Research of the process of axisymmetric forming of thin-walled flat blanks into the conical parts with minimal thickness variation

E G Demyanenko, I P Popov and V S Menshikov

Samara University, 34, Moskovskoye roadway, Samara, 443086, Russian Federation
E-mail: ^e-dem@mail.ru, ^igr_popov@mail.ru, ^me-vs@yandex.ru

Abstract. In this paper, the method based on the process of forming a flat blank into the thin-walled conical part is proposed. The forming method is based on two stages. At the first stage, forming of the free portion of the blank is carried out until it fully contacts the conical surface of the punch. During this stage, thickness unevenness is created, which can be compensated during the second stage by the action of active friction forces. The shaping of the workpiece during the forming of the conical part is performed by thinning. The thinning increases with the increase of the penetration depth of the punch, i.e. the final part will be thinner, but its thickness variation will be reduced. This method allows achieving minimal thickness variation in the walls of the part.

1. Introduction

Thin-walled conical parts with the $S_{\text{blank}}/D < 0.008$ (where $S_{\text{blank}}$ – thickness of a blank; $D$ – larger edge diameter of a part) thickness ratio are widely used in aircraft and rockets manufacturing, especially for liquid rocket engines (LRE) [1 – 3]. Various methods of manufacturing of these parts [4 – 20], based on welding of conical or flat ring-shaped blanks, are known. Conical blanks are used for manufacturing tall tapering parts, flat blanks are used for relatively low parts ($H/R < 0.25$, where $R$ – the larger edge diameter of a part, $H$ – the height of a part). Both cases demonstrate significant thickness variations leading to reduced specific strength of the part or a necessity of additional mechanical processing. In this paper, the method (shown in Figure 2) of manufacturing of these parts is investigated.

The forming method is based on two stages. At the first stage, forming of the free portion of the blank is carried out until it fully contacts the conical surface of the punch. During this stage, thickness unevenness is created, which can be compensated during the second stage by the action of active friction forces. In the maximum thickness area near the clamp, additional tensile stresses are created, leading to thinning of that area and equalization of the thickness in the entire volume of the conical portion of a part. Height $h$ of the emerging cylindrical-like shaped portion depends on deformation during the second stage. The determination of the thinning value during the second stage in the vicinity of radial transition of the punch is the primary goal under given parameters (geometric: conic angle, $D/r$ ratio; mechanical: relative elongation, anisotropy coefficient). Both stages provide forming by thinning of a blank. As the thinning increases, the achieved height of a part increases as well. This depends primarily on mechanical properties of the material being used in the process (such as $\delta_U$ – relative uniform elongation; anisotropy of the material and the number of stamping steps).
2. Theoretical foundations

The equation for the conical shell blanks is as follows [21]:

$$\rho (d \sigma_\rho / d \rho) + \sigma_\rho - \sigma_\theta - \sigma_\theta \tan \alpha = 0,$$

where $$\sigma_\rho$$ and $$\sigma_\theta$$ – stresses in meridian and tangential directions, accordingly;

$$f$$ – the friction coefficient;

$$\alpha_{part}$$ – the cone angle of the part;

$$\rho$$ – the independent variable.

In the immobile portion of the blank, between the die and the clamp, tangential deformation equals zero, and from stress-strain equation, the following ratio takes place:

$$\sigma_\theta / \sigma_\rho = \mu$$

(2)

where, $$\mu$$ – the coefficient of a transversally isotropic body.

In the flat bottom portion of the workpiece, stress equals:

$$\sigma_\theta / \sigma_\rho = 1.$$

(3)

By applying the linear relation of stresses due to the minimal length of the free conical portion, we obtain:

$$\frac{\sigma_\theta}{\sigma_\rho} = 1 - \frac{1 - \mu}{R - 1}.$$  

(4)

Solution (1) with consideration of (4) for the first stage takes the following form:

$$\sigma_{\rho 1} = \sigma^*_{\rho 1} (\rho)^{-\mu+1} \exp \left[ (1 - \rho) \frac{1 - \mu}{R - 1} \right].$$

(5)
where, $\sigma_{\rho_1}^*$ – boundary stress on the smaller edge of the workpiece during the end of the first stage, when $\bar{\rho} = \rho / R = R / \bar{R}$

Considering that at the second stage, the free portion is formed and condition (3) is applied to the whole conical region, and solution (1) takes the following form:

$$\sigma_{\rho_2} = \sigma_{\rho_2}^* (\bar{\rho})^{\frac{k_{\text{ega}}}{4}},$$

where, $\sigma_{\rho_2}^*$ – boundary stress on the smaller edge of the conical portion at $\bar{\rho} = 1$ during the second stage.

