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FORMATION OF STAGNANT ZONES IN VISCOPLASTIC MATERIALS ON THE CONVEX AND CONCAVE PARTS OF RIGID BOUNDARIES

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The flow of viscoplastic media [1] in channels with perturbed boundaries has been considered previously in [2, 3], using the small-parameter method, and the flow in channels of elliptical cross section has been studied and solved in [4].

1. The rheological relation for a Bingham viscoplastic medium has the form

$$\sigma_{ij} = (\sqrt{2}k/\sqrt{\varepsilon_{ql}\varepsilon_{ql}} + 2\eta)\varepsilon_{ij} + P\delta_{ij}, 3P = \sigma_{ii}, \tag{1.1}$$

where σ_{ij} are the components of the stress tensor, ε_{ij} are the components of the deformation rate tensor, k is the yield point, and η is the viscosity.

The deformation rate tensor is related to the components of the flow velocity vector of the medium v_i by Cauchy's equation

$$\varepsilon_{ij} = (1/2)(v_{i,j} + v_{j,i}).$$

In both problems, considered in this paper, only the component of the velocity vector v_z will differ from zero, and must be sought in a cylindrical system of coordinates in the form of a series in powers of the small parameter δ

$$v_z(r, \varphi) = v^0(r) + \delta v'(r, \varphi) + \dots$$

To formulate the problem in dimensionless form we will refer the stresses to the yield point k, the variable lengths to the radius of the tube R, and the velocity to the quantity kR/η. Then, Eq. (1.1) in terms of the dimensionless variables will take the form

$$\sigma_{ij} = (1 + I^{-1/2})2\varepsilon_{ij} + P\delta_{ij},\ 3P = \sigma_{ii}, \tag{1.2}$$

where $I = 2\varepsilon_{ij}\varepsilon_{ij}$.

We will assume that the medium adheres to the surface at the rigid boundaries of the channels. In the flow regions the components of the deformation rate tensor

$$\varepsilon_{rz} = \frac{1}{2}\left(v^0_{,r} + \delta v'_{,r}\right) + \dots,\ \varepsilon_{\varphi z} = \frac{1}{2}\delta\frac{1}{r}v'_{,\varphi} + \dots \tag{1.3}$$

will differ from zero.

Substituting (1.3) into (1.2), we obtain

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$$\sigma_{rr} = \sigma_{\varphi\varphi} = \sigma_{zz} = P,\ \sigma_{r\varphi} = 0,\ \sigma_{\varphi z} = (1 + I^{-1/2})\,\delta \frac{1}{r} v'_{,\varphi} + \ldots \tag{1.4}$$
$$\sigma_{rz} = (1 + I^{-1/2})(v^0_{,r} + \delta v^1_{,r}) + \ldots,\quad I = v^{02}_{,r} + 2\delta v^0_{,r} v'_{,r} + \ldots$$

Of the three equilibrium equations only one remains, viz.,

$$\frac{\partial\sigma_{rz}}{\partial r} + \frac{\sigma_{rz}}{r} + \frac{1}{r}\frac{\partial\sigma_{\varphi z}}{\partial\varphi} + \frac{\partial\sigma_{zz}}{\partial z} = 0. \tag{1.5}$$

2. Suppose at the boundary of the tube there is a small perturbation $r = R(1 + \delta\cos m\varphi)$, $\delta \ll 1$. The medium flows under the action of a constant pressure drop p and in expressions (1.4) we will have

$$P = pz. \tag{2.1}$$

We will write the boundary conditions in dimensionless variables. On the surface of the tube we will assume adhesion of the medium

$$v_z(1 + \delta\cos m\varphi,\ \varphi) = 0. \tag{2.2}$$

On the boundary of the rigid core the following conditions must be satisfied:

$$v_z(r, \varphi) = v_* = \text{const},\quad \partial v_z(r, \varphi)/\partial n = 0 \ \text{ for } \ r = f(\varphi), \tag{2.3}$$

where $f(\varphi)$ is the contour of the rigid core of the flow.

