

1. Attainment of the creep limit and the type of failure of a broad class of glassy polymers are determined by the appearance of crazing (silver cracks) (CR) or the development of shear flow in the form of discrete shear bands (SB) or a diffuse shear zone consisting of microbands [1]. The difference between ordinary cracks and CR (crazing) was pointed out in [2, 3]. The first detailed studies of the structure of CR [4-6] permitted concluding that the folds of cracks which give a mirror sheen are fastened over the entire surface "by something like a system of individual filaments" separated by microcavities, and the disappearance of visually observed cracks after heating is due to "contraction of oriented filaments" [4, p. 1446]; the existence of a correlation between the structure of CR and the microstructure of the polymer was hypothesized, and a view of CR as a region of cold drawing was formulated. Subsequent studies revealed the quantitative characteristics of the structure of CR correlated with the structure of the starting material [1, 7, 8].

The localization of strains in the form of SB was first indicated in [9]. Subsequent studies in general showed that both CR and SB are regions of fibrillated oriented material [1, 10-13].

Despite the many studies, there is still no single opinion concerning the phenomena of CR and SB. Two groups of empirical criteria of plasticity are recommended in the traditional approach as a function of the conditions of loading and the mechanism of deformation, and selection of the criterion for each concrete case is an independent problem [1, 14]. These criteria do not explain, but only state the appearance of CR or SB as unrelated mechanisms of deformation.

Nevertheless, the analysis of the experimental data indicates that CR and SB belong to one class of localized orientation transformations. This is indicated by the orientation and fibrillar structure of CR and SB [11, 12], the similarity of the molecular rearrangements with which their formation is correlated [15], the discovery of SB in CR on stretching in a direction perpendicular to the SB [16]; the similar structure of the failure surfaces along SB and CR [16-18]; the controlling role of the same features of the microstructure of the polymer (linkage network parameters) [8, 12, 19].

The distinct localization of spontaneously occurring regions of a material with different properties and structure permits considering the appearance of CR and SB from unified positions: based on laws characteristic of phase transitions (orientational, accompanied by an expansion effect) [14, 20]. The temperature-time dependences of initiation of CR and SB indicate the role of the methods of preparation and the necessity of examining the phase transitions in the relaxing material.

The possibility of separating the processes into fast (described as a phase transition) and slow could be correlated with the preparation of large-scale rearrangements by processes which take place on other structural levels. The conditions of the phase transition can be satisfied in the trajectory of the relaxation process [21]; according to [22], induced elastic deformation begins after completion of more elementary processes; from the point of view of the analysis in [23], this means that nonlinearity of one type results in another, stronger nonlinearity: discontinuous. Considerations of CR and SB as regions of a new phase or regions of intense relaxation processes in this approach do not alternate with but instead supplement each other. Modeling of CR and SB by equilibrium layers of a new phase in an elastic material is one approximation.

The orientation transition is accompanied by "phase" deformation: elongation in the direction of orientation and narrowing in the transverse directions. An environment with slightly deformed material generates tensile stresses inside the orientation nucleus. If

Okhta Plastpolimer Scientific and Industrial Association, Leningrad. Translated from *Mekhanika Kompozitnykh Materialov*, No. 1, pp. 3-10, January-February, 1989. Original article submitted June 14, 1988.

they result in separation of oriented molecular chains, then a cavity-fibrillar structure of the nucleus of the CR with elongation phase deformation without any change in the cross section is formed. It has been shown that an equilibrium layer of a phase which satisfies the additional condition of the lowest potential energy of deformation of the starting phase ("boundary" layer) is perpendicular to the direction of the greatest tensile stress. If the stresses inside the orientation nucleus do not cause separation of molecular chains, then the phase transition is not accompanied by a significant change in volume; the boundary layer is positioned at an angle to the direction of extension. The conditions of the existence of the corresponding layers determine the criteria of the appearance of CR and SB.

2. The problem of the equilibrium two-phase configuration (TC) which consists of determination of the shape of area V occupied by the material of the new phase and the stressed state which satisfies the equilibrium conditions [24] in the case of small deformations can be reduced to the relations from the theory of elasticity for an inhomogeneous medium with the additional condition of thermodynamic equilibrium at the phase boundary [25]:

$$\nabla \cdot \sigma = 0; \quad n \cdot [\sigma] = 0; \quad [u] = 0; \quad [\theta] = 0; \quad (1)$$

$$\sigma(x) = [C^+ + C_1 \chi(x)] \cdot [\varepsilon(x) - \varepsilon^f(x)]; \quad (2)$$

$$\rho_0 [f] - \sigma \cdot [\varepsilon] = 0; \quad (3)$$

$$\rho_0^{\pm} = \rho_0 f_0^{\pm} + 1/2 (\sigma^{\pm} \cdot B^{\pm} \cdot \sigma^{\pm}). \quad (4)$$

Here σ is the Cauchy stress tensor; n , unit vector of the normal to the phase boundary; u , displacement vector; f , free energy density; ρ_0 , density of phase material "-" in the absence of stresses at temperature θ ; C^{\pm} and B^{\pm} , tensors of the moduli of elasticity and compliance of the phases; $C_1 = C^+ - C^-$; x , point of a solid; $\chi(x)$, characteristic function of area V; ε^f , "phase" deformation tensor: the deformation in a hypothetical transition from one unstressed state to another; f_0^{\pm} , free energy densities of unstressed phases; the materials of the starting and new phases are indicated by indexes "-" and "+"; the square brackets indicate the change in the value in going from phase "-" to phase "+"; the signs "." and "..." are the scalar and binary scalar products. It follows from the second and third conditions of (1) that

$$[\sigma] \cdot [\varepsilon] = 0. \quad (5)$$

The conditions of mechanical equilibrium in (1) are satisfied by determination of stresses σ^{\pm} with any shape of area V, and the conditions of phase equilibrium (3) are satisfied by the special and unambiguous selection of the shape of V.

