On task of thick-walled aluminum pipe deformation

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ABSTRACT: The aim of the presented research is determination of force parameters for process of thick-walled aluminum pipe deformation under the control superplasticity within the mathematical model establishing the relationship between stress, temperature and kinetic variables developed with engaging the bifurcation theory and theory of elasto-plastic processes of small curvature.

1 INTRODUCTION

Processes of the isothermal bulk metal forming under superplasticity conditions belong to one of the most perspective technological operations directed to improvement of the advanced production and which are of a certain interest to development of the bulk metal forming processes theory (Langdon 2016). As a result of the mentioned above processes it is possible to increase plastic properties of material, reduce deformation force and to realize a large strain degree.

Two basic methods for providing the superplasticity effect are known. The first one consists in the preliminary preparation of fine-grained structure in the alloys (structural superplasticity) (Padmanabhan et al. 2001, Valiev & Semenova 2016, Ganieva et al. 2017). The other one method called by “dynamic superplasticity” consists in the combination of deformation processes and phase transformations. At the last case the initial structure of the processed material does not matter.

The utilization of the dynamic superplasticity effect is one of the most perspective technological techniques of metal processing (Kuneev et al. 2002, Kitaeva et al. 2014). The purpose of such processes is creation of the resource-saving metal forming processes to produce metal billets and parts with predetermined grain structure and mechanical properties (Kaibyshev & Malopheyev 2014, Kitaeva et al. 2016). Design of similar operations is required the preliminary theoretical substantiation based on the development of mathematical theories applied of hot forming.

Technological tasks certainly belong to physically and geometrically nonlinear ones (Hirkovskis et al. 2015, Rudskoy et al. 2015, Kukhar et al. 2018, Rudskoy et al. 2018).

2 RESEARCH METHODS

The cylindrical pipe with length $\overline{l}$ stretches by axial force $\overline{F}$ and exposed to external pressure intensity $\overline{q}$ at a given rate of radial movement $\overline{V}_0$ (Fig. 1), where: R = the outer radius of the pipe, R_0 = the inner radius of the pipe, r = current radius.

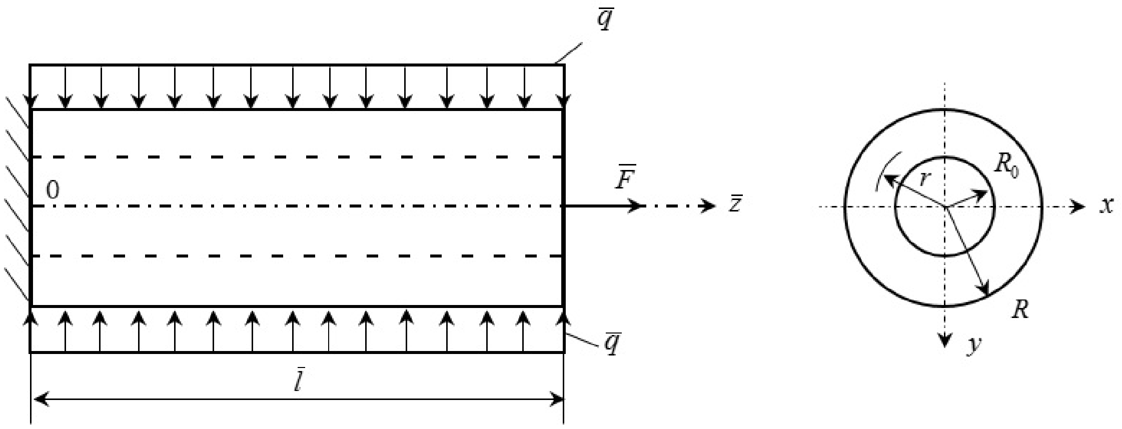

Figure 1. Scheme of the pipe loading.

All geometric sizes are assumed to be divided by the outer radius of the pipe (Fig. 1):

$$\rho = \frac{r}{R}; \quad l = \frac{\bar{l}}{R}; \quad \rho\big|_R = 1; \quad \rho\big|_{R_0} = \rho_0; \quad z = \frac{\bar{z}}{R}. \tag{1}$$

By introducing a cylindrical coordinate system $\rho\alpha z$, we consider the problem of determining the power and kinematic parameters of the process of forming.

It is assumed that the velocity of the horizontal displacement V_z depends linearly on the coordinate and is determined by the expression:

$$V_z = b\left[z - \psi\left(\rho\right)\right], \tag{2}$$

where b = const, $\psi\left(\rho\right)$ = is an unknown function to be determined.

The representation of the velocity V_z in the Equation 2 was used to solve the problem of the reverse extrusion of a cylindrical product with a bottom in the superplasticity modes (Rudskoy et al. 2015).