The condition for the forces on the rigid core to be in equilibrium gives the following expression:

$$l = pS, \tag{2.4}$$

where l and S are the contour length and the cross-sectional area of the rigid core.

Substituting (1.4) into (1.5) and taking (2.1) into account and expanding (1.5) in powers of the small parameter δ, we obtain for the zero and first approximations of the system of equations

$$\frac{d^2v^0}{dr^2} + \frac{1}{r}\frac{dv^0}{dr} - \frac{1}{r} + p = 0; \tag{2.5}$$

$$v'_{,rr} + \frac{1}{r}v'_{,r} - \frac{1}{r^2}\left(\frac{1}{v^0_{,r}} - 1\right)v'_{,\varphi\varphi} = 0. \tag{2.6}$$

The boundary conditions are obtained by expanding (2.2)–(2.4) in series in powers of the small parameter

$$v^0(r) = v^0_*,\quad dv^0/dr = 0 \ \text{ with } \ r = b,\ b = 2/p,\ v^0(1) = 0, \tag{2.7}$$

where b is the radius of the rigid core of flow in the circular tube

$$v'(1, \varphi) = -v^0_{,r}(1)\cos m\varphi,\ v'(2/p, \varphi) = 0,$$
$$\int\limits_0^{2\pi/m} [\lambda + \psi(\varphi)]\,d\varphi = 0,\ \ \psi(\varphi) = (2/p)\,v'_{,r}(2/p, \varphi), \tag{2.8}$$

where we have represented the boundary of the rigid core in the form

$$f(\varphi) = 2/p + \delta[\lambda + \psi(\varphi)] + \ldots$$

The condition for flow to exist in the tube $b < 1$ (the radius of the rigid core is less than the radius of the tube) imposes a limitation on the pressure drop: $p > 2$.

Solving (2.5) taking the boundary conditions (2.7) into account, we obtain the zero approximation for the velocity

$$v^0(r) = (1 - r)[(p/4)(1 + r) - 1]. \tag{2.9}$$

Substituting into (2.9) the value of the radius on the rigid core $r = 2/p$, we obtain the velocity of the rigid core in a circular tube

$$v^0_* = (p - 2)^2/4p.$$

Using the zero approximation $v^0(r)$ from (2.9), we reduce the equation of the first approximation (1.6) to the form

$$r(1 - pr/2)\,v'_{,rr} + (1 - pr/2)\,v'_{,r} - p/2v_{,\varphi\varphi} = 0. \tag{2.10}$$

We will make the change of variables $pr/2 = \rho$. The first approximation, taking into account the boundary conditions (2.8), will be sought in the form

$$v'(\rho, \varphi) = T(\rho) \cos m\varphi. \tag{2.11}$$

For function $T(\rho)$ after substituting (2.11) into (2.10), we obtain the hypergeometric equation

$$\rho(\rho - 1)T'' + (\rho - 1)T' - m^2 T = 0. \tag{2.12}$$

The boundary conditions for Eq. (2.12) are obtained from (2.8)

$$T(1) = 0, \; T(p/2) = p/2 - 1, \; \lambda = O(\delta), \; \psi(\varphi) = (2/p)T'(1) \cos m\varphi. \tag{2.13}$$

The general solution of Eq. (2.12) will be a linear combination of two linearly independent hypergeometric functions

$$T_1(\rho) = \rho^{-m} F(m, \; m, \; 1 + 2m, \; 1/\rho),$$
$$T_2(\rho) = \rho^{m-1}(\rho - 1) F(1 - m, \; 1 - m, \; 1 - 2m, \; 1/\rho).$$

