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Stamping-Forging Processing of Sheet Metal Parts

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1. Introduction

1.1. Principle of stamping-forging processing (SFP) for sheet metal

SFP is a combined metal forming technology of stamping and forging for sheet metal parts. In an SFP, generally, stamping or drawing is used to form the spatial shape of the part first, and followed by a bulk forming employed to form the local thickened feature. It is suitable for making sheet metal parts which have local thickened feature, such as single or double layers cup parts with thickened inner or outer wall, disc-like parts with thickened rim, etc.

1. SFP principle of thickening in axial direction

It is difficult to manufacture cup part whose wall thickness is greater than that of its bottom by general sheet metal forming technology. As is well known, on the one hand, making the thickness of sheet metal reduction by compression is almost impossible due to the great metal flow resistance. On the other hand, it is not able to obtain different thicknesses of wall and bottom by stamping, although it is very effective to form the spatial shape of sheet metal part. The SFP of thickening in axial direction is just feasible to manufacture this type part.

The SFP principle of forming this kind of parts is shown in Fig .1. Firstly, a disk blank is formed to a single or double layer cylinder cup by a conventional drawing or hole flanging process. And then the inner or outer wall is thickened by an axial upsetting process. In the thickening step, the non-freestyle upsetting process such as hydraulic pressure assistant upsetting and small gap upsetting with rigid support will be used. In the former upsetting, a hydraulic pressure is adopted to make the blank stick with the sidewall of die to ensure stability (see Fig.1 a). In the latter upsetting, a mandrel is placed in the center hole. When the wall comes with a slight local thickening, the other cavity wall will contact it immediately to stop a further instability causing folding defect.

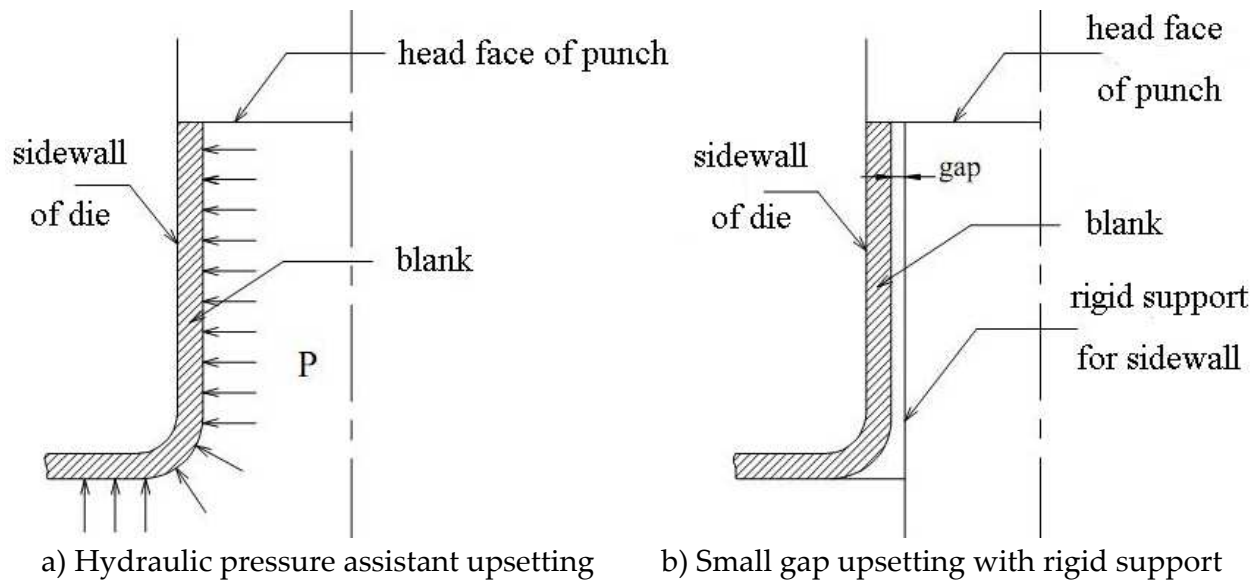
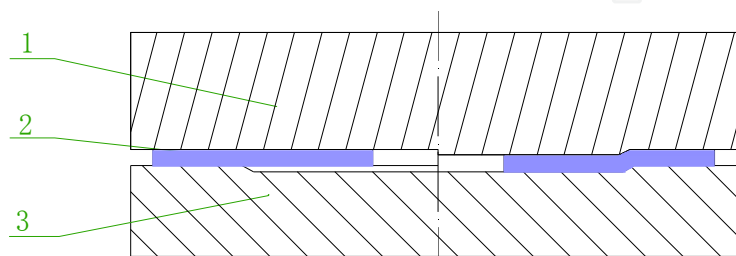


Figure 1. Diagram of axial thickening SFP

In the hydraulic pressure assistant upsetting, the sidewall will be thickened greatly because the stabilities of sidewall of the blank can be guaranteed effectively by the assist of hydraulic pressure. The die for this upsetting process is complicated and its application is greatly restricted by high sealing requirements of the whole structure. Whereas, the instability of the parts wall in a small gap upsetting with rigid support can be controlled by increasing the upsetting step or decreasing the amount of thickening. Compared with the hydraulic pressure assistant upsetting, the dies of small gap upsetting with rigid support are simpler, in which, only a mandrel is needed to put in the center hole of part, and the gap between punch and mandrel could be changed by changing the diameter of the tooling.

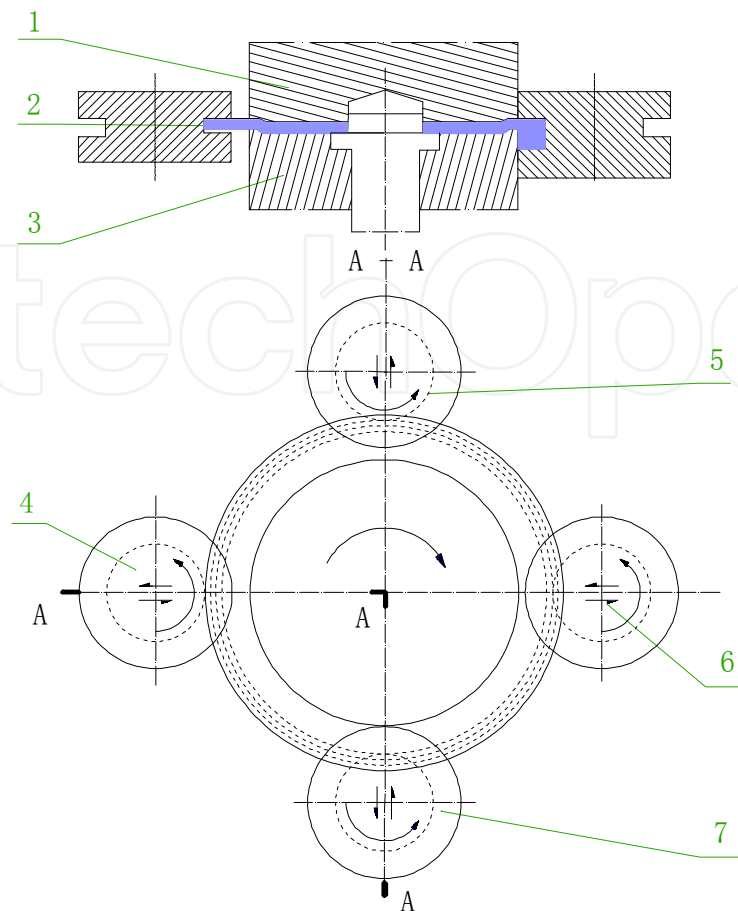
2. SFP principle of radial thickening process

The principle of radial thickening process is shown in Fig. 2 and Fig. 3. Firstly, a conventional drawing is used to form a lower boss in the center of the preformed part (Fig. 2). Then the preformed part is clamped in the center by the upper spindle and lower spindle of spinning machine (Fig. 3). When the preformed part rotates together with the spindles, the rollers feed in radial direction and thicken the rim one by one. The lower mandrel inserted into lower spindle can stop the part sliding in the radial direction between the spindles when bears asymmetric radial force during spinning.



1- Upper die 2-Blank 3-Lower die

Figure 2. Perform by stamping



1-Upper spindle 2-Preformed part 3-Lower spindle 4,5,6,7-Rollers

Figure 3. Radial thickening by spinning

1.2. Classification of SFP

In terms of the combination mode of stamping and forging, the SFP process can be classified as compound SFP and sequence SFP. In the compound SFP, the stamping process and local bulk forming are carried out in one die-set. In the sequence SFP, the stamping process and subsequent local bulk forming are carried out in different die-sets.

In terms of the tool movement, the SFP can be also classified as linear SFP and rotational SFP. In the linear SFP, the tools move along a line and thicken the local feature wholly in one or more axial upsetting steps. In the rotational SFP, the tools feed along a radial direction and thicken the rim of the blank incrementally.

