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SECTION 7. Mechanics and machine construction.

MULTI-STEP PLASTIC DEFORMATION OF A SHEET METAL BLANK

Abstract: The manufacturing process of a steel case-shaped part by multi-step plastic deformation is presented in the article. Condition describing of outer and inner surfaces of a semi-finished product after each step of plastic deformation is given. Areas ratios of the inner surfaces of the semi-finished product with and without wrinkles were obtained.

Key words: a semi-finished product, drawing, calibration, plastic deformation, wrinkles, an area.

Language: English

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Introduction

Steel thin-walled hollow parts of medium sizes are mainly manufactured by plastic deformation methods [1]. Multi-step drawing is used for formation of several inner cavities of the part [2 – 4]. Essence of multi-step drawing is sequential changing of a shape and the sizes of a sheet metal blank by means of variety special drawing, calibration and other dies. Special automated equipment is recommended to use in conditions of serial or mass production of these parts. An entire volume of the sheet blank material is subject to deformations of various kinds in a short period of time. This amount of works on plastic deformation of the sheet metal blank in real production is rationally performed by the method of reverse drawing [5 – 6]. Significant plastic deformations lead to formation of microcracks in material, walls thinning of a semi-finished product and other defects [7 – 8]. Analysis of the outer and inner surfaces of the semi-finished product after each step of deep drawing will allow to give characteristic of stress-strain condition of material. This will allow to give a conclusion about suitability of the part in accordance with the technical requirements for manufacturing of the product.

Materials and methods

The part "Case" is used to protection of an engine from dust and mechanical damage. The technological process of manufacturing of the part "Case" consists of plastic deformation operations and machining. The blanking operation is cutting down of the sheet blanks of round section from a cold-rolled sheet. Low-carbon high-quality steel was adopted as material of the sheet blank. Overall dimensions of the sheet metal blank before plastic deformation were: the outer diameter – 174 mm and the thickness – 2.5 mm. The drawing of tooling for cutting down of the sheet metal blank on a double column crank stamping press is presented in the Fig. 1.

The sheet blank after cutting down was considered suitable if there is no visible mechanical defects on flange (chips, deep dents and etc.). The operation of multi-step drawing was performed on the eight-position automatic press Paust-320. Steps of drawing of the sheet blank are presented in the Fig. 2.

The first step is drawing of the sheet metal blank to the depth of 73 mm with formation of the radius of 55 mm. The second step is drawing of the semi-finished product to the depth of 91.5 mm with formation of the inner cavity by the diameter of 87.5 mm and the radius of 12 mm at bend.

