

Deep drawing of a rectangular cup with a small radius at the bottom circular arc by employing a locally-thickened plate

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Abstract. A rectangular cup with a small radius at the bottom circular arc is a common sheet metal structure in aerospace components. However, when aluminum alloy plates are used for deep drawing of this type of rectangular cups, the wall thickness around the bottom circular arc is severely decreased. Hence, in this paper, locally-thickened plates were adopted for deep drawing of aluminum alloy rectangular cups with a relatively small radius at the bottom circular arc. The effect of thickening parameters of a locally-thickened plate on the radius at the bottom circular arc and the forming load was investigated by employing finite element simulations and deep drawing experiments. The results indicate that a smaller radius at the bottom circular arc is obtained by increasing the angle or reducing the thickness of the thickened convex rib of a plate. Moreover, the aforementioned is achieved when the side length of the thickened convex rib is equal to the punch width. The forming load is closely related to the thickening parameters of a locally-thickened plate. A small radius of 5 mm at the bottom circular arc was successfully obtained by optimizing the thickening parameters. Furthermore, the forming load during the deep drawing was significantly reduced.

Keywords: Locally-thickened plate / deep drawing / rectangular cup / aluminum alloy / small radius

1 Introduction

Aluminum alloys are characterized by low density, high specific strength, and good corrosion resistance. They are widely utilized in aviation, aerospace, transportation, and other fields [1–3]. To effectively reduce energy consumption and environmental pollution, the demand for aluminum alloy sheet parts has increased [4]. However, the plasticity of aluminum alloy sheets at room temperature is relatively low [5,6]. Consequently, parts with large deformation or complex shapes cannot be formed by the cold drawing process. Moreover, the spring-back of aluminum alloy sheet parts formed at room temperature is often large [7,8]. Therefore, dimensional accuracy requirements of the parts cannot often be met. Since increasing the temperature can improve the plasticity of aluminum alloy sheets and reduce the spring-back of formed aluminum alloy parts, the hot forming process is more frequently used for aluminum alloy sheets [9–16].

However, aluminum alloy sheets usually bear tensile deformation in the deep drawing. Thus, the wall thickness around small corners of drawn parts is seriously thinned. The wall thickness severely decreases, especially for deep drawing of rectangular cups with a small radius at the bottom circular arc. When these rectangular cups are used as important support structural components in aerospace satellites, high strength requirements for the rectangular cups cannot be met. Consequently, the reliability of space satellites is significantly reduced. Although increasing the thickness of the original plate can increase the wall thickness around the bottom circular arc of the rectangular cups, this also increases the consumption of the original material. More importantly, the weight of the deep-drawn rectangular cup is increased, and the effective load of the space satellite is seriously reduced.

Previous researches have demonstrated that the radius at the bottom circular arc can be reduced by upsetting the side wall of a drawn part. For example, to decrease the radius at the bottom circular arc of a rectangular cup, Mori et al. [17] upset the sidewall of a drawn rectangular cup. For the same purpose, Wu and Wang et al. [18–21] also upset the side wall after drawing during forming clutch hubs and

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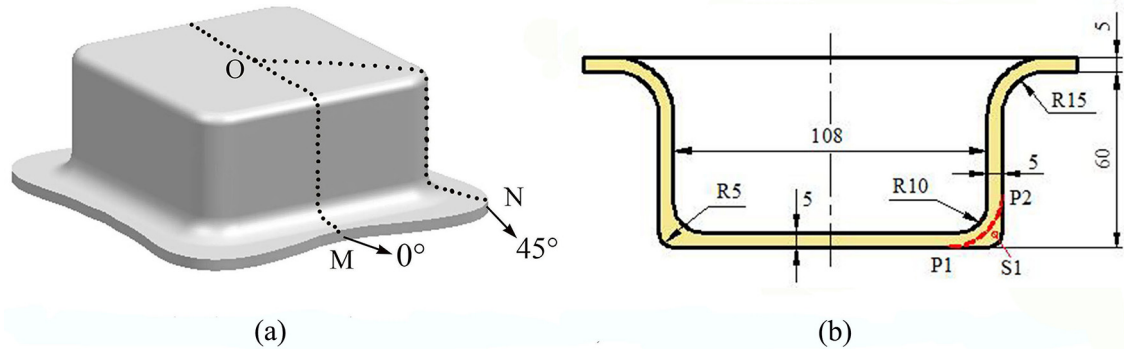


Fig. 1. (a) The aluminum alloy rectangular cup with a small radius at the bottom circular arc, and (b) the sectional dimension in the 0° direction of the rectangular cup.

flywheel parts. Although the radius of the bottom circular arc can be reduced by upsetting the sidewall, it is easy to cause the die structure to be complicated and the process to be numerous.

If a locally-thickened blank is used (i.e., the blank thickness in the locations requiring a small corner radius is increased), the thickness around the bottom circular arc of a rectangular cup can be increased. Tan et al. used locally-thickened blanks to increase the wall thickness at the bottom circular arc of a wheel disk [22]. The authors obtained an 11% increase in the wall thickness. Mori et al. [23] used locally-thickened blanks for rectangular cup deep drawing to increase the thickness at the bottom circular arc. Compared to the flat blank, the thickness at the bottom circular arc was increased by 20%. The metal flow was controlled by Wang et al. during hot stamping of rectangular cups with locally-thickened plates [24]. The authors aimed to improve the metal filling ratio at the bottom circular arc. Although locally-thickened plates can effectively increase the wall thickness around the bottom circular arc of rectangular cups, the required forming load is also significantly increased. The reason is that the punches severely squeezed the thickened metal material around the bottom circular arc of the rectangular cup at the last forming stage. Thus, the metal flows towards the bottom circular arc [24]. However, it is often desirable that the forming load is as small as possible in the actual production. This is done to decrease the requirements of tonnage for the forming equipment. Moreover, the aforementioned also reduces the damage to the molds and energy consumption. Therefore, a small radius at the bottom circular arc of rectangular cups and reducing the forming load are necessary to bring new challenges to the drawing of locally-thickened plates.

In this paper, the effect of thickening parameters of locally-thickened plates (i.e., the side length, the angle, and the thickness of the thickened convex rib) on the radius of the bottom circular arc of rectangular cups and forming load are studied. Both FE simulations and experimental investigations of the deep drawing of 2024 aluminum alloy locally-thickened plates are conducted. Lastly, the optimized thickened parameters of locally-thickened plates are obtained. These parameters may be utilized to produce rectangular cups with a small radius at the bottom circular arc and low values of forming load.

2 Methods

2.1 Rectangular cup

The aluminum alloy rectangular cup with a small radius at the bottom circular arc is shown in Figure 1a. The sectional dimension in the 0° direction of the rectangular cup is shown in Figure 1b. As shown in Figure 1b, the radius at the bottom circular arc is 5 mm. If a 5 mm thick flat plate is used for deep drawing, the bottom circular arc radius is approximately equal to 15 mm, as marked by P1P2. A locally-thickened plate can be used to obtain a 5 mm bottom circular arc radius. In other words, a certain volume of extra metal is added to the bottom circular arc, as represented by S1.

2.2 Locally-thickened plates

The shape design of locally-thickened plates is shown in Figure 2 [24]. A thickened convex rib is designed, i.e., the plate thickness in the locations requiring a small radius is increased. The side length of the thickened convex rib is defined as L . The angle of the thickened convex rib (i.e., the angle between CD and DE) is defined as θ . The thickness of the thickened convex rib (i.e., the length of CG) is defined as T . The width of the convex ribs (i.e., the length of DE) is designed to be 28 mm. The values of L , θ , and T are shown in Table 1 [24].

The longitudinal section area of the convex ribs is defined as S_{CDEF} . To obtain a radius of 5 mm at the bottom circular arc of the rectangular cup, the value of S_{CDEF} should be greater than $S1$ ($S1$ is shown in Fig. 1b). The calculation results show that when the values of L , θ and T in Table 1 are adopted for the convex ribs, $S_{CDEF} \geq S1$ can be met.