1.3. State-of-the-art of SFP

With the increasing demand of lightweight and high properties of parts, SFP has become a research hotspot in the field of metal forming [1]. More and more parts were made by SFP instead of conventional method [2]. Tan et al. developed a two-stage forming process of tailor blanks having local thickening for controlling the distribution of wall thickness of

stamping parts. In the first stage, the target portion of the sheet for the local thickening was drawn into the die cavity, and then the bulging ring was compressed with the flat die under the clamping of the flange portion in the second stage ^[3]. Mori et al. developed a two-stage cold stamping process for forming magnesium alloy cups having a small corner radius from commercial magnesium alloy sheet. In the first stage, a cup having large corner radius was formed by deep drawing using a punch having large corner radius, and then the corner radius of the cup was decreased by compressing the side wall in the second stage. In the deep drawing of the first stage, fracture was prevented by decreasing the concentration of deformation with the punch having large corner radius. The radii of the bottom and side corners of the square cup were reduced by a rubber punch for applying pressure at these corners in the second stage ^[4]. Mori et al. also developed a plate forging process of tailored blanks having local thickening for the deep drawing of square cups to improve the drawability. A sheet having uniform thickness was bent into a hat shape of two inclined portions, and then was compressed with a flat die under restraint of both edges to thicken the two inclined portions. The bending and compression were repeated after a right-angled rotation of the sheet for thickening in the perpendicular direction. The thickness of the rectangular ring portion equivalent to the bottom corner of the square cup was increased, particularly the thickening at the four corners of the rectangular ring undergoing large decrease in wall thickness in the deep drawing of square cups became double ^[5]. Wang et al. prompted a drawing-thickening technology with axial force for double-cup shape workpieces by combining the characteristics of cold extrusion with drawing process ^[6]. An axial thrust was exerted to the sidewall during backward drawing to achieve the purpose of drawing and thickening ^[7]. Wang et al. also adopted SFP to form a flywheel plate and a sleeve with thickened wall instead of a traditional process, such as cutting and weld assembling ^[8,9].

Compared with traditional metal forming methods joining parts of different thickness by welding, the SFP method mentioned above can not only decrease the cost, but also can produce high quality sheet metal parts with shorten supply chains. With the development of industry, especially automotive industry, large quantities of parts with different wall thickness are needed. Thus, it is important to research SFP technology to manufacture such kind of sheet metal parts.

2. Thickening of outer wall of cup parts with axial upsetting

2.1. Design of thickening process and thickening ratio in single upsetting

In the SFP of cup parts with thickened wall, the axial upsetting of the wall is similar to tube upsetting. There are four situations of the forged piece formed from tube stock by upsetting processing: inner diameter remained and outer diameter enhanced, inner diameter decreased and outer diameter remained, inner diameter decreased and outer diameter enhanced, both inner and outer diameter enhanced and the thickness of the wall of tube is unchanged simultaneously. For the sheet metal upsetting thickening processing, there is no deformation mode that both inner and outer diameter enhanced and thickness is basically

unchanged. In this section we mainly talk about the sheet metal upsetting thickening processing that inner diameter decreased and outer diameter remained.

For the cup part with thickened outer wall, the axial upsetting can be used to thicken the wall after drawing. The schematic of outer wall thickening process is shown in Fig. 4. At first stage, the sheet metal with uniform thickness is drawn into the die cavity by large round corner punch for preventing the occurrence of fracture. At second stage, the formed cup is ironed firstly by small round corner punch to make bottom to specified dimension. Then, a circular upsetting punch compress the outer wall to a thickened dimension and make the outer round corner to a specified radius.

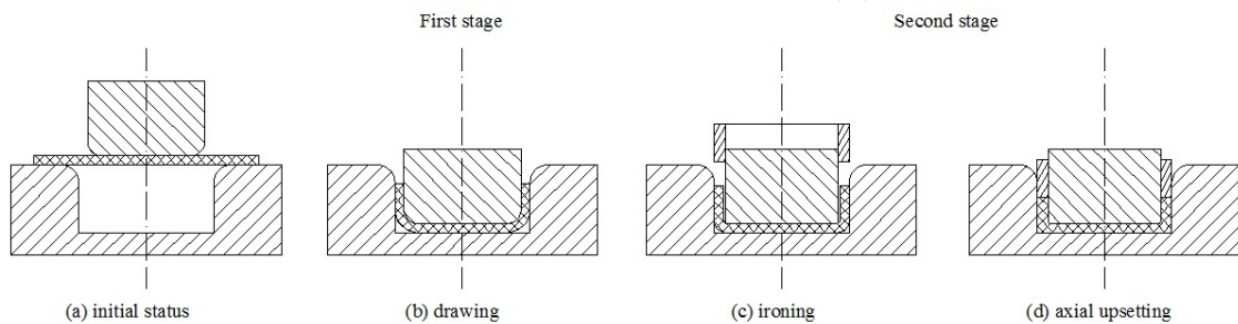


Figure 4. Schematic of outer wall thickening process.

Due to the wrinkling is easy to occur during axial upsetting, it's important to determine the limitation of thickening. In this section, thickening ratio of upset thickness to initial thickness is presented to define the formability. There are several geometry parameters play important roles in thickening ratio, such as wall height and inner corner radius, etc. The allowable thickening ratio under different conditions is shown in Fig. 5. The digits in the

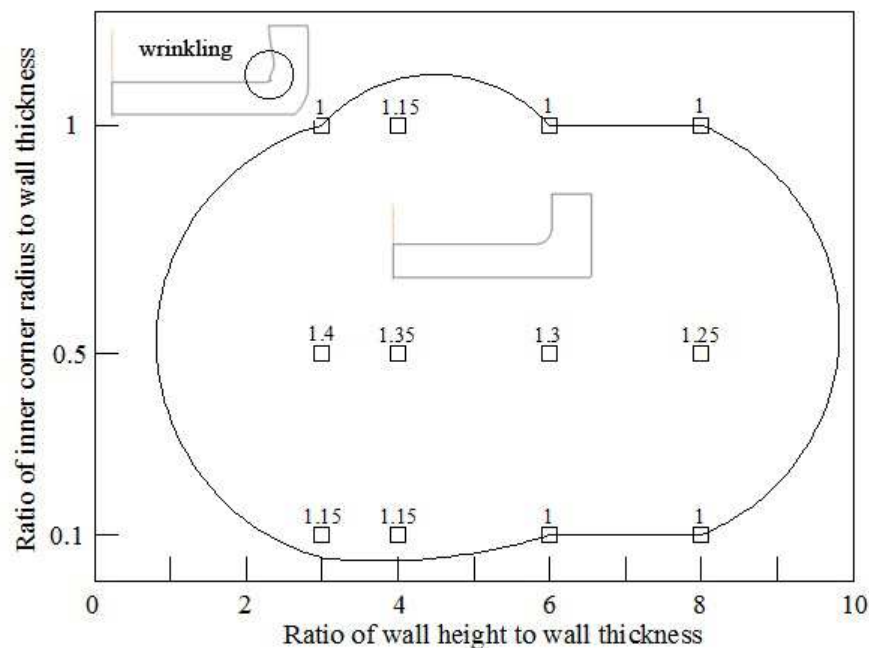


Figure 5. Allowable thickening ratio under different conditions.

figure are the thickening ratios obtained from simulation results in which the outer diameter of part is 120 mm. The number 1 represents the part occurred folding under corresponding conditions. It can be seen that the zone enclosed by lines is suitable for thickening the outer wall. When the ratio of inner corner radius to wall thickness is about 0.5, the thickening ratio has the largest value, which achieves to 1.4. With the increasing of wall height, the thickening ratio decreases under the condition of any inner corner radius.

2.2. Calculation of forming load

2.2.1. Upsetting force F_u

The axial upsetting is a closed-die forging process. Although the metal flow is different from that of tubing upsetting at beginning, the final upsetting force is similar to tubing upsetting force. So, according to calculation method of tubing upsetting force, the upsetting force can be expressed as an empirical formula:

$$F_u = 1.3pA$$

where p is the average upsetting stress (MPa), A is the area of wall section (mm²).

2.2.2. Methods for reducing forming load

Because the axial upsetting is a closed-die forging process, the upsetting force increases rapidly at the end of metal forming. Relief cavity can be set in dies or blank to increase free flow surface and avoid full closing realizing reduction of upsetting force. The design of relief cavity can adopt the following three styles: a) center hole relief at the bottom of cup, b) relief cavity at the dies corresponding to outer corner between wall and bottom, c) combined relief style.

1. Hole relief

If there is a center hole at the bottom of cup, hole relief method can be used to reduce upsetting force. In this method, piercing process must be carried out before axial upsetting. Then, while the outer wall is upset axially, the metal is enforced to flow to the center of the bottom, at where there is a free flow surface. The metal forming is no longer a closed die forging. So, the upsetting force can be decreased. Certainly, as a result of axial upsetting, the diameter of hole is decreased during the wall thickening. It is suggested that the center hole of part can be obtained by means of designing a proper relief hole which will be shrunk to specified dimension. This is able to reduce the upsetting force as well as avoid piercing again.

2. Relief cavity

From the metal flow of upsetting process mentioned in above section, outer corner between wall and bottom is the last formed position of part. During forming this position, the upsetting force increases rapidly. It can be considered to adding a relief

cavity in the die corresponding outer corner, which can increase free flow surface and decrease the upsetting force. After upsetting, machining should be carried out to clear the unnecessary metal away.

The position and shape of relief cavity can be designed as two modes as shown in Fig. 6: a) at the bearing plate under the bottom of the cup, which needs to manufacture a circular cavity in bearing plate; b) at the die and bearing plate, which needs to manufacture circular cavities in bearing plate and cylinder die respectively.



1-Bearing plate, 2-Cylinder die

Figure 6. Mode of relief cavity.

As using relief cavity method, the metal flow is similar to that of without relief cavity before the die fully filled. There is just a few of material enforced to flow into relief cavity after the wall formed. Finally, the cavity is not fully filled, which remain a little of free surface resulting in a decrease in upsetting force.

3. Combined relief method

The two relief methods mentioned above can be used together. A center hole is pierced before upsetting, as well as a relief cavity is designed in the dies. In this way, the upsetting force relief can be more than that of single method, just not significant.