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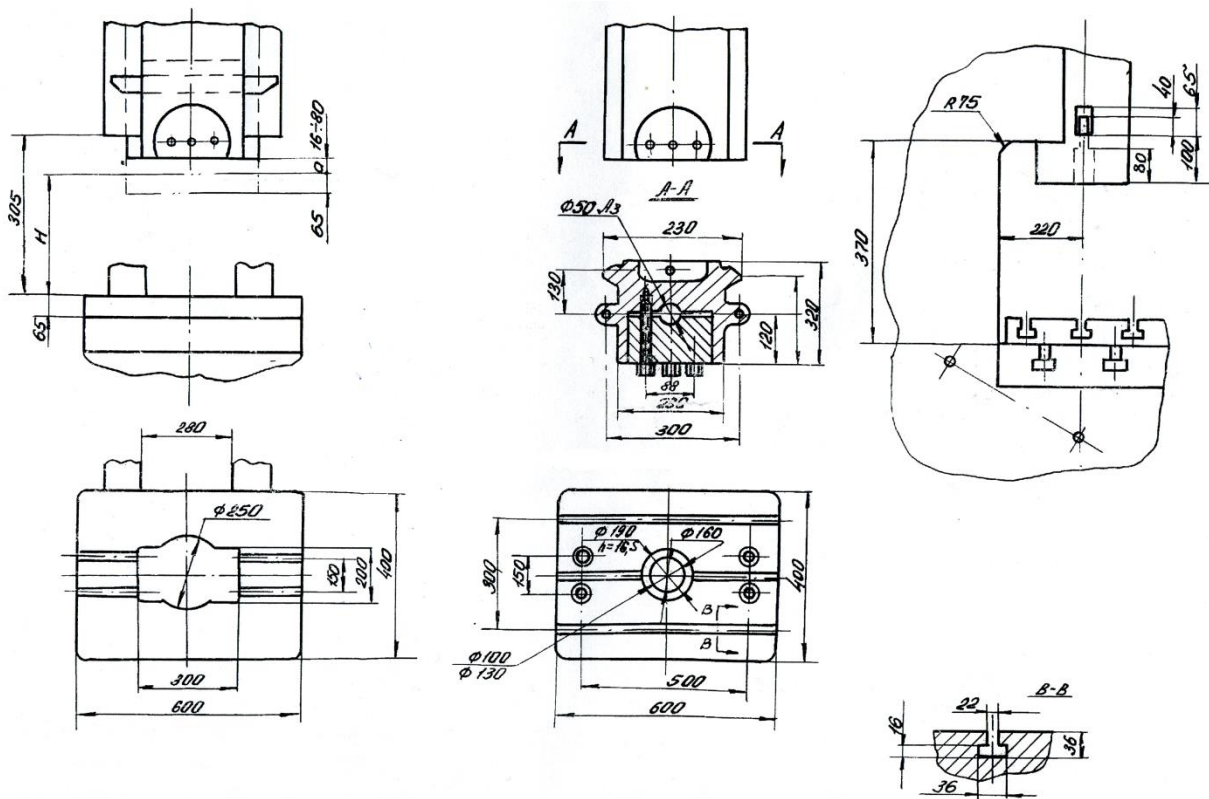


Figure 1 – The drawing of the cutting die.

