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STRESS STATE IN THE DEFORMATION REGION OF A SHEET BLANK DURING ROTATIONAL DRAWING OF AXISYMMETRIC PARTS

The paper deals with investigation of the stress state in the deformation region during rotational drawing of axisymmetric parts made from a sheet blank Regularities in the distribution of stress state indices have been determined. The value of the used plasticity resource has been estimated depending on the geometric characteristics of the roller, sheet blank thickness and mechanical characteristics of the blank material.

Key words: *rotational drawing, stress, deformation region, stress state indices, conical part.*

Axisymmetric thin-wall products have found wide application in various branches of the machine-building industry. Strict requirements are set to their quality and operation characteristics. For manufacturing such products rotational drawing methods are widely used. A considerable number of current literary sources deal with experimental investigation of the rotational drawing process [1 – 3]. However, the methods of evaluating the stress state pattern and the used plasticity resource value in the deformation region and of their influence on the end product quality are practically absent.

It should be noted that a special feature of the process of rotational drawing of axisymmetric parts, made from sheet blanks, is as follows: plastic deformation occurs in the local volume of the tool contact with the blank. The stress state pattern in this volume depends on the shape and size of the blank and the tool, their mutual location and processing modes.

This study aims at determining regularities in the distribution of stress state indices and the used plasticity resource values in the deformation region depending on the parameters of rotational drawing process.

The paper considers the process of rotational drawing of a thin shell made from a sheet blank. The deformation region is divided into three zones (Fig. 1). Zone 1 is under volumetric stress conditions and zone 2 is in s in the plane strain state. In [4, 5] the stress state is determined for zone 2 in a polar system of coordinates ρ, α with the origin in the center of the curvature of the roller working surface (Fig. 2). In the shaded element of the blank, limited by radii ρ_1 and ρ_2 and by angles $\alpha=0$ and $\alpha=\alpha_m$, the action of radial stresses σ_ρ, tangential stresses σ_α and shearing stresses $\tau_{\rho\alpha}$ is observed. Difference between radii ρ_2 and ρ_1 is equal to thickness δ of the sheet blank.

The balance equations for 2D-problem in the polar coordinates are given by [4, 5]:

$$\begin{aligned}&\frac{\partial\sigma_\rho}{\partial\rho}+\frac{1}{\rho}\cdot\frac{\partial\tau_{\rho\alpha}}{\partial\alpha}+\frac{\sigma_\rho-\sigma_\alpha}{\rho}=0;\\&\frac{\partial\sigma_\alpha}{\partial\alpha}+\rho\cdot\frac{\partial\tau_{\rho\alpha}}{\partial\rho}+2\tau_{\rho\alpha}=0.\end{aligned}\tag{1}$$

In this problem plasticity condition takes the form of

$$\sigma_\alpha-\sigma_\rho=2\tau_s.\tag{2}$$

After differentiation of the first equation of system (1) with respect to α, taking into account the plasticity condition (2), and after differentiation of the second equation of system (1) with respect to ρ and subtraction of the first equation from the obtained second equation we obtain the equation for determining the shearing stresses [4, 5]:

$$\rho^2\cdot\frac{\partial^2\tau_{\rho\alpha}}{\partial\rho^2}-\frac{\partial^2\tau_{\rho\alpha}}{\partial\alpha^2}+3\rho\frac{\partial\tau_{\rho\alpha}}{\partial\rho}=0.\tag{3}$$