2.3 Finite element model of rectangular cup deep drawing

In this paper, the commercial ABAQUS software is used to establish a three-dimensional elastic-plastic FE model for the deep drawing of rectangular cups with locally-thickened plates. The FE model is shown in Figure 3 [24]. In the FE simulation, the material used for the locally-thickened plate is 2024 aluminum alloy. The mechanical,

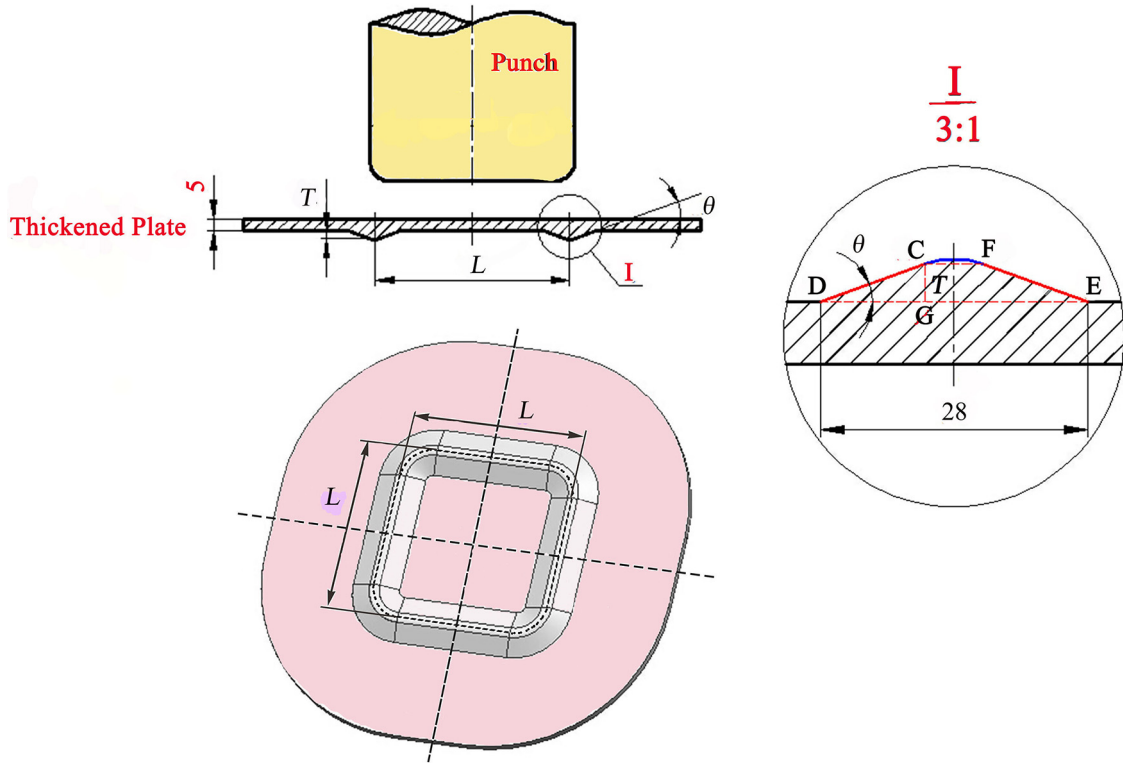


Fig. 2. Shape design of locally-thickened plates [24].

Table 1. Values of L , θ , and T [24].

Thickening parameters	Values
Side length of thickened convex rib (mm), L	100, 104, 108, 112
The angle of thickened convex rib ($^{\circ}$), θ	20, 25, 30
Thickness of thickened convex rib (mm), T	2.5, 3.0, 3.5, 4.0, 4.5

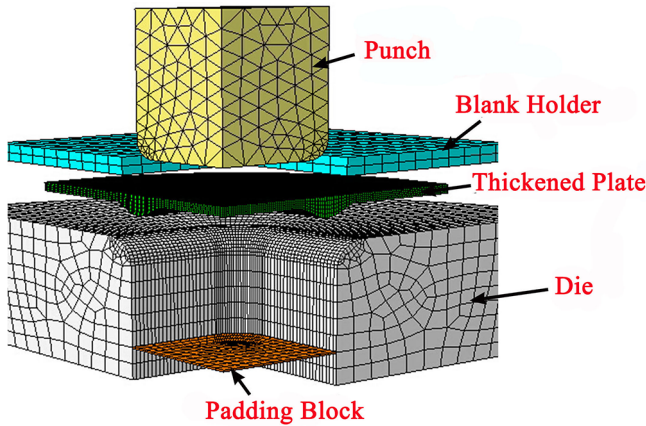


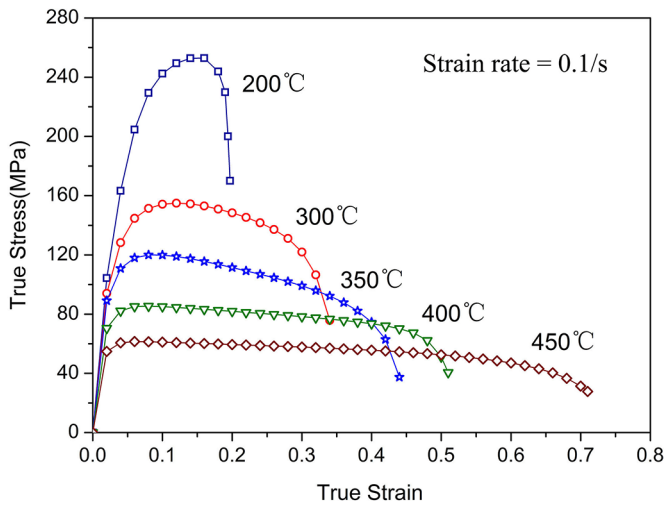
Fig. 3. FE model for the deep drawing of the rectangular cup with locally-thickened plates [24].

physical, and thermal properties of the material, such as poisson's ratio, density, and thermal conductivity, are listed in Table 2 [24]. Due to symmetrical boundary conditions, only a quarter of the model is employed. During the FE simulation, the punch, the die, the blank holder, and the padding block are set as rigid bodies and non-isothermal. 2024 aluminum alloy locally-thickened plate is defined as elastic-plastic, homogeneous, and isotropic. It also follows the von Mises yield criterion. The true stress-true strain relations of 2024 aluminum alloy at temperatures ranging from 200 to 450 $^{\circ}\text{C}$ are shown in Figure 4 [25].

At the interfaces between the locally-thickened plate and the tools (the punch, the die, the blank holder, and the padding block), friction and contact heat conduction are defined. During the FE simulation, the Coulomb friction model is used. Meanwhile, the friction coefficient between the plate and tools is assumed to be constant. The

Table 2. The mechanical, physical, and thermal properties of 2024 aluminum alloy [24].

Parameters	Values
Poisson's ratio	0.31
Density (kg/m ³)	2780
Young modulus (GPa)	40–72 (temperature-dependent)
Thermal conductivity (W/(m·K))	190
Specific heat (J/(kg·K))	924
Thermal expansion coefficient (1/K)	6.6e-5
Heat transfer coefficient (plate-environment) (W/(m ² ·K))	40
Heat transfer coefficient (plate-tools) (W/(m ² ·K))	2000

**Fig. 4.** True stress-true strain relations at elevated temperatures [25].

temperatures of the locally-thickened plate and the tools, the punch radius, the blank holder force, the friction coefficient, etc., are listed in Table 3 [24].

3 Results and discussion

3.1 Determination of thickening parameters

During the deep drawing of a rectangular cup, the plate is subjected to stretch-bending deformation at the bottom circular arc, while the wall thickness around the bottom circular arc tends to decrease. The smaller the radius at the bottom circular arc, the more serious the wall thickness reduction is. Therefore, it is necessary to increase the thickness of the plate at the portion of the bottom circular arc. When $L = 120$ mm, the locally-thickened plate ruptured around the bottom circular arc during deep drawing, as shown in Figure 5a. Since, for a large value of L , the metal thickness at the thickened part of the plate is much greater than the gap between the punch and die, the metal of the thickened part is difficult to flow into the die cavity, causing the occurrence of severe necking at the bottom circular arc and thus, leading to sheet rupture.