Since $1 \leq \rho \leq p/2$, the hypergeometric series for $T_1(\rho)$ converges uniformly, while $T_2(\rho)$ is a polynomial of degree m. Hence, the general solution of Eq. (2.12) has the form

$$T(\rho) = c_1 T_1(\rho) + c_2 T_2(\rho).$$

From the boundary conditions (2.13), we obtain the integration constants

$$c_1 = 0, \; c_2 = (p/2)^{1-m} F^{-1}(1 - m, 1 - m, 1 - 2m, 2/p).$$

Changing to the variable r, we obtain

$$T(r) = r^{m-1}\left(\frac{p}{2} r - 1\right) \frac{F(1 - m, 1 - m, 1 - 2m, 2/pr)}{F(1 - m, 1 - m, 1 - 2m, 2/p)}.$$

From the last condition of (2.13), we find the effect of perturbations of the boundary on the form of the rigid core of the flow

$$\psi(\varphi) = \left(\frac{2}{p}\right)^m \frac{F(1 - m, 1 - m, 1 - 2m, 1)}{F(1 - m, 1 - m, 1 - 2m, 2/p)} \cos m\varphi + O(\delta^2).$$

Consider the behavior of the rigid core of flow when the pressure drop changes from the least value ($p = 2$) to the highest values ($p \to \infty$)

$$f(\varphi) = \frac{2}{p} + \delta \left(\frac{2}{p}\right)^m \frac{F(1 - m, 1 - m, 1 - 2m, 1)}{F(1 - m, 1 - m, 1 - 2m, 2/p)} \cos m\varphi + O(\delta^2). \tag{2.14}$$

As $p \to 2$ the boundary of the rigid core approaches the boundary of the perturbed surface of the tube $f(\varphi) \to 1 + \delta \cos m\varphi$. Since $F(a, b, c, 0) = 1$, it follows from (2.14) that $\lim\limits_{p \to \infty} f(\varphi) = 0$, i.e., as the pressure drop increases the dimensions of the rigid core decrease $f(\varphi) \to 0$.

For the velocity function, we obtain two approximations

$$v_z(r, \varphi) = (1 - r)\left[\frac{p}{4}(1 + r) - 1\right] + \delta r^{m-1}\left(\frac{p}{2} r - 1\right) \frac{F(1 - m, 1 - m, 1 - 2m, 2/pr)}{F(1 - m, 1 - m, 1 - 2m, 2/pr)} \cos m\varphi + O(\delta^2).$$

According to the analysis carried out in [2], the flow of a viscoplastic medium is characterized by the fact that for a certain ratio of the flow parameters, at the peaks of the perturbations ($\cos m\varphi = 1$, $r = 1 + \delta$) there will be stagnant zones. At these points the condition on the stagnant zone [3] must be satisfied, viz.,

$$\partial v_z(r, \varphi)/\partial n = 0 \quad \text{for} \quad r = 1 + \delta, \; \varphi = 2\pi n/m.$$

When this condition is satisfied, we obtain the criterion for stagnant zones to appear on the rigid boundary of the tube

$$\delta_* (m - 1)\left[1 + \frac{m - 1}{2m - 1} \frac{2}{p} \frac{F(2 - m, 2 - m, 2 - 2m, 2/p)}{F(1 - m, 1 - m, 1 - 2m, 2/p)}\right] = 1. \tag{2.15}$$

The criterion holds for $m > 1$, and when $m = 1$ at the peaks of the depressions the condition on the rigid zone is satisfied identically. To find the critical relation in this case one must obtain a second approximation for the velocity function.

It should be noted that in this problem the critical parameter δ_* is independent of the viscosity η.

When the pressure drop p changes from the least value ($p = 2$) to the greatest values p ($p \to \infty$) the critical value of δ_* varies in the limits

$$\left(\left[(m-1)\left(1+\frac{m-1}{2m-1}\frac{F(2-m,2-m,2-2m,1)}{F(1-m,1-m,1-2m,1)}\right)\right]^{-1};\ (m-1)^{-1}\right).$$

For small values of m (m = 2-6) the critical value of δ_* from (2.15) increases monotonically within these limits.