Thickness values can be calculated by assuming that, according to plasticity condition [22]:

$$\sigma_S^2 = \sigma_{\rho_1}^2 + \sigma_{\theta}^2 - 2\mu\sigma_{\rho}\sigma_{\theta},$$

the following ratio takes place:

$$\sigma_{\rho} = \sigma_S / (1 - \mu^2).$$

At the second stage,

$$\sigma_{\rho} = \sigma_S / \sqrt{2(1 - \mu)}.$$  

The thickness deformation is take as the intensity of deformation $e_i = e_S$. The linear hardening condition is [23]

$$\sigma_S = \sigma_{\tau_0} + e_S = \sigma_{\tau_0} + 1 - S.$$  

Applied to the first stage,

$$S_1 = \left(\sigma_{\tau_0} + 1 - \sigma_{\rho_1}^2 \sqrt{1 + \mu^2}\right) S_{\text{blank}}.$$  

And the second stage,

$$S_2 = \left(\sigma_{\tau_0} + 1 - \sigma_{\rho_2}^2 \sqrt{2(1 - \mu)}\right) S_1,$$

where the following is accepted:

$$\sigma_{\tau_0} = \sigma_{\tau_0} / \Pi; \sigma_{\rho_1} = \sigma_{\rho_1} / \Pi; \sigma_{\rho_2} = \sigma_{\rho_2} / \Pi;$$

where $S_1, S_2$ – thicknesses of a workpiece at the first and the second stages;

$\sigma_{\tau_0}$ – extrapolated yield stress;

$\Pi$ – the hardening modulus.

In Figure 6, the thickness curves, including the one of the first stage, are shown.

It is possible and advisable to regulate the thickness of the conical portion during the second stage. The condition of providing minimal thickness variation can be written as:

$$\left(S_{\text{part}} - S_2\right)^2 d\bar{\rho} \to \min,$$

where:

$$S_{\text{part}} = \left[\sigma_{\tau_0} + 1 - \sigma_{\rho_2}^* \sqrt{2(1 - \mu)}\right] \left[\sigma_{\tau_0} + 1 - \sigma_{\rho_1}^*\right] S_{\text{blank}}.$$  

This means that the part thickness is determined by the minimal value in the area of radial transition of a punch.

If we assume $\sigma_{\rho_2} = \sigma_{\rho_2}^* / \Pi$ as a variable parameter, which determines thinning of the workpiece, after derivation, we get:

$$\partial / \partial x = 0 \cdot \int_1^\infty \left(\frac{a - c^2}{\rho} - \left(\frac{a - c c^2}{\rho - \rho^p} \cdot e\right) \left(-cb + \rho^p c \left(a - \rho^p \cdot e\right)\right) \left(\frac{a - c c^2}{\rho - \rho^p} \cdot e\right)\right) d\rho = 0,$$  

(13)
where

\[ x = \sigma_{\rho^2}; a = \sigma_{TO} + 1; b = \sigma_{TO} + 1 - \sigma_{\rho^1}; c = \sqrt{2(1 - \mu)}; d = \sqrt{1 - \mu^2}; e = \sigma_{\rho^1}\sqrt{1 - \mu^2}; \]

\[ \rho^k = \rho^{-\text{ctg} \alpha}, \rho^p = \rho^{\frac{1 - \mu}{R - 1}} \exp \left( (1 - \rho) \frac{1 - \mu}{R - 1} \right) \]  

(14)

After replacing the integrals with the finite sums, let us find:

\[ \bar{\sigma}_{\rho^2} = \frac{1}{n} \sum_{i=1}^{n} E_i \rho^k_i - \frac{1}{n} \sum_{i=1}^{n} E_i \rho^{+k}_i - cb \sum_{i=1}^{n} E_i \rho^{k+p}_i \]  

(15)

where

\[ E_i = ab - a^2 + a\rho \rho^p; M_i = -cb + a\rho \rho^k_i - c\rho \rho^{k+p}_i. \]

In order to use expression (15), not only mechanical property values, but also stress values in the radial transition area of the punch (boundary conditions) must be known. To establish boundary conditions at the first stage, we use the volume constancy condition. In addition, let us assume that the bottom part of the workpiece is thinned equally.

Then, the thickness value equals:

\[ S_{Bot} = S_{\text{blank}} \left( \sigma_{TO} + 1 - \sigma_{\rho^1}\sqrt{1 - \mu^2} \right) = S_{\text{blank}} b. \]  

(16)

The emerged conical part has its thickness complying with the linear law, and its volume can be calculated using the average thickness of the conical portion.

