Quality improvement and evaluation of stress-strain state of cylindrical shells during drawing with local wall thinning

V N Zhernosek, I V Yurkov, V E Podtyagin and A E Nikishkin
Tula State University, 92, Lenina ave., Tula, 300012, Russia

E-mail: fiz-site@yandex.ru

Abstract. One of the urgent tasks in the manufacture of cylindrical shells is to improve their performance and quality by developing technological processes based on new methods of metal treatment by pressure, for example, on drawing. A distinctive feature of drawing with thinning was the use of dies with a periodically changing profile of the bearing. The use of such dies creates additional shear strain during the forming, which affects the structure of the material and the performance of the product. This article presents the results of simulating the drawing with wall thickness reduction in QForm 7 and analyzes the effect of die geometry on technological force and stress-strain state.

1. Introduction
The most pressing challenge in pressure treatment of metals is to obtain high-strength and high-quality metal cylindrical shells with a fine grain structure. Such products are ubiquitous in mechanical engineering, shipbuilding, arms production, aerospace and are manufactured using a variety of technologies associated with both metal forming and cutting. However, pressure treatment makes it possible to obtain parts with a fine-grained structure by applying severe plastic deformation. The results of studies of similar technologies for obtaining products with high operational and quality characteristics are represented in [1-7]. However, the technologies under consideration either do not allow obtaining exactly cylindrical shells, or the productivity and complexity of the process are high. An alternative technology for obtaining such parts is local wall thinning [8-9] with special dies.

In this case, there is a process of drawing with local wall thinning, which leads to significant stress intensity and, as a consequence, to high level of shear deformations. Due to the latter, the grain size decreases and the strength characteristics of the finished product are improved.

With local wall thinning of the workpiece it is possible to use dies with different geometry and shape of protrusions. These factors significantly affect the entire process, therefore, it is relevant to study the influence of the size of die’s wedge on the force parameters and stress-strain intensity.

2. Materials and methods
To study the force parameters and stress and strain intensity the finite element method was implemented in the QForm 3D. In this software, three-dimensional computer simulations of the drawing process were carried out using a simplified stamp (figure 1). The simulation was performed using dies (figure 2) with different diameters of the bearing along the depressions ($D_2$): 33 mm, 34 mm and 35 mm. The number of protrusions equaled 16. The diameter of the bearing of the die along the protrusions was 32 mm in all cases ($D_2$). Workpiece wall thickness – 3 mm, outer diameter – 36 mm. The workpiece was made of
The material was isotropic, with the following values of mechanical properties at 20°C: ultimate strength \( \sigma_u = 370 \text{ MPa} \), relative elongation \( \delta = 34\% \). Thus, the coefficients of wall thinning along the depressions of the bearing of the die equaled \( m_{s2} = 0.5, 0.6 \) and 0.83, and along the protrusions they were \( m_{s1} = 0.33 \).

3. Results and discussion
Figures 3-9 present the curves of the force and stress and strain intensity according to the data obtained as a result of the simulation.

Based on the graph (figure 3), the dependence of the maximum technological force on the value of the maximum diameter \( D_2 \) of the die bearing was defined, which shows that with an increase in the diameter \( D_2 \) of the bearing, the technological force of drawing also decreases, due to a decrease in the area of deformed sections.

Thus, when the diameter \( D_2 \) grows from 33 mm to 35 mm, the maximum technological force decreases from 100 kN to 86 kN, i.e. by about 14%. Forming took long in cases where \( D_2 = 33 \) and 34.
mm, due to the greatest thinning of the workpiece wall, as a result of which the height of the part increases.

Figure 4. Stress intensity (MPa) vs. the movement of the punch (mm) during the drawing through the die with $D_2 = 33\ mm$.

Figure 5. Stress intensity (MPa) vs. the movement of the punch (mm) during the drawing through the die with $D_2 = 34\ mm$.

Figure 6. Stress intensity (MPa) vs. the movement of the punch (mm) during the drawing through the die with $D_2 = 35\ mm$.

When using dies with different diameters $D_2$ the maximum value of the stress intensity was observed at the peaks of the protrusions of the dies (points P1), and the highest value of the stress intensity occurred in the case of the die with $D_2 = 33\ mm$. In the depressions (points P1), the stress intensity is less than at points P0. The gap between the stress intensities at points P0 and P1 increases with increasing diameter $D_2$ and the inhomogeneity of the stress field also increases.

Figure 7. Intensity of deformations vs. the movement of the punch (mm) during the drawing through the die with $D_2 = 33\ mm$.

Figure 8. Intensity of deformations vs. the movement of the punch (mm) during the drawing through the die with $D_2 = 34\ mm$.

Figure 9. Intensity of deformations vs. the movement of the punch (mm) during the drawing through the die with $D_2 = 35\ mm$. 
The graphs show that the intensity of strain reaches the maximum value towards the protrusions of the die, and this value increases with decreasing diameter $D_2$. Towards the depressions of the bearing of the die, the deformation intensity is always less than that in the direction of the protrusions, and the difference in the deformation rates along the protrusion and depression increases with increasing diameter $D_2$. This leads to an increase in the inhomogeneity of the strain intensity field.

