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Improving shape formation under conditions of plane tensile stress

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Abstract: Thin-walled axisymmetric truncated parts made of sheet billets are actively used in rocket and aerospace engineering. Improvement to their shape formation, based on directed material thickness change will ensure the production of parts with minimum thickness variation. This will also enable aviation and space industry enterprises to attain leading positions, as well as reduce labor costs. This work studies the possibility of obtaining thin-walled axisymmetric parts of truncated tapered shape using one of the methods of sheet metal stamping under flat tensile stress conditions (flanging). The mechanism was identified and the analysis of the stress-strain state of the billet during deformation was carried out. This takes into account the minimizing of the difference between the specified and technologically possible thicknesses. A mathematical model was developed to consider the shaping method based on the process of flanging. Theoretical studies were based on the principles of the plastic deformation theory of sheet materials. This was achieved by the following factors: approximate differential equations of force equilibrium; equations of constraint; plasticity conditions; and fundamental constitutive relations under given initial and boundary conditions. The process of flanging was simulated using the LS-DYNA software package with the following initial data of a conical billet made of 12Kh18N10T steel: cone angle 16.4°, thickness $S_{\text{billet}} = 0.3$ mm. The aim was to eliminate errors in designing a tool for future implementation of the method on a manufactured die tooling, as well as to confirm the theoretical conclusions on the selection of technological parameters and achieve minimal thickness variation. The steps of computer modeling are presented, indicating the main process parameters such as material model, mechanical characteristics of the workpiece material, type of elements, kinematic loads, conditions of contact interaction of elements with each other, etc.

Keywords: flanging, thickness, thin-walled, minimization, shape formation, process, engineering method, stresses, LS-DYNA, simulation.

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Совершенствование процесса формообразования в условиях плоского напряженного состояния растяжения

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Аннотация: В ракетно-космической и авиационной технике активно применяются тонкостенные осесимметричные детали усеченной сужающейся формы, изготовленные из листовых заготовок. Совершенствование процессов их формообразования, в основе которых направленное изменение толщины материала с целью получения деталей с минимальной разнотолщинностью, позволит обеспечить ведущие позиции предприятий авиационной и космической отраслей промышленности, а также гарантирует снижение трудозатрат. Данная работа посвящена исследованию возможности получения тонкостенных осесимметричных деталей усеченной сужающейся формы одним из способов листовой штамповки в условиях плоского напряженного состояния растяжения (отбортовкой). Выявлен механизм и проведен анализ напряженно-деформированного состояния заготовки в процессе формоизменения с учетом выражения минимизации между заданной и технологически возможной толщинами. Разработана математическая модель рассматриваемого способа формообразования, основанного на процессе отбортовки. Теоретические исследования основывались на положениях теории пластического деформирования листовых материалов путем совместного решения приближенных дифференциальных уравнений равновесия сил, уравнений связи, условия пластичности и основных определяющих соотношений при заданных начальных и граничных условиях. С целью исключения ошибок при проектировании инструмента для перспективной реализации способа на изготовленной штамповой оснастке, а также для подтверждения теоретических выводов по выбору технологических параметров и достижения минимальной разнотолщинности проведено моделирование процесса отбортовки в программном комплексе LS-DYNA с исходными данными конической заготовки из стали 12Х18Н10Т: угол конусности 16,4°, толщина $S_{\text{заг}}$ = 0,3 мм. Представлены этапы компьютерного моделирования с указанием основных параметров процесса, таких как модель материала, механические характеристики материала заготовки, тип элементов, кинематические нагрузки, условия контактного взаимодействия элементов между собой и т.д.

Ключевые слова: отбортовка, толщина, тонкостенная, минимизация, формообразование, процесс, инженерный метод, напряжения, LS-DYNA, моделирование.

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Introduction

Components such as compartment shells, fairings, fuel tanks of various shapes and sizes, gas storage cylinders, nozzle shells, engine combustion chamber shells and other parts used in the rocket, space and aviation industry must fulfill preset performance characteristics. They must also meet design requirements that determine the technological feasibility of their manufacture [1—4]. The known methods of shape formation [5—7] of such parts do not fully provide the necessary and uniformly distributed thickness (for example, at multiple drawing the thickness variability can reach 80 %). This entails an increase in the number of technological transitions, a decrease in the material utilization rate due to subsequent machining and a general increase in production costs. Associated problems are corrugation (local loss of deformation stability) and deterioration of surface quality.