The center hole relief method is suitable for single wall part having center hole at the bottom. After axial upsetting, the formed part does not need more machining and can keep complete streamline. However, the effect of this method on reducing force is less than that of relief cavity. This is because the material has to flow to the center of the bottom, nevertheless, in the relief cavity method, the unnecessary material flow to relief cavity directly; the flow distance of the former method is longer than that of the later method. But the part manufactured by relief cavity method has to be machined to clear the unnecessary material away, which will break the streamline. In brief, it is necessary to take into account part structure and performance requirements when choose relief method.

2.3. Application

In this section, an application of axial upsetting is presented. The application object is flywheel plate used in self-changing gearbox. The dimensional drawing and three dimension model of

part are shown in Fig. 7 and Fig. 8, respectively. It can be seen from figures that the flywheel plate is a cup type part with large diameter, 273.3 mm, while the wall thickness is 11 mm, and the bottom thickness is 10mm. The corner between wall and bottom is very small, inner round radius is 5 mm and outer round radius 2.5 mm. Moreover, there is one center hole and three auxiliary holes at the bottom of cup. The part material is 45 high quality carbon steel, which will has good mechanical properties after quenching and tempering.

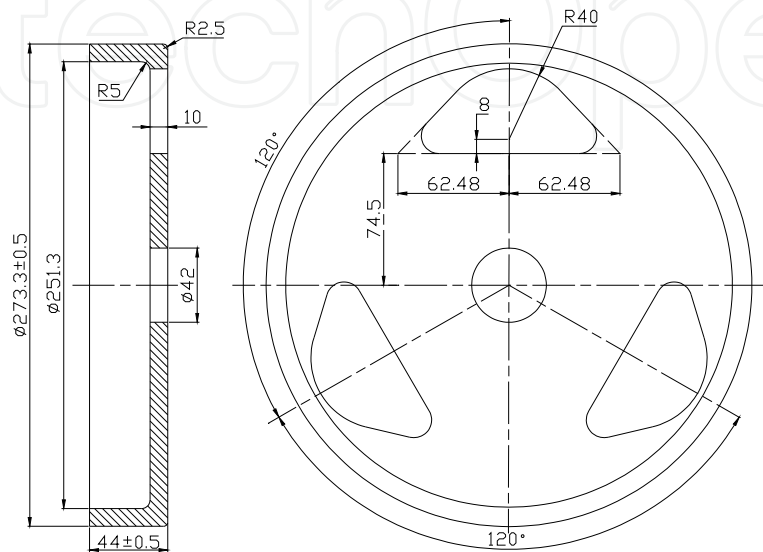


Figure 7. Dimensional drawing of flywheel plate.

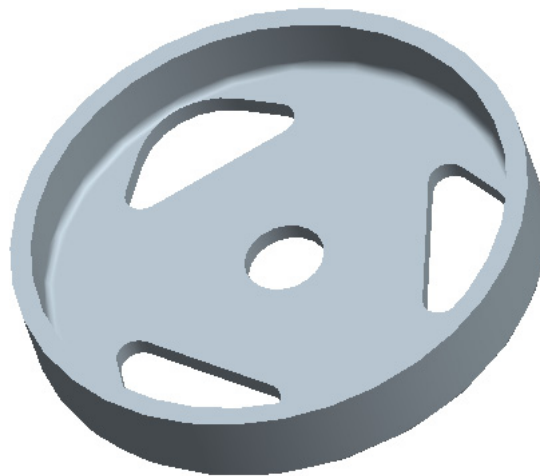


Figure 8. Three dimensional model of flywheel plate.

Due to the part has different thickness in the wall and the bottom, and a small corner radius, traditional drawing process can not obtain desired part. If employing machining, the material usage is very low about 35%. Moreover, machining will cut streamline, which may lower mechanical properties. If the bottom and the wall are formed, respectively, and then combined to a complete flywheel plate by welding, the weld seam has a harmful effect on mechanical properties, which may not satisfy the performance requirement.

The thickening ratio of flywheel plate is 1.1. According to thickening ratio criterion, the wall thickness can be upset to designed value in one pass. So, the flywheel plate can be manufactured by sheet stamping-forging technology. Taking 10 mm circular plate as blank, firstly is drawn to a cup with uniform thickness, then the wall of cup is thickened to 11 mm by axial upsetting.

In order to decrease deformation stress, the warm forming was used in drawing and upsetting processes. Generally, the warm forming is a technology carried out at temperature between room temperature and recrystallization temperature, during which the deformation stress of material is significantly lower than that at room temperature.

The stamping-forging processes are as follows: blanking, heating, drawing, finishing inner corner and axial upsetting, piercing.

1. Blanking

Due to the thickness of bottom is 10 mm, the circular blank with 10 mm thickness is chosen. The diameter of blank is 337.8 mm calculated by constant volume principle. To obtain high quality circular blank, fillet edge dies with small clearance between punch and die was used for blanking. The dimensional accuracy reached grade IT9-IT11, and the surface roughness was Ra3.2-0.8 μm .

2. Heating

The electric resistance furnace full of protective atmosphere was used for heating the blank in order to reduce oxidization. The blank was heated to 800-850 $^{\circ}\text{C}$ and hold for 30 minutes. Meanwhile, the dies were heated to about 200 $^{\circ}\text{C}$.

3. Drawing

A 1000 kN mechanical press was employed to carry out the drawing process. The key process parameters, such as radius of punch and die, were determined by empirical principle.

As blank thickness larger than 6 mm, the radius of punch can not less than 1.5-2 times of the thickness. In this application, the radius of punch must larger than 15-20 mm. So, the radius of punch was chosen as 15 mm to reduce the amount of finishing.

The radius of die was determined by the following empirical equation:

$$r_d = (2 \sim 4)t = (2 \sim 4) \times 10 = 20 \sim 40 \text{ mm}$$

where t is the thickness of blank (mm). In this application, the radius was 20 mm.

4. Finishing inner corner and axial upsetting

An 8000kN mechanical press was used to finish inner corner and upset the wall. After the inner corner was ironed by a punch with 5 mm radius, the side wall was upset to desired dimension while the bottom of cup was clamped. Because the relief cavity reduces upsetting force significantly, the relief cavity method was adopted in this application.

5. Piercing

After axial upsetting, four holes at bottom were formed by piercing.

The flywheel plate manufactured by stamping-forging technology is shown in Fig. 9. It can be seen that there is no defect in forging surface, and the thickness of outer wall reaches the specified dimension.



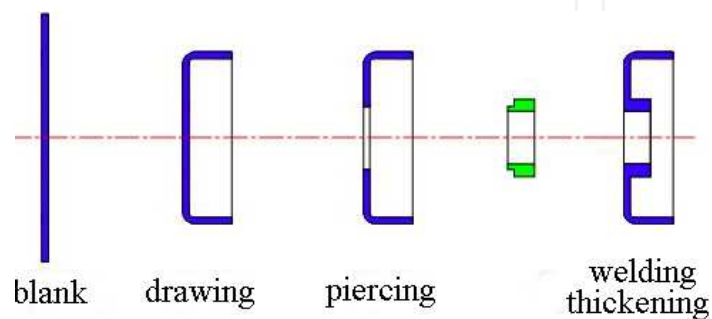
Figure 9. Flywheel plate of car with outer wall thickening.

3. Thickening of inner wall of cup parts with axial upsetting

3.1. Design of thickening process for inner wall of cup parts

The forming process and methods of typically double-layer cup with inner wall thickened by axial upsetting are introduced in this section.

As shown in Fig. 10a, the traditional metal forming method for manufacture double-cup-shape part with thickened inner wall is that several partitions divided from the part is formed separately and assembled by the welding to a whole part. The part made by this method would decrease the mechanical performance of the part and production efficiency. In stamping-forging processing (see Fig. 10b), an initial blank is formed to a cup firstly by forward drawing. Then the bottom of the formed cup is drawn backward to form a double-layer cup by powerful drawing. While backward drawing, the material of outside wall is pushed to the inner wall making the inner wall as thick as possible. Subsequently, the center hole is formed by piercing and the inner wall is straightened by flanging. Finally the inner wall of the cup is thickened by upsetting.



a) Traditional processing

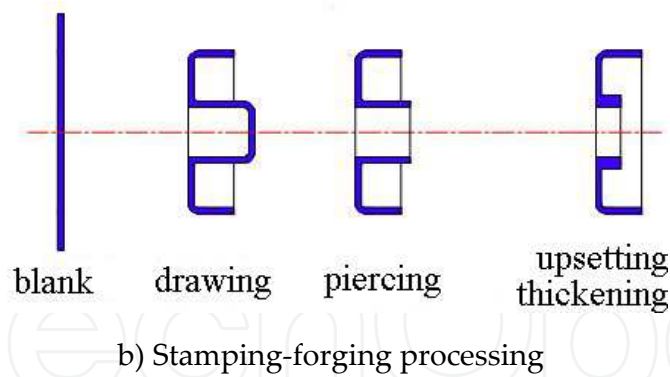


Figure 10. Scheme of forming process

3.2. Material store-up for inner wall using reverse drawing

In the forming of double-cup-shape part, the reverse cup-shape partition is formed by backward drawing to a certain height, which is prepared for subsequent thickening process. However, because it's difficult for the material of the outside wall flows to the bottom through the fillet, the backward drawing causes severe decrease in the thickness of inner wall. In order to improve stiffness of the inner wall and make the upsetting carried out latter more smoothly, the thickness of inner wall after backward drawing should be as thick as possible. Namely, it's necessary to store material during backward drawing.