The mathematical formulation of the problem in terms of the theory of elastoplastic small-curvature processes includes the following:

- differential equations of equilibrium

$$\frac{\partial \sigma_\rho}{\partial \rho} + \frac{\partial \tau_{\rho z}}{\partial z} + \frac{\sigma_\rho - \sigma_\alpha}{\rho} = 0; \quad \frac{\partial \tau_{\rho z}}{\partial \rho} + \frac{\partial \sigma_z}{\partial z} + \frac{\tau_{\rho z}}{\rho} = 0; \tag{3}$$

- kinematic relations, establishing connection between strain rates and displacements

$$\dot{\varepsilon}_\rho = \frac{\partial V_\rho}{\partial \rho}; \quad \dot{\varepsilon}_\alpha = \frac{V_\rho}{\rho}; \quad \dot{\varepsilon}_z = \frac{\partial V_z}{\partial z}; \quad \dot{\gamma}_{\rho z} = \frac{\partial V_z}{\partial \rho} + \frac{\partial V_\rho}{\partial z}; \tag{4}$$

- the condition of incompressibility in strain rates

$$\dot{\varepsilon}_\rho + \dot{\varepsilon}_\alpha + \dot{\varepsilon}_z = \frac{\partial V_\rho}{\partial \rho} + \frac{V_\rho}{\rho} + \frac{\partial V_z}{\partial z} = 0; \tag{5}$$

- defining relations

$$\sigma_\rho - \sigma_0 = \frac{2}{3}\frac{\sigma_u}{\dot{\varepsilon}_u}\dot{\varepsilon}_\rho; \sigma_\alpha - \sigma_0 = \frac{2}{3}\frac{\sigma_u}{\dot{\varepsilon}_u}\dot{\varepsilon}_\alpha; \sigma_z - \sigma_0 = \frac{2}{3}\frac{\sigma_u}{\dot{\varepsilon}_u}\dot{\varepsilon}_z; \tau_{\rho z} = \frac{\sigma_u}{3\dot{\varepsilon}_u}\dot{\gamma}_{\rho z}; \tag{6}$$

- equation of state (Kitaeva et al. 2014) in the form of the dependence of stress intensity σ_u on strain rate intensity $\dot{\varepsilon}_u$

$$\sigma_u = 1 - m_0 - \beta + (3m_0 + \beta)\dot{\varepsilon}_u - 3m_0\dot{\varepsilon}_u{}^2 + m_0\dot{\varepsilon}_u{}^3. \tag{7}$$

Here, $\sigma_{ij}, \dot{\varepsilon}_{ij}$ = are the stress and the strain-rate tensors components respectively, v_i = are the components of the velocity vector, σ_0 = is the average stress, m_0 = is the material constant, β = is the temperature-dependent control parameter (it is constant under isothermal conditions and β <0 under superplasticity).

All values at Equations 1-7 are accepted dimensionless. The stress and strain-rate components are attributed to alternative internal state parameters $\sigma^*, \dot{\varepsilon}^*$ (Kitaeva et al. 2017), and motion velocity to $R\dot{\varepsilon}^*$. Besides, external power factors are defined so:

$$q = \frac{\overline{q}}{\sigma^*}; \quad F = \frac{\overline{F}}{A\sigma^*}, \tag{8}$$

where A = pipe cross-sectional area.

Boundary conditions will be formulated in solving the problem.

3 RESEARCH FINDINGS

Using Equation 6, we can write the incompressibility condition (Equation 5) in the form:

$$\frac{dV_\rho}{d\rho} + \frac{V_\rho}{\rho} + b = 0, \tag{9}$$

The solution of the received linear non-uniform equation of the first order taking into account a boundary condition $V_\rho\big|_{\rho=1} = -V_0$:

$$V_\rho = \frac{b}{2\rho}(C - \rho^2), \tag{10}$$

where constant value C is:

$$C = 1 - \frac{2V_0}{b}. \tag{11}$$

At the known the horizontal (Equation 2) and the radial (Equation 10) motion velocity vector the strain-rate tensors components will be equal:

$$\dot{\varepsilon}_\rho = -\frac{b}{2\rho^2}(C + \rho^2); \quad \dot{\varepsilon}_\alpha = \frac{b}{2\rho^2}(C - \rho^2); \quad \dot{\varepsilon}_z = -b; \quad \dot{\gamma}_{\rho z} = -b\psi'(\rho). \tag{12}$$

For the stress tensor components we have:

$$\sigma_\rho - \sigma_0 = -\frac{1}{3}bT(\rho)\left(1 + \frac{C}{\rho^2}\right); \tag{13}$$

$$\sigma_\alpha - \sigma_0 = -\frac{1}{3}bT(\rho)\left(1 - \frac{C}{\rho^2}\right); \tag{14}$$

$$\sigma_z - \sigma_0 = -\frac{2}{3}bT(\rho); \tag{15}$$

$$\tau_{\rho z} = -\frac{1}{3}bT(\rho)\psi'(\rho); \tag{16}$$

$$\sigma_0 = \frac{1}{3}b\left\{T'(\rho)\psi'(\rho) + T(\rho)\left[\psi''(\rho) + \frac{\psi''(\rho)}{\rho}\right]\right\}z + F - \frac{2}{3}bT(\rho). \tag{17}$$

For the resolving function $\psi(\rho)$ entering in Equations 12-17 we obtain:

$$\psi(\rho) = \frac{C_1}{2}\rho^2 + C_2 \ln \rho + C_3 . \tag{18}$$

Thus, the components of stresses, strain rates and displacements will be established after the determination of the five constants C, C_1, C_2, C_3, b.

4 CONCLUSIONS

The objective of the presented research is the mathematical formulation of the problem on thick-walled pipe loading by the external pressure and by the stretching force in the thermal super-plasticity range: differential balance equations; the kinematic ratios establishing the relationship between strain rates and displacements; an incompressibility condition in rates; the defining ratios in the form of the equations of the theory of elasto-plastic processes of small curvature; the state equation which is a consequence of the dynamic model associated to isothermal process. Joint consideration of these equations leads to definition of one allowing function which finding allows to establish stress fields, strain rates and displacements rates.

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