In order to avoid defects [8—10] in thin-walled parts with a ratio of the preset billet thickness to its major diameter at $S_{\text{preset}}/D < 0.08$, shape formation is carried out under conditions of stress state close to the plane tensile stress state. This can be achieved, for example, using processes of flanging and forming. In addition, it is important to design the process in such a way that the thickness of the workpiece varies in the direction associated with a preset part thickness. For this purpose, in real deformation processes, it is important to ensure the minimum thickness variation of the part, defined as a minimization equation in the form of an integral quadratic difference between the preset and technologically possible thicknesses.

The aim of this work was, therefore, to develop a technique for obtaining parts with a preset thickness from a conical billet by flanging.

Theoretical studies of the flanging process to obtain thin-walled axisymmetric parts of a truncated tapering shape

This paper presents the results of the study only for relatively low parts (the ratio of height to major diameter $H/D \approx 1$ and diameter to relative curvature $D/R_\rho < 0.045$). Let us consider a method for manufacturing thin-walled axisymmetric parts of a truncated tapering shape with a minimum thickness difference from a conical billet using the flanging process. In this case, we use the theory of plastic deformation of sheet materials, taking into account the anisotropy of the mechanical properties of the initial billet and the assessment of the conditions for stable shape formation upon plane tensile stress state. By minimizing the equation for the difference between the preset and technically possible thicknesses, the possibilities of process analysis are expanded. Figure 1 illustrates a schematic view of the method of part flanging from a conic billet.

The tapered billet *4* is clamped between die *3* and clamp *2*, providing a stationary portion of the billet flange under the clamp during shape formation. For example, when punch *1* is lowered, due to the different configuration of the punch and billet geometry, the billet is at first contacted and deformed in the elements of

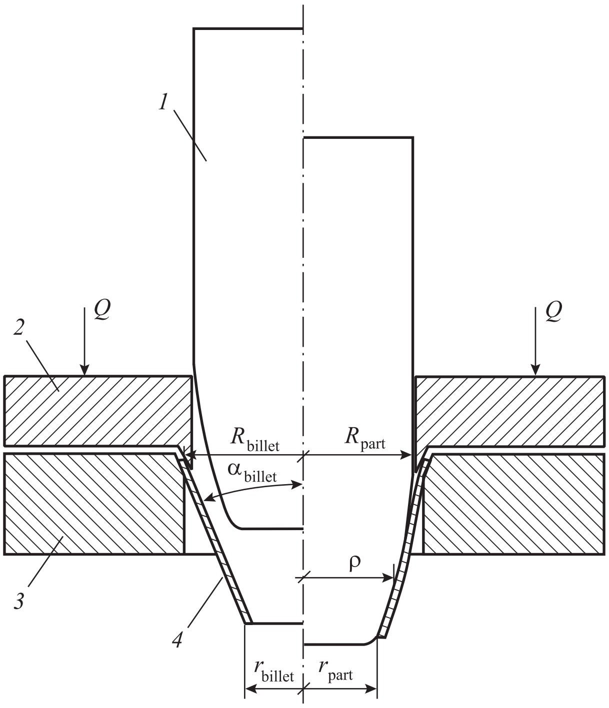

Fig. 1. Geometric layout of shape formation

1 – punch, *2* – blank holder, *3* – mold, *4* – workpiece/part
R_{billet} and R_{part} are the major radii of billet and part, mm;
α_{billet} is the billet cone angle, deg.; r_{billet} and r_{part} are the minor radii of billet and part, mm; Q is the force and direction of clamping, N;
ρ – is the current radius of part, mm

Рис. 1. Геометрическая схема формообразования

1 – пуансон, *2* – прижим, *3* – матрица, *4* – заготовка/деталь
$R_{\text{заг}}$ и $R_{\text{дет}}$ – наибольшие радиусы заготовки и детали, мм;
$\alpha_{\text{заг}}$ – угол конусности заготовки, град; $r_{\text{заг}}$ и $r_{\text{дет}}$ – наименьшие радиусы заготовки и детали, мм; Q – усилие и направление прижима, Н; ρ – текущий радиус детали, мм

minor diameter. As the punch is lowered, the billet elements with major diameter coordinates enter the zone of deformation center. The process stops when the plastic deformation of the billet edge begins.

