and leveled to the sheet sides gradually as upper die pressed in different holes processes. In the process of joining, aluminum sheet created plastic deformation significantly and then embedded into the holes of stainless steel sheet. At the same time, extended deformation of aluminum sheet occurred along the width direction, and the oddments formed the flash.

According to these results, the embedded depth of different joints was different because of the differences of holes styles. Taking the hole of stainless steel convex for example, the aluminum embedded depth gradually reduced in round hole process, the hexagonal hole process and the square hole process. Rest aluminum sheet flew out and formed flash along width direction. The flash volume of round hole was the maximum, square hole was the second one, and hexagonal hole was the minimum. When pressure was loaded on the joint region, the sheet was in a compression deformation state of "one pressure and two tensile". Therefore, the joint region deformed along width direction as well as length direction, as shown in Fig. 5.

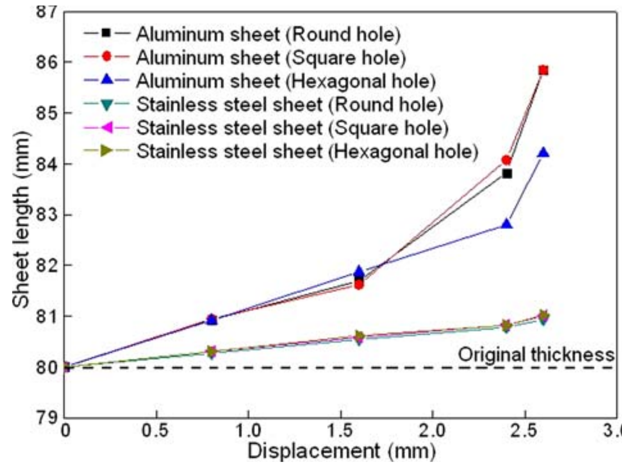

Fig. 5. Comparisons of sheet length change.

From the data in Fig. 5, the elongations of stainless steel sheets with different holes along length direction were all about 1.0 mm when the displacement of up-