As the required part could not be obtained by conventional backward drawing in one procedure, the process of powerful drawing in which a downward thrust is exerted on the outside wall to make metal flow to the inner wall is presented to get the thickened inner wall, as shown in Fig. 11. A pressure ring and a punch moves down and up, respectively, while the blank is clamped by blank holder. The die which is given an axial upside back pressure moves with pressure ring.

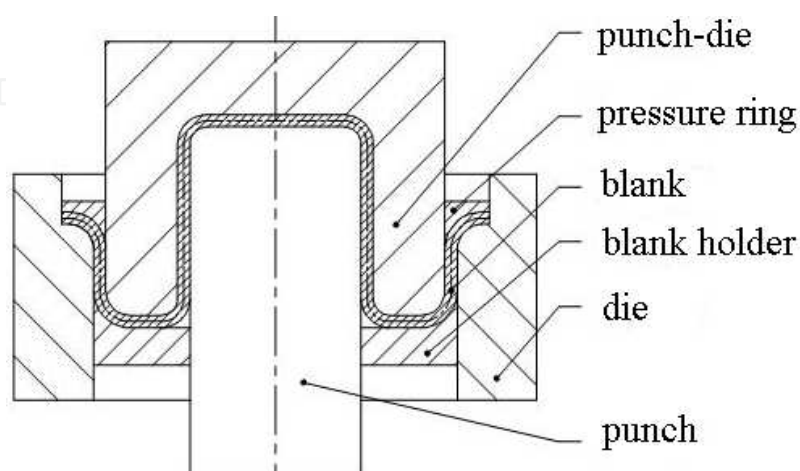


Figure 11. Diagram of thickening by powerful backward drawing

3.3. Application

3.3.1. Simulation of stamping-forging processing for the center hole edge of clutch hub

Stamping-forging processing for the center hole edge of car clutch hub was presented in this section. The schematic of clutch hub is shown in Fig. 12. As we can see in view B, the center hole edge is 3.5 mm in height and 1 mm in thickness, while in other position of part the thickness is 2.5 mm. There is a bevel of 45° to the center hole and a right angle shape around the hole. According to the features of the component, SFP technology should be employed. So, drawing, piercing, and spinning processes were used to obtain its structure of hollow shape, and then flanging and upsetting were used to obtain the required part.

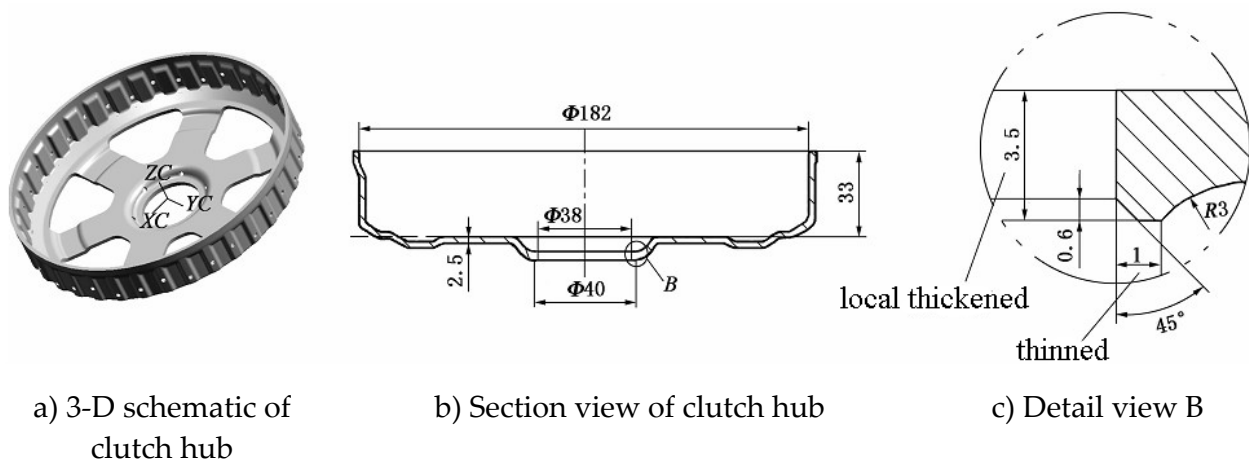


Figure 12. Schematic of clutch hub

As shown in Fig. 13, the shape of upper-punch and die cavity is in accord with the component, while the upsetting-punch (shown in Fig. 13b) is with ladder shape. Two steps were applied to implement the procedure: in the first step, the flanging-punch moved down to complete flanging process while other dies stayed where they were, and then it moved up; in the second step, the center hole edge was thickened and the right angle of it was formed with the upsetting-punch moving up. Since the thickness of the inner wall is not thinned by flanging, machining was needed to obtain the diameter 38 mm as well as the angle 45°.

The FEM software MSC.Marc can be used to simulate the forming process by taking half of the part because of the axisymmetric shape. Four-node quadrangles were available, and the mesh adaptive function was activated considering the large deformation in the process of forming. The initial thickness of the blank was 2.5 ± 0.1 mm, and the stress-strain curve was obtained by tensile test. As we described before, the flanging-punch moved down and returned for the first 400 steps to finish flanging, and then in the last 200 steps of simulation, the upsetting-extruding punch moved up to complete upsetting process. The friction coefficient was set as 0.1.

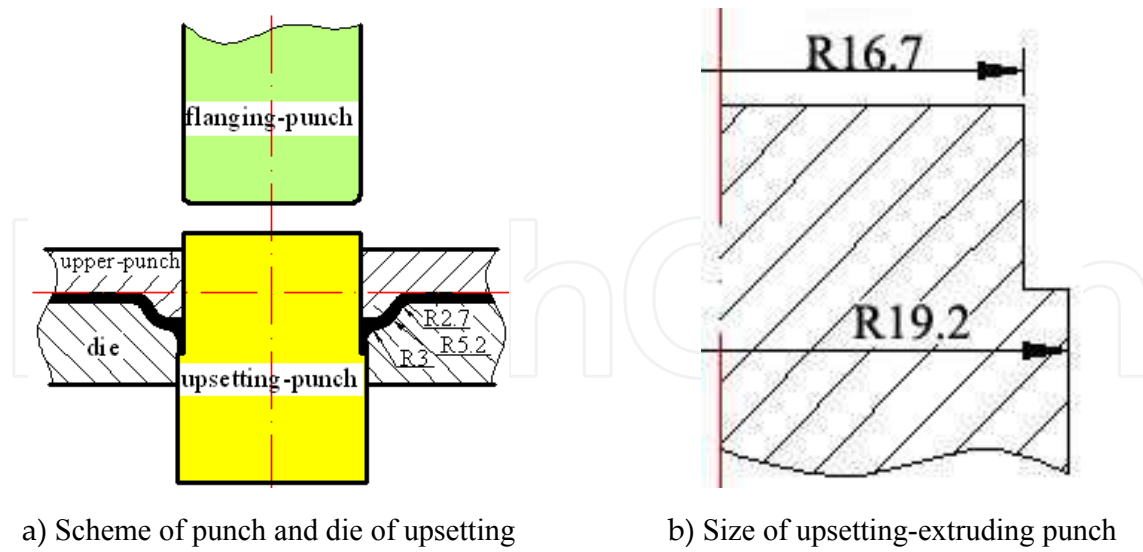


Figure 13. Scheme of punch and die when upsetting

The result of finite element simulation is shown in Fig. 14. It can be observed that there is no folding at the bottom and the right-angle shape is formed perfectly. The load for the upsetting-extruding punch predicted by FEM is given in Fig. 15, of which the maximum is about 526.7 kN.

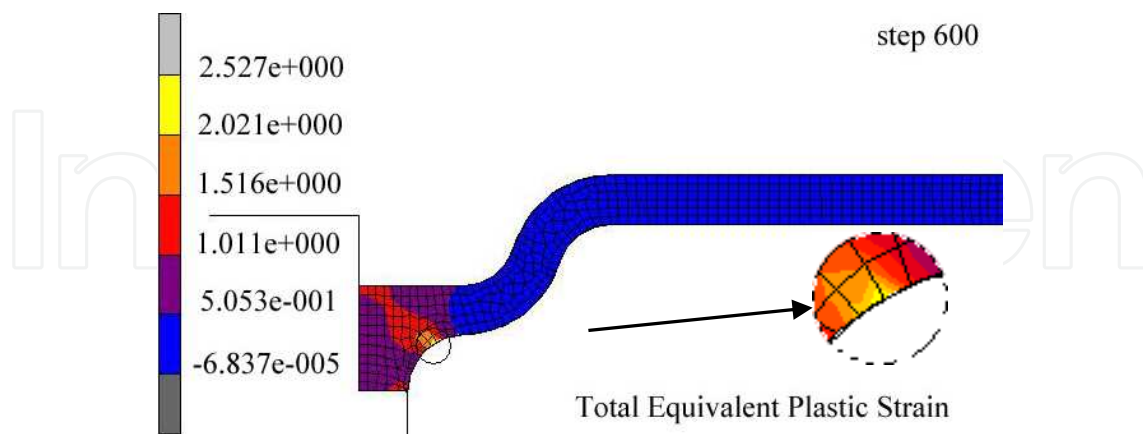


Figure 14. Result of upsetting-extruding

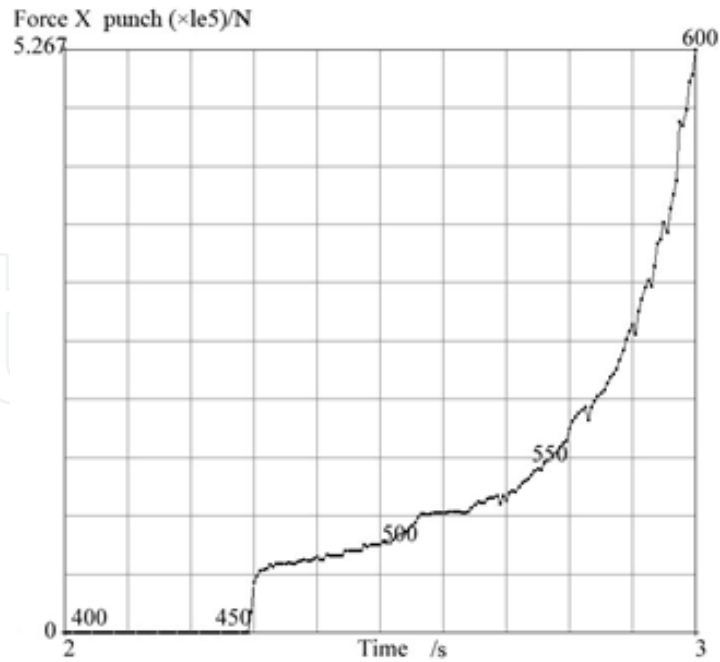


Figure 15. Forming load curve (from step 400 to step 600)

