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EXTENDING TECHNOLOGICAL CAPABILITIES OF PRODUCING BENT PROFILES WITH A COATING

The paper analyzes influence of the coating parameters on the stress-strain state of a sheet blank during bending. To decrease the critical radius of curvature at the outer surface of the base it is proposed to apply a coating having lower strength than that of the base material. The optimum base/coating strength ratios are found in order to achieve the minimum bending radii.

Key words: *stress, sheet material, bending, plane-stress state, coating.*

Problem statement

Sheet stamping is considered to be one of the promising methods of producing light and strong products of complex configuration. This allows using constructions, made on the basis of sheet blanks, for solving a wide range of design problems [1]. However, it should be noted that in most cases sheet materials with coatings are used, which can improve corrosion resistance, have better antifriction properties and appearance, higher temperature resistance, etc. Today there are many different ways of applying coatings to various surfaces, the most efficient and cheapest being their application to flat and cylindrical surfaces. At the same time, deformation of the sheet materials with a coating is not common as there are no methods of selecting physicomechanical properties of the coating to provide minimum curvature radii of the product elements.

Potential limit deformation in the modern pressure treatment is estimated with the use of dimensionless criteria which are based on the diagrams of limit deformation and parameters of the stress-strain state of products [2]. In general case the stress-strain state of the parts is determined by balance and coupling equations of equilibrium and coupling, continuity of the environment and critical conditions of deformation [3, 4].

Fluidity curve and the surface of limit deformations are main physical-mechanical parameters of the metal that determine its stress-strain state and the possibility of subsequent deformation. These basic characteristics depend on the material structure, chemical composition, heat treatment, the speed of application, location and type of the load. From this it follows that by controlling this parameters it is possible to increase and decrease limit bending radii of sheet blanks in order to achieved the required results.

In this paper we analyze the influence of the parameters of the coating fluidity curve on the stress-strain state of the substrate during the formation of regular profiles with curved sections.

Stress-strain state of the coated sheet during bending

During working stroke of the punch between the surfaces of the blank (base + coating) and both of the punch and the matrix normal reaction and friction forces appear which for a broad sheet in the process of its bending create a plane-sress state [3, 5, 6], i.e. the deformation $\varepsilon_z = 0$.

If we assume that thickness of the base and the coating is constant and uniform, then, assuming that the blank does not move relative to the punch [6], we can consider the stress in the contact zone of the punch and the base to be evenly distributed.

Mathematical model of the stamping process is based on the balance equations for plane-sress state, the coupling equations and the continuity condition and that are supplemented by physical balance equations for the base portion and the coating that are subjected to bending (fig. 1). For the case when contact stresses at the outer surface of the blank are absent balance equations will be of the form

$$\begin{cases} \sigma'_{\rho 1} \cdot \sin\alpha \cdot r - \sigma''_{\rho 1} \cdot \sin\alpha \cdot (r + s_1) + 2 \int\limits_{r}^{r+s_1} \sigma_{\theta 1} d\rho \cdot \sin\alpha = 0, \\ \sigma'_{\rho 2} \cdot \sin\alpha \cdot (r + s_1) + 2 \int\limits_{r+s_1}^{r+s_1+s_2} \sigma_{\theta 1} d\rho \cdot \sin\alpha = 0, \end{cases} \quad (1)$$

where $\sigma_{\theta 1}, \sigma_{\theta 2}$ are tangential normal stresses in the base and coating correspondingly; $\sigma_{\rho 1}, \sigma_{\rho 2}$ - radial normal stresses in the base and the coating correspondingly; $\sigma'_{\rho 1}$ - radial normal stresses in the base in the base-punch contact zone; α – bending angle of the blank.