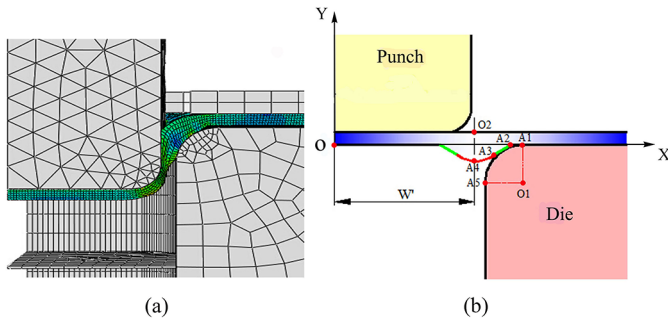
An X-Y coordinate system is established to avoid the occurrence of necking and even the rupturing of locally-thickened plates due to a very large L value, as shown in Figure 5b. In this paper, the principle used to determine the maximum value of L can be explained as follows. In the longitudinal section of the rectangular cup along the 0° direction, when the thickened materials just come into contact with the circular die profile (i.e., when the line A2A3 and circular arc A1A5 are tangent or the circular arc A3A4 and circular arc A1A5 are externally-tangent), the materials of the plate at the flange portion are in complete contact with the die, to ensure the blank holding effect. The substitution of the equation of line A2A3 (i.e., $(x - W' - 14) \cdot \tan\theta$) in the equation of circular arc A1A5 (i.e., $x^2 + y^2 - 149x + 30y + 5550.25 = 0$) gives one variable quadratic equation $f(x) = 0$. W' is equal to $1/2L$. According to the principle for determining the maximum value of L , $f(x) = 0$ should satisfy $\Delta = b^2 - 4ac \leq 0$. The radius of circle O1 is given by: $r1 = 15$ mm, while the radius of circle O2 is given by: $r2 = \sqrt{(5 + T)^2 + (14 - \frac{T}{\tan\theta})^2}$ mm. The distance between the centers of the circles is given by: $O1O2 = \sqrt{(74.5 - W')^2 + (-15 - 5)^2}$. According to the principle, the condition of $O1O2 \geq r1 + r2$ should be satisfied. The calculations indicated that the maximum value of L ($L = 112$ mm), which is listed in Table 1, can simultaneously satisfy the conditions: $\Delta = b^2 - 4ac \leq 0$ and $O1O2 \geq r1 + r2$, while the values of θ and T are determined.

3.2 Effect of thickening parameters on wall thickness distribution

The distributions of wall thickness along 0° and 45° directions of rectangular cups under various side lengths of thickened convex rib (L) are depicted in Figure 6a and b. The values of L were set as 100 mm, 104 mm, 108 mm, and 112 mm, respectively. Due to the influence of a single thickening parameter (L) on the wall thickness distribution of rectangular cups were studied, the values of θ and T were randomly set as 30° and 4 mm, respectively. When a flat plate is used, the wall thickness around the bottom circular arc of rectangular cups is severely decreased. As shown in Figure 6a, the wall thickness value at the bottom circular arc is 4.30 mm in the 0° direction of a rectangular cup when

Table 3. Deep drawing parameters of rectangular cups [24].

Parameters	Values
Initial dimensions of the plate (mm)	240×240
Punch radius (mm), R_p	10
Punch length and width (mm)	108×108
Die entrance radius (mm), R_d	15
Die corner radius (mm), R_c	15
Die inner length and width (mm)	119×119
Blank holder force (kN)	32
Punch speed (mm/s)	10
Punch stroke (mm)	60
Initial temperature of plate (°C)	400
Temperature of punch (°C)	25
The temperature of the die, blank holder, and padding block (°C)	200
The temperature of the environment (°C)	25
The friction coefficient between plate and tools	0.17

**Fig. 5.** (a) Results of deep drawing of the locally-thickened plate when $L = 120$ mm, $\theta = 30^\circ$, and $T = 4$ mm, and (b) the established X-Y coordinate system.

a flat plate is employed. More importantly, the wall thickness value at the bottom circular arc is 2.74 mm in the 45° direction of a rectangular cup, as displayed in Figure 6b. Due to the excessive thinning of the wall around the bottom circular arc, the rectangular cup cannot meet the strength requirements during service. When locally-thickened plates are used, the wall thickness around the bottom circular arc can significantly increase. As shown in Figure 6a, in the 0° direction of a rectangular cup, the wall thickness at the bottom corner increases from 4.30 mm to 11.12 mm when utilizing a locally-thickened plate instead of a flat plate. In the 45° direction, the wall thickness at the bottom circular arc can be increased from 2.74 mm to 8.24 mm, as shown in Figure 6b.

According to Figure 6, when $L = 108$ mm, maximum wall thickness values of 11.87 mm and 9.16 mm can be obtained at the bottom circular arc in the 0° and 45° direction of rectangular cups, respectively. Thus, when $L = 108$ mm, the wall thickness is the largest at the bottom circular arc. Consequently, a smaller radius at the bottom circular arc can be obtained more successfully.

Wall thickness distributions along 0° and 45° directions of rectangular cups under various angles of thickened convex rib (θ) are shown in Figure 7a and b, respectively. The values of θ were set as 20° , 25° , and 30° respectively. Due to the influence of a single thickening parameter (θ) on the wall thickness distribution of rectangular cups were studied, the values of L and T were randomly set as 112 mm and 4 mm respectively. As shown in Figure 7, increasing the value of θ can increase the value of wall thickness at the bottom circular arc of a rectangular cup. For $\theta = 30^\circ$, the maximum wall thickness values of 11.18 mm and 8.49 mm can be obtained at the bottom circular arc in the 0° and 45° direction of a rectangular cup, respectively. Thus, it is demonstrated that with an increase in the value of θ , the greater the wall thickness at the bottom circular arc. Consequently, a smaller radius at the bottom circular arc can be obtained more successfully.

Wall thickness distributions along 0° and 45° directions of rectangular cups under various thicknesses of thickened convex rib (T) are shown in Figure 8a and b, respectively. The values of T were set as 2.5 mm, 3.0 mm, 3.5 mm, 4.0 mm and 4.5 mm respectively. Due to the influence of a single thickening parameter (T) on the wall thickness distribution of rectangular cups were studied, the values of L and θ were randomly set as 112 mm and 30° respectively. According to Figure 8, when $T = 2.5$ mm, the maximum wall thickness values of 11.46 mm and 10.20 mm can be obtained at the bottom circular arc in the 0° and 45° directions of a rectangular cup, respectively. When the value of T decreases, the wall thickness at the bottom circular arc of a rectangular cup increases. Thus, a smaller radius at the bottom circular arc can be obtained more successfully.

3.3 Effect of thickening parameters on the bottom circular arc radii

According to the analysis conducted in Section 3.2, a larger value of θ , a smaller value of T , and when the value of L is equal to 108 mm are all beneficial to obtain smaller radius

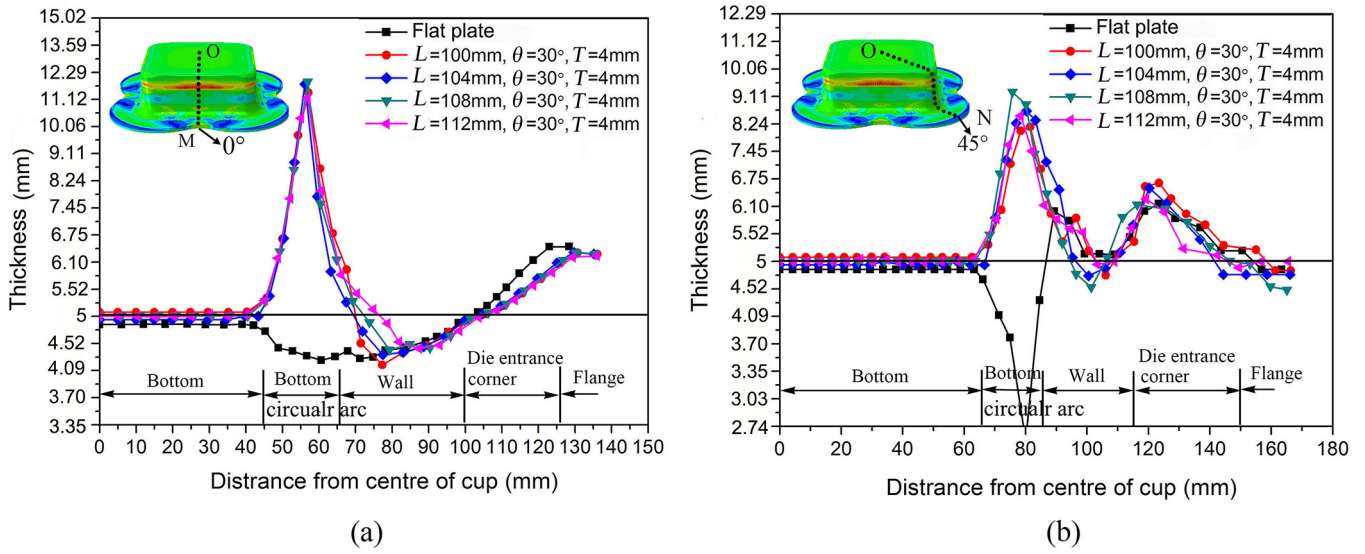


Fig. 6. Wall thickness distributions along: (a) 0° direction of rectangular cups, and (b) 45° direction of rectangular cups under various L values.