Thus, we get:

\[ \pi R^2 S_{\text{blank}} = \pi \rho^2 S_{Bot} + \pi \frac{R^2 - r^2}{\sin \alpha} S_{med}, \]  

(17)

where \( S_{med} = (S_{BOT} + S_k)/2 \), \( S_k = S_{\text{blank}} \left( \sigma_{TO} + 1 - \sigma_{\rho^1}\sqrt{1 - \mu^2} R^{\frac{1 - \mu}{R - 1}} \exp \left( (1 - \rho) \frac{1 - \mu}{R - 1} \right) \right) \) 

(18)

From expressions (17,18), let us find:

\[ \bar{\sigma}_{\rho^1} = \frac{\sigma_{TO} + 1 - \bar{\rho}^2 + \frac{R^2 - 1}{2 \sin \alpha} (\sigma_{TO} + 1)}{\sqrt{1 - \mu^2} \left[ 1 + 0.5 \left( \frac{R^2 - 1}{2 \sin \alpha} \left( 1 + \frac{1 - \mu}{R - 1} \rho^{\mu - 1} \right) \right) \right]} \]  

(19)

Considering \( \bar{\sigma}_{\rho^2} \), found earlier, the thickness value of the bottom portion, calculated using expression (11), should not exceed the boundary value. In case stresses ratio is \( \sigma_{\rho}/\sigma_{\theta} = 1 \), thinning should not exceed [24]:

\[ e_S = (S_{\text{blank}} - S_{Bot})/S_{\text{blank}} \leq 2n, \]  

(20)

where \( n = \delta_u \) – the exponential function of hardening rate, equal to the relative uniform elongation. From (20), we can find:

\[ S_{Bot} = 1 - 2\delta_u. \]  

(21)

According to the found \( \bar{\sigma}_{\rho^2} \) value for the second stage, let us calculate the part thickness, considering it as a constant value. After that, we calculate the height \( h \) value of the free cylinder-like portion using the volume constancy condition. To the expression (17) summand, representing the volume of the cylindrical portion, we must add:
\[ \pi R^2 S_{\text{blank}} = \pi R^2 S_{\text{blank}} + \pi \frac{R^2 - r^2}{\sin \alpha} S_{\text{part}} + 2\pi R S_{\text{blank}} h, \]

where \( S_{\text{blank}} = S_2 \).

Thus, we get:

\[
\bar{h} = (R^2 - \left( R^2 - 1 \right) / \sin \alpha) / \left( 2 R S_{\text{part}} \right). \quad (22)
\]

3. Experimental studies

The experimental technique.

For conducting the experiment according to the presented schematic (Figure 2), the experimental dies were used (Figure 3).

**Figure 3.** Experiment dies: 1 – Part; 2 – Dies; 3 – Blank.

![Figure 3](image)

Fixation of the flanges of a blank was performed using bolts, with enough force to render flanges immobile during the stamping process. Working surfaces of the die and the holder clamp must be strictly parallel to conduct equal fixation of the flange on the whole surface, and rigid enough to prevent significant elastic strains caused by the forces applied to the fixation bolts, which are placed around the blank. The holder clamp and the die are made of U7 Steel, which then was thermally treated to hardness HRC = 40 – 45. The height of the conical portion of the punch is 5.0 mm with the radial transition of 1 mm (Figure 4).

**Figure 4.** The geometry of the punch.

![Figure 4](image)

Deformation of the blank was carried out using hydraulic press CDMPU-10.

The blank was obtained using the sheet of the aluminum AD0 alloy with 0.5 mm of thickness rolled on rolling mill Quarto K220/75-300 DUO up to a 0.325 mm thickness. After cutting out the blank with the 58 mm diameter, we annealed it at 420° ± 5° C for 30 min, and cooled in the furnace.

The samples for estimating the transversally isotropic body anisotropy coefficient were prepared for 3 dimensions: along, across and at a 45° angle to the rolling direction [25].

The transversally isotropic body anisotropy coefficient was calculated using the following expression:

\[
e_{\text{width}} = \ln \left| \frac{b_k}{b_0} \right|, \quad e_{\text{length}} = \ln \left| \frac{l_k}{l_0} \right|, \quad (23)
\]

where \( b_k \) – the width of the sample after the tensile test;
$b_0$ – the width of the sample before the tensile test;  
$l_k$ – the calculated length after the tensile test;  
$l_0$ – the calculated length before the tensile test.

$$
\mu_{\text{along}} = \frac{e_{\text{width}}}{e_{\text{length}}}, \mu_{\text{across}} = \frac{e_{\text{width}}}{e_{\text{length}}}, \mu_{k_0} = \frac{e_{\text{width}}}{e_{\text{length}}}, \mu = \frac{\mu_{\text{along}} + \mu_{\text{across}} + \mu_{k_0}}{3}.
$$

Measurements of the absolute thickness and width values for the calculation were performed using the electronic tool with a 0.001 mm accuracy and the micrometer with a 0.01 mm accuracy. The mean square error value did not exceed 1%.