Due to the size and geometry of the punch and the workpiece, it is possible to adjust the thickness of the latter along the generatrix length. As a result, the part obtained has a thickness either close to constant, with minimal thickness variation, or with a variable (monotonic) thickness that is close to the preset thickness. It has a minimal thickness variation (with its decrease from the minor diameter edge elements to the elements with the major diameter, and vice versa). The main factors affecting the above-described distribution of part wall thickness are the inclination angle of the tapered billet face, friction, and the mechanical properties of the billet (e.g., anisotropy coefficient of a transversal isotropic body) [11].

Directed change in billet thickness with regard to preset thickness is possible by varying the constants in the process of technological parameters [12] (billet size, tool geometry, coefficient of friction, boundary conditions, mechanical property indicators, etc.). It also requires an analytically [13—15] presented and resolved expression of minimum thickness difference [16—18]:

$$\iint_F (S_{\text{preset}} - S_{\text{Th}})^2 dF \to \min, \tag{1}$$

where S_{preset} is the preset part thickness, mm; S_{Th} is the technologically possible thickness, obtained after the shape formation of the billet, mm; F is the area of the part across the median surface, mm^2.

The mathematical condition for achieving a given distribution of the constant wall thickness of the part for implementation of the proposed method is written as follows:

$$\int\int_{r_{\text{part}}}^{1} \left[(\bar{S}_{\text{preset}} - 1) - Q\left(1 - \frac{\bar{r}_{\text{billet}}}{\bar{\rho}}\right)\right]^2 d\rho \to \min, \tag{2}$$

where $\bar{S}_{\text{preset}} = S_{\text{preset}}/S_{\text{billet}}$, $\bar{r}_{\text{billet}} = r_{\text{billet}}/R_{\text{part}}$ and $\bar{\rho} = \rho/R_{\text{part}}$.

Let us denote Q:

$$Q = (1-\mu)[(1+\bar{\sigma}_{\rho k})/(\mu\bar{\sigma}_{\rho k} - 1)] = \text{const}, \tag{3}$$

where $\sigma_{\rho k} = \sigma_\rho/\sigma_\theta$ is the ratio of stresses determined by the engineering method using the equation of equilibrium in polar coordinates [19]. In the case of billet shape formation, assuming that the additional pressure $q = 0$, it will take the following form:

$$\rho\frac{d\sigma_\rho}{d\rho} + d\sigma_\rho - d\sigma_\theta - \frac{f\rho}{\sin\alpha_0}\left(\frac{\sigma_\rho}{R_\rho} + \frac{\sigma_\theta}{R_\theta}\right) = 0,$$

where R_ρ and R_θ are the radii of the part in the meridional and tangential directions; σ_ρ and σ_θ are the stresses in meridional and tangential directions, Pa; f is the coefficient of friction on the inner surface of the workpiece; α_0 is the angle of generatrix inclination of the part to the axis, deg.

Let us write the plasticity condition for flanging:

$$\beta\sigma_s = \sigma_\theta, \tag{4}$$

where $\beta = 2/\sqrt{7-6\mu}$ is the coefficient determining the stress-strain state of the process taking into account the anisotropy of mechanical properties of the initial billet [20].

With the geometrical ratio $\rho = R_\theta \cos\alpha$ and assumption that $\sigma_\rho / R_\rho = 0$ the equilibrium equation is written as:

$$\bar{\rho}\frac{d\sigma_\rho}{d\bar{\rho}} + \sigma_\rho - \beta\sigma_s(1 + f\text{ctg}\alpha) = 0, \qquad (5)$$

where α is the angle of inclination of the tangent to the axis of the part, drawn in the middle part of the deformation zone, deg.

