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MECHANICS OF ELECTROSTIMULATED WIRE DRAWING

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Abstract—A phenomenological model of the wire-drawing process with force parameters sensitive to the influence of the electric current is proposed. The basis of this is the introduction of an external stimulation power, acting opposite to the viscous resistance to flow into the constitutive equation of the viscoplastic material. The finiteness of the deformation and the material's incompressibility are taken into account. A specific design model is compared with the experimental data. We summarize that the level of sensitivity to the influence of the electric current depends on the equality of the external electrostimulation powers and the internal dissipation energy.

It is also noted that the electroplastic effect is caused by that micromechanism of deformation which is characterized by a shear delay time of 10^{-3} s (or by somewhat less than the relaxation time).

INTRODUCTION

The study of the influence of electric current on the plasticity of metals and alloys when undergoing treatment by pressure (Spitsyn and Troitsky, 1985) is of great interest to researchers. It is stated that the effect of the growth of plasticity and decrease of force is not an explicit thermal phenomenon, but is determined to a great extent by the action of directed electron motion on microdeformation mechanisms. Electric stimulation of wire-drawing is most useful for research due to its simplicity (Gromov *et al.*, 1984).

To date, many current action micromechanisms of deformation have been suggested, such as skin, pinch and magnetostrictive effects, enhancement of dislocation mobility due to the action of drift electrons, etc. (Sprecher *et al.*, 1986). It is clear that the main mechanisms are those for which the theoretically expected shear delay time coincides with the experimental time.

The authors of this article offer a phenomenological model of wire drawing together with an electrostimulation which gives the possibility of evaluating the microstructural mechanisms in view of one rheological parameter.

Usually, in descriptions of the treatment of metals with large deformations, the plasticity is taken as the main property of the metal, and the elasticity is neglected. Because of stationary motion and practical homogeneity of temperature in the zone of deformation, the thermal stresses are not taken into account.

As the electroplastic effect is characterized by a reduction in acting stresses and the presence of their relaxation, from a phenomenological view this effect must be considered as a change of viscous properties of the material. Therefore, viscoplastic materials sensitive to the outer energy stimulation are examined.

The condition of local incompressibility is assumed for the metals and alloys used.

GEOMETRY OF DEFORMATION

Because of axial symmetry, Cartesian material and space coordinates and also cylindrical material R, φ, Z and space r, φ, s coordinates are used (Fig. 1). The derivatives with respect to the coordinates are marked in touch and with respect to time are marked in point. The condition of local incompressibility gives the following restrictions on the functions $r = \hat{r}(R, Z)$, $S = \hat{S}(R, Z)$:

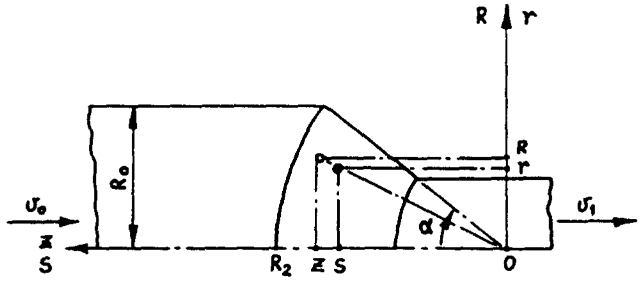

Fig. 1. The geometry of the deformation zone in the drawing model, axial cross-section. The parameters are: R_0 = radius of wire on input; R_2 = radius of deformation zone; α = angle of matrix conicity.

$$r'_R s'_Z - r'_Z s'_R = \frac{R}{r}. \tag{1}$$

The countercovariant components (Pobedrya, 1986) of the speed deformation tensor D are of the form:

$$D^{1}_{.1} = \frac{1}{2}\frac{r^2}{R^2}(B\dot{a} - c\dot{c}),\quad D^{1}_{.3} = \frac{1}{2}\frac{r^2}{R^2}(\dot{c}B - c\dot{B}),\quad D^{3}_{.1} = \frac{1}{2}\frac{r^2}{R^2}(\dot{c}a - c\dot{a}),$$

$$D^{2}_{.2} = \frac{\dot{r}}{r},\quad D^{3}_{.3} = \frac{1}{2}\frac{r^2}{R^2}(a\dot{B} - c\dot{c}),\quad D^{1}_{.2} = D^{2}_{.1} = D^{3}_{.2} = D^{2}_{.3} = 0,\quad a = (r'_R)^2 + (s'_R)^2,$$