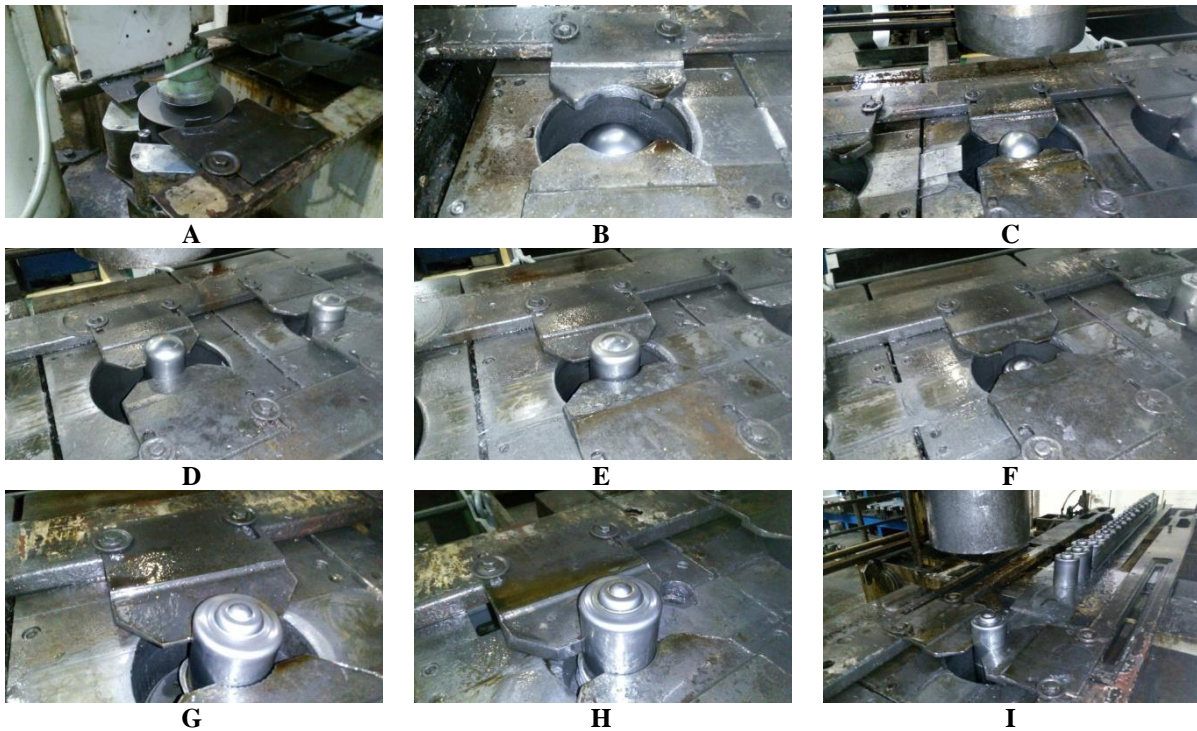


Figure 2 – The steps of drawing of the sheet metal blank and the dies for plastic deformation: A – the sheet metal blank in the die; B – the first drawing (the first step); C – the second drawing (the second step); D – the third drawing (the third step); E – the first calibration (the fourth step); F – the second calibration (the fifth step); G – the third calibration (the sixth step); H – cutting of flange (the seventh step); I – height calibration (the eighth step).

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The third step is drawing of the semi-finished product to the depth of 105.6 mm with formation of the inner cavity by the diameter of 71.3 mm and the radii of 30 mm (at bottom) and 8 mm (at bends). The fourth step is preliminary calibration of shaped bottom of the semi-finished product to the depth of 15.1 mm with formation of the inner cavity by the diameter of 35 mm and the radii at bends of 2.5 mm, 3 mm and 5 mm. The fifth step is preliminary calibration of shaped bottom of the semi-finished product with formation of the radii at bends of 2.5 mm and 3 mm. The sixth step is preliminary calibration of shaped bottom of the semi-finished product to the depth of 14 mm with formation of the radii at bends of 0.5 mm, 1.5 mm and 2.5 mm. The seventh step is flange cutting of the semi-finished product. The semi-finished product has the maximum outer diameter of 76.8 mm and the height of 86 ± 0.4 mm after multi-step drawing (the eighth step).

The drawing, calibration and cutting dies were used as technological tooling. The steps of plastic deformation of the semi-finished product were

carried out by the reverse method (movement of a punch bottom-up).

Results and discussion

Condition of the outer and inner surfaces of the semi-finished product after plastic deformation is presented in the Fig. 3 – 10. Cutting of the semi-finished product into two parts after each step of plastic deformation was carried out on an electrical-discharge machine. This allows to reduce random plastic deformation of material in conditions of cutting of the semi-finished product by the mechanical method (for example, cutting by a disk milling cutter).

Deep wrinkles are formed on the outer and inner surfaces of the semi-finished product (after the first drawing of the sheet metal blank). Wrinkles formation occur due to excess material on flange of the sheet metal blank. This leads to curvature of flange of the semi-finished product. The wrinkles height is 17 mm. Reduction of the wall thickness of the semi-finished product is not observed due to smooth bending of the sheet metal blank.

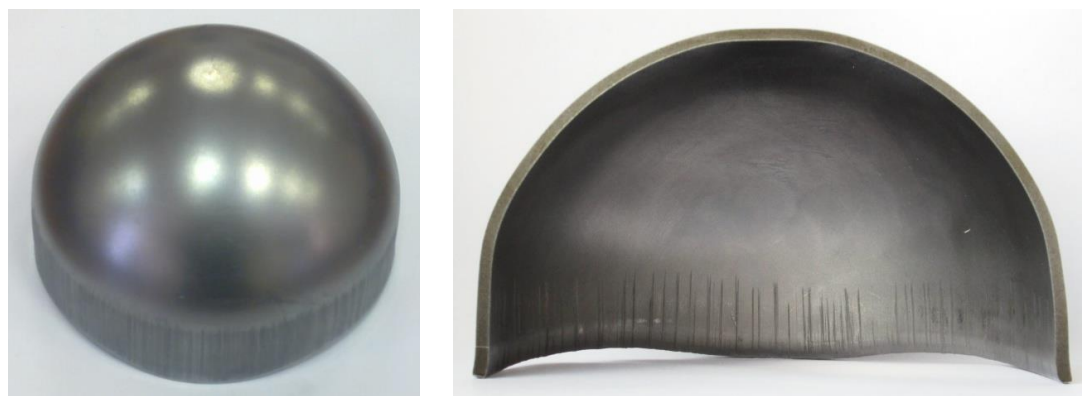


Figure 3 – Condition of the outer and inner surfaces of the semi-finished product after the first drawing.