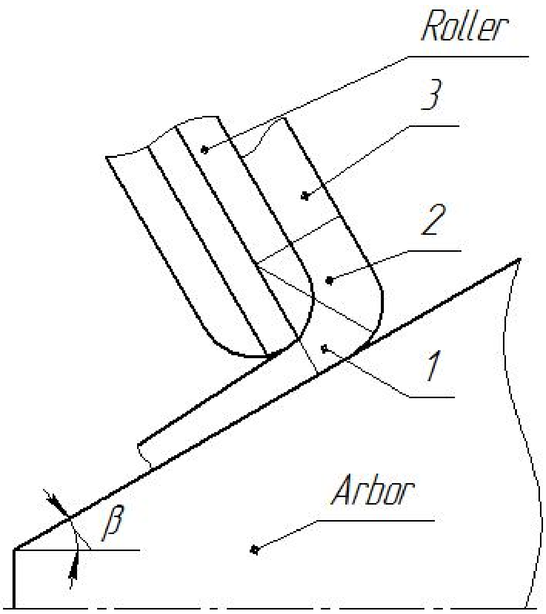

Fig. 1. The sheme of the deformation region division into zones

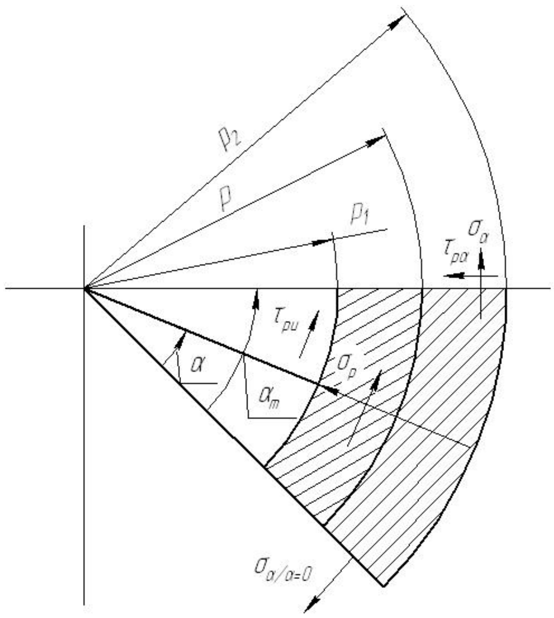

Fig. 2. The pattern of the stress state in zone 2 during rotational drawing process

The solution of equation (3) has been obtained under the following limit conditions. In the zone of the blank contact with the roller shearing stresses for $\rho = \rho_1$are equal to $\tau_{\rho\alpha}= -m\tau_s$, where m – Prandtl friction factor. On the free surface of the blank shearing stresses for $\rho = \rho_2$ are equal to $\tau_{\rho\alpha}=0$. For $\alpha=0$ shearing stresses $\tau_{\rho\alpha}=0$ as this region is the main one, and for $\alpha = \alpha_m$ shearing stresses take maximal values $\tau_{\rho\alpha} = -\tau_s$. After solving equation (3) for the adopted limit conditions for shearing stress $\tau_{\rho\alpha}$ the following expression was obtained in [5]:

$$\tau_{\rho\alpha} = -\tau_s\sqrt{1-c}\,\frac{\alpha}{\alpha_m} + \frac{\tau_s\sqrt{1-c}\cdot\sin\left(\frac{\pi\alpha}{\alpha_m}\right)}{\rho\cdot\sin\left(\omega\ln\frac{\rho_2}{\rho_1}\right)}\cdot\left[\rho_1\left(m-\frac{\alpha}{\alpha_m}\right)\cdot\sin\left(\omega\cdot\ln\frac{\rho}{\rho_2}\right)+\rho_2\cdot\frac{\alpha}{\alpha_m}\cdot\sin\left(\omega\ln\frac{\rho}{\rho_1}\right)\right]. \quad (4)$$

In [4, 5] for determining σ_ρ problem (1) is solved using the method of separation of variables for homogeneous boundary conditions:

$$\sigma_\rho = \frac{\tau_s\cdot\sqrt{1-c}}{\alpha_m}\cdot\left[\ln\frac{\rho}{\rho_2}+\left(\frac{\rho_1}{\rho\left(1+\omega^2\right)}\cdot\frac{\sin\left(\omega\ln\frac{\rho}{\rho_2}\right)+\omega\cdot\cos\left(\omega\ln\frac{\rho}{\rho_2}\right)}{\sin\left(\omega\ln\frac{\rho_2}{\rho_1}\right)}-\frac{\rho_1\cdot\omega}{\rho_2\left(1+\omega^2\right)\cdot\sin\left(\omega\ln\frac{\rho_2}{\rho_1}\right)}\right)\times\right.$$

$$\times\left[\pi\cdot\cos\left(\frac{\pi\alpha}{\alpha_m}\right)\left(m-\frac{\alpha}{\alpha_m}\right)-\sin\left(\frac{\pi\alpha}{\alpha_m}\right)\right]+$$