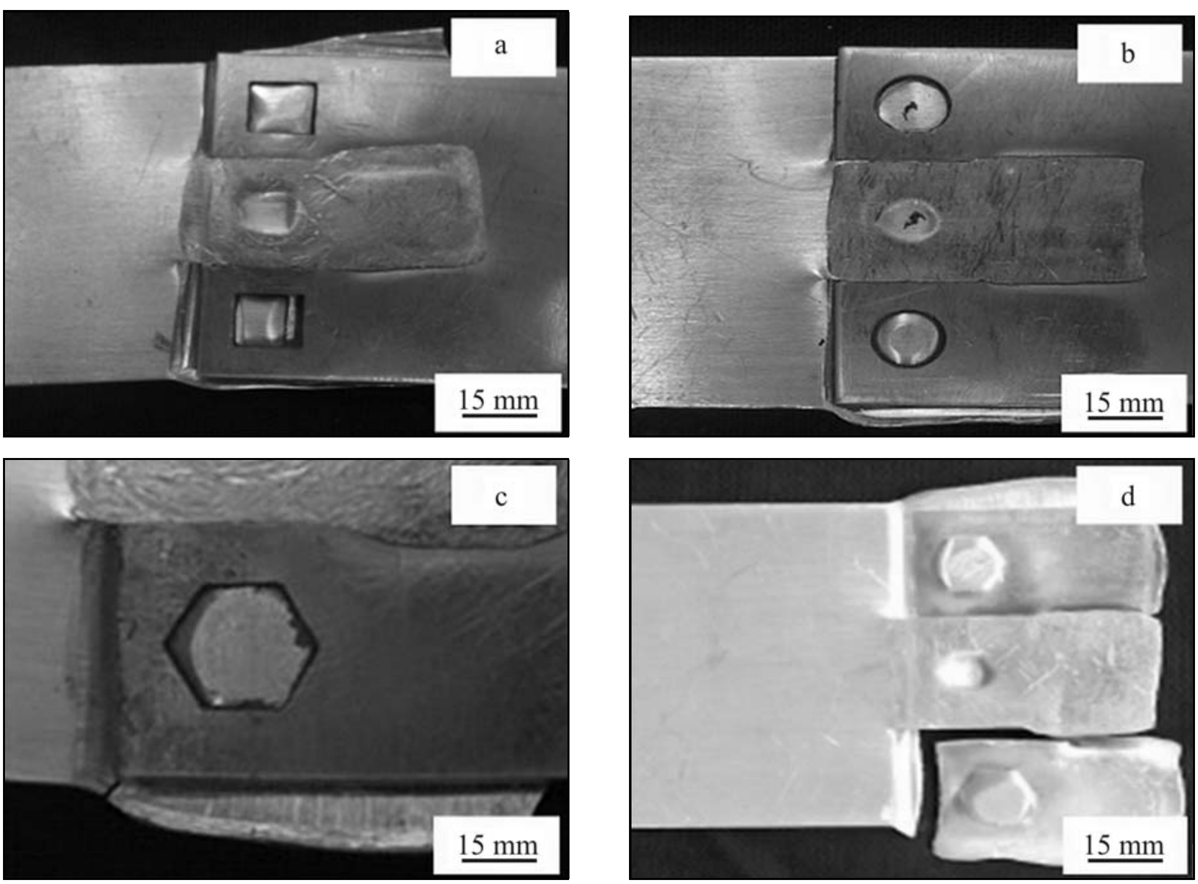

Fig. 6. Typical defects: (a) offset, (b) unbalanced load, (c) partial cracking, (d) partial shedding.

per die was 2.6 mm. But the styles of holes have more obvious influence on joint length of aluminum. For round and square holes, the elongations of aluminum sheet are 5.86 mm and 5.85 mm, respectively. Meanwhile, it is 4.2 mm for the hexagonal hole. Therefore, compared with stainless steel sheets, the elongation of aluminum sheets after joining was larger. Under the same load conditions, the elongation of aluminum sheets in round and square holes was larger than that in the hexagonal hole along length direction.

4. Quality and reliability research of the cold press joining

4.1. Analysis of quality and defects

Figure 6 shows the main defects in embedded deformation joining process. There are many process parameters that affect the joint quality, and it is hard to avoid defects in the connection between different sheets.

Figure 6a shows the lapped sheets preprocessed at the ends. Due to the size error at the end of sheets, the centerlines were difficult to overlap, and the offset defects appeared. Therefore, the positions of sheets should be checked after being processed. Though the load could be conducted on different sheets by briquetting in the press, it might lead to unbalanced--partial load defects along sheet width direction if the briquetting surface was not flat, shown in Fig. 6b. It meant that one side of the aluminum sheets embedded into hole completely while the other side was rarely changed. Therefore, it was necessary to use briquetting with smooth and larger area. In order to improve the depth of aluminum sheet that embedded into stainless steel sheet hole, it was necessary to increase joint pressure, and stainless steel sheet had a tendency to embed into aluminum sheets. It might lead to partial cracks, as shown in Fig. 6c. At the same time, it also had a great influence on the joint strength, and created micro-cracks in joining process. As shown in Fig. 6d, crack extension or even partial shedding was accelerated with load increasing or long time pressure. Therefore, the load pressure should be carefully controlled, and the interrelationship among process parameters should be comprehensively considered. The reasonable experimental results of each process are shown in Fig. 7.

4.2. Analysis of joint reliability

Figure 8 shows the embedded joint test for round hole process as an example, the result shows that the joint strength was 362 N when load pressure reached 200 kN. The joint strength increased by 3.9 % when the load pressure reached 250 kN. When load pressure increased to 290 kN, the joint strength increased by 88.7 %. Accordingly, when load pressure increased from 250 kN to 290 kN, the increasing degree of joint strength was more obvious.