$$B = (r'_Z)^2 + (s'_Z)^2,\quad c = r'_R r'_Z + s'_R s'_Z.$$

In order to find the functions $\dot{r}$, $\dot{s}$, the following assumptions are made: the matrix is conical; the regime of drawing with input speed V_0 is stationary; cylinders of radius R are deformed into a set of cones with a common tope (Fig. 1); and the boundary of the deformation zone and an input is part of a sphere of radius R_2. On account of these assumptions, one obtains the following equations from the condition of incompressibility (1):

$$r = R\sqrt[3]{\frac{z_0 - V_0 t}{R_2}\sqrt{1 - \frac{R^2}{R_2^2}} + 3\frac{R^2}{R_2^2} - 2},$$

$$s = r\frac{R_2}{R}\sqrt{1 - \frac{R^2}{R_2^2}}, \tag{2}$$

where Z_0 is the initial axial material coordinate of a point connected with the flowing point by the equation $Z = Z_0 - V_0 t$, where t is the time.

Figure 2 illustrates the deformation in accordance with formula (2). The system of mutual perpendicular straight lines is transformed into a family of radial lines and a family of cubic curves (the latter can be constructed without difficulty in polar coordinates).

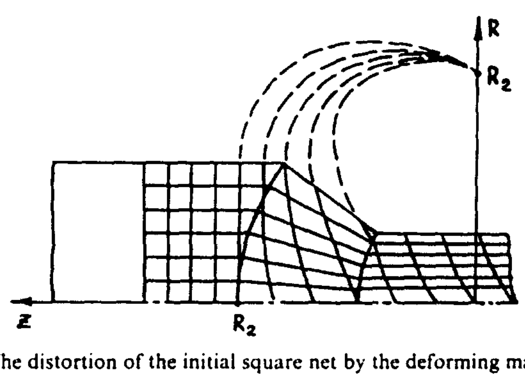

Fig. 2. The distortion of the initial square net by the deforming mapping.

CONSTITUTIVE EQUATION

The Bingham medium is the simplest initial model of viscoplastic medium (Germain, 1973). We assume the following modification to it:

$$S = \tau\left[\frac{1}{\sqrt{D_{\parallel}}} + Q(1-q)\right]D \equiv \kappa D, \tag{3}$$

where S is the tensor-deviator of stresses, $D = 0.5 \text{ tr } D^2$ is the second invariant of the speed deformation tensor D, and $\tau^2 \equiv S_{\parallel}^{0}$ is the second invariant of tensor S in the absence of viscous properties ($Q = 0$). If the outer stimulation is absent ($q = 0$), then $\mu = 0.5\tau Q$ is the coefficient of viscosity. The relative part of the stimulation is

$$q = \frac{W_0}{W} = \frac{W_0}{2\tau(1+Q\sqrt{D_{\parallel}})\sqrt{D_{\parallel}}},$$

where W_0 is the power of the outer stimulation and W is the power of the dissipation of the energy deformation.

In accordance with (3), the material flows if $S_{\parallel} \geqslant \tau\kappa D_{\parallel}$ and stays rigid otherwise; τ is a purely plastic constant of the material. The material has a local variable yield point in one-axial tension equal to $\sqrt{3S_{\parallel}}$.

If the polar effect and anisotropy action of the current are neglected, then

$$W_0 = I^2\rho,$$

where I is the value of the current density at that particular point and also at that moment, and ρ is the specific electroresistance of the material.

STRESSES

The equations of motion, together with constitutive equation (3), lead to a system of two equations for the place functions T^{13}, Q (where Q is related to κ):

$$\begin{cases} -P_{11}\dfrac{\partial\kappa}{\partial R} - P_{12}\dfrac{\partial T^{13}}{\partial R} + \dfrac{\partial T^{13}}{\partial Z} + P_{13}\kappa + P_{14}T^{13} = 0, \\ \dfrac{\partial T^{13}}{\partial R} - P_{21}\dfrac{\partial\kappa}{\partial Z} - P_{22}\dfrac{\partial T^{13}}{\partial Z} + P_{23}\kappa + P_{24}T^{13} = -2v_0^2\dfrac{\nu}{R_2}\dfrac{R^3}{r^3}\sqrt{1-\dfrac{R^2}{R_2^2}}, \end{cases} \tag{4}$$

where the coefficients P_{ij} are expressed through r, s. The diagonal countervariant components of Cauchy's stresses tensor T are related to T^{13}:

$$cT^{11} = \frac{1}{2}\frac{r^2}{R^2}\kappa(\dot{c}B - c\dot{B}) - BT^{13},$$

$$r^2T^{22} = \kappa\left[2\frac{\dot{r}}{r} + \frac{1}{2}\frac{\dot{c}}{c}\right] - \frac{R^2}{cr^2}T^{13},$$