Assuming that the stress ratio $\sigma_\rho / \sigma_\theta$, as shown in [19], is not affected by hardening [21—23] and thickness variation, we can find the stresses σ_ρ in the billet under boundary conditions: $\sigma_\rho = 0$, $\bar{\rho} = \bar{r}_{\text{part}}$ and $\bar{\rho} = \rho / R_{\text{part}}$.

We will assume that the stress in the deformation center is constant and equals the average integral value. Its value is determined by the known formula [19] taking into account that the meridional stress is equal to:

$$\sigma_\rho = \beta(1 + f\text{ctg}\alpha)(1 - \bar{r}_{\text{part}}/\bar{\rho}), \qquad (6)$$

then the average integral value is:

$$\bar{\sigma}_{\rho k} = \frac{\sigma_{\rho k}}{\sigma_\theta} = \frac{(1 + f\text{ctg}\alpha)\int_{\bar{r}_{\text{part}}}^{1}(1 - \bar{r}_{\text{part}}/\bar{\rho})d\bar{\rho}}{1 - \bar{r}_{\text{part}}}. \qquad (7)$$

After algebraic transformations we obtain:

$$\bar{\sigma}_{\rho k} = (1 + f\text{ctg}\alpha)\frac{1 - \bar{r}_{\text{part}}(1 - \ln\bar{r}_{\text{part}})}{1 - \bar{r}_{\text{part}}}. \qquad (8)$$

Next, it is necessary to determine the ratio $\bar{r}_{\text{billet}}/\bar{\rho}$. Let us make the following assumption:

$$\bar{r}_{\text{billet}} = a + b\bar{\rho}. \qquad (9)$$

At $\rho = \rho/R_{\text{part}}$ and $\bar{r}_{\text{billet}} = r_{\text{billet}}/R_{\text{part}} = 1$ Eq. (7) is rewritten as follows:

$$\bar{b} = 1 - \bar{a}. \qquad (10)$$

Taking into account Eq. (10), Eq. (9) will be presented in the following form:

$$\bar{r}_{\text{billet}} = \bar{a} + (1 - \bar{a})\bar{\rho} = \bar{a}(1 - \bar{\rho}) + \bar{\rho}. \qquad (11)$$

Let us carry out a minimization for the case of changing the preset thickness of the part: decrease from the major diameter. With such a flanging scheme (Fig. 1), the defining function of a given thickness is described by the following equation:

$$\bar{S}_{\text{preset}} = 1 - [m/(1 - \bar{r}_{\text{part}})](1 - \bar{\rho}), \qquad (12)$$

where $m = 1 - S_{\text{preset}}/S_{\text{billet}} < 1$.

Let us write the minimization condition (2), taking into account Eq. (12):

$$\int_{\bar{r}_{\text{part}}}^{1}\left[-\frac{m}{1 - \bar{r}_{\text{part}}}(1 - \bar{\rho}) + Q\left(1 - \frac{\bar{r}_{\text{billet}}}{\bar{\rho}}\right)\right]^2 d\rho \to \min. \qquad (13)$$

Equation (14) with consideration for Eq. (11) will be rewritten as follows:

$$\int_{\bar{r}_{\text{part}}}^{1}\left[-\frac{m}{1 - \bar{r}_{\text{part}}}(1 - \bar{\rho}) + Q\bar{a}\left(\frac{1}{\bar{\rho}} - 1\right)\right]^2 d\rho \to \min. \qquad (14)$$

Varying $\bar{a}$ and taking the derivative, we obtain the following equation:

$$\bar{a} = \frac{\frac{m}{1 - \bar{r}_{\text{part}}}\int_{\bar{r}_{\text{part}}}^{1}\left[(1 - \bar{\rho})\left(\frac{1}{\bar{\rho}} - 1\right)\right]d\rho}{\left[Q\int_{\bar{r}_{\text{part}}}^{1}\left(\frac{1}{\bar{\rho}} - 1\right)^2\right]d\bar{\rho}}. \qquad (15)$$