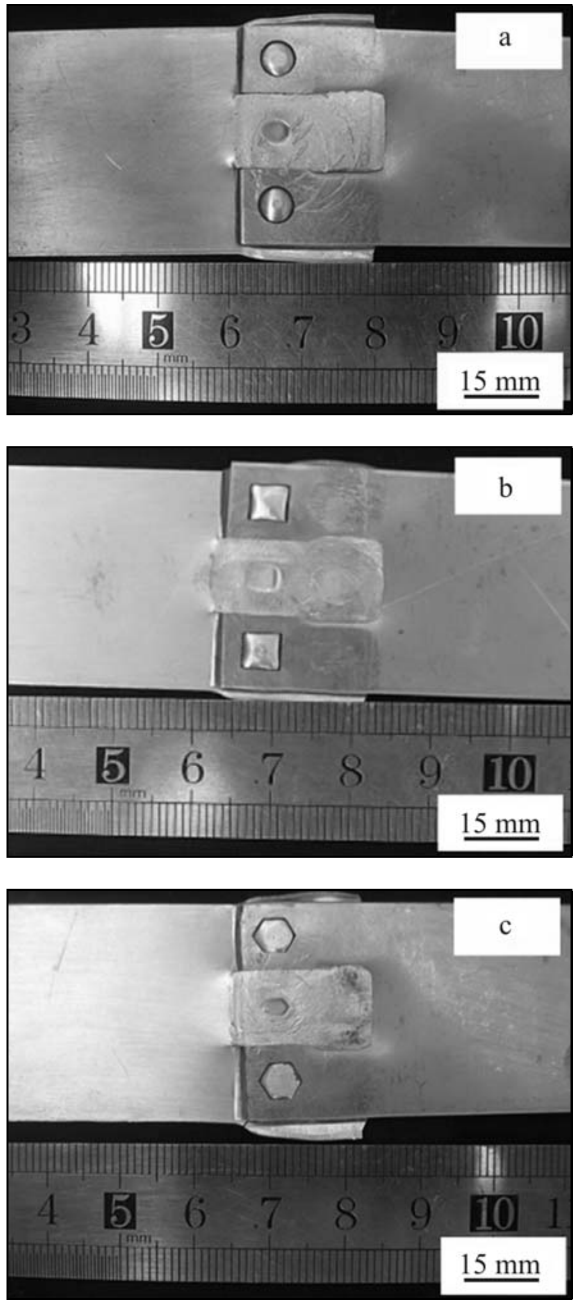

Fig. 7. Embedded cold joint results: (a) round hole, (b) square hole, (c) hexagonal hole.

As illustrated before, excessive load pressure is prone to reduce the thickness of joint regions, which might lead to defects such as partial cracks, and might also affect the reliability of connections. Therefore, comparisons were made on thickness distribution of joint region when load pressures were 200 kN, 250 kN and 290 kN, respectively, as shown in Fig. 9. The loc-

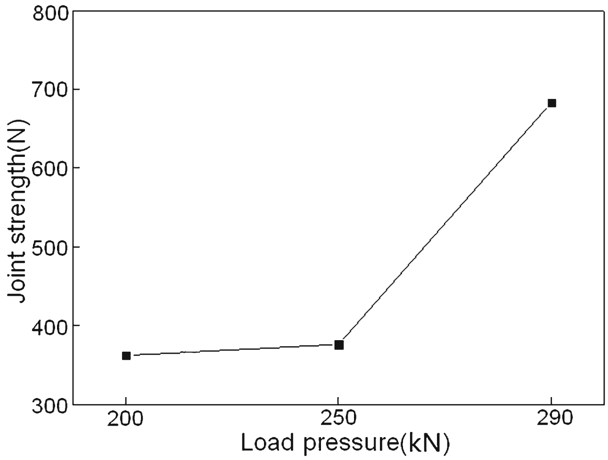

Fig. 8. Influence of load pressure on joint strength.

ation and order of the spots are shown in Fig. 4a.

As illustrated in Fig. 9a, the thickness of joint region reduced with load pressures for round hole process. When the load pressure was 200 kN, the thinning rates of point 1 and 3 were 14.8 % and 9.6 %, respectively. When load pressure reached 290 kN, the thinning rates changed into 26.9 % and 12.2 %. Comparing the thickness distribution along the width direction, the thickness of joint region reduced from point 3 to two sides. The thinning rate increased with the pressure of the upper die. Among them, point 3, the central part, was hard to deform due to the restrictions by two sides. Meanwhile, points 1 and 5 were restricted by one side, and the thinning rates of thickness were higher than that of point 3.

In the square hole process, as shown in Fig. 9b, the thinning rates of points were mostly the same and the deformation of this part was mostly average when the die pressure was 200 kN. When the die pressure increased to 250 kN, each point showed an obviously thinning trend. The thinning rate of point 3 was 9.6 %, and the thinning rates of point 1 and 5 reached 18.3 % and 20 %, respectively. Due to the increase of die pressure, the thickness at each point decreased, and the thinning rates of point 1 and point 5 were large, 22.6 % and 23.5 %, respectively. Because of the inevitable error, the thinning rate of point 2 was 18.3 %, which was the smallest one.