Subsequent drawing (the second step) leads to increasing of wrinkles intensity on the larger area of the inner surface of the semi-finished product. This

deformation is consequence of the inner cavity formation by the punch. Visible defects are not found on the outer surface of the semi-finished product.

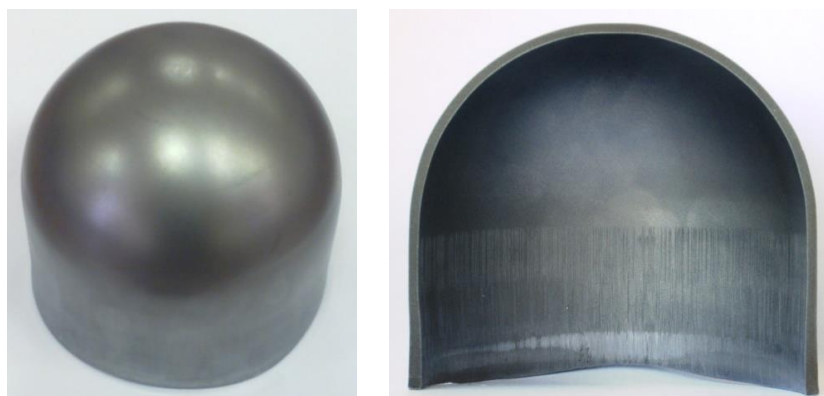


Figure 4 – Condition of the outer and inner surfaces of the semi-finished product after the second drawing.

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Plastic deformation after the third step leads to reduction of the inner diameter and increasing of the semi-finished product length with formation of flange. The outer surfaces of the semi-finished product are deformed less than the inner surfaces.



Figure 5 – Condition of the outer and inner surfaces of the semi-finished product after the third drawing.

Calibration of bottom of the semi-finished product with formation of an inner end face leads to reduction of the side wall thickness. The inner cylindrical surface of the semi-finished product is

almost all subjected to deep wrinkles. The flange area of the semi-finished product increases. Wrinkles on the outer surface of the semi-finished product do not observe.



Figure 6 – Condition of the outer and inner surfaces of the semi-finished product after the first calibration.

The second calibration leads to some increasing of the wrinkles area on the inner surface of the semi-finished product. Wrinkles were not found in the forming small shaped inner cavity of the semi-

finished product. Critical reduction of the wall thickness of the semi-finished product is not observed.

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Figure 7 – Condition of the outer and inner surfaces of the semi-finished product after the second calibration.

The cylindrical and conical cavities at bottom of the semi-finished product are formed by the third calibration. Formation of the end surface between these cavities leads to significant reduction of the

wall thickness of the semi-finished product. The wrinkles area on the inner surface of the semi-finished product remains the same as after the previous step of plastic deformation.



Figure 8 – Condition of the outer and inner surfaces of the semi-finished product after the third calibration.

Cutting of excess material (flange) is carried out by means of a special knife setting in the cutting die. Rough longitudinal burrs are observed on the inner surface of the semi-finished product. These

deformations do not belong to the step of cutting flange, but there were received on the previous steps of plastic deformation of the semi-finished product.



Figure 9 – Condition of the outer and inner surfaces of the semi-finished product after cutting of flange.

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Figure 10 – Condition of the outer and inner surfaces of the semi-finished product after height calibration.

Final calibration of the semi-finished product in the length does not affect to the quality of the outer and inner surfaces.

