ROTARY DRAWING OF AXISYMMETRIC PARTS OF COMPLEX SHAPE FROM ANISOTROPIC MATERIALS

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Abstract
The results of theoretical and experimental research operations rotary drawing with wall thinning of axisymmetric parts of complex shape from anisotropic materials.

Keywords: anisotropic material, rotary extractor, pipe roller, mandrel, force, feed step, the degree of deformation, stress, destruction

1. INTRODUCTION
In the process of manufacturing thin-walled axisymmetric parts rotary drawing is finding an increasingly wider use. Theoretical study of the process of rotary drawing with wall thinning is complicated by presence of local deformation and by the voluminous nature of the stressed and deformed state of the material in the plastic domain [1-4, 6-10]. Rolled pipes subjected to rotary drawing display anisotropy of mechanical properties, as conditioned by the mark of the material and by the technological modes of the production. The anisotropy of the mechanical properties of the piping blank material may produce both a positive, as well as a negative, effect upon the stable conduct of the technological processes used for metal working by pressure [5].

2. MAIN PART
We consider the process of rotary drawing of a thin-walled pipe blank made out of anisotropic material by tapered rolls with the taper angle \( \alpha_p \) and amount of deformation \( \varepsilon = 1 - t_k/t_0 \) for straight drawing (Drawing 1). During one turn of the blank the roller moved the length of the cutting feed \( S \). When the roller is moved by value \( S \), the actual feed is \( S_{\phi} = S t_k/t_0 \). This is true under the assumption that plane-strain deformation takes place along the axis line.

It will not be difficult, proceeding from geometrical considerations, to find the maximal angle of contact with the blank \( \theta_{n} \) [4]:

\[
\theta_{n} = \left[ \frac{2S_{\phi} R_p \tan \alpha_p}{R_\varepsilon (R_\varepsilon + R_p)} \right]^{1/2}, \text{if } S_{\phi} \tan \alpha_p \leq \Delta t ;
\]

\[
\theta_{n} = \left[ \frac{2R_p \Delta t}{R_\varepsilon (R_\varepsilon + R_p)} \right]^{1/2}, \text{if } S_{\phi} \tan \alpha_p \geq \Delta t .
\]

It must be noted that formulas (1) and (2) have been obtained considering that magnitudes \( \Delta t \) and \( S_{\phi} \) are small quantities as against the magnitude of the roller radius \( R_p \).

Proceeding from source [4], let us consider the aspect of distribution of the material flow speeds in the deformation zone under an established deformation. The speed of the pressing-in of the roller into the blank is determined in the blank cross-section as made at angle \( \theta \) relative to the centers line:
\[ V_R = R_e \theta (\omega_p + \omega_n), \]

where \( \omega_p \) is the roller angulator; \( \omega_p = \omega_n R_e / R_p \); \( \omega_n \) is the blank angulator; \( \omega_n = 2\pi n \); \( n \) is the spindle rpm.

In the cylindrical coordinates \( \rho, \theta, z \) linked to the blank, the radial speed in the contact zone between the roller and the metal equals in every section of the deformation zone to

\[ V_{rk} = -V_R \cos \theta. \]

Let us write down the radial speed in the plastic area of the deformation zone

\[ V_r = -R_e \theta (\omega_p + \omega_n) \frac{r - r_0}{r_k - r_0} \cos \theta, \]

where \( r_k \) is the radius of the contact zone in the cylindrical system of coordinates in plane \( z = \text{const} \).

Let us assume that in the plastic area in the cylindrical system of coordinates there takes place a quasi-plane deformation, that is, \( \xi_0 = 0; \xi_\rho \neq 0; \xi_z \neq 0 \).