3. Suppose the external cylinder with a generating surface $r=R[b+\delta\lambda_2\cos(m_2\varphi+\varphi_0)]$ moves with a constant velocity v_* along its axis, while the internal cylinder with a generating surface $r=R[1+\delta\lambda_1\cos m_1\varphi]$ remains at rest. We will assume that in this case $\delta \ll 1$, $\lambda_1, \lambda_2 \sim 1$, $b > 1+\delta(\lambda_1+\lambda_2)$. In a problem of pure shear between two cylinders with small longitudinal perturbations of the boundaries in dimensionless variables the boundary conditions have the form

$$v_z(1+\delta\lambda_1\cos m_1\varphi,\ \varphi)=0,\ v_z(b+\delta\lambda_2\cos(m_2\varphi+\varphi_0),\ \varphi)=a^{-2}, \tag{3.1}$$

where $a^2 = kR/\eta v_*$.

In this problem P = const, so that after expanding (1.7) in series in terms of the small parameter δ we obtain a system of equations for the zeroth and first approximations

$$\frac{d^2v^0}{dr^2}+\frac{1}{r}\frac{dv^0}{dr}+\frac{1}{r}=0; \tag{3.2}$$

$$v'_{,rr}+\frac{1}{r}v'_{,r}+\frac{1}{r^2}\left(\frac{1}{v^0_{,r}}+1\right)v'_{,\varphi\varphi}=0.$$

The boundary conditions after expanding (3.1) in series have the form

$$v^0(1)=0,\quad v^0(b)=a^{-2};\quad v'(1,\varphi)=-v^0_{,r}(1)\lambda_1\cos m_1\varphi, \tag{3.3}$$

$$v'(b,\varphi)=-v^0_{,r}(b)\lambda_2\cos(m_2\varphi+\varphi_0).$$

The solution of Eqs. (3.2) with boundary conditions (3.3) have the form

$$v^0(r)=q\ln r-r+1,\ q=(b-1+a^{-2})/\ln b. \tag{3.4}$$

From the condition that the rate of deformation should be positive we obtain the following limitation on the parameters of the problem:

$$v^0_{,r}\geqslant 0,\ \text{i.e.,}\ r\ln b\leqslant b-1+a^{-2}.$$

Since $1 \le r \le b$, the condition for a flow of a viscoplastic medium to exist over the whole region is

$$b(\ln b-1)+1-a^{-2}\leqslant 0. \tag{3.5}$$

If inequality (3.5) is violated, a stagnant zone is formed on the surface of the external cylinder. In this case the problem reduces to the problem of extracting a perturbed cylinder from viscoplastic space, considered in [2]. In the boundary conditions (3.1) it is necessary to supplement the conditions on the surface of the stagnant zone [3], to put $m_1=m_2$, $\varphi_0=0$, and assume λ_2 and b to be unknown, and to find them when solving the boundary value problem.

We will henceforth assume that inequality (3.5) is strictly satisfied. The equation and boundary conditions for the first approximation (taking into account (3.4), have the form

$$v'_{,rr}+\frac{1}{r}v'_{,r}+\frac{1}{r^2(1-r/q)}v'_{,\varphi\varphi}=0; \tag{3.6}$$

$$v'(1,\varphi)=(1-q)\lambda_1\cos m_1\varphi,\ v'(b,\varphi)=(1-q/b)\lambda_2\cos(m_2\varphi+\varphi_0). \tag{3.7}$$

Separating the variables in (3.6) $v'(r,\varphi)=T(r)X(\varphi)$, we obtain the following system of equations:

$$d^2X/d\varphi^2+\mu^2X=0, \tag{3.8}$$

$$T''+\frac{1}{r}T'-\frac{\mu^2}{r^2(1-r/q)}T=0.$$

Hence it follows that

$$X_n(\varphi)=a_n\cos\mu_n\varphi+b_n\sin\mu_n\varphi.$$

In the second equation of (3.8) we will make the change of variable r = qt, and we then obtain for T(r(t)) the following hypergeometric equation for each eigenvalue μ_n:

$$t^2(t-1)T''+t(t-1)T'+\mu_n^2T=0.$$

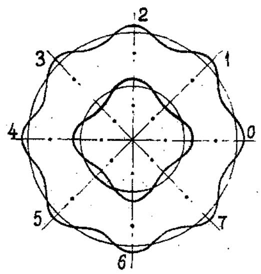

Fig. 1

The general solution of this equation is

$$T_n(t) = c_{1n} t^{\mu_n} F_{1n}(\mu_n, \mu_n, 1 + 2\mu_n, t) + c_{2n} t^{-\mu_n} F_{2n}(-\mu_n, -\mu_n, 1 - 2\mu_n, t). \tag{3.9}$$