Let us find out the quality ratios of the surfaces of the semi-finished product. So as the outer surfaces of the semi-finished product are not subjected to wrinkles formation after plastic deformation, then the calculation of the areas ratios of the semi-finished product is performed for the inner surfaces (with and without wrinkles). The calculation was carried out after each step of plastic deformation:

1. After the first step.

The total area of the inner surfaces is given by the formula

$$S_{total} = S_{cylinder} + S_{hemisphere},$$

where S_{total} is the total area of the inner surfaces of the semi-finished product, mm^2 ; $S_{cylinder}$ is the area of the cylinder, mm^2 ; $S_{hemisphere}$ is the area of the hemisphere, mm^2 .

$$H_{cylinder} = H_{total} - R_{cylinder},$$

where $H_{cylinder}$ is the height of the cylinder, mm; H_{total} is the total height of the semi-finished product, mm; $R_{cylinder}$ is the radius of the cylinder, mm.

Let us substitute values in the formula

$$H_{cylinder} = 73 - 55 = 18 \text{ mm.}$$

The areas of the cylinder and hemisphere are given by the formulae

$$S_{cylinder} = 2\pi \times R_{cylinder} \times H_{cylinder} = 2\pi \times 55 \times 18 = 1980\pi \text{ mm}^2.$$

$$S_{hemisphere} = 2\pi \times (R_{cylinder})^2 = 2\pi \times 55^2 = 6050\pi \text{ mm}^2.$$

Then

$$S_{total} = 1980\pi + 6050\pi = 8030\pi \text{ mm}^2.$$

The total area of the inner surfaces without taking into account wrinkles is given by the formula

$$S_{total1} = S_{cylinder1} + S_{hemisphere},$$

where S_{total1} is the area of the inner surfaces of the semi-finished product without taking into account wrinkles, mm^2 ; $S_{cylinder1}$ is the area of the cylinder without taking into account wrinkles, mm^2 .

The height of the cylinder without taking into account wrinkles

$$H_{cylinder1} = (H_{total} - H_{cylinder2}) - R_{cylinder},$$

where $H_{cylinder1}$ is the height of the cylinder without taking into account wrinkles, mm; $H_{cylinder2}$ is the height of the cylinder with taking into account wrinkles, mm.

$$H_{cylinder1} = (73 - 17) - 55 = 1 \text{ mm.}$$

$$S_{cylinder1} = 2\pi \times R_{cylinder} \times H_{cylinder1} = 2\pi \times 55 \times 1 = 110\pi \text{ mm}^2.$$

Then

$$S_{total1} = 110\pi + 6050\pi = 6160\pi \text{ mm}^2.$$

The quality ratio of the inner surfaces of the semi-finished product is $(S_{total1})/(S_{total}) = (6160\pi)/(8030\pi) = 0.767$.

2. After the second step.

The total area of the inner surfaces

$$S_{total} = S_{cylinder} + S_{ball \text{ segment}},$$

where $S_{ball \text{ segment}}$ is the area of the ball segment, mm^2 .

$$R_{cylinder} = (D_{cylinder})/2 = 87.5/2 = 43.75 \text{ mm,}$$

where $D_{cylinder}$ is the diameter of the cylinder, mm.

$$H_{ball \text{ segment}} = 30 \text{ mm,}$$

where $H_{ball \text{ segment}}$ is the height of the ball segment, mm.

$$H_{cylinder} = H_{total} - H_{ball \text{ segment}} - t = 91.5 - 30 - 2.5 = 59 \text{ mm,}$$

where t is the wall thickness of the semi-finished product, mm.

$$S_{cylinder} = 2\pi \times R_{cylinder} \times H_{cylinder} = 2\pi \times 43.75 \times 59 = 5162.5\pi \text{ mm}^2.$$

$$S_{ball \text{ segment}} = 2\pi \times R_{cylinder} \times H_{ball \text{ segment}} = 2\pi \times 43.75 \times 30 = 2625\pi \text{ mm}^2.$$

$$S_{total} = 5162.5\pi + 2625\pi = 7787.5\pi \text{ mm}^2.$$

The total area of the inner surfaces without taking into account wrinkles

$$S_{total1} = S_{cylinder1} + S_{ball \text{ segment}}$$

$$H_{cylinder1} = (H_{total} - H_{ball \text{ segment}} - t) - H_{cylinder2} = (91.5 - 30 - 2.5) - 38 = 21 \text{ mm.}$$

$$S_{cylinder1} = 2\pi \times R_{cylinder} \times H_{cylinder1} = 2\pi \times 43.75 \times 21 = 1837.5\pi \text{ mm}^2.$$

$$S_{total1} = 1837.5\pi + 2625\pi = 4462.5\pi \text{ mm}^2.$$

The quality ratio of the inner surfaces of the semi-finished product is $(S_{total1})/(S_{total}) = (4462.5\pi)/(7787.5\pi) = 0.573$.