The equation of the contact line in the cylindrical system of coordinates in cross-section \( z = \text{const} \) is as follows

\[ r_k = (R_d + z \tan \phi_p) / \cos \theta. \]

Let us write down the final formulas for finding the radial \( V_r \), tangent \( V_\theta \) and axis \( V_z \) speeds of material flow:

\[ V_r = -(R_d + S_\phi \tan \alpha_p + z \tan \alpha_p) \theta (\omega_p + \omega_n) \frac{r - r_0}{R_d + z \tan \alpha_p - r_0}; \]

\[ V_\theta = -\omega_n r + (\omega_p + \omega_n) \frac{R_d + S_\phi \tan \alpha_p + z \tan \alpha_p}{R_d + z \tan \alpha_p - r_0} \frac{r_0^2}{2}; \]

\[ V_z = \theta (\omega_p + \omega_n) \left[ z + (S_\phi + r_0 \tan \alpha_p) \ln \frac{z \tan \alpha_p + R_d - r_0}{R_d - r_0} \right] - (R_d + S_\phi \tan \alpha_p) \frac{t_0}{\left( t_0 + S_\phi \right) \left( r_0 \right)^2} - 1. \quad (3) \]
Let us take note of the fact that the formulas in case were obtained with taking into consideration the small magnitude of angle θ in relation to 1.

The components of the deformation speeds are found from the known material flow speeds in the cylindrical system of coordinates:

$$\xi_r = \frac{\partial V_r}{\partial r}; \quad \xi_\theta = \frac{1}{r} \frac{\partial V_\theta}{\partial \theta} + \frac{V_r}{r}; \quad \xi_z = \frac{\partial V_z}{\partial z} = -\xi_r - \xi_\theta;$$

$$\xi_{r\theta} = \frac{\partial V_\theta}{\partial r} + \frac{1}{r} \frac{\partial V_r}{\partial \theta}; \quad \xi_{r\theta z} = \frac{1}{r} \frac{\partial V_z}{\partial \theta} + \frac{\partial V_\theta}{\partial z}; \quad \xi_{r\theta z} = \frac{\partial V_r}{\partial z} + \frac{\partial V_z}{\partial r},$$

(4)

The material of the pipe blank is taken as plastic-rigid, incompressible, cylindrically orthotropic and conforming to the von Mises-Hill plasticity model and the associated plastic flow rule [5].

We assume that there is realized in the seat of plastic deformation a quasi-2D floatation of material, that is,

$$\xi_0 = 0; \quad \xi_{r\theta} \neq 0; \quad \xi_{r\theta z} = 0; \quad \sigma_0 = \frac{F\sigma_r + H\sigma_z}{F + H}; \quad \xi_r = -\xi_z.$$  

When we introduce the characteristics of anisotropy $c_{r\theta}$, $c_{r\theta \theta}$ and $c_{r\theta z}$ under conditions of flat deformed state

$$c_{r\theta} = 1 - \frac{M(H + F)}{2(FG + GH + HF)}; \quad c_{r\theta \theta} = 1 - \frac{L(H + G)}{2(FG + GH + HF)}; \quad c_{r\theta z} = 1 - \frac{N(F + G)}{2(FG + GH + HF)};$$

and when we take into account the fact that

$$F = \frac{1}{\sigma_{r\theta}^2(1 + R_0)}; \quad R_0 = \frac{H}{F}; \quad R_z = \frac{H}{G}; \quad G = R_0; \quad 2M = \frac{1}{S^2}; \quad 2N = \frac{1}{T^2}; \quad 2L = \frac{1}{R^2} = \frac{1}{r^2_{z0r}},$$

the formula for determining the intensity of the deformation speed $\xi_1$ will look as follows:

$$\xi_1 = \left[ \frac{2(R_z + R_0 + R_z R_0)(1 + R_0)}{3 R_0(R_0 + R_z + 1)(1 - c_{r\theta})} \times \left(1 - c_{r\theta}\right)^2 + \frac{1}{4} \xi_z^2 + \frac{1}{4} R_0(R_0 + 1)(1 - c_{r\theta}) \xi_{z0r}^2 + \frac{1}{4} R_z(R_0 + 1)(1 - c_{r\theta}) \xi_{z0\theta}^2 + \frac{1}{4} (R_z + R_0)(1 - c_{r\theta}) \xi_{z0z}^2 \right]^{1/2}.$$