From the boundary conditions (3.7) we obtain

$$\mu_1 = m_1,\ \mu_2 = m_2,\ \mu_3 = \mu_4 = \ldots = 0,\ a_1 = 1,\ a_2 = \cos\varphi_0,$$
$$a_3 = a_4 = \ldots = 0,\ b_1 = 0,\ b_2 = -\sin\varphi_0,\ b_3 = b_4 = \ldots = 0.$$

The eigenfunctions will then be

$$X_1(\varphi) = \cos m_1\varphi,\ X_2(\varphi) = \cos\varphi_0 \cos m_2\varphi - \sin\varphi_0 \sin m_2\varphi = \\ = \cos(m_2\varphi + \varphi_0).$$

The boundary conditions for the functions (3.9) are obtained from conditions (3.7) by separating the variables

$$T_1(1/q) = \lambda_1(1 - q),\ T_1(b/q) = 0,$$
$$T_2(1/q) = 0,\ T_2(b/q) = \lambda_2(1 - q/b). \tag{3.10}$$

Satisfying conditions (3.10) and determining the integration constants we obtain

$$T_k(r) = c_{1k}\left(\frac{r}{q}\right)^{m_k} F_{1k}(m_k, m_k, 1 + 2m_k, r/q) + c_{2k}\left(\frac{r}{q}\right)^{-m_k} F_{2k}(-m_k, -m_k, 1 - 2m_k, r/q),$$
$$c_{1k} = (-1)^{k+1}\lambda_k(1 - qb^{1-k})(qb^{k-2})^{m_k} F_{2k}(b^{2-k}/q) D_k^{-1},$$
$$c_{2k} = (-1)^k \lambda_k (1 - qb^{1-k})(qb^{k-2})^{-m_k} F_{1k}(b^{2-k}/q) D_k^{-1},$$
$$D_k = b^{-m_k} F_{1k}(1/q) F_{2k}(b/q) - b^{m_k} F_{1k}(b/q) F_{2k}(1/q),$$

in which k=1,2 is not summed, and we have denoted the corresponding hypergeometric functions by $F_{ij}(r)$.

Hence, we have obtained two approximations for the velocity function

$$v_z(r, \varphi) = q \ln r - r + 1 + \delta[T_1(r)\cos m_1\varphi + T_2(r)\cos(m_2\varphi + \varphi_0)] + O(\delta^2).$$

If we consider the line v=const, $0 \le v \le a^{-2}$, then apart from small terms of the second order $O(\delta^2)$ they repeat the configuration of the internal cylinder when v=0, and gradually change to the configuration of the external cylinder as v increases to a^{-2}.

We will obtain the criterion for stagnant zones to form in the depressions of the internal cylinder ($\cos m_1\varphi = -1$, $r = 1 - \delta\lambda_1$), and on the convex parts of the external cylinder ($\cos(m_2\varphi + \varphi_0) = 1$, $r = 1 + \delta\lambda_2$). According to [3], at these points at the instant when a stagnant zone is formed the condition $\partial v_z/\partial r = 0$.