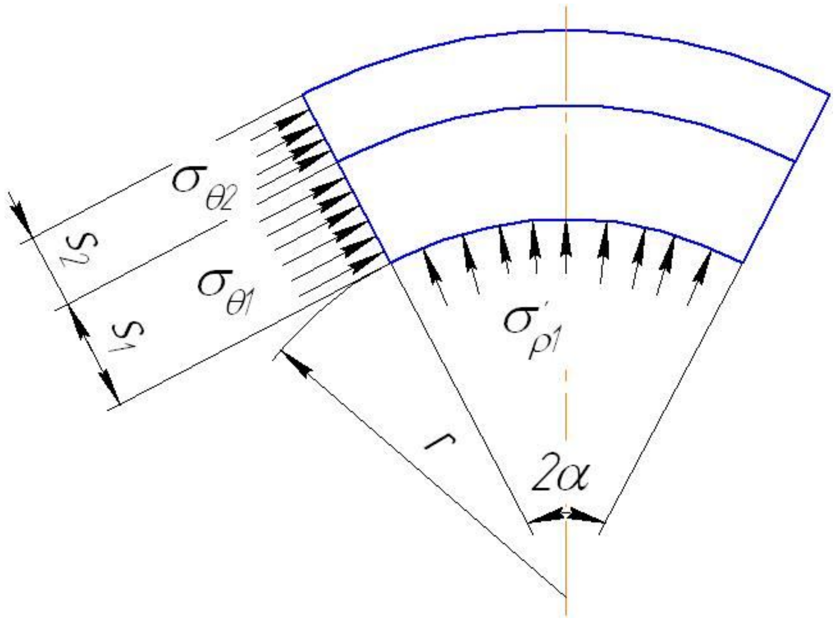

Fig. 1. Schematic representation of the blank element during bending

In the process of bending in the region adjacent to the neutral surface with a radius ρn a zone of elastic deformations is formed. The distance from the neutral surface to the edge of the zone Δel of elastic deformations can be calculated [3]

$$\Delta_{el} = 2\rho_n \cdot \left(\frac{A}{E}\right)^{\frac{1}{1-n}}, \quad (2)$$

where A and n are parameters of the material hardening curve; E – Young's modulus of elasticity.

For the variation range of the hardening curve parameters A = 100 – 3000 MPa and n = 0 – 0,5, which are characteristic for the majority of construction materials, coefficient $\left(\frac{A}{E}\right)^{\frac{1}{1-n}}$ in equation (2) varies in the range from 0 to 0,015 (fig. 2). For small curvature radii, commensurate with the thickness of the sheet, elastic deformation zone could be ignored. In [7] it is shown that radial and tangential normal stresses in the bending zone are weakly dependent on the angle of the cross-section rotation and therefore we can assume that the tangential normal stresses have linear distribution over the thickness (for sheets up to 3 mm) and can be represented as

$$\begin{aligned} \sigma_{\theta 1} &= a_1(\rho - \rho_n), \\ \sigma_{\theta 2} &= a_2(\rho - \rho_n), \end{aligned} \quad (3)$$

where a_1 and a_2 are constants.

From the condition of the absence of discontinuities at the coating – base interface $\sigma''_{\rho 1} = \sigma'_{\rho 2}$.

Transforming (1) we obtain

$$\frac{\sigma'_{\rho 1}\cdot r}{s_1\cdot s_2}+\frac{2}{s_2}\frac{\int_r^{r+s_1}\sigma_{\theta 1}d\rho}{s_1}+\frac{2}{s_1}\frac{\int_{r+s_1}^{r+s_1+s_2}\sigma_{\theta 2}d\rho}{s_2}=0, \tag{4}$$

where $\frac{\int_r^{r+s_1}\sigma_{\theta 1}d\rho}{s_1}$ and $\frac{\int_{r+s_1}^{r+s_1+s_2}\sigma_{\theta 2}d\rho}{s_2}$ are average tangential normal stresses.

Force in the section plane, with which the punch acts on the sheet, can be represented as (5).