The meaning of the symbols is as follows: $F, G, H, L, M, N$ - are the parameters of anisotropy; $\sigma_z, \sigma_{r\theta}, \sigma_r, \tau_{r\theta}, \tau_{r\theta \theta}, \tau_{r\theta z}$ - are the axial, circumferential, radial and shear stresses accordingly; $\xi_z, \xi_{r\theta}, \xi_r, \xi_{z0\theta}, \xi_{z0r}, \xi_{z0z}$ - are the deformation speeds in the respective directions.
We can show that for the adopted conditions of deformation, the plasticity equations establishing connections between stresses and deformation speeds will be presented as follows for an anisotropic body:

\[
\begin{align*}
\sigma_z - \sigma &= 2\mu_\theta \xi_z; \quad \sigma_r - \sigma = -2\mu_\theta \xi_z; \quad \sigma_0 - \sigma = -2\mu_\theta \xi_\theta; \\
\tau_{r\theta} &= \mu_\theta \xi_\theta; \quad \tau_{0r} = \mu_\theta \xi_\theta; \quad \tau_{rz} = \mu_\theta \xi_z.
\end{align*}
\]  

(5)

where \( \sigma \) - is average stress;

\[
\begin{align*}
\mu_\theta &= \frac{2\mu_\theta}{2\tau_{sr}} \frac{1}{\psi}; \\
\mu_{0\theta} &= \frac{2\mu_\theta}{2\tau_{sr}} \frac{1}{\psi}; \\
\mu_z &= \frac{\tau_{sr}}{2\psi}; \\
\mu_r &= \frac{1}{3} \frac{(2 + R_0)(1 - c_{rr})}{1 + R_0} \frac{1}{\psi}; \\
\mu_{0r} &= \frac{1}{3} \frac{(2 + R_0)(1 - c_{rr})}{1 + R_0} \frac{1}{\psi}; \\
\psi &= \frac{\dot{\lambda}}{2\tau_{sr}}; \\
\tau_{sr} &= \frac{R_0(1 + c_{rr})}{1 + R_0}; \\
\tau_{00} &= \frac{R_0(1 + c_{rr})}{1 + R_0}.
\end{align*}
\]

(6)

By solving formulas (5) relative to the components of the stress tensor, we obtain

\[
\begin{align*}
\sigma_z &= \sigma + 2\mu_\theta \xi_z; \\
\sigma_r &= \sigma + 2\mu_\theta \xi_z; \\
\sigma_0 &= \sigma + 2\mu_\theta \xi_\theta; \\
\tau_{0r} &= \mu_\theta \xi_\theta; \\
\tau_{0r} &= \mu_\theta \xi_\theta; \\
\tau_{rz} &= \mu_\theta \xi_z.
\end{align*}
\]  

(6)

By introducing the plasticity equations establishing connections between stresses and deformation speeds (6) into the equations of equilibrium in the cylindrical coordinate system (6), we obtain a system of equations for determining the average stress

\[
\begin{align*}
\frac{\partial \sigma}{\partial r} + 2\frac{\partial (\mu_\theta \xi_z)}{\partial r} + \frac{1}{r} \frac{\partial (\mu_\theta \xi_\theta)}{\partial \theta} + \frac{\partial (\mu_\theta \xi_z \xi_\theta)}{\partial \theta} + 2\frac{\xi_z}{r} (\mu_r - \mu_\theta) &= 0; \\
\frac{\partial (\mu_\theta \xi_\theta)}{\partial r} + \frac{\partial \sigma}{\partial \theta} + 2\frac{\partial (\mu_\theta \xi_z)}{\partial \theta} + \frac{\partial (\mu_\theta \xi_\theta \xi_z)}{\partial \theta} + 2\mu_\theta \xi_\theta &= 0; \\
\frac{\partial (\mu_\theta \xi_\theta \xi_z)}{\partial r} + \frac{1}{r} \frac{\partial \sigma}{\partial \theta} + \frac{\partial \sigma}{\partial \theta} + 2\frac{\mu_\theta \xi_z}{\partial \theta} + \mu_\theta \xi_\theta &= 0.
\end{align*}
\]  

(7)

By writing down the system of equations as finite differences, and by solving each one of them as relative to average stress, we obtain the formula to find the value of the average stress \( \sigma(m,n) \).