On the inner cylinder stagnant zones are formed when the following equation is satisfied:

$$\delta_{*1}\left[T_1'(1)\, T_2'(1)\cos\left(\frac{m_2\pi(2n+1)}{m_1} + \varphi_0\right) - q\lambda_1\right] = q - 1. \tag{3.11}$$

On the outer cylinder stagnant zones will form when the following critical relation between the flow parameters holds:

$$\delta_{*2}\left[T_1'(b)\cos\frac{m_1}{m_2}(2\pi n - \varphi_0) + T_2'(b) - q\lambda_2/b^2\right] = 1 - q/b, \tag{3.12}$$

$$T_k'(r) = c_{1k} m_k \frac{1}{q}(r/q)^{m_k - 1}\left[F_{1k}(r/q) + (r/q)\frac{m_k}{2m_k + 1} F_{1k}'(r/q)\right] - c_{2k} m_k \frac{1}{q}(r/q)^{-m_k - 1}\left[F_{2k}(r/q) + (r/q)\frac{m_k}{2m_k - 1} F_{2k}'(r/q)\right],$$

if $F_{ik}(r/q) = F_{ik}(a, b, c, r/q)$, then $F'_{ik}(r/q) = F_{ik}(a+1, b+1, c+1, r/q)$.

The case when only one of the cylinders is perturbed is obtained if in the solution we always put λ_1 or λ_2 equal to zero.

By analyzing conditions (3.11) and (3.12) we see that the first stagnant zone is formed at those peaks of the depressions of the inner cylinder for which $\cos[(m_2/m_1)\pi(2N+1)+\varphi_0)]$ takes its greatest value, and for the outer cylinder, conversely, when $\cos[(m_1/m_2)(2\pi n-\varphi_0)]$ takes its least value.

Figure 1 shows the case then $m_1=4$, $m_2=8$, and $\varphi_0=0$. On the surface of the inner cylinder the stagnant zones are formed in all depressions simultaneously, since $\cos 2\pi(2n+1)=1$ for any n. On the outer cylinder stagnant zones are formed first at points 1, 3, 5, and 7, since at these points $\cos n\pi=-1$, and criterion (3.12) is satisfied for the least values of δ_*.

If m_1 and m_2 do not have a common divider, a stagnant zone is first formed at one point. If $m_1=m_2$, stagnant zones are formed simultaneously at all peaks of the perturbations of the inner or outer cylinder. If for assigned parameters it turns out that $\delta_{*1}<\delta_{*2}$, stagnant zones will first be formed on the inner cylinder, and if $\delta_{*1}>\delta_{*2}$ stagnant zones will first be formed on the outer cylinder. If $\delta_{*1}=\delta_{*2}$, stagnant zones will be formed on the inner and outer cylinders simultaneously. Eliminating δ from (3.11) and (3.12) we obtain a relation between the parameters for the simultaneous formation of stagnant zones on the rigid boundaries of both cylinders.

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RELATIONSHIPS BETWEEN THE CREEP STRAIN INCREMENTS AND THE STRESSES FOR NONSTATIONARY LOADING MODES

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It is known that the similarity of deviators of any tensors is a necessary and sufficient condition for a quasilinear isotropic relationship between them [1]. Experimental investigations performed in both domestic and foreign laboratories on the creep in isotropic materials in stationary loading modes (under simple loading conditions for plasticity) confirmed sufficiently well the similarity hypothesis between the deviators of the stress tensor and the strain increment tensor [2]. This justifies extensive propagation of the theories of plasticity and creep which are based on a quasilinear relationship between these tensors. The similarity between the deviators of the above-mentioned tensors is spoiled for nonstationary loading modes and its absence is apparently associated with the nonlinear nature of the relation. The purpose of the experimental investigation performed is to set up the regularity of the deviation of the ratio between the creep strain increments from the similarity condition and the stress deviator for a step change in the stress state with different combinations of the axial tension σ and shear τ.

The experiments were performed at room temperature on tubular specimens (17- and 15-mm outer and inner diameters, respectively, and 50-mm length of the working section). The initial blanks for the specimens were cut from 20-mm-thick slabs of one of the titanium alloys. After fabrication, the specimens were not subjected to any heat treatment. Some data on the elastoplastic properties and the creep properties of this material are presented in [3]. Despite a certain anisotropy in the creep properties of this material, the

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