3.3.2. Experiment on stamping-forging process of double-cup-shape part with thickened inner wall

The typical double-cup-shape part with thickened inner wall is shown in Fig.16. It is a rotary part, in which the thickness of the inner wall is larger than that of other region. In order to improve the mechanical properties of the part, material utilization and production efficiency, the stamping-forging hybrid forming process mentioned before was used. As described earlier, the process was divided into three stages: forward drawing, then backward drawing, piercing and flanging, finally upsetting to get the inner wall thickened (shown in Fig. 17).

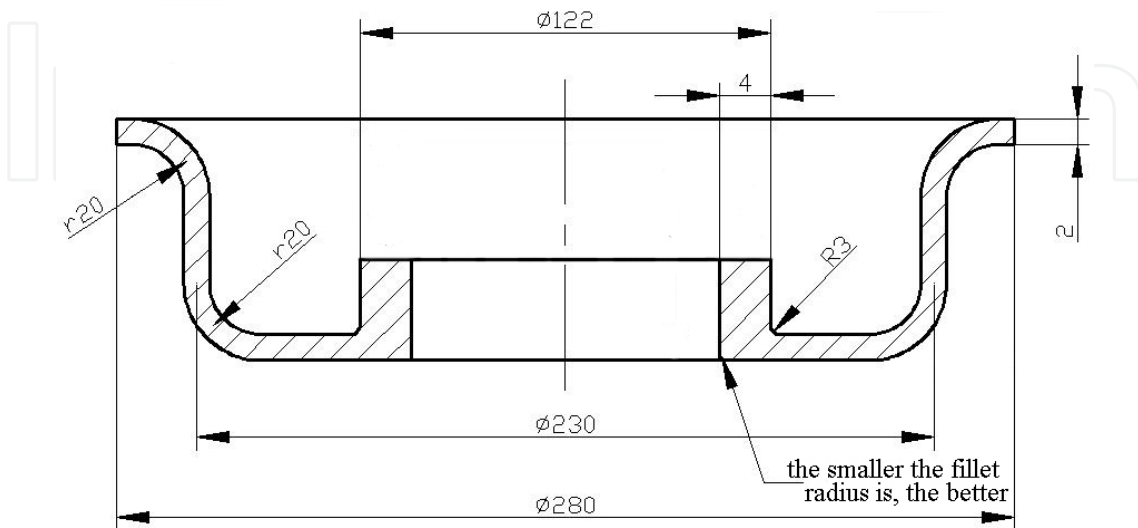
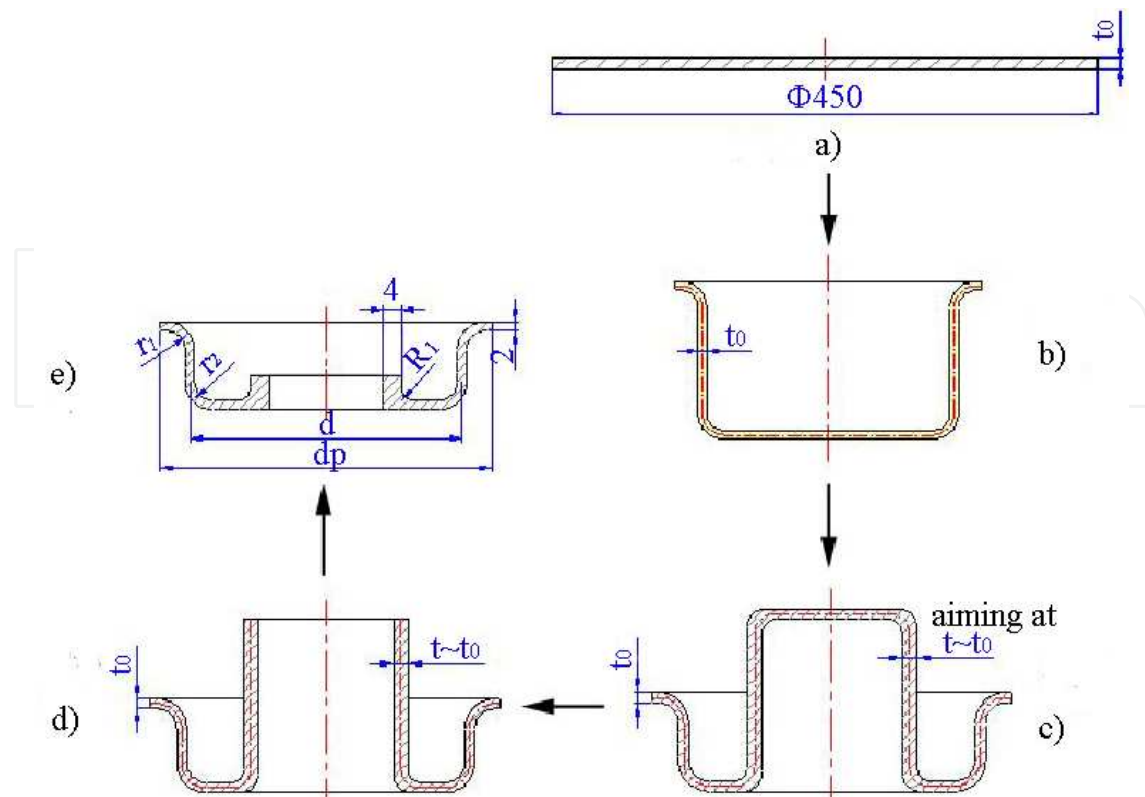


Figure 16. Scheme of double-cup-shape part



a) Blanking b) Forward drawing c) Powerful backward drawing
d) Piercing and flanging e) Thickening by upsetting

Figure 17. Scheme of stamping-forging processing of double-cup-shape part

The mechanical properties of the material are shown in Table 1. The experiment was conducted at a dual-action deep drawing hydraulic press (see Fig. 18), and the sheet metal material was 08AL steel with initial thickness of 2 mm. The nominal pressure of inner slider is 3000 kN and the outer is 2000 kN. The velocity and maximum effective stroke of the inner and outer slider are 10 mm/s and 500 mm, respectively. The nominal pressure of ejector of the hydraulic machine is 1000 kN, while the ejection stroke is 160 mm, and the velocity is 30 mm/s.

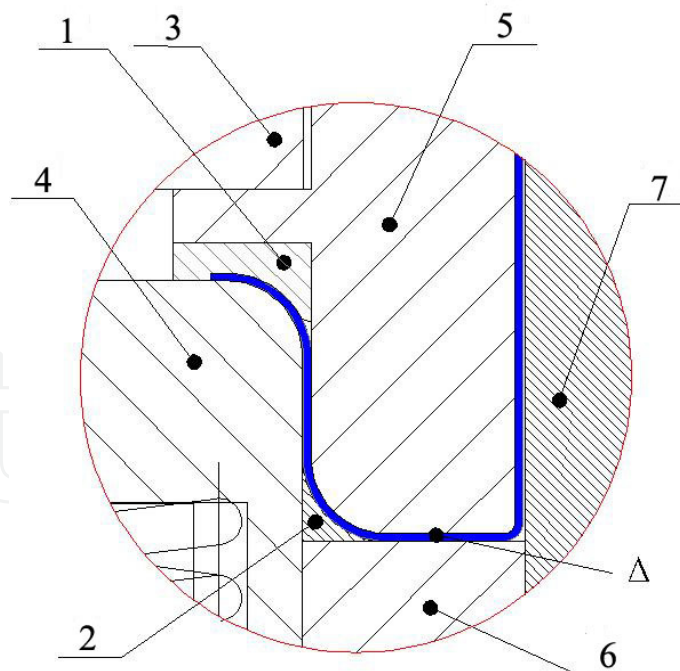
| Parameter | Density/kg/mm ³ | Young's modulus /N/mm ² | Poisson ratio | Yield stress /N/mm ² |
|-----------|----------------------------|---------------------------------------|------------------|---------------------------------|
| Value | 7.8×10^{-6} | 2.07×10^5 | 0.28 | 1.713×10^2 |

Table 1. Mechanical properties of the material

The partial view of backward drawing and upsetting die is shown in Fig. 19. Δ is clearance which influences the flow of material in powerful backward drawing between punch-die and the die. If the gap is too much, wrinkling and folding defect may happen more easily. Instead, the resistance force will be increased, which leads to thinning or even rupture of the inner wall in backward drawing process. According to the thickness of the sheet metal is 2 mm, experiments on the gap were conducted more than once until the most satisfied clearance 3.5 mm was obtained. The formed part is shown in Fig. 20.