At the border line where material enters the source of plastic deformation under \( r = R_s \), \( \theta = 0 \) the value of the axial stress \( \sigma_z = 0 \). This condition allows us to determine the spread of the magnitudes of average stress \( \sigma(m,n) \) of the material into a source of plastic deformation and stresses \( \sigma_r \), \( \sigma_0 \), \( \sigma_z \) и \( \tau_{0\theta} \), \( \tau_{rz} \), after computing the components of the deformation speeds according to values (6), and the average value of the stored deformation intensity in the source of the plastic deformation:

\[
\varepsilon_{iBP} = \frac{1}{N_z} \sum_{i=1}^{N_z} \xi_{iz} \Delta_{ob} \frac{i}{i},
\]

where \( \Delta_{ob} \) - is the time for processing a material point in the source of deformation at the \( i \) turn of the spindle; \( N_z \) - is the number of spindle revolutions needed for passing by a material point of the path from the entrance to the local source of plastic deformation to its exit.

The trajectory equation for a material point under stationary process in the local source of plastic deformation during a rotational pulling by a conical roller shall be recorded as following:

\[
\frac{dr}{V_r} = \frac{r \, d\theta}{V_\theta} = \frac{dz}{V_z}.
\]
The time for processing a material point in the deformation source at the \( i \) turn of the spindle is calculated according to

\[
\Delta t_{\text{ob}i} = S_{\phi} \tan \alpha_p / V_{Rcp} ,
\]

where \( V_{Rcp} \) - is the average value of the speed for the roller to be impressed into the blank; \( V_{Ri} \) - is the speed for the roller to be impressed into the blank at section \( i \);

\[
V_{Rcp} = \frac{1}{\theta_{e}} \int_{0}^{\theta_{e}} V_{Rid\theta} d\theta .
\]

When we have at our disposal the curve of material hardening, we can find the average value for the material resistance to plastic deformation at the source of deformation according to the following formula:

\[
\sigma_{sp,cp} = \sigma_{0,20} + Q (\varepsilon_{cp})^n ,
\]

and we find the stress intensity

\[
\sigma_{kp} = \sigma_{sp,cp} \sqrt{\frac{3}{2} \left( \frac{R_z (1 + R_0)}{R_z + R_0 + R_z R_0} \right) ,}
\]

as well as the values for material resistance to plastic deformation during shear

\[
\tau_{sp,cp} = \sigma_{sp,cp} / 2 \sqrt{\frac{R_z}{R_0 (R_0 + R_z + 1) (1 - c_{zt})} ,}
\]

\[
\tau_{sp,cp} = \sigma_{sp,cp} / 2 \sqrt{\frac{R_z (1 + R_0)}{R_0 (R_0 + R_z + 1) (1 - c_{zt})} ,}
\]

where \( \sigma_{0,20} \) and \( Q \), \( n \) - represent the conventional limit of fluidity, and the constants of the hardening curve for the material under examination.

The accumulated intensity of deformation of the point under consideration when it leaves the local source of plastic deformation is found according to

\[
\varepsilon_i = \sum_{i=1}^{N_z} \varepsilon_{zt} \Delta t_{\text{ob}i} .
\]

The information about the average stress and deformation velocities, taken together with the curve for material strengthening, allows us to calculate the stressed state at every point in the source of deformation. All the above-listed characteristics of stress and deformation states are calculated numerically by the method of finite differences.

The components of the rotary drawing forces are found after the following formulas:

radial

\[
P_R = \int \int \sigma_R r d\theta \sin \theta d\zeta ,
\]

(8)

tangential

\[
P_{\zeta} = \int \sigma_{\zeta|\theta=0} d\rho \cos \theta d\zeta ,
\]

(9)

axial

\[
P_{\text{ax}} = \int \int \sigma_{\text{ax}} (r, \theta) r dr d\theta ,
\]

(10)
where \( \sigma_\epsilon = \sigma_s \sin^2 \theta + \sigma_0 \cos^2 \theta + \tau_{\theta \theta} \sin 2 \theta ; \) \( \sigma_R = \sigma_s \cos^2 \theta + \sigma_0 \sin^2 \theta - \tau_{\theta \theta} \sin 2 \theta ; \) \( \sigma_\zeta = \sigma_\zeta. \)

Taking account of the component of the frictional force, the axial force is
\[
P_z = P_z' + \mu_o P_R,
\]
where \( \mu_o \) is the friction ratio between the surfaces of the blank and the case.