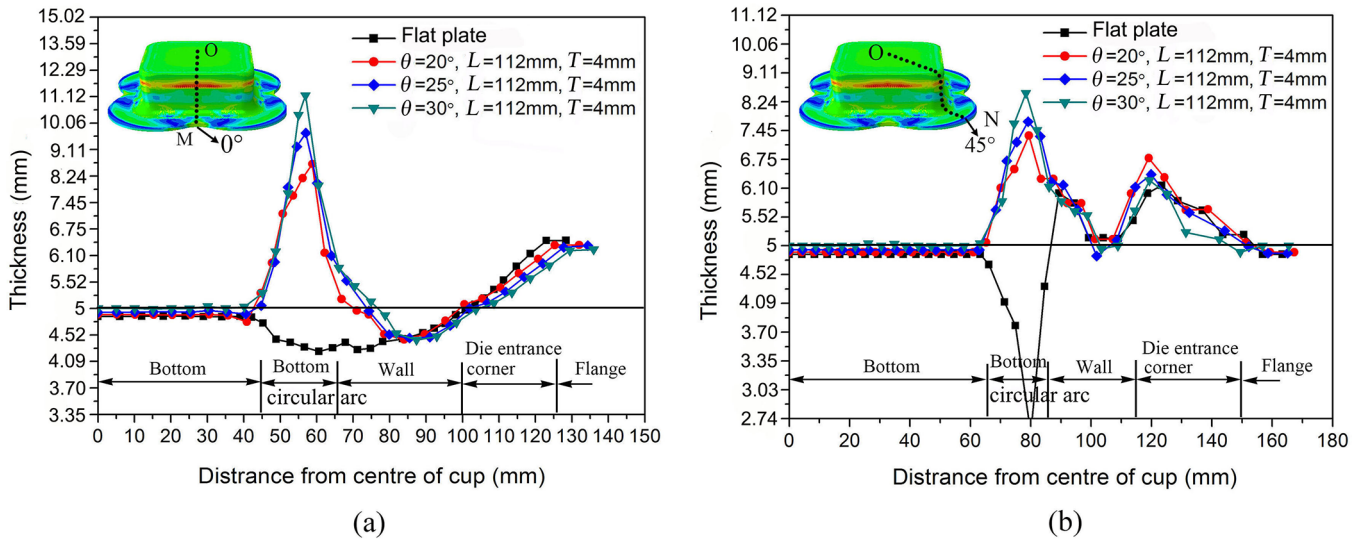


Fig. 7. Wall thickness distributions along: (a) 0° , and (b) 45° direction of rectangular cups under various values of θ .

at the bottom circular arc. To quantitatively compare the values of the bottom circular arc radius, in this paper, the bottom circular arc width is represented by a , the height is represented by b , and the area is represented by $S = a \times b / 2$, as shown in Figure 9a. The values of a , b , and S in 0° and 45° directions of rectangular cups under various values of L are presented in Figure 9a and b respectively. According to Figure 9a, smaller values of a , b , and S can be obtained when $L = 104$ mm or 108 mm in the 0° direction of a rectangular cup. On the other hand, smaller values of a , b , and S can be obtained when $L = 108$ mm or 112 mm in the 45° direction of a rectangular cup, as displayed in Figure 9b. However, when $L = 108$ mm, the minimum

value of S equal to 0 and 19.44 mm^2 can be obtained in 0° and 45° directions of rectangular cups, respectively. Thus, when $L = 108$ mm, a smaller radius at the bottom circular arc can be obtained. When the value of L equals 108 mm, the side length of the thickened convex rib equals the punch width of 108 mm. The thickened metal material is accurately supplemented at the bottom circular arc at the beginning stage of deep drawing. The thickened metal material is slightly extruded in the further deep drawing, and a smaller volume of thickened metal material flows to the bottom center and the cup wall. Therefore, a smaller radius at the bottom circular arc of rectangular cup can be obtained when the value of L is equal to 108 mm.

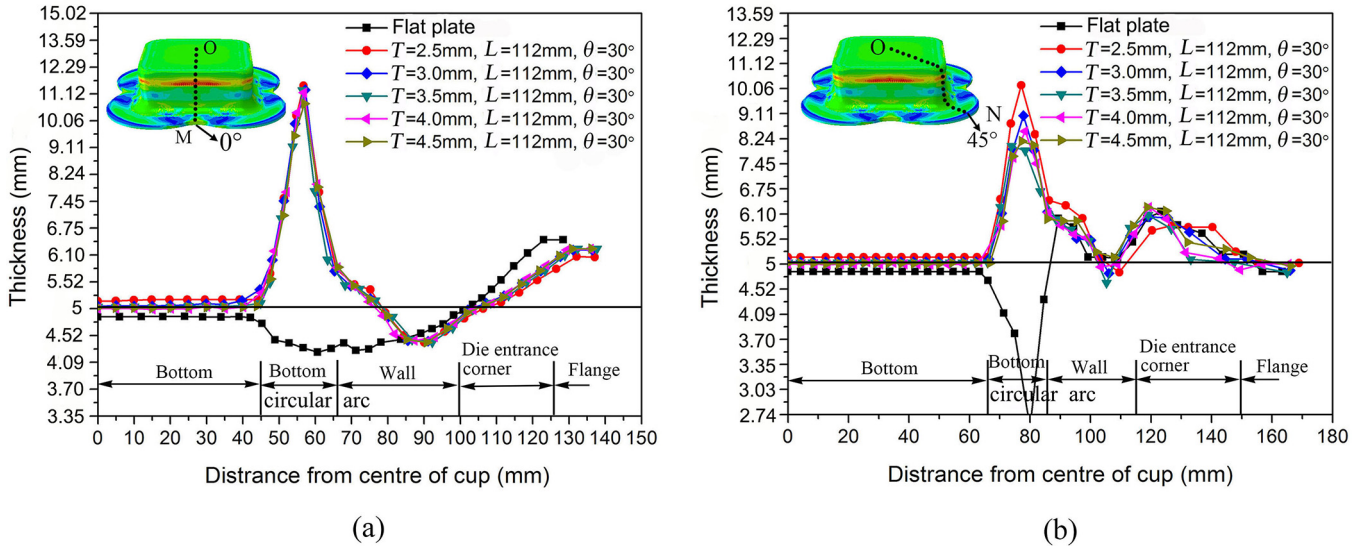


Fig. 8. Wall thickness distributions along: (a) 0° , and (b) 45° direction of rectangular cups under various values of T .

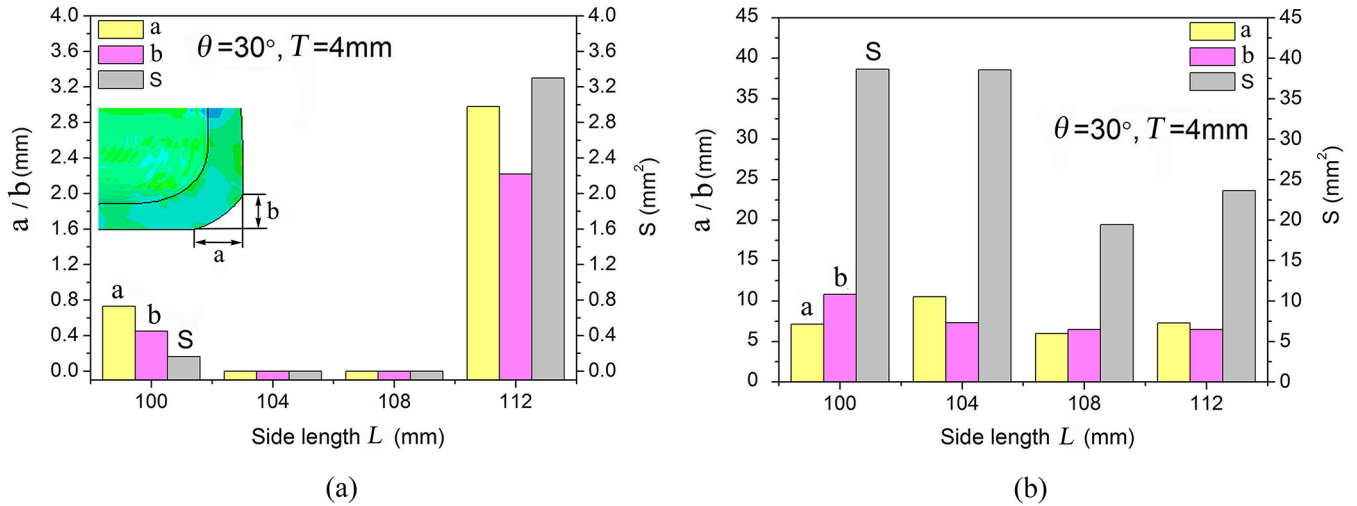


Fig. 9. Values of a , b , and S for: (a) 0° , and (b) 45° direction of rectangular cups for various values of L .