$$+\left[\frac{\rho_2\left(\sin\left(\omega\ln\frac{\rho}{\rho_1}\right)+\omega\cdot\cos\left(\omega\ln\frac{\rho}{\rho_1}\right)\right)}{\rho\left(1+\omega^2\right)\cdot\sin\left(\omega\ln\frac{\rho_2}{\rho_1}\right)}-\frac{\sin\left(\omega\ln\frac{\rho_2}{\rho_1}\right)+\omega\cdot\cos\left(\omega\ln\frac{\rho_2}{\rho_1}\right)}{\left(1+\omega^2\right)\cdot\sin\left(\omega\ln\frac{\rho_2}{\rho_1}\right)}\right]\times \quad (5)$$

$$\times\left\{\frac{\pi\alpha}{\alpha_m}\cdot cos\left(\frac{\pi\alpha}{\alpha_m}\right)+sin\left(\frac{\pi\alpha}{\alpha_m}\right)\right\}\Bigg]+2\tau_s\cdot\sqrt{1-c}\,ln\frac{\rho}{\rho_2}.$$

Normal stress σα was determined from the equation (2).

In this paper the obtained values of σα, σρ, τρα are used for analyzing the stress state pattern in zone 2 of the deformation region and for the evaluation of permissible forming limit. The stress state index η was calculated by the formula [6, 7]

$$\eta=\frac{3\sigma}{\sigma_u},\tag{6}$$

where $\sigma=\frac{1}{3}\sigma_{i,j}\cdot\delta_{i,j}$ – average stress, σ_u – stress intensity.

The parameter of Nadai-Lode is given by:

$$\mu_\sigma=\frac{2\sigma_2-\sigma_1-\sigma_3}{\sigma_1-\sigma_3}.\tag{7}$$

Main stresses σ_1, σ_2, σ_3 were calculated by the formula [6]:

$$\sigma_{\frac{max}{min}}=\frac{\sigma_\alpha+\sigma_\rho}{2}\pm\sqrt{(\sigma_\alpha+\sigma_\rho)^2+4\tau_{\rho\alpha}^2}.\tag{8}$$

Regularities in the distribution of stress state index η and parameter of Nadai – Lode μ_σ in the deformation region have been obtained depending on radius ρ and angle α for sheet blanks with thicknesses $\delta=0,8$ *mm*, $\delta=1,0$ *mm* and $\delta=1,2$ *mm* from aluminium АД1 and steel 10. Calculations were performed for the radii of the roller working surface $R_{rol}=1,5$ *mm* and $R_{rol}=4,0$ *mm.* Angle β of the arbor is taken $\beta=45°$.

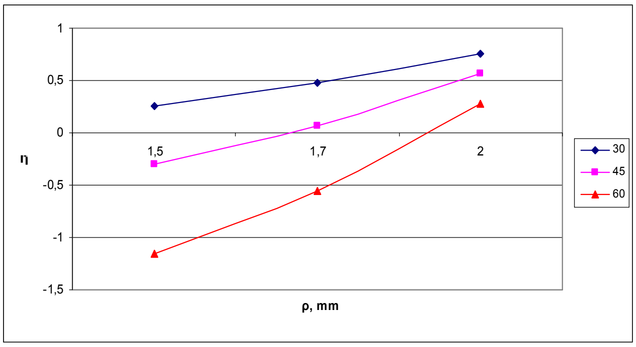

Fig. 3. Distribution of the stress state index η in the deformation region depending on radius ρ and angle α for thickness of the blank $\delta=0,8$ *mm*

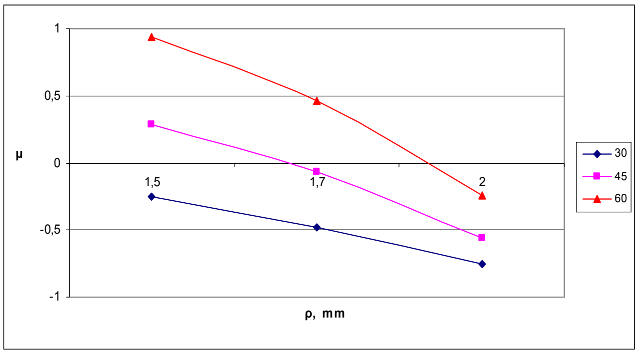

Fig. 4. Distribution of the stress state index μ_σ in the deformation region depending on radius ρ and angle α for thickness of the blank $\delta=0,8$ *mm*

Calculation results for the roller with the working surface radius $R_{rol}=1,5$ *mm* and different thicknesses of the sheet blank are presented in Fig. 3 – 8. Analysis of the obtained results shows that regularities in the distribution of indices η and μ_σ throughout the volume of the deformation region do not depend on the sheet blank material.