Drawings 2 and 3 show the characteristic curves for various values of the radial \( P_R \), tangential \( P_\tau \) and axial \( P_z \) components as depending upon the degree of deformation \( \epsilon \) and the roller cone angle \( \alpha_p \) -- for rotational extraction by one roller of axisymmetric parts made out of steels 10Х3ГНМФБА and 12Х3ГНМФБА respectively. Used here are the following formulas: \( P_R = P_R / [(R_a - 0.5t_0)u_0 \theta_o \sigma_{o_0_20}] \); \( P_\tau = P_\tau / [(R_a - 0.5t_0)u_0 \theta_o \sigma_{o_0_20}] \); \( P_z = P_z / [(R_a - 0.5t_0)u_0 \theta_o \sigma_{o_0_20}] \).

The calculations have been made for a blank pipe of steel 12Х3ГНМФБА with the blank outer radius of \( R_a = 114.4 \) mm, pipe wall thickness being \( t_0 = 9 \) mm, roller diameter being \( D_p = 280 \) mm; spindle rotation speed being \( n = 60 \text{ min}^{-1} \); \( \mu_o = 0.15 \). The mechanical characteristics of the studied materials are shown in source [5]. The values for the radial \( P_R \), tangential \( P_\tau \) and axial \( P_z \) component forces were found out of formulas (8), (9) and (11) respectively.

![Fig. 2 Dependence of \( P_R, P_\tau, P_z \) as relative to \( \epsilon \) for steel 10 ( \( \alpha_p = 10^\circ ; S = 1 \text{ мм/об}; n = 75 \text{ мин}^{-1} \))](image1)

![Fig. 3 Dependence of \( P_R, P_\tau, P_z \) as relative to \( \epsilon \) for steel 12Х3ГНМФБА ( \( \epsilon = 0.40 ; S = 1 \text{ мм/об}; n = 75 \text{ мин}^{-1} \))](image2)
Analysis of the diagrams and calculation results shows that when the degree of deformation increases, the radial values for the radial $P_R$, axial $P_z$ and tangential $P_t$ component forces grow rapidly. The growth intensity of the studied component forces depends substantially upon the roller cone angle $\alpha_p$. Thus for the roller cone angle $\alpha_p = 15^\circ$ the increase in the degree of deformation from 0.2 to 0.6 ($S = 1 \text{ mm}/\text{o6}$) results in a growth of the relative radial force component $P_R$ by more than 2.5 times; 3 times for the axial $P_z$, and 2 times over for the tangential component. It has been established that when grows the working feed $S$ and when decreases the roller cone angle $\alpha_p$ -- all the three relative component forces do grow. Calculations of force powers have shown that changed conditions of friction at the contact surface of the blank and the case affect considerably the relative magnitude of the axial force $P_z$. When there grows the case friction ratio $\mu_c$, there also grows the value of the relative force $P_z$. It has been shown that taking account of the anisotropy of the mechanical properties of the initial pipe blank adds precision for the values of the radial $P_R$, axial $P_z$ and tangential $P_t$ component forces of the rotary drawing, with the wall becoming thinner by more than 25%.

Experimental research of the force parameters of the rotary drawing were conducted on an installation assembled on the bases of a lathe, model 165. As blanks were processed, measurements were made of three component forces of rotation drawing - radial $P_R$, axial $P_z$ and tangential $P_t$. Tangential force $P_t$ was determined in an indirect procedure using measurements of the relative powers consumed by the electric drive for the part processing and for idle run of the case with the part in it. The experimental values of the axis $P_z$ and radial $P_R$ component forces were obtained with the help of tension sensors placed on sensitive elements -- rings installed in the block of the roller attachment points.

Comparison of the results of theoretical calculations and experimental data for power regimens of rotary drawing witnesses to their satisfactory combination (up to 10 percent).

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LITERATURE