3. After the third step.

The total area of the inner surfaces

$$S_{total} = S_{cylinder} + S_{ball \text{ segment}}$$

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$H_{ball\ segment} = 22.5\text{ mm}$, $R_{sphere} = 30\text{ mm}$, $R_{cylinder} = (D_{cylinder})/2 = 71.3/2 = 35.65\text{ mm}$,
where R_{sphere} is the radius of the sphere, mm.

$$H_{cylinder} = H_{total} - H_{ball\ segment} - t = 105.6 - 22.5 - 2.5 = 80.6\text{ mm}.$$

$$S_{cylinder} = 2\pi \times R_{cylinder} \times H_{cylinder} = 2\pi \times 35.65 \times 80.6 = 5746.78\pi\text{ mm}^2.$$

$$S_{ball\ segment} = 2\pi \times R_{sphere} \times H_{ball\ segment} = 2\pi \times 30 \times 22.5 = 1350\pi\text{ mm}^2.$$

$$S_{total} = 5746.78\pi + 1350\pi = 7096.78\pi\text{ mm}^2.$$

The total area of the inner surfaces without taking into account wrinkles

$$S_{total} = S_{cylinder1} + S_{ball\ segment}$$

$$H_{cylinder1} = (H_{total} - H_{sphere} - t) - H_{cylinder2} = (105.6 - 22.5 - 2.5) - 50 = 30.6\text{ mm}.$$

$$S_{cylinder1} = 2\pi \times R_{cylinder} \times H_{cylinder1} = 2\pi \times 35.65 \times 30.6 = 2181.78\pi\text{ mm}^2.$$

$$S_{total1} = 2181.78\pi + 1350\pi = 3531.78\pi\text{ mm}^2.$$

The quality ratio of the inner surfaces of the semi-finished product is $(S_{total1})/(S_{total}) = (3531.78\pi)/(7096.78\pi) = 0.497$.

4. After the fourth step.

The total area of the inner surfaces

$$S_{total} = S_{cylinder} + (S_{large\ circle} - S_{small\ circle}) + S_{ball\ segment}$$

where $S_{large\ circle}$ and $S_{small\ circle}$ are the areas of the large and small circles, mm^2 .

$$H_{cylinder} = 87.2\text{ mm}, R_{cylinder} = 35.75\text{ mm}, H_{ball\ segment} = 7\text{ mm}, R_{sphere} = 21.5\text{ mm}, R_{large\ circle} = 36\text{ mm}, R_{small\ circle} = 21.5\text{ mm},$$

where $R_{large\ circle}$ и $R_{small\ circle}$ are the radii of the large and small circles, mm.

$$S_{total} = 2\pi \times 35.75 \times 87.2 + (\pi \times 36^2 - \pi \times 21.5^2) + 2\pi \times 21.5 \times 7 = 6234.8\pi + 833.75\pi + 301\pi = 7369.55\pi\text{ mm}^2.$$

The total area of the inner surfaces without taking into account wrinkles

$$S_{total} = S_{cylinder1} + (S_{large\ circle} - S_{small\ circle}) + S_{ball\ segment}$$

$$S_{total} = 2\pi \times 35.75 \times (87.2 - 76) + (\pi \times 36^2 - \pi \times 21.5^2) + 2\pi \times 21.5 \times 7 = 800.8\pi + 833.75\pi + 301\pi = 1935.55\pi\text{ mm}^2.$$

The quality ratio of the inner surfaces of the semi-finished product is $(S_{total1})/(S_{total}) = (1935.55\pi)/(7369.55\pi) = 0.263$.