Figure 18. Dual-action deep drawing hydraulic press



1- Upper pressure ring 2- Lower pressure ring 3- Blank holder
4- Floated die 5- Punch and die 6- Fixed die 7- Mandrel

Figure 19. Partial view of upsetting die

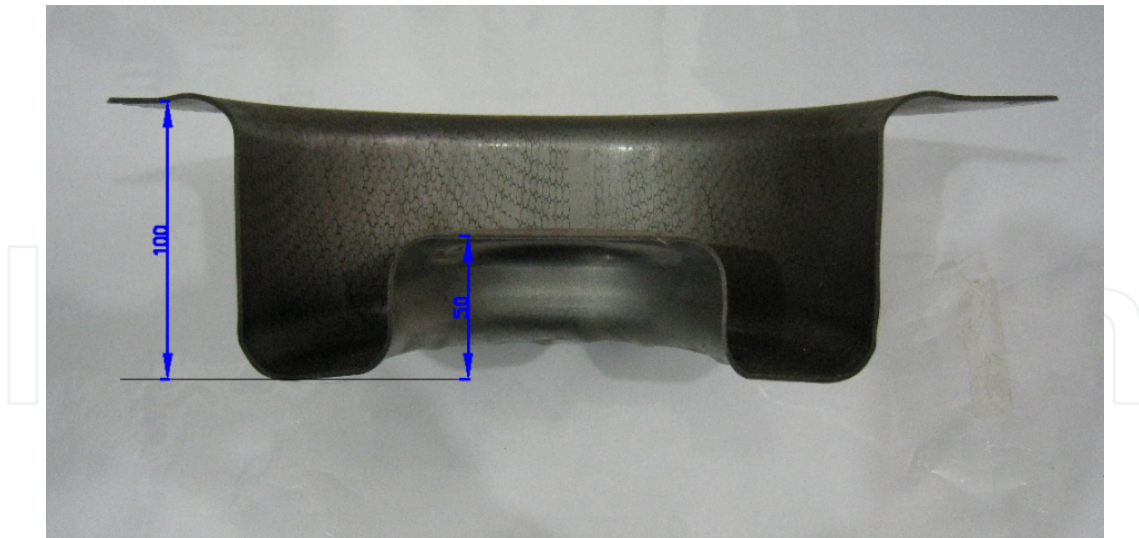


Figure 20. Section plan of double-cup-shape part by backward drawing

After powerful backward drawing, material of outer wall flowed into inner wall. The height of outer wall was decreased from 128 mm to 100 mm, while the height of inner wall was increased to 50 mm. Fig. 21 shows the measurement path of wall thickness along radial direction, and Fig. 22 shows the distribution of wall thickness. It can be seen that the wall thickness is not homogeneous along the radial direction, showing characteristics of shock fluctuation obviously. In the flange region from point 1 to point 10, the wall thickness is larger than that of initial blank due to composite effect of hoop pressure stress and tension stress in the radial direction during forward drawing. In the outer wall region from point 10 to point 23, the wall thickness is less than that of initial blank and it goes down from top to bottom. The diameter of the region point 23 to point 26 decreases with round corner of bottom, because this region is mainly suffered from hoop pressure stress resulting in thickening in the thickness. In the bottom region from point 26 to point 35, the wall thickness first decreases and then increases, and the thinnest place is at the center of bottom plane. In the inner wall region from point 35 to point 52, the wall thickness is severely thinned because of large tension stress in the radial direction; the closer near the central

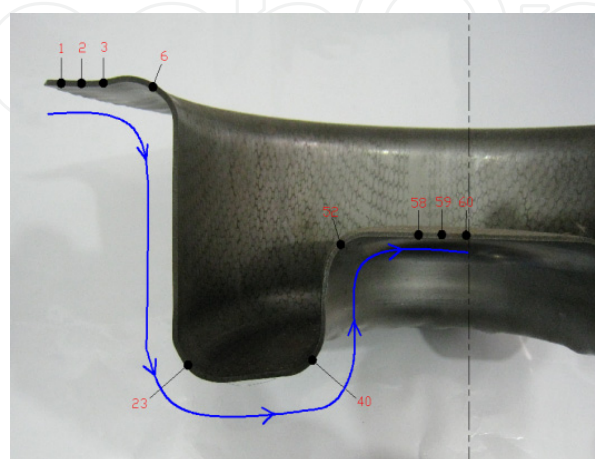


Figure 21. Measurement path of wall thickness of part

region, the thinner the wall is; and the thinnest point is the round corner of backward drawing punch. The region from point 52 to point 60 is also mainly suffered from tension stress, thus the entity wall is thinned. But close to the center, away from round corner of backward drawing punch, the blank is subjected to less deformation, so the wall thickness increases slightly compared with that of round corner.

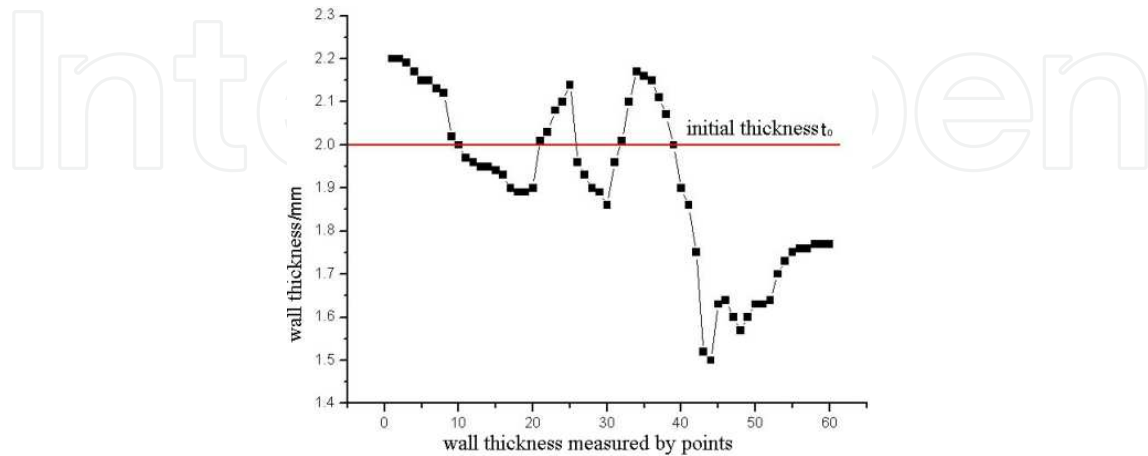


Figure 22. Distribution of wall thickness of part

According to the analysis above, thickness of inner wall is still thinned after powerful backward drawing due to various factors, such as stress in different region and friction between tools and material. However, if we do not use powerful backward drawing, the thickness of inner wall will be thinned more severely. Although the thinning of inner wall during backward drawing is not beneficial to the upsetting of this region, the double-cup-shape part with the inner wall of 4 mm was made successfully with optimized processing parameters. To avoid folding defect caused by bending of the blank, an upsetting with small gap and rigid support was used. The thickened part compared with non-thickened part is given in Fig. 23.



a) Part with inner wall non-thickened



b) Part with inner wall thickened by upsetting

Figure 23. Comparison of double-cup-shape part before thickening and after thickening

The forming process of the double-cup part is shown in Fig. 24. It is indicated that the double-cup part can be successfully formed by the mentioned stamping-forging hybrid processing.

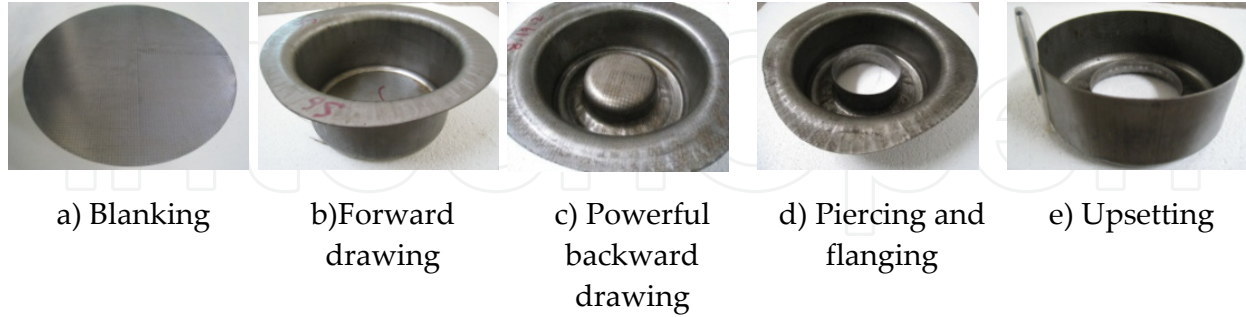


Figure 24. Forming process of the part

4. Thickening of flange of disc-like parts with spinning

The forming process and methods of typically disc-like part with thickened rim thickened by spinning are introduced in this section.

The following calculations in section 4.1. and 4.2. are based on the assumption of plane deformation which the meridian plane of the work-piece keeps planar during forming process. That is, the deformation can be treated as a process of axisymmetric radial compression.

4.1. Design of multi-step process

Thickening ratio is also a key factor during the process design of thickening spinning. It is defined as $\lambda_n = t_n / t_{n-1}$, where t_n is the thickness of the rim after the n time thickening step, t_{n-1} is the thickness of the rim before the n time thickening step. The number of forming step required for rim thickening depends on the total thickening ratio $\lambda = t_N / t_0$, where t_N is the target thickness and t_0 is the initial thickness. Generally, the recommend value in a single thickening for low carbon steel is $\lambda \leq 1.4$. If $\lambda > 1.4$, the thickening could not be obtained in one forming step, a multi-step thickening process will be needed.