After integration, it will take the following form:

$$\bar{a} = \frac{-\frac{m}{1 - \bar{r}_{\text{part}}}\left[-\ln\bar{r}_{\text{part}} - 2(1 - \bar{r}_{\text{part}}) + 0{,}5 - \frac{\bar{r}_{\text{part}}^2}{2}\right]}{Q(1/\bar{r}_{\text{part}} + 2\ln\bar{r}_{\text{part}} - \bar{r}_{\text{part}})}. \qquad (16)$$

Let us determine the relative technologically possible thickness of the part according to the following equation:

$$\bar{S}_{\text{Th}} = 1 + Q(1 - \bar{r}_{\text{billet}}/\rho). \qquad (17)$$

Using Eqs. (3), (9), (12) and (16), $m = 0.1$, $\sigma_{\rho k} = 0.3311$, $Q = -0.7976$, $a = -0.1497$ are obtained, and the distribution of the technologically possible and specified thicknesses of the convex part is plotted with the following parameters: major radius $R_{\text{part}} = 22.35$ mm; minor radius $r_{\text{part}} = 11.05$ mm; radius of curvature of the part in the meridional direction $R_\rho = 1000$ mm. The part was obtained from a billet with a taper angle $\alpha_{\text{billet}} = 16.4°$ during shape formation with a coefficient of friction on the inner surface of the workpiece $f = 0.05$ and taking into account the anisotropy coefficient of the transversely isotropic body $\mu = 0.5$.

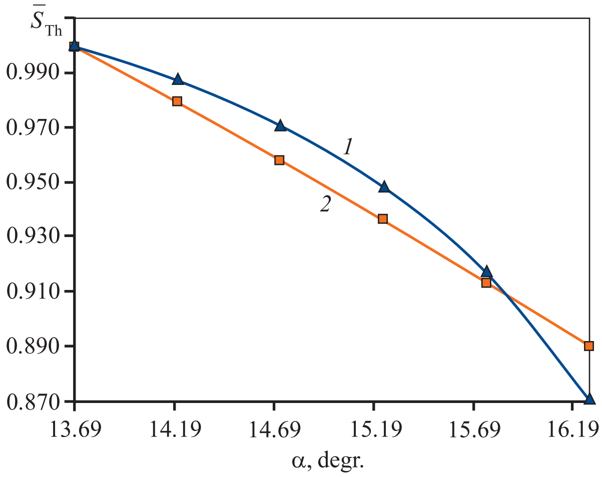

Fig. 2. Distribution of relative technologically possible at $f = 0.05$ and $\mu = 0.5$ (*1*) and relative preset (*2*) thickness of a thin-walled convex part

Рис. 2. Распределение относительной технологически возможной при $f = 0{,}05$ и $\mu = 0{,}5$ (*1*) и относительной заданной (*2*) толщин тонкостенной выпуклой детали

The data obtained made it possible to plot the distribution of the relative technologically possible thickness of the part along the deformation zone, according to the proposed method (Fig. 2).

Simulation of shape formation in LS-DYNA software

In order to eliminate errors in the design of a tool for the future implementation of the method on manufactured die tooling [24], we applied the method of simulating shape formation in specialized finite element software systems. A variety of programs, such as LS-DYNA, ANSYS, Abaqus, QFORM, DEFORM, etc., are used for calculation of process variables. Despite the fact that much scientific literature is devoted to the study of plastic flow, theoretical equations can be derived only for relatively simple processes (bending, drawing, precipitation), and with significant assumptions for billets of simple shape (round, cylindrical, square). However, when using billets of a complex shape and developing more advanced metal forming technologies (MPT), such equations give significant errors, and it is difficult to obtain a solution with approximate methods.

The solution to this problem can be to use programs based on the finite element method, such as ANSYS / LS-DYNA, which is one of the best in its field. It is intended for calculations of high-speed and dynamic processes and ideal for solving problems of mechanical engineering, including cold sheet stamping. The software enables dangerous zones and segments of the model in which destruction is possible to be identified. It can also determine all the necessary parameters:

— stress-strain state of the billet and tool at any point and at any time;

— energy parameters of the process;

— values of efforts and torques, normal and tangential forces;

— contact parameters;

— many other factors necessary for an understanding of the processes occurring in the billet.