From the dependencies, presented in Fig. 3 – 8, it is evident that stress state index η increases with the increase of angle α. Parameter of Nadai – Lode decreases with the growth of radius ρ and increases with increasing angle α. E.g. for δ = 0,8 *mm* $R_{rol}=1,5mm$ as ρ changes from $\rho=1,5mm$ to $\rho=2,0$ *mm* index η increases from $\eta=-1,152$ to $\eta=0,283$ for $\alpha=60°$ and from $\eta=0,258$ to $\eta=0,755$ for $\alpha=30°$ (Fig. 3). Parameter of Nadai – Lode μ_σ decreases under the same conditions from $\mu_\sigma=0,939$ to $\mu_\sigma=-0,239$ for $\alpha=60°$ and from $\mu_\sigma=-0,253$ to $\mu_\sigma=-0,755$ for $\alpha=30°$ (Fig. 4). For fixed value of radius ρ, e.g. for $\rho=1,5$ *mm,* index η decreases from $\eta=0,258$ to $\eta=-1,152$ as α increases from α=30° to α=60° (Fig. 3), and under the same conditions parameter of Nadai – Lode μ_σ increases from μ_σ=-0,253 to μ_σ=0,939 (Fig. 4). With increased thickness of the sheet blank the value of index η decreases and the values of the parameter of Nadai – Lode μ_σ are increased (Fig. 3 – 8), i. e. the greater the thickness of the blank, the softer the stress state p[attern in the deformation region, the smaller damage accumulation intensity and, respectively, the smaller the value of the used plasticity resource will be. Such a result is important since the obtained workpiece is planned to be used for manufacturing parts with a more complicated shape by means of further plastic deformation.

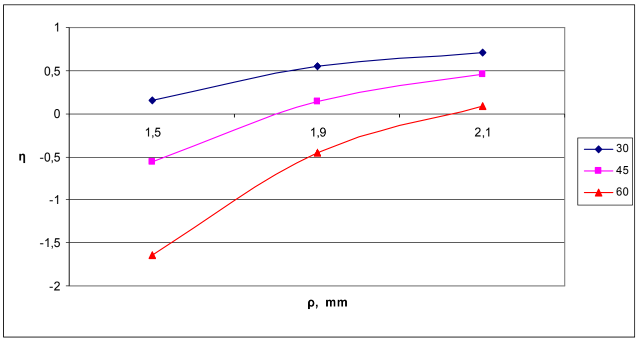

Fig. 5. Distribution of the stress state index η in the deformation region depending on radius ρ and angle α for thickness $\delta=1,0$ *mm* of the blank

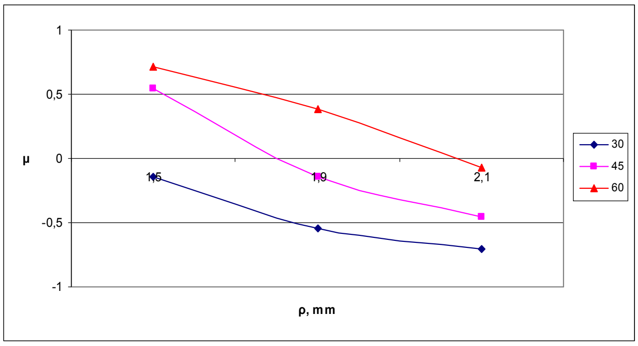

Fig. 6. Distribution of the stress state index μ_σ in the deformation region depending on radius ρ and angle α for thickness $\delta=1,0$ *mm* of the blank

When a roller with the working surface radius $R_{rol}=4,0$ *mm* is used for rotational drawing, character of the dependencies of stress state index η and Nadai – Lode parameter μ_σ on radius ρ and angle α is analogous to those presented in Fig. 3 – 8. However, numerical values of index η are, on the average, by 75 – 80 % higher and numerical values of Nadai – Lode parameter μ_σ are, on the average, by 60 – 80 % lower than those presented in Fig. 3 – 8 .

Analysis of the stress state calculation results shows that load in the deformation region is close to a simple load and, therefore, the used plasticity resource value ψ could be determined by Smirnov – Aliayev criterion [8]:

$$\psi = \frac{e_u}{e_p(\eta, \mu_\sigma)}, \tag{9}$$

where e_u – deformation degree, e_p – limit deformation for the given stress state pattern.