3. Let us examine the equilibrium TC with plane layers of the new phase. At the boundary of an arbitrary inclusion

$$[\sigma] = S(n) \cdot m \quad (m \equiv B_1 \cdot \sigma^+ + \varepsilon^f), \quad (6)$$

where $B_1 = B^+ - B^-$; the tetraivalent tensor is

$$S(n) = C \cdot K(n) \cdot C - C^-; \quad K(n) = \{n(n \cdot C \cdot n)^{-1} n\}^s \quad (7)$$

(s designates symmetrization with respect to permutation of the indexes within pairs) [27]; m has the sense of a tensor of the density of dislocation moments induced by the region of the new phase.

With an arbitrary position of the layer in an unlimited medium in a homogeneous stress field σ_0 , the conditions are observed

$$\sigma^- = \sigma_0; \quad \sigma^+ = \sigma_0 + S(n) \cdot m; \quad m = [I - B_1 \cdot S(n)]^{-1} \cdot m_0, \quad (8)$$

where $m_0 = B_1 \cdot \sigma_0 + \varepsilon^f$; I is a tetraivalent unit vector.

It is possible to show that

$$S(n) \cdot [I - B_1 \cdot S(n)]^{-1} = S^+(n).$$

Here $S^+(n)$ is determined by the moduli of elasticity of the "+" phase and vector n , like $S(n)$, with relations (7). Then due to (6) and (8)

$$[\sigma] = S^+(n) \cdot m_0. \quad (9)$$



Fig. 1

Fig. 1. Layer of a new phase.

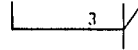


Fig. 2

Fig. 2. Appearance of CR (---) and SB (—) in the plane stressed state: 1) $v < 0$; 2) $v = 0$; 3) $v > 0$.

The condition of equilibrium (3) in consideration of (4)-(9) becomes

$$\gamma - 1/2\sigma_0 \cdot B_1 \cdot \sigma_0 - \sigma_0 \cdot \epsilon' - 1/2m_0 \cdot S^+(n) \cdot m_0 = 0, \quad (10)$$

where $\gamma = \rho_0[f_0]$ (a different examination of the problem of the equilibrium layer of a new phase is proposed in [26]). Equation (10) with the given principal values of tensor ϵ' and values of the moduli of elasticity can be satisfied with different stresses σ_0 and different n and major directions of ϵ' .

For an illustration, let us examine an equilibrium layer with elongation phase deformation ϵ in direction e on extension with stresses σ in direction r with $B_1 = 0$. It follows from (10) that

$$\sigma r_e^2 = \Gamma + \mu \epsilon (1 - n_e^2)^2 / (1 - \nu) \quad (\Gamma = \gamma / \epsilon), \quad (11)$$

where μ and ν are the shear modulus and Poisson ratio of phase "-"; r_e and n_e are the projections of r and n in direction e . Equation (11) can be satisfied when $\sigma \geq \Gamma$. A layer for which $n = e = r$ corresponds to the minimum stress $\sigma = \Gamma$ when $\Gamma > 0$. When $\sigma > \Gamma$, different directions of n and e are possible.

A different degree of metastability of the starting phase $\psi = \rho_0[g^-(\sigma_0) - g^+(\sigma_0)]$, the difference in the Gibbs energy densities $\rho_0 g = \rho_0 f - \sigma \cdot \epsilon$ of one-phase configurations, corresponds to different stresses σ_0 , which allow the existence of equilibrium layers and different TC due to (10). It follows from (2) and (4) in consideration of (9) and (10) that

$$\psi = 1/2\sigma_0 \cdot B_1 \cdot \sigma_0 + \sigma_0 \cdot \epsilon' - \gamma = -1/2m_0 \cdot S^+(n) \cdot m_0 = -1/2[\sigma] \cdot m_0.$$

Since for the layer $m_0 = [\epsilon] - B^+ \cdot [\sigma]$, by virtue of (5) and the positive determinacy of the compliance tensor

$$2\psi = -[\sigma] \cdot [\epsilon] + [\sigma] \cdot B^+ \cdot [\sigma] \geq 0$$

the appearance of a layer of a new phase is only possible in the metastable phase (in a "re-stressed" material) or when $\psi = 0$. An analogous condition is obtained for the equilibrium ellipsoidal nucleus of the solid phase [25].

4. The requirement of the least potential deformation energy (the work completed at the time of appearance of the equilibrium layer) results in determination of