In a multi-step forming, t_n is decisive to the roller design and success of the process. Assuming the average strain in each forming step is equivalent, there is $\ln(t_1 / t_0) = \dots = \ln(t_{N-1} / t_N)$. So, the t_n equals to

$$t_n = t_N^{n/N} t_0^{N-n} \quad (1)$$

where, N is the total number of forming steps, n is the number of forming step, $1 \leq n \leq N$.

4.2. Radial feeding force calculation

The feeding force is critical to the choice and design of the capacity of the spinning equipment. An analytical model for calculating the forming forces is very useful, especially when a quick prediction of forming force is required.

As shown in Fig. 25, the final filled zone is the corner enclosed by roller, spindles and workpiece. A small sector body with thickness of one unit is analyzed to calculate the feeding force by slab method.

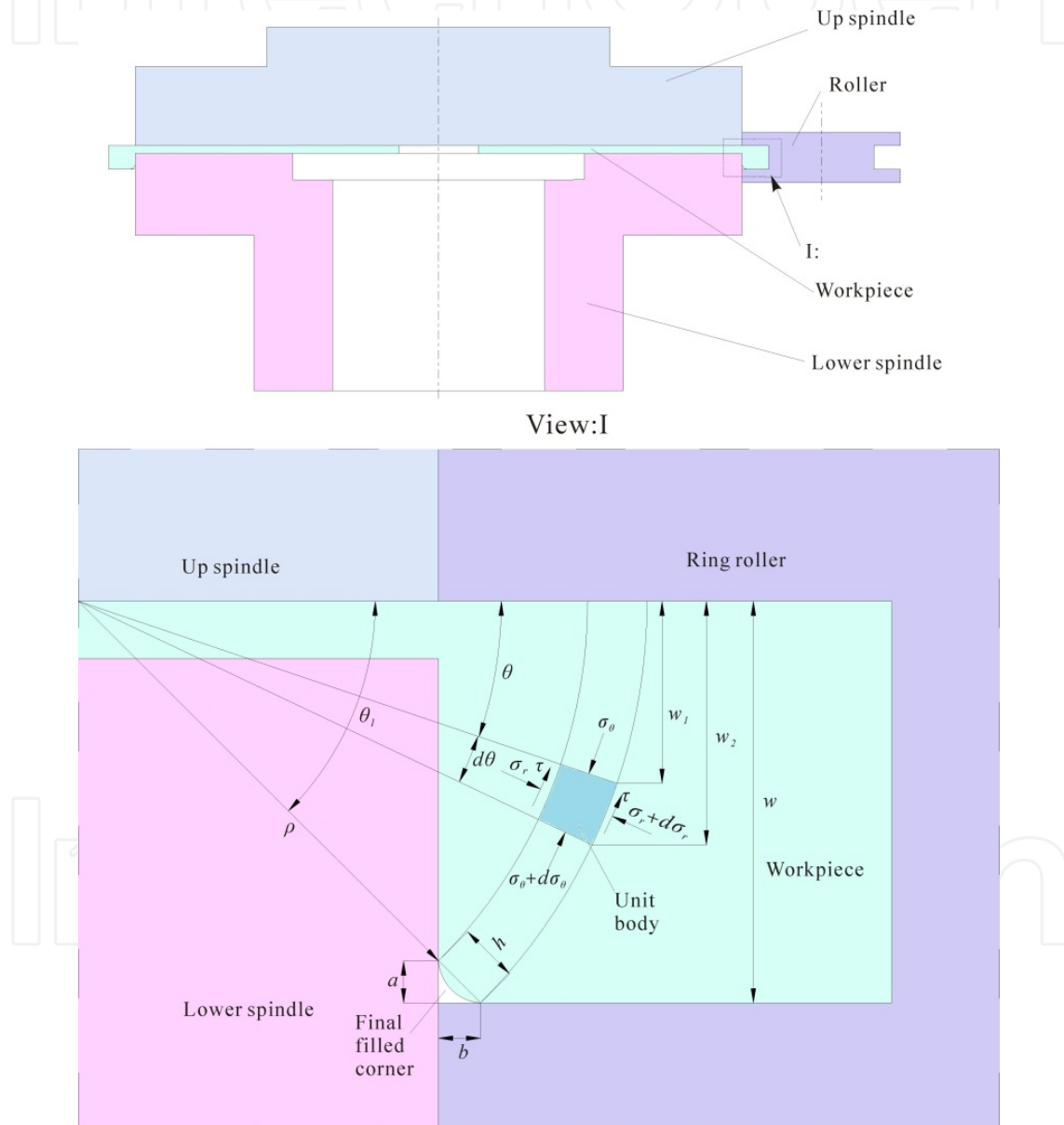


Figure 25. Sketch of principal stress on sector unit body

According to Fig. 25, the force equilibrium equation of the small sector body in θ direction is

$$\tau(2\rho + h)d\theta \times 1 + (\sigma_\theta + d\sigma_\theta)h \times 1 - \sigma_\theta h \times 1 = 0 \tag{2}$$

Substituting boundary condition $\theta = \theta_1, \sigma_\theta = 0$, plasticity condition $\sigma_\theta - \sigma_r = \sigma_s = 2\tau$, and integrating σ_r along the cylinder surface, the mean feeding force f on the body of one unit can be expressed as:

$$f = \int_0^{\theta_1} \sigma_r \rho \cos \theta d\theta = \sigma_s \rho \left[\frac{m}{2} + \frac{m\theta_1}{2} \sin \theta_1 - \sin \theta_1 - \frac{m}{2} \cos \theta_1 \right] \quad (3)$$

where $m = -(2\rho + h)/h$, $\theta_1 = \tan^{-1}(a/b)$, $h = \sqrt{a^2 + b^2}$, $\rho = (w-a)h/a$. h is the width of the sector body in radial direction, σ_θ and σ_r are stresses in tangential direction and radial direction, respectively. σ_s is the tensile strength, τ is the shear yield stress.

Fig. 26 shows the compressed zone of the workpiece, the total feeding force F can be expressed as

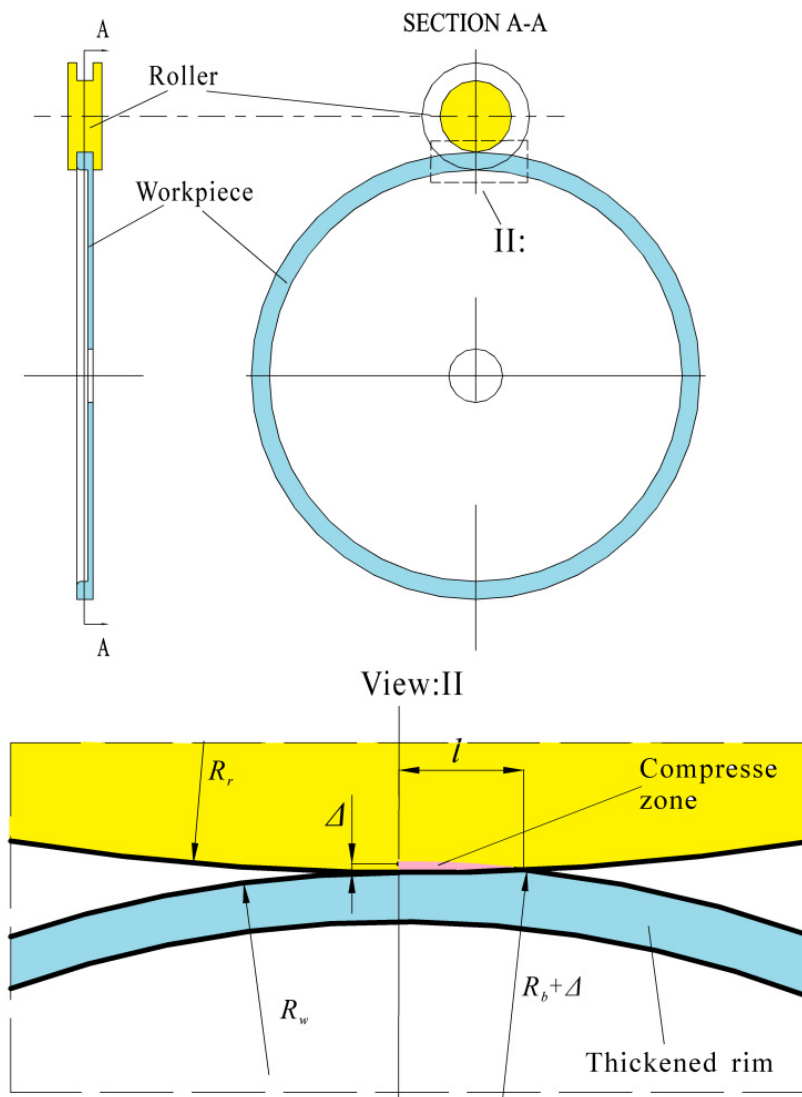


Figure 26. Sketch of compressed zone

$$F = \int_0^l p dt = \sigma_s \rho \left[\frac{m}{2} + \frac{m\theta_1}{2} \sin \theta_1 - \sin \theta_1 - \frac{m}{2} \cos \theta_1 \right] l \tag{4}$$

where, R_r and R_w are the radius of roller groove and final workpiece, respectively. Δ is the feeding distance of the roller in one circle of the work-piece. The radii of the workpiece before the last circle is $R_w + \Delta$, according to Heron's Formula, the length of contacted zone is

$$l = \sqrt{(2r_r + 2r_w + \Delta)\Delta(2r_r - \Delta)(2r_w + \Delta)} / [2(r_r + r_w)]$$

The key to using the equation 4.4 is to obtain the values of a and b . In fact, it could be supposed that a equals to b , and set the value to be the allowable radii r_c of the required parts. Then $\theta_1 = \pi / 4$, $a = b = r_c$.