$$cT^{33} = \frac{1}{2}\frac{r^2}{R^2}\kappa(\dot{c}a - c\dot{a}) - aT^{13}.$$

The boundary conditions of system (4) are formulated at the place where the matrix material and the boundary of the inlet deformation zone meet. Here we set $T^{13} = 0.1\sigma_0$, where σ_0 is the yield point in one-axial tension at a given temperature. At the boundary of the deformation zone, we take $T^{13} = 0$. Constant values of Q are taken at the place of contact and at boundary of the deformation zone.

Problem (4) was solved numerically by using the difference method. In one-sided differences the difference system approximates the system of differential equations to first order in relation to the net steps. It is too difficult to prove the conditions of stability of the differential problem with the chosen boundary conditions; therefore, convergence was controlled according to the vibration of calculated values at the nodes of the decreasing quadrant network.

EXPERIMENT AND CALCULATION

The experiment was carried out, whereby we calculated the geometry of deformation and the drawing force of a wire made of low carbon steel with a reduction in diameter from 6.5×10^{-3} to 5.8×10^{-3} m. The angle of taper of the matrix was taken as 6°. The constants of material and drawing process are as follows:

$$\sigma_0 = 0.3 \times 19^9 \text{ Pa at a temperature of } 373 \text{ K}, \quad \rho = 0.11 \times 10^{-6} \text{ Ohm} \cdot \text{m},$$

$$V_0 = 3 \text{ m s}^{-1}, \quad I = 0.5 \times 10^8\text{–}0.5 \times 10^{10} \text{ A m}^{-2}.$$

The calculation chart of net distortion corresponds to our experiment and the data in Perlin and Ermanok (1971).

To obtain the required values of the specific drawing force P, the physical stresses (Pobedrya, 1986) in the outlet section of the wire were calculated.

At a given density current variation, only the value $Q = 10^{-3}$ s at the boundary gave a decrease of P that could be adequately observed. The calculated values of Q in the inner zone varied slightly – $(0.9–1.2) \times 10^{-3}$ s. This gives the possibility of considering the number $0.5 \times 10^{-3}\ \tau = 0.865 \times 10^5$ kg (m · sec)$^{-1}$ as a global coefficient of steel viscosity for the drawing process without stimulation. Figure 3 demonstrates the influence of I on the drawing force. Values of $I > 2 \times 10^9$ A m^{-2} noticeably decrease the drawing force. The experimental curve is shown by a dotted line. The force has been recorded at a moment of current impulse peak run. Values of the duration (120 μs) and frequency (500 Hz) of the impulses were selected so as to not cause any heating (not above 390 K).

DISCUSSION AND CONCLUSIONS

Mechanisms of microdeformation sensitive to electrostimulation are responsible for a change in viscous properties. From a rheological viewpoint, Q represents the shear delay time. The results of this paper show that the mechanism of microdeformation, giving a shear delay time of $\sim 10^{-3}$ s, makes a real contribution to the electroplastic effect. Thus there is a need to make a comparative analysis of electroplasticity mechanisms (Sprecher *et al.*, 1986) with respect to the duration of the shear delay time (relaxation time).

The real mechanism must be unpolar, i.e. insensitive to changes in current direction. A threshold value of $I = 10^9$ A m^{-2} (Fig. 3) in the model frame is defined such that for

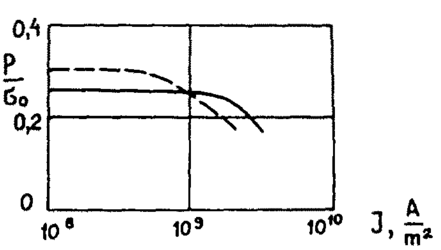

Fig. 3. The dependence of the relative mean stresses' intensivity value in the outlet zone of deformation on the electric current density (1 is the experimental curve, whilst 2 is the calculated curve). The current density is considered to be constant.

$I = 1.1 \times 10^9$ A m^{-2} (for a given material), the stimulation power $I^2\rho$ is equal to the inner dissipation power $2\tau\sqrt{D_1}\cdot(1+Q\sqrt{D_1})$.

The amount of disagreement between the experimental and calculated data of a specific force P is determined by a rough calculation of W_0. The current density I was taken as a constant through a section. As a matter of fact, with respect to the skin effect, I for a periodic current must be specified as a function of space coordinates as well as a function of time.

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