5. After the fifth step.

The total area of the inner surfaces

$$S_{total} = S_{cylinder} + (S_{large\ circle} - S_{small\ circle}) + S_{ball\ segment}$$

$$H_{cylinder} = 87.2\text{ mm}, R_{cylinder} = 36\text{ mm}, H_{ball\ segment} = 10\text{ mm}, R_{sphere} = 20\text{ mm}, R_{large\ circle} = 36\text{ mm}, R_{small\ circle} = 20\text{ mm}.$$

$$S_{total} = 2\pi \times 87.2 \times 36 + (\pi \times 36^2 - \pi \times 20^2) + 2\pi \times 20 \times 10 = 6278.4\pi + (1296\pi - 400\pi) + 400\pi = 7574.4\pi\text{ mm}^2.$$

The total area of the inner surfaces without taking into account wrinkles

$$S_{total} = S_{cylinder1} + (S_{large\ circle} - S_{small\ circle}) + S_{ball\ segment}$$

$$S_{total} = 2\pi \times 36 \times (87.2 - 76) + (\pi \times 36^2 - \pi \times 20^2) + 2\pi \times 20 \times 10 = 806.4\pi + 896\pi + 400\pi = 2102.4\pi\text{ mm}^2.$$

The quality ratio of the inner surfaces of the semi-finished product is $(S_{total1})/(S_{total}) = (2102.4\pi)/(7574.4\pi) = 0.277$.

6. After the sixth step.

The total area of the inner surfaces

$$S_{total} = S_{cylinder} + (S_{circle}') + (S_{cylinder}') + (S_{circle})'' + S_{ball\ segment},$$

where $(S_{circle})'$ and $(S_{circle})''$ are the areas of the first and the second circles, mm^2 ; $(S_{cylinder})'$ is the area of the small cylinder, mm^2 .

$$H_{cylinder} = 86.7\text{ mm}, R_{cylinder} = 36\text{ mm}, H_{ball\ segment} = 5\text{ mm}, R_{sphere} = 9\text{ mm}, (H_{cylinder})' = 9\text{ mm}, (R_{cylinder})' = 18\text{ mm},$$

where $(H_{cylinder})'$ is the height of the small cylinder, mm; $(R_{cylinder})'$ is the radius of the small cylinder, mm.

$$(S_{circle})' = \pi(R_{cylinder})^2 - \pi(R_{cylinder}')^2 = 1296\pi - 324\pi = 972\pi\text{ mm}^2.$$

$$(S_{circle})'' = \pi(R_{cylinder}')^2 - \pi(R_{sphere})^2 = 324\pi - 81\pi = 243\pi\text{ mm}^2.$$

$$S_{total} = 2\pi \times 36 \times 86.7 + 972\pi + 2\pi \times 18 \times 9 + 243\pi + 2\pi \times 9 \times 5 = 7871.4\pi\text{ mm}^2.$$

The total area of the inner surfaces without taking into account wrinkles

$$S_{total} = S_{cylinder1} + (S_{circle})' + (S_{cylinder})' + (S_{circle})'' + S_{ball\ segment}$$

$$S_{total} = 2\pi \times 36 \times (86.7 - 80) + 972\pi + 2\pi \times 18 \times 9 + 243\pi + 2\pi \times 9 \times 5 = 2111.4\pi\text{ mm}^2.$$

The quality ratio of the inner surfaces of the semi-finished product is $(S_{total1})/(S_{total}) = (2111.4\pi)/(7871.4\pi) = 0.268$.

The quality ratio of the inner surfaces of the semi-finished product does not change after the seventh and the eighth steps.

Conclusion

1. Wrinkles are formed on the inner surfaces of the semi-finished product after plastic deformation. The more cavity area of the semi-finished product, the more intense wrinkles are formed. Wrinkles occur on the outer surface of the semi-finished product after the first step in accordance with the technology of plastic deformation of material.

2. The quality ratio of the inner surfaces of the semi-finished product change in the range of 0.263 – 0.767. Wrinkles distribution on the inner cylindrical surface of the semi-finished product increases by 23.4% after the fourth step of drawing (maximum increasing in comparison with the other values of the quality ratio of the inner surfaces of the semi-finished product).

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