The mechanical properties of the samples were evaluated by the tensile tests according to GOST7855-55 and GOST1497-61, using the Tinius Olsen H5KT machine. After the series of experiments, the results were processed using the PC software, stored and printed out as charts. The obtained diagrams of linear elongation of the material (force – time dependence) were used to calculate the constant value in expression (9) and evaluate the mechanical properties, such as: $\sigma_{0.2}, \sigma_u, \delta_u$.

Using obtained values of stresses and strains, the linear relation was found:

$$
\Pi = \frac{\sum_{i=1}^{k} \sigma_i \cdot e_i - \left( \sum_{i=1}^{k} \sigma_i \right) \cdot \left( \sum_{i=1}^{k} e_i \right)}{\left( \sum_{i=1}^{k} e_i \right)^2} \left( \sum_{i=1}^{k} \sigma_i \right)^2
$$

where $e_i$ – the intensity of deformation at the considered interval of deformation.

The forming process was conducted in multiple steps with a 1 mm penetration depth of the punch at each step up to a 5.5 – 6 mm depth. The height of the cylinder-like shaped portion was in accordance to the value, calculated using expression (22). At the moment of complete contact with the workpiece at 4 – 4.5 mm of depth along the conical part, the thickness measurement for the first stage was performed. The next measurement was conducted after increasing the penetration depth by 1 – 1.5 mm; then, the height of the part reached 5.5 – 6 mm (the second stage). The conical surface along the generatrix was marked on 5 circular sections from a smaller to larger diameter (Figure 5). Rings were marked on 4 sections, two of which were markers along the rolling direction of the sheet, and two were marked perpendicular to the first two. Thickness measurements were performed using the electronic measurement tool with a 0.001 mm accuracy. The average thickness values for the four sections of each ring were calculated. According to the values of relative thicknesses after the measurements, the regression equation of the first degree was build, using the PC software. For comparison, the equations of relative thicknesses for the first and second stages, found analytically, are presented in Figure 6. The movement distance of the punch was determined by the scale, attached to the press.

![Figure 5. The measurements scheme.](image)
Figure 6. Thickness values of the workpiece.

4. Results of the experiments

Table 1. Mechanical properties of the tested material.

| Material     | $\delta_u$ | $\mu$ | $\sigma_u$ (MPa) | $\sigma_{0.2}$ (MPa) | Thermal treatment $(^\circ C) - t$ (min) |
|--------------|------------|-------|------------------|----------------------|----------------------------------------|
| Aluminium AD0 | 0.22       | 0.44  | 167.9            | 61.3                 | 410 – 20                                |
| $S_{blank} = 0.325\text{ m}$ |            |       |                  |                      |                                        |

In Table 2, the thickness values for the first and second stages are presented.

Table 2. Thickness values per stage

| Stage | Average thickness values per circular portions (mm) |
|-------|-----------------------------------------------------|
|       | 1  | 2  | 3  | 4  | 5  |
| I     | 0.272 | 0.274 | 0.266 | 0.263 | 0.26 |
| II    | 0.263 | 0.261 | 0.262 | 0.259 | 0.253 |

5. Analysis and conclusion

The shaping of the workpiece during the forming of the conical part takes place due to thinning. With the increase of the penetration depth of the punch, thinning also increases, i.e. the final part will be thinner, but its thickness variation will be reduced. At the I stage, the thickness variation value was 4.6 %, at the II stage – 3.9 %. With the exclusion of the ring elements on the borders of the curvature radii and the conical portion (circular portions 1 and 5), the average thickness values demonstrate the thickness variation of 4.1% at the first stage, and 0.77% — at the second stage. A sharp decrease of the thickness unevenness occurs on the conical surface.

Using the formation of the flat blank into the conical part, we demonstrate the possibility of obtaining the parts with relative height $H/R \approx 0.1 - 0.15$ and relatively small conical angle $\alpha \approx 25^\circ \pm 1^\circ$ and thickness variations less than 1%, which in combination with the other modern improvements [26] could benefit to better and possibly cheaper manufacturing processes of thin-walled conical parts for aviation and rocket applications.
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