Nowadays, there is a wide choice of programs for simulating various scenarios [25—31], successfully used in various fields of mechanical engineering.

The need to resolve these problems in LS-DYNA system can be explained, among other things, by the possibility of calculating thin-walled shells. The kinematic diagram of the simulation process is shown in Fig. 3.

The billet and tool geometry (clamp, die, punch) were designed using ASCON Compass-3D 3D modeling system [32] and exported in a common data exchange format between CAD/CAE applications: Iges. Directly using ANSYS/LS-DYNA, the punch, mold, and billet were assigned the element type - Shell, a shell element. The BOUNDARY_SPC constraint was set on the billet flange nodes to prevent movement along

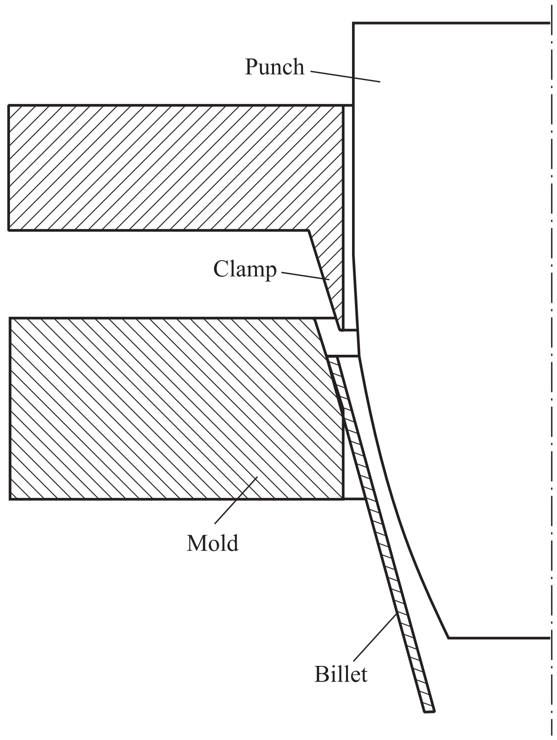

Fig. 3. Kinematic diagram of flanging

Рис. 3. Кинематическая схема процесса отбортовки

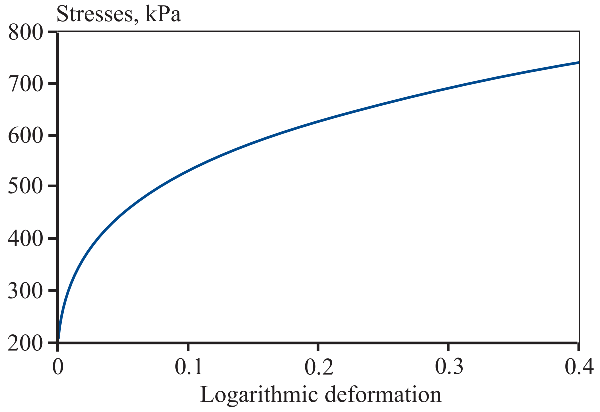

Fig. 4. Experimental hardening curve of 12Kh18N10T steel

Рис. 4. Экспериментальная кривая упрочнения стали 12Х18Н10Т

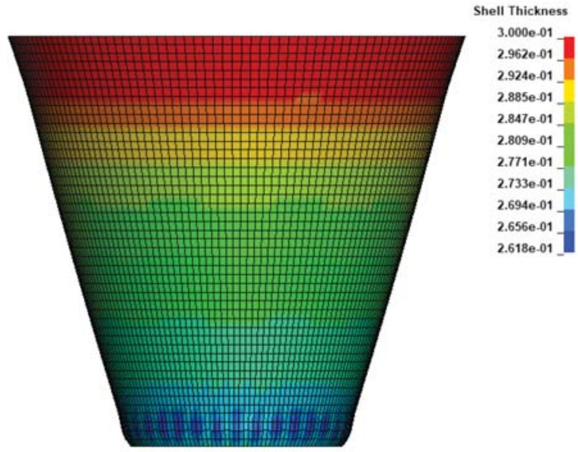

Fig. 5. Distribution of wall thickness (mm) of an axisymmetric part

Рис. 5. Распределение толщины (мм) стенки осесимметричной детали

and rotation around axes. The command performs the clamping and mold functions. The boundary conditions and constraints on the degrees of freedom of the punch are set in such a way that the tool moves only along the *OZ* axis. The coefficient of friction between the punch and the billet was 0.05. After positioning the objects along the *OZ* axis, a regular (quadrilateral) finite element mesh with an edge length of 1 mm for the workpiece and a mixed mesh with an edge length of 2 mm for the punch were plotted for them. A rigid model was chosen as the material model of the punch and workpiece: MAT_RIGID and transversely anisotropic: MAT_TRANSVERSELY_ANISOTROPIC_ELASTIC_PLASTIC, respectively.

In order to specify the properties [33] of the material of the billet (12Kh18N10T), an experimental hardening curve for this structural steel was introduced, obtained during a simple tensile test (Fig. 4).