4.3. Application

In this section, an application example of SFP to manufacture a disc-like part of car with thickened rim will be introduced.

Fig. 27 shows a typical part manufactured by rim thickening. The rim thickness is 3.33 times that of the center portion. The material is 1045 steel, whose Young's modulus is 210 GPa. The relationship of true stress to true strain at room temperature is $\sigma = C\varepsilon^{-n}$ with $C=1019.7$ MPa and $n=0.11$, respectively. Firstly, a pre-formed part shown in Fig. 28 was made by stamping.

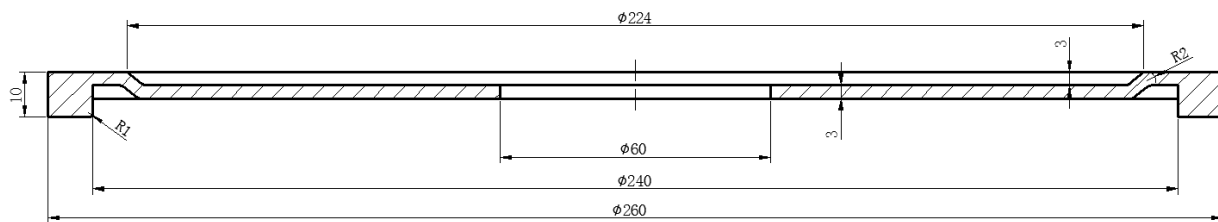


Figure 27. Sketch of part manufactured by rim thickening

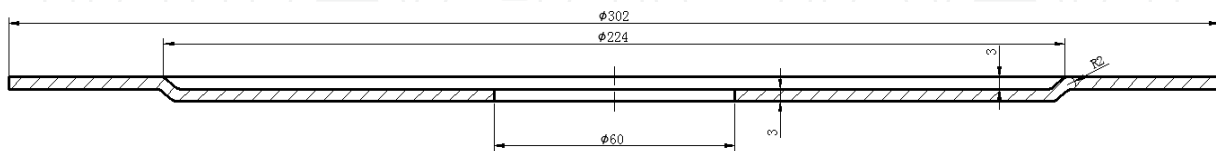


Figure 28. Pre-formed parts by stamping

Because of $\sqrt[3]{\lambda} = \sqrt[3]{t_N / t_0} = 1.494 > 1.4$ and $\sqrt[4]{\lambda} = \sqrt[4]{t_N / t_0} = 1.351 < 1.4$, according to section 4.1, a four-step thickening process is required. The diameter of the spindle was 240 mm, which had the same value with the inner diameter of the thickened rim. The rollers' shape and parameters are shown in Fig. 29, two angular parameters c_1 and c_2 between the groove walls and middle plane, and a fillet with r_1 are designed to avoid scratch of the work-piece.

The middle span b_1 of the groove was calculated by equation (4.1). The parameter values of the tooling are given in Table 2.

| Step No. | a | b_1 | c_1 | c_2 | r_1 | r_2 | d |
|----------|-----|-------|-------|-------|-------|-------|------|
| 1 | 1.5 | 4.10 | 4 | 5 | 0.5 | 1.5 | 17.4 |
| 2 | 1.5 | 5.56 | 4 | 5 | 0.5 | 2.0 | 14.4 |
| 3 | 1.5 | 7.57 | 3 | 4 | 0.5 | 2.6 | 12.1 |
| 4 | 1.5 | 10.2 | 2 | 3 | 0.5 | 0 | 10 |

Table 2. Values of die dimension

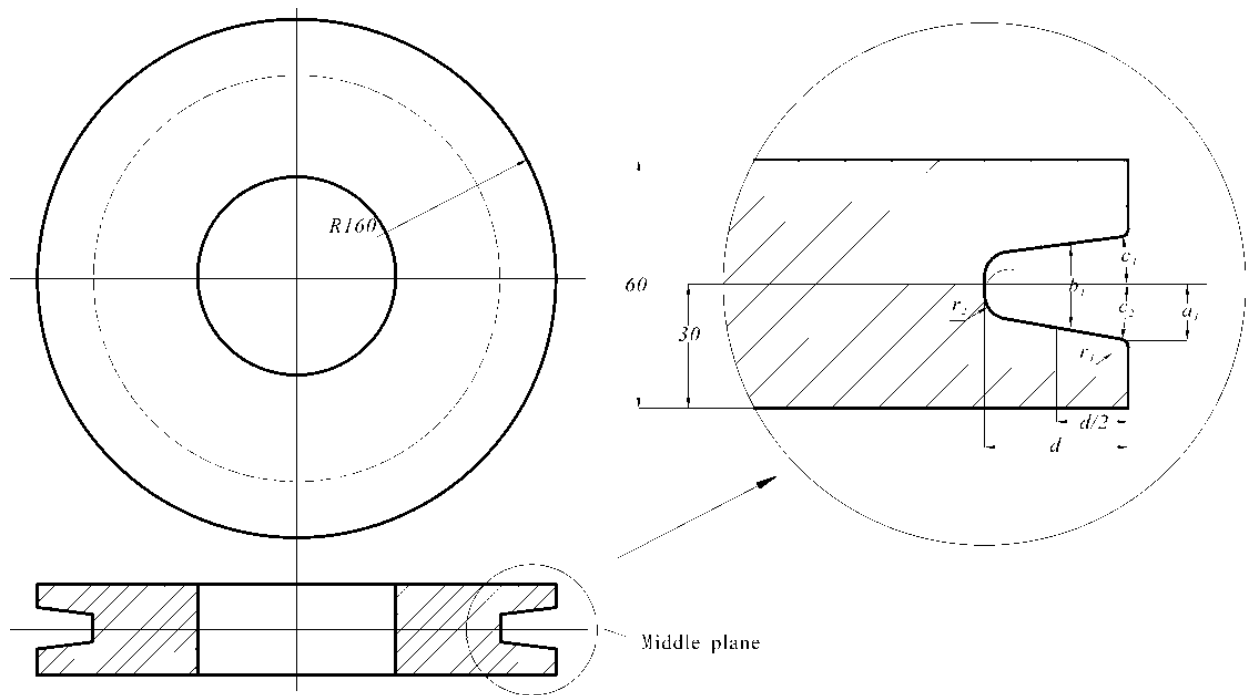


Figure 29. Shape of ring roller

The spinning machine with clamping capacity of 1000 kN was employed, as shown in Fig. 30. The tooling action is controlled by a PLC unit. The groove of the roller was heat-treated to hardness of HRC 58-62, and polished to surface roughness of $0.4\ \mu\text{m}$. The clamping force was set to be 500 kN during the rotary forming process. Graphite emulsion was used for lubricant and cooling. Feed speed was 0.05 mm per circle.

Fig. 31 shows the parts manufactured by multi-step spinning. According to section 4.2 and the shape of the final part, we can get $a = b = r_c = 1\text{mm}$, and the final feeding force is 86 kN calculated by equation 4.4 and 90 kN measured in experiment. The value of experiment is 4.6% higher than that calculated by equation 4.4.



Figure 30. Multi-step spinning machine

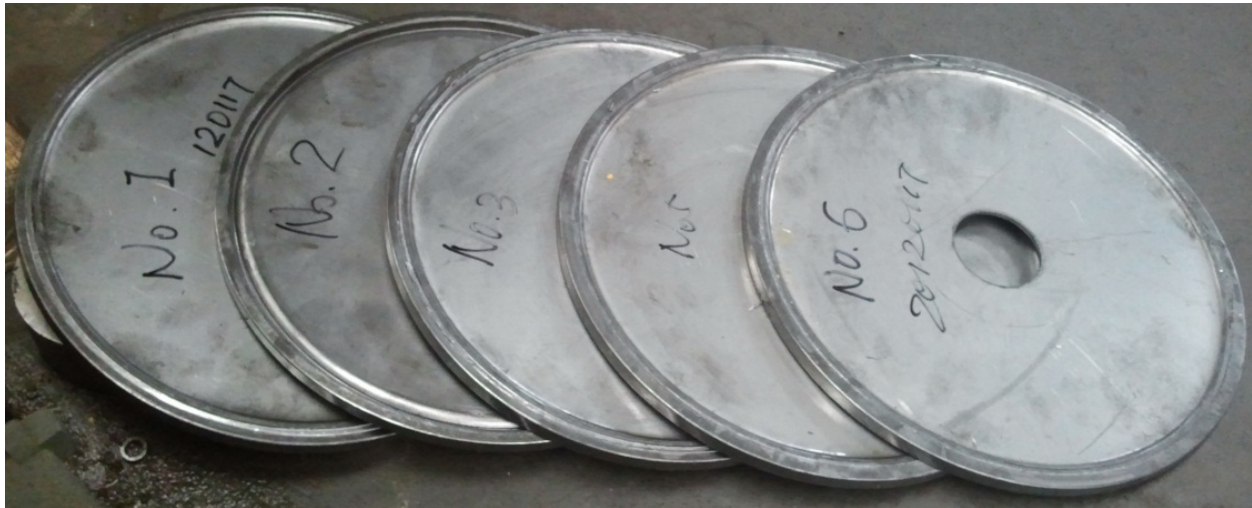


Figure 31. Parts with thickened rim made by multi-step spinning

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