Values of a , b , and S in 0° and 45° directions of rectangular cups under various values of θ are displayed in Figure 10a and b. The values of a , b , and S in 0° and 45° directions of rectangular cups decrease gradually as the value of θ increases. The minimum S values of 3.3 and 23.62 mm² can be obtained in 0° and 45° directions of a rectangular cup, respectively, when $\theta = 30^\circ$. Thus, when $\theta = 30^\circ$, a smaller radius at the bottom circular arc can be obtained. As shown in Figure 2 in the manuscript, increasing the value of θ can increase the area of the longitudinal section of thickened convex ribs (S_{CDEF}). That is, the volume of the thickened convex rib is increased. Thus, a larger volume of metal material can be supplemented at the bottom circular arc of the rectangular cup. Consequently, a smaller radius at the bottom circular arc can be obtained more successfully.

The values of a , b , and S in 0° and 45° directions of rectangular cups for various T values are depicted in Figure 11a and b, respectively. Values of a , b , and S in 0° and 45° directions of rectangular cups gradually decrease with the value of T from 4.5 to 2.5 mm. When T decreases from 3.0 mm to 2.5 mm, the values of a , b , and S decrease significantly. The minimum S values of 0 and 10.75 mm² can be obtained in 0° and 45° directions of rectangular cups, respectively, when $T = 2.5$ mm. Thus, when $T = 2.5$ mm, a smaller radius at the bottom circular arc can be obtained. As shown in Figure 2 in the manuscript, decreasing the value of T can increase the area of the longitudinal section of thickened convex ribs (S_{CDEF}). That is, the volume of the thickened convex rib is increased. Thus, a larger volume of metal material can be supplemented at the bottom circular arc of the rectangular cup. Consequently, a smaller radius at the bottom circular arc can be obtained more successfully.

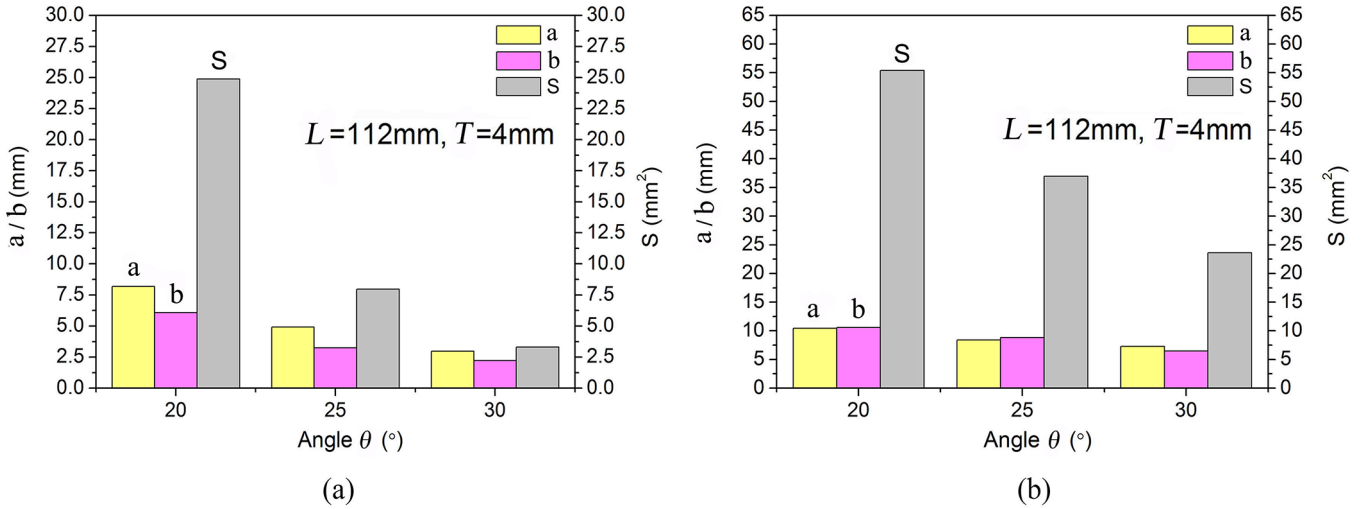


Fig. 10. Values of a , b , and S for: (a) 0°, and (b) 45° direction of rectangular cups for various values of θ .

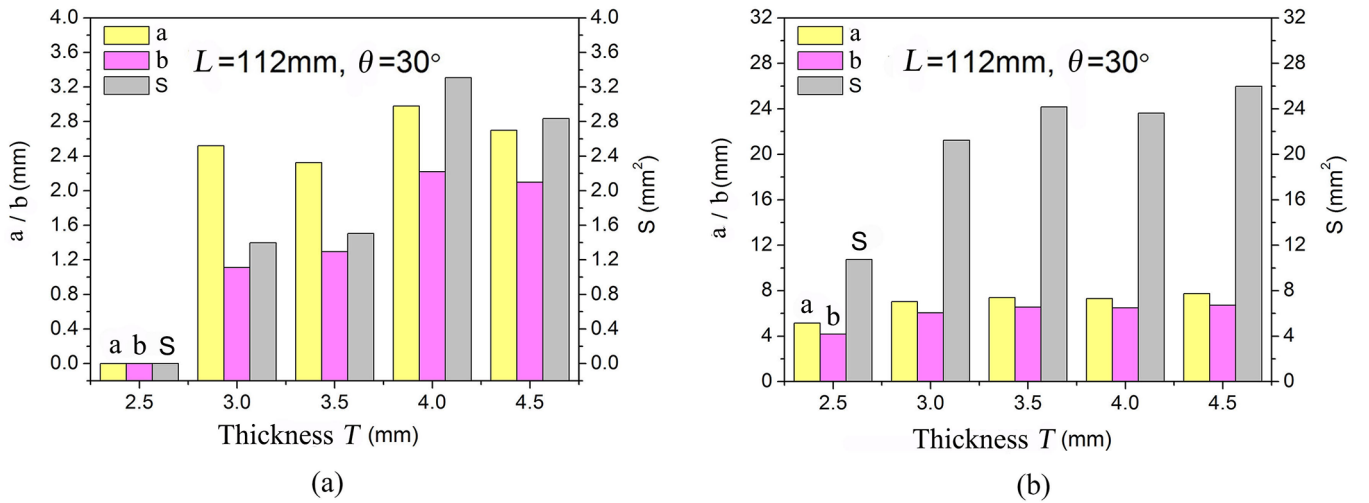


Fig. 11. Values of a , b , and S for: (a) 0°, and (b) 45° direction of rectangular cups for various values of T .

3.4 Effect of thickening parameters on the punch load

According to the analysis results in Section 3.3, when $L=108\text{ mm}$, $\theta=30^\circ$, and $T=2.5\text{ mm}$, it is beneficial to obtain a smaller radius at the bottom circular arc of a rectangular cup. Values of a , b , and S in 0° and 45° directions of rectangular cups with $L=108\text{ mm}$, $\theta=30^\circ$, and $T=2.5\text{ mm}$ are shown in Figure 12a. The punch load-stroke curve is shown in Figure 12b. As displayed in Figure 12a, in 0° and 45° directions of rectangular cups, the values of a and b are less than 5 mm, while the value of S is less than 12.5 mm^2 . It is confirmed that when the locally-thickened plate with $L=108\text{ mm}$, $\theta=30^\circ$, and $T=2.5\text{ mm}$, a small radius of 5 mm at the bottom circular arc can be achieved. However, according to Figure 12b, the maximum punch load ($F_{\max}$) is 978.06 tons. In other words, nearly 1000 tons of pressure is required to achieve a radius of 5 mm under this thickening parameter. However, to reduce the require-

ments of forming equipment tonnage during the actual production, it is often expected that the forming load is as small as possible. Moreover, the damage to the molds is reduced and the energy consumption is lowered. Therefore, it is necessary to study the influence of thickening parameters on the punch load.