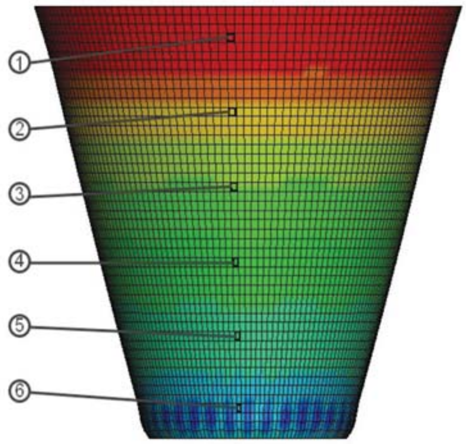

Fig. 6. Selection of points along the generatrix of an axisymmetric part

Рис. 6. Выбор точек по образующей осесимметричной детали

Results and discussion

To describe the properties of the material of a thin-walled billet with a thickness of S_{billet} = 0.3 mm from steel 12Kh18N10T, the following parameters were introduced:

— steel density: 7920 kg/mm2;
— elasticity modulus: 198 GPa;
— Poisson's ratio: 0.29;
— coefficient taking into account the anisotropy of a transversely isotropic billet: 0.5.

The simulation results are illustrated in Fig. 5.

For a comparative analysis of the simulation results, we selected points along the generatrix of the axisymmetric part (Fig. 6) and plotted the function reflecting the thickness at these points (Fig. 7). For illustration, let us add the relative specified thickness of the part to the plot, which will enable a conclusion about the minimum deviation obtained of the thickness of the part from a given value, not exceeding 2.0 %.

Conclusions

The following conclusions were drawn from the study.

1. The maximum discrepancy between the simulation and theoretical data does not exceed 1.5 %. The minimum variation in thickness is observed at a punch angle of 15.36°, and the maximum at 16.79° (see Fig. 7).

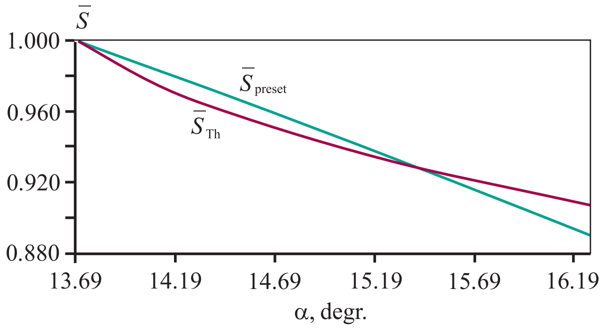

Fig. 7. Distribution of relative technologically possible thickness according to the results of simulation and relative preset thickness of a thin-walled convex part

Рис. 7. Распределение относительных значений технологически возможной толщины (по результатам моделирования) и заданной толщины тонкостенной выпуклой детали

2. A comparison of simulation results and theoretical studies using the proposed method indicates their satisfactory agreement.

3. The required thickness distribution was achieved (see Fig. 6): it decreases from major to minor radii with a minimum deviation from the specified value.

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