The thicknesses for hexagonal hole process are shown in Fig. 9c. Experimental results indicate that when the pressure is lower, the thinning degree of connection is smaller and the thickness of joint region is more uniform. When the pressure of upper die reached 250 kN, the thinning degrees of each point increased greatly. The thinning rate of point 2 was 17.4 %, and the thinning rates of point 1 and 5 increased to 26.1 %. As illustrated before, persistent pressure accelerated the thinning of connection at each point. When the pressure of upper die was 290 kN, the thinning rate of point 3 was 21.7 %, which was still the smallest. But the thinning rates of point 1 and 5 reached 31.3 % and 32.2 %.

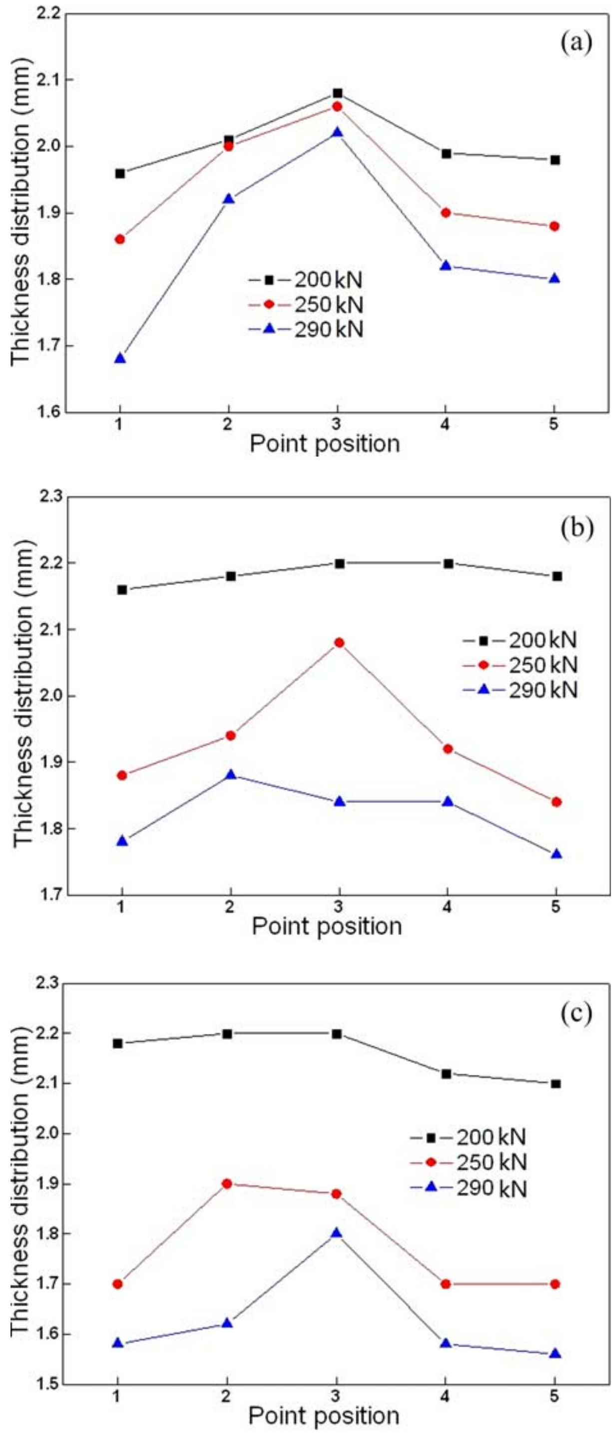

Fig. 9. Influence of hole shapes on the thickness distribution: (a) round hole, (b) square hole, (c) hexagonal hole.

According to geometric symmetry, taken as core, the thickness distribution should be the same opposite from point 3, the center of connection, to the two sides of joining region. However, there was an asymmetry because of inevitable errors, such as the process error of sheets.

5. Conclusions

1. Embedded cold press joining can realize connection of heterogeneous sheets with multi-layers and difference thicknesses. But unreasonable process conditions or mechanical processing error may lead to defects of offset, unbalanced load, partial cracking, and partial shedding.

2. Plastic deformation region of aluminum sheet was significantly larger than that of stainless steel sheet during joining process. The embedded depth and flash volumes in round hole process were larger than those of other two processes. For three processes, the embedded depth in square hole process was the smallest, and the flash volume in hexagonal hole process was the smallest. According to the elongations of the sheets before and after joining, the elongation in hexagonal hole process was the smallest.

3. Strength test results of the connections in round hole process showed that the joint strength improved with increasing load pressure. Under the same load conditions, the joining strength in hexagonal hole process was significantly higher than that in round and square hole processes. Additionally, the thinning degree of connection thicknesses at different points of joint region increased with the increasing load pressure.

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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