The inhomogeneity of the stress intensity fields in certain sections of the workpiece is characterized by the inhomogeneity indicator:

$$\Delta \sigma_i = \frac{(\sigma_{i \text{ max}} - \sigma_{i \text{ min}})100\%}{(\sigma_{i \text{ max}} + \sigma_{i \text{ min}})/2}$$

where $\sigma_{i \text{ max}}$ and $\sigma_{i \text{ min}}$ are the maximum and minimum values of the stress intensity, respectively.

And the heterogeneity of the deformation intensity fields is characterized by the indicator:

$$\Delta \varepsilon_i = \frac{(\varepsilon_{i \text{ max}} - \varepsilon_{i \text{ min}})100\%}{(\varepsilon_{i \text{ max}} + \varepsilon_{i \text{ min}})/2}$$

where $\varepsilon_{i \text{ max}}$ and $\varepsilon_{i \text{ min}}$ are the maximum and minimum values of the stress intensity, respectively.

The results of the analysis of the graphs are shown in the table.

**Table 1.** Maximum values of stress and strain intensity at points P1 and P0, depending on the diameter $D_2$.

| Diameter $D_2$, mm | Strains $\varepsilon$ | Inhomogeneity | Stresses $\sigma$, MPa | Inhomogeneity |
|-------------------|----------------------|---------------|-------------------|---------------|
|                   | Point P1 | Point P0     | Indicator, %      | Point P1 | Point P0 | Indicator, % |
| 33                | 0.96     | 1.13         | 16.3             | 587      | 598      | 1.9          |
| 34                | 0.79     | 0.95         | 18.4             | 571      | 590      | 3.3          |
| 35                | 0.60     | 0.95         | 45.0             | 560      | 588      | 4.9          |

Having information about the mechanical properties of the metal according to the results of tensile tests makes it possible to determine the change in the intensity of stresses and strains along the protrusion and depression of the bearing of the die, which can be taken into account for various geometric dimensions of parts. For this, we used the relative values of the stress intensity:

$$\bar{\sigma}_i = \frac{\sigma_i}{\sigma_b}$$

and strain intensity:

$$\bar{\varepsilon}_i = \frac{\varepsilon_i}{\ln(1 + \delta)}$$

Based on the results of computer simulation and the mechanical properties of the material, the graph of the relative intensity of stress $\bar{\sigma}_i$ and strain $\bar{\varepsilon}_i$ vs. the non-uniformity of the workpiece wall thinning along the perimeter was obtained (figure 10 and figure 11).
4. Conclusions
The results of the studies make it possible to define the technological modes of drawing with severe plastic deformation, at which the required heterogeneity of deformations is reached, on which the operational characteristics of the product largely depend.

The following conclusions were also made:

- With an increase in the non-uniformity of the wall thinning along the perimeter, the power parameters linearly decrease.
- It has been established that the non-uniform wall thinning along the perimeter has a significant effect on the inhomogeneity of the stress and strain intensity.
- The greatest value of the inhomogeneity of deformations occurs when the non-uniformity of the wall thinning is equal to 60%.

Acknowledgement
This work was carried out within the framework of the grant NSh-2601.2020.8.

References
[1] Günyay Bulutsuz A and Chrominski W 2021 Incremental Severe Plastic Deformation Effect on Mechanical and Microstructural Characteristics of AA6063 *Trans Indian Inst Met* **74** 69-77
[2] Bagherpour E, Pardis N and Reihanian M 2019 An overview on severe plastic deformation: research status, techniques classification, microstructure evolution and applications *Int J Adv Manuf Technol* **100** 1647-94
[3] Torabzadeh H, Faraji G and Zalnezhad E 2016 Cyclic Flaring and Sinking (CFS) as a New Severe Plastic Deformation Method for Thin-walled Cylindrical Tubes *Trans Indian Inst Met* **69** 1217-22
[4] Zhang M, Liu L and Liang S 2020 Evolution in Microstructures and Mechanical Properties of Pure Copper Subjected to Severe Plastic Deformation *Met. Mater. Int.* **26** 1585-95
[5] Rudskoy A I, Bogatov A A and Nukhov D S 2016 New Method of Severe Plastic Deformation of Metals Met Sci Heat Treat 60 3-6

[6] Dobromyslov AnV and Taluts N I 2017 Structure of Al–Fe alloys prepared by different methods after severe plastic deformation under pressure Phys. Metals Metalloigr 118 564-71

[7] Babaei A, Jafarzadeh H and Esmaeili F 2018 Tube Twist Pressing (TTP) as a New Severe Plastic Deformation Method Trans Indian Inst Met 71 639-48

[8] Korotkov V A and Yakovlev S S 2018 Simulation of severe plastic deformation during drawing with thinning Bul. of the Tula St. Univ. 5 31-7

[9] Korotkov V A, Larin S N and Yakovlev S S 2017 Pat. of the Russian Federation No 2638720 appl. 21.09.2016, publ. 15.12.2017