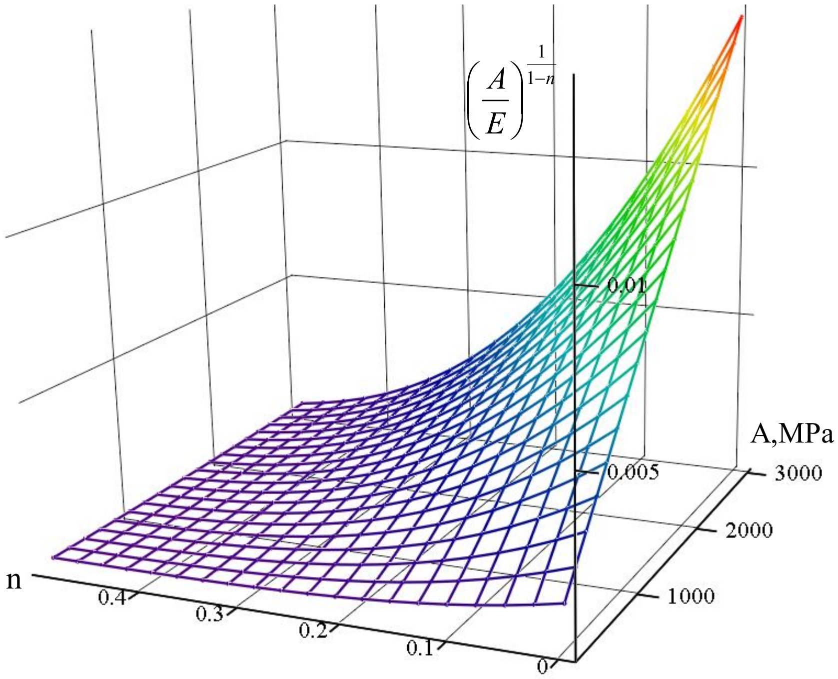

Fig. 2. Dependence of the relative length of the elastic deformation zone of the steel sheet on the hardening curve parameters A and n

$$P=\int_{0_1}^{\alpha} r\cdot\sigma'_{\rho 1}\cdot\cos\theta d\theta-2\sin\alpha\int_{r+s_1}^{r+s_1+s_2}\sigma_{\theta 2}d\rho-2\sin\alpha\int_{r}^{r+s_{12}}\sigma_{\theta 1}d\rho. \tag{5}$$

Proceeding from the assumption about uniform distribution of the normal radial stress in the sheet – punch contact zone and also from (4),

$$\sigma'_{\rho 1}=\frac{P}{3r\cdot\sin\alpha}. \tag{6}$$

Substituting expressions (3) and (6) into (4) and transforming them we obtain

$$a_2=-\frac{\frac{P}{3\sin\alpha}+2a_1\left(0{,}5s_1^2+r\cdot s_1-\rho_n\cdot s_1\right)}{2\left(0{,}5s_2^2+r\cdot s_2+s_1\cdot s_2-\rho_n\cdot s_2\right)}. \tag{7}$$

Since, as it was mentioned above, the stress state is plane and the sheet – punch contact is static in all directions, then on the basis of coupling equations and compatibility of deformations in the base – punch contact zone we obtain

$$\sigma'=\sigma'_z=\sigma'_{\rho 1}\cdot f, \tag{8}$$

$$\sigma'_{\rho 1} = -\sigma'_{\theta 1} + 2\sigma', \tag{9}$$

where f is coefficient of friction between the sheet and the punch; σ' – hydrostatic pressure in the punch – blank contact zone.