Ability of the blank material to be plastically formed without damage during rotational drawing is usually characterized by the value of thinning, which should not exceed limit deformation e_p of the metal being deformed for the given stress state pattern. In a general case the thinning value is given by the dependence [9]:

$$e_u = \ln \frac{h_0}{h}, \tag{10}$$

where h_0 – the initial thickness of the sheet blank; h – thickness of the wall of the part after rotational drawing.

Plasticity dependence on the stress state pattern was described by the surfaces of limit deformations which, for the materials under study, were approximated by the dependencies [10]:

For steel 10

$$e_p(\eta, \mu_\sigma) = 0.78 \exp(0.59 \cdot \mu_\sigma - 0.71 \cdot \eta), \tag{11}$$

For aluminium alloy АД1

$$e_p(\eta, \mu_\sigma) = 1{,}2 \exp(0.42 \cdot \mu_\sigma - 0.5 \cdot \eta). \tag{12}$$

Calculations of limit deformations e_p by criterion (9) have shown that maximally permissible thinning value, with which the material will not be damaged, does not exceed $e_p \leq 0{,}35$ for sheet blanks from steel 10 under given conditions of forming for the radius of the roller working surface $R_{rol} = 1{,}5\ mm$ and $e_p \leq 0{,}26$ for $R_{rol} = 4\ mm$. For the blanks, made from aluminium alloy АД1, the maximal permissible thinning value does not exceed $e_p \leq 0{,}60$ for $R_{rol} = 1{,}5\ mm$ and $e_p \leq 0{,}50$ for $R_{rol} = 4\ mm$.

For the investigated thicknesses of sheet blanks $\delta = 0{,}8\ mm$, $\delta = 1{,}0\ mm$, $\delta = 1{,}2\ mm$ the maximal permissible thinning value does not practically depend on he blank thickness.

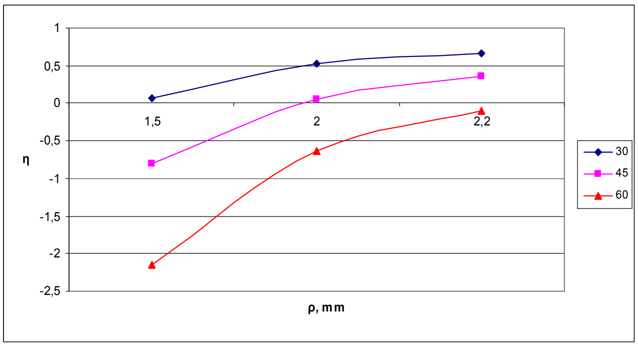

Fig. 7. Distribution of the stress state index η in the deformation region depending on radius ρ and angle α for blank thickness $\delta = 1{,}2\ mm$

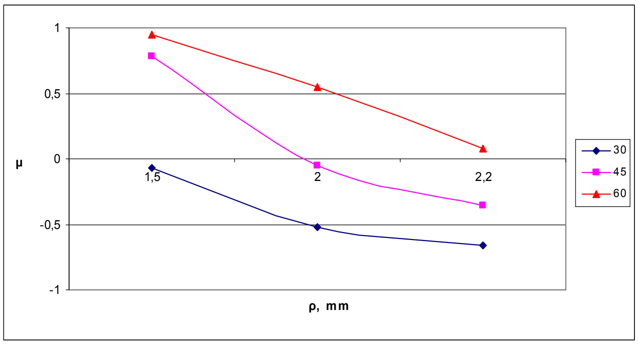

Fig. 8. Distribution of stress state index μ_σ In the deformation region depending on radius ρ and angle α for blank thickness $\delta = 1{,}2\ mm$

Conclusions

It has been determined that during rotational drawing of sheet blanks index η decreases and Nadai – Lode parameter μ_σ increases when thickness of the sheet blank is increased. With the increased radius of the roller working surface index η also grows in the deformation region and Nadai – Lode parameter μ_σ decreases irrespective of the thickness. It should be noted that the blank material does not influence the character of distribution of indices η and μ_σ in the deformation region. The used plasticity resource value ψ in the deformation region grows as the radius of the roller working surface R_{rol} is increased and does not essentially depend on the blank thickness, all other conditions being equal.

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