Maximum punch load $F_{\max}$ and values of S under various thickening parameters are shown in Figure 13. According to Figure 13a, the value of $F_{\max}$ gradually decreases as the value of L increases. This is because the thickened metal material is closer to the bottom circular arc of the rectangular cup at the end of the deformation (punch stroke = 55–60 mm) when the value of L increases. Thus, the thickened metal material flow distance to the bottom circular arc is reduced. Consequently, the forming load is decreased. When L increases from 108 mm to 112 mm, the $F_{\max}$ is reduced from 395.2 tons to 207.25 tons, i.e., 47.56%. However, the value of S in the 45° direction

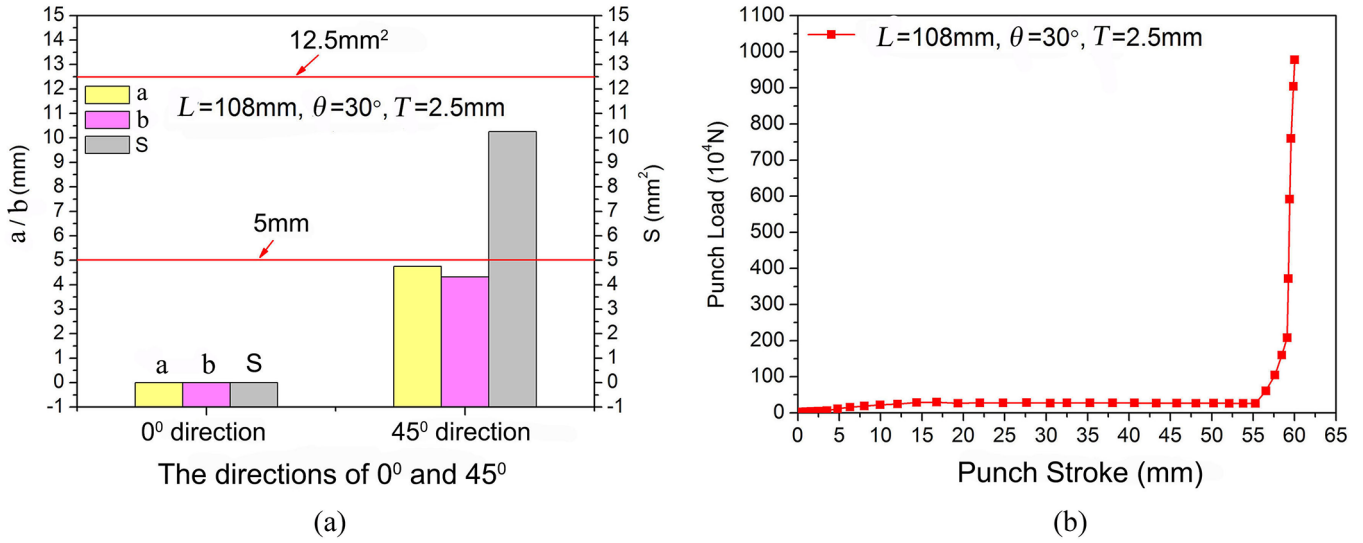


Fig. 12. (a) Values of a , b , and S in 0° and 45° directions of rectangular cups with $L=108\text{mm}$, $\theta=30^\circ$, and $T=2.5\text{mm}$, and (b) the punch load-stroke curve.

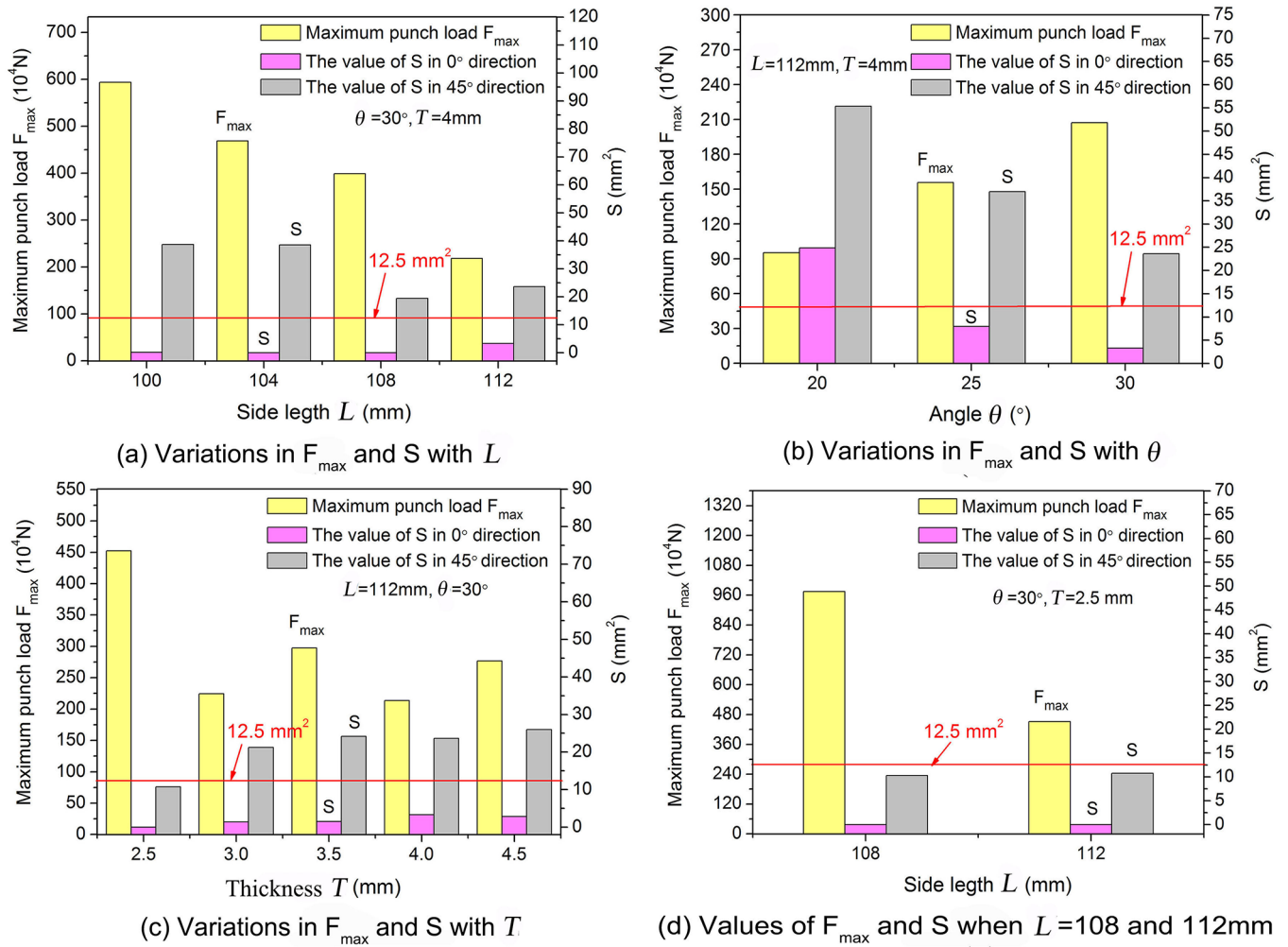


Fig. 13. Maximum punch load $F_{\max}$ and values of S under various thickening parameters.

increases by 21.55% (S increases from 19.44 mm² to 23.63 mm²). The value of L is temporarily taken as 112 mm to reduce the punch load.

It is shown in Figure 13b that the value of $F_{\max}$ gradually increases as the value of θ increases. According to Figure 2 in the manuscript, increasing the value of θ can increase the area of the longitudinal section of thickened convex ribs (S_{CDEF}). Thus, the volume of the thickened convex rib is increased. Accordingly, at the end of the deformation, more volume of thickened metal material should be squeezed and flows to the bottom circular arc of the rectangular cup. Therefore, the forming load is increased. When θ increases from 25° to 30°, the $F_{\max}$ increases from 156.6 tons to 207.25 tons, i.e., by 32.28%. However, the value of S in the 45° direction decreases by 36.07% (S decreases from 36.96 mm² to 23.63 mm²). The value of θ is taken as 30° to obtain the required small radius of 5 mm at the bottom corner of a rectangular cup.

As displayed in Figure 13c, when $T=2.5$ mm ($L=112$ mm, $\theta=30^\circ$), the values of S in 0° and 45° directions of rectangular cups can both meet the condition of $S < 12.5$ mm², i.e. a small radius of 5 mm at the bottom circular arc can be obtained. According to Figure 13d, the $F_{\max}$ can be reduced from 978.06 tons ($L=108$ mm, $\theta=30^\circ$, $T=2.5$ mm) to 452.8 tons when $L=112$ mm, $\theta=30^\circ$, $T=2.5$ mm. The value of $F_{\max}$ is thereby reduced by 53.70%.

In conclusion, when a locally-thickened plate with $L=112$ mm, $\theta=30^\circ$, $T=2.5$ mm is used, a small radius of 5 mm at the bottom circular arc of the rectangular cup can be obtained. Furthermore, the forming load during the deep drawing is significantly reduced. The forming load is reduced by 53.70% compared to the rectangular cups before the optimization process.

3.5 Deep drawing experiments and validation

During the deep drawing experiments, the same processing parameters and die size parameters were employed within the FE simulations. Figure 14 is the schematic diagram for the deep drawing of rectangular cups [26]. In this study, the purchased 2024 aluminum alloy plate was machined into a 5 mm thick flat plate, a locally-thickened plate with the thickening parameters of $L=112$ mm, $\theta=30^\circ$, and $T=2.5$ mm, and a locally-thickened plate with $L=108$ mm, $\theta=30^\circ$, and $T=2.5$ mm, respectively.

Deep drawing experiments were carried out on a 500-ton and an 800-ton hydraulic press. For the first experimental group, a deep drawing of a rectangular cup was conducted via a locally-thickened plate with thickening parameters of $L=108$ mm, $\theta=30^\circ$, and $T=2.5$ mm on an 800-ton hydraulic press. For the second experimental group, deep drawing of rectangular cups were conducted via a flat plate, and a locally-thickened plate with thickening parameters of $L=112$ mm, $\theta=30^\circ$, and $T=2.5$ mm on a 500-ton hydraulic press. Before the deep drawing experiments, the flat plate and the locally-thickened plates were heated to 400°C in a cup-type

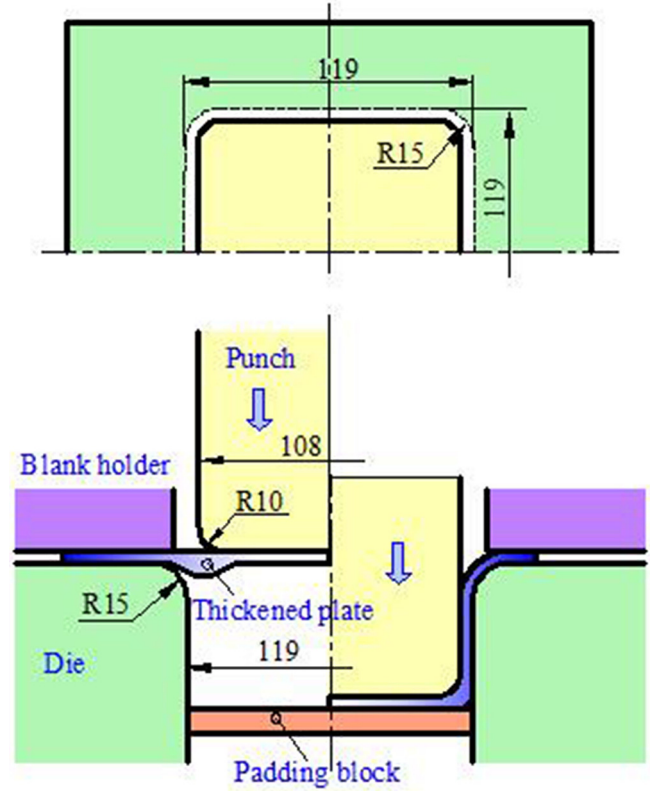


Fig. 14. The schematic diagram for the deep drawing of rectangular cups [26].

resistance furnace. The blank holder, the die, and the padding block were all heated to 200 °C, but the punch was not heated.

The deep drawing experiments can be divided into the following three steps. Firstly, water-based graphite lubricant was sprayed on the surfaces of the punch, the die, the blank holder, and the padding block for lubrication purposes. Secondly, the pre-heated flat plate and locally-thickened plates (400 °C) were quickly placed on the upper surface of the die and immediately formed, respectively. The speed of the punch is 10 mm/s, and the displacement of the punch is 60 mm. Finally, the deep-drawn rectangular cup was pushed out of the die cavity using the padding block and then cooled to room temperature.

Longitudinal section profiles of the bottom circular arcs along the 0° and 45° directions of rectangular cups, obtained from a flat plate and a locally-thickened plate ($L=112$ mm, $\theta=30^\circ$, and $T=2.5$ mm) are shown in Figure 15. It is seen in Figure 15 that, for both 0° and 45° directions of rectangular cups, longitudinal section profiles of the bottom circular arcs obtained from finite element simulations agrees well with the deep drawing experimental results. The values of a , b , and S of bottom circular arcs, obtained from FE simulations or experiments, were compared in Table 4. By comparing FE simulation data with experiment results, it is implied that their magnitudes are roughly the same. Moreover, the thickness distributions along the 0° and 45° directions of rectangular cups were

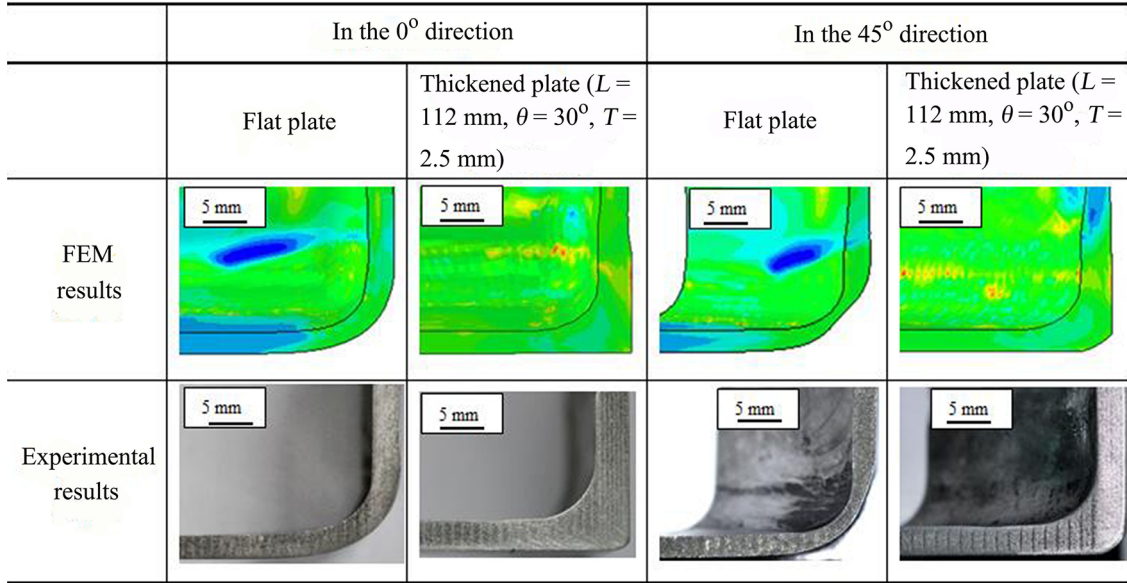


Fig. 15. Longitudinal section profiles of the bottom circular arcs along the 0° and 45° directions of rectangular cups obtained from a flat plate and a locally-thickened plate.

Table 4. The values of a , b , and S of bottom circular arcs obtained from FE simulations or experiments.

	In the 0° direction		In the 45° direction	
	Flat plate	Thickened plate ($L = 112 \text{ mm}$, $\theta = 30^\circ$, $T = 2.5 \text{ mm}$)	Flat plate	Thickened plate ($L = 112 \text{ mm}$, $\theta = 30^\circ$, $T = 2.5 \text{ mm}$)
FEM results	$a = 15.6 \text{ mm}$	$a = 1.6 \text{ mm}$	$a = 17.8 \text{ mm}$	$a = 4.5 \text{ mm}$
	$b = 14.7 \text{ mm}$	$b = 1.2 \text{ mm}$	$b = 16.7 \text{ mm}$	$b = 4.2 \text{ mm}$
	$S = 114.66 \text{ mm}^2$	$S = 0.96 \text{ mm}^2$	$S = 148.63 \text{ mm}^2$	$S = 9.45 \text{ mm}^2$
Experimental results	$a = 15.3 \text{ mm}$	$a = 1.5 \text{ mm}$	$a = 17.5 \text{ mm}$	$a = 4.4 \text{ mm}$
	$b = 14.6 \text{ mm}$	$b = 1.2 \text{ mm}$	$b = 16.8 \text{ mm}$	$b = 4.1 \text{ mm}$
	$S = 111.69 \text{ mm}^2$	$S = 0.90 \text{ mm}^2$	$S = 147.00 \text{ mm}^2$	$S = 9.02 \text{ mm}^2$

obtained from a flat plate and a locally-thickened plate was measured, as shown in Figure 16a and b. It can be seen in Figure 16 that the thickness distributions measured in the experiment are in good agreement with the finite element simulation results.

The forming results of the above two groups of experiments with locally-thickened plates are shown in Figure 17 and Table 5 respectively. For deep drawing of the rectangular cup by using a locally-thickened plate with $L = 108 \text{ mm}$, $\theta = 30^\circ$, and $T = 2.5 \text{ mm}$ on an 800-ton hydraulic press, the values of a and b in the 45° direction of the rectangular cup are both higher than 5 mm, as listed in Table 5. This indicates that under this thickening parameter, the forming load must be greater than 800 tons to obtain a small radius of 5 mm at the bottom circular arc. This is consistent with the simulation result of 978.06 tons. According to Table 5, when a deep drawing of a rectangular cup is conducted by using a locally-thickened plate with $L = 112 \text{ mm}$, $\theta = 30^\circ$, $T = 2.5 \text{ mm}$ on a 500-ton hydraulic

press, the values of a and b in the 0° and 45° directions of rectangular cups are both less than 5 mm. This indicates that under this thickening parameter, the forming load can be less than 500 tons to obtain a small radius of 5 mm at the bottom circular arc. This is consistent with the simulation result for 452.8 tons.

Compared to flat plates, using locally-thickened plates can significantly reduce the radius at the bottom circular arc of rectangular cups. According to the experimental measurement results, the values of a and b in the 0° direction of rectangular cups can be reduced from 15.3 mm and 14.6 mm (flat plate) to 1.5 mm and 1.2 mm, respectively, when a thickened plate with $L = 112 \text{ mm}$, $\theta = 30^\circ$, $T = 2.5 \text{ mm}$ is employed. Values of a and b in the 45° direction of rectangular cups can be reduced from 17.5 mm and 16.8 mm to 4.4 mm and 4.1 mm, respectively, when using a thickened plate instead of a flat plate. The experimental results confirm that the obtained rectangular cup can achieve a small radius of 5 mm at the bottom circular arc.

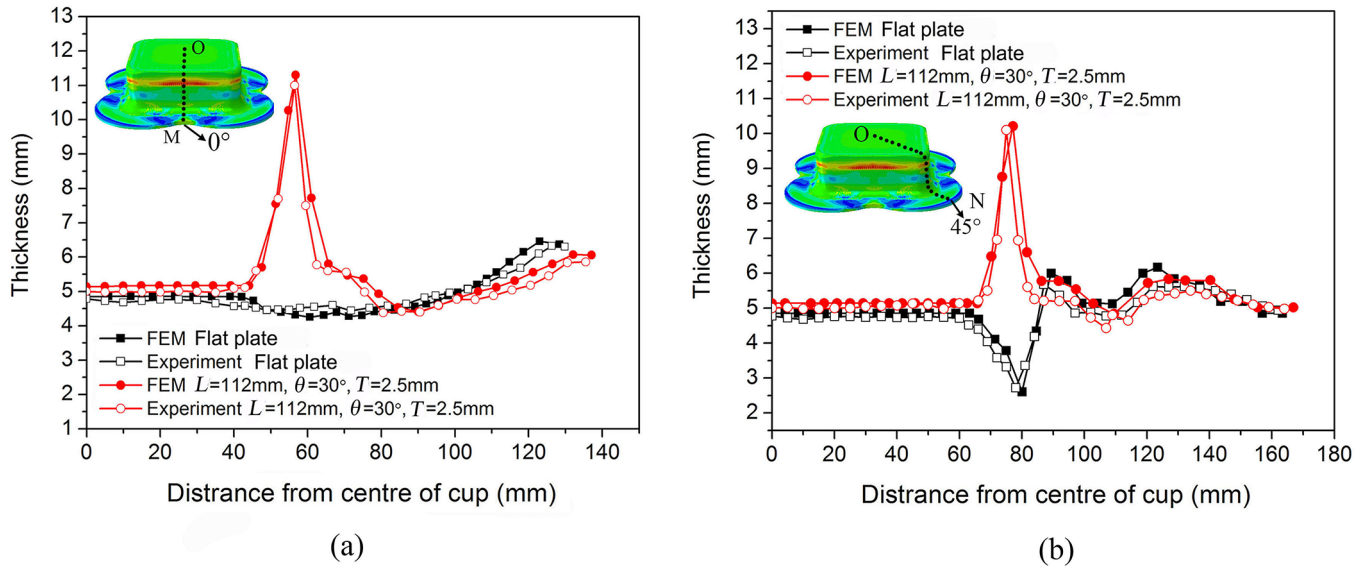


Fig. 16. Thickness distributions along: (a) 0° , and (b) 45° direction of rectangular cups obtained from a flat plate and a locally-thickened plate.

Table 5. The values of experimentally obtained a , b , and S of bottom circular arcs.

In the 0° direction		In the 45° direction	
$L = 108\text{ mm}$, $\theta = 30^\circ$, $T = 2.5\text{ mm}$, on an 800-ton hydraulic press	$L = 112\text{ mm}$, $\theta = 30^\circ$, $T = 2.5\text{ mm}$, on a 500-ton hydraulic press	$L = 108\text{ mm}$, $\theta = 30^\circ$, $T = 2.5\text{ mm}$, on an 800-ton hydraulic press	$L = 112\text{ mm}$, $\theta = 30^\circ$, $T = 2.5\text{ mm}$, on a 500-ton hydraulic press
$a = 4.5\text{ mm}$	$a = 1.5\text{ mm}$	$a = 7.2\text{ mm}$	$a = 4.4\text{ mm}$
$b = 4.1\text{ mm}$	$b = 1.2\text{ mm}$	$b = 6.3\text{ mm}$	$b = 4.1\text{ mm}$
$S = 9.22\text{ mm}^2$	$S = 0.90\text{ mm}^2$	$S = 22.68\text{ mm}^2$	$S = 18.04\text{ mm}^2$

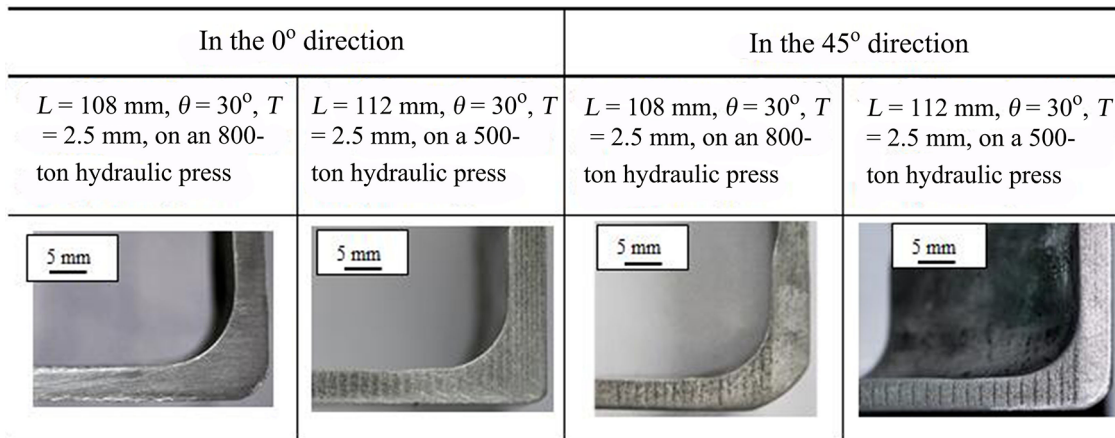


Fig. 17. Longitudinal section profiles of the bottom circular arcs along the 0° and 45° directions of rectangular cups obtained from locally-thickened plates.

4 Conclusions

In this paper, the effect of thickening parameters of locally-thickened plates on the radius of the bottom circular arc of rectangular cups and the forming load was studied. The aforementioned aims to decrease the forming load and achieve a small radius at the bottom circular arc. The following results were obtained:

- The wall thickness around the bottom circular arc of rectangular cups can be significantly increased when locally-thickened plates are used. For example, when using a locally-thickened plate ($L = 108\text{ mm}$, $\theta = 30^\circ$, $T = 2.5\text{ mm}$) instead of a flat plate, the thickness strain at the bottom circular arc can be increased from -0.15 to 0.8 in the 0° direction of a rectangular cup. Moreover, the thickness strain can be increased from -0.6 to 0.5 in the 45° direction.
- Within the range of thickening parameters investigated in this study, increasing the angle of thickened convex rib, reducing its thickness, and setting the side length of the thickened convex rib equal to the punch width is beneficial for obtaining a smaller radius at the bottom circular arc of a rectangular cup.
- The forming load during deep drawing is closely related to the thickening parameters of a locally-thickened plate. When the locally-thickened plate with optimized thickening parameters of $L = 112\text{ mm}$, $\theta = 30^\circ$, $T = 2.5\text{ mm}$ was used, a small radius of 5 mm at the bottom circular arc of a rectangular cup was successfully obtained. Moreover, the forming load during the deep drawing was significantly reduced. Under the optimized thickening condition, the forming load was reduced by 53.70% .

Declarations of competing interests

The corresponding author states that there is no conflict of interest on behalf of all authors.

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