From (8) and (9) it follows that

$$a_1 = \frac{P \cdot (1-2f)}{3r \cdot \sin\alpha \cdot (r - \rho_n)}. \tag{10}$$

In equation (10) the curvature radius of the neutral surface is the only unknown value. To find it, the following expression is used [8]

$$\rho_n = r + K \cdot s, \tag{11}$$

where $K = \frac{t}{s}$ is a constant that depends on the properties of the fluidity curve, curvature radius of the internal surface of the sheet and the method of bending; t – distance from the internal surface of the blank to the neutral surface. In [8] it is noted that with increasing strength of the material or radius r K-factor increases and varies from 0.33 to 0.5. For $r < 2s$ the authors of [9] recommend to adopt coefficient $K = 0{,}33$, and for $r > 2s$ $K = 0{,}5$. However, in expression (11) thickness s of the homogeneous metal layer is used, so for its application it is necessary to determine the reduced thickness of the coating s_{red}. The authors proposed to determine s_{red} on the basis of the equal stress intensity for the coating and the sheet of replacement.

$$\int_{r+s_1}^{r+s_1+s_2} \sigma_{u2} d\rho = \int_{r+s_1}^{r+s_{red}} \sigma_{u1} d\rho , \tag{12}$$

or

$$A_2 \int_{r+s_1}^{r+s_1+s_2} \left(ln\left(\frac{\rho}{\rho_n}\right)\right)^{n_2} d\rho = A_1 \int_{r+s_1}^{r+s_{red}} \left(ln\left(\frac{\rho}{\rho_n}\right)\right)^{n_1} d\rho , \tag{13}$$

where $\sigma_u = Ae_u^n$ is stress intensity; $e_u = ln(\rho/\rho_n)$ – deformation degree; A_1 и n_1 – parameters of the flow curve of the coating material.

The solution of equation (13) could be used to determine ρ_n from (11) or by the expression $\rho_n = \sqrt{r(r + s_1 + s_{red})}$ [4] (r – curvature radius of the internal surface; s_{red} – the reduced thickness of the coating; s_1 – thickness of the base).

Therefore, on the basis of expressions (6), (7) and (10) and numerical solution of equation (13) we obtain boundary conditions for determining the stress-strain state during bending. The analysis of (13) shows that the coating is stronger than the base and makes it possible to shift the curvature radius to the outer surface and in this way to reduce tensile strain that facilitates very fast utilization of plasticity resource.

For flat stressed state the stress intensity can be calculated as

$$\sigma_{u1} = A_1 \cdot \left(\ln\frac{\rho}{\rho_n} \right)^{n_1} = \frac{\sqrt{2}}{2}\sqrt{(\sigma_{\rho 1} - \sigma_{\theta 1})^2 + (\sigma_{\theta 1} - \sigma_{z1})^2 + (\sigma_{z1} - \sigma_{\rho 1})^2 + \frac{3}{2}\tau_{\rho\theta 1}^2} . \tag{14}$$

Taking into account that $\sigma_{z1} = \sigma_1 = \frac{\sigma_{\rho 1} + \sigma_{\theta 1}}{2}$, from (14) we write

$$\tau_{\rho\theta 1} = \sqrt{\frac{4}{3} A_1^2 \left(\ln\frac{\rho}{\rho_n} \right)^{2n_1} - (\sigma_{\rho 1} - \sigma_{\theta 1})^2} . \tag{15}$$

From balance equations for plane stress state after transformations it could be written

$$\sigma_{\rho 1} = a_1\left(\frac{\rho}{2} - \rho_n\right) - \int_0^{\theta}\left(\rho \cdot \frac{\partial \tau_{\rho\theta 1}}{\partial \rho} + 2\tau_{\rho\theta 1}\right)d\theta . \qquad (16)$$

From the set of expressions (15), (16) and (3), substituting (7) and (10), with the application of numerical methods stress-strain state of the blank during deformation process can be determined and coating with such hardening curve parameters can be selected, which provide the possibility to obtain minimal curvature radii.

Conclusion

1. The presented mathematical model of forming blanks from the sheet material with a coating makes it possible to calculate the stress-strain state in the sheet zones subjected to bending
2. The analysis has shown that selection of the coating with definite characteristics of the hardening curve enables influencing the value of the stress tensor components and, accordingly, the value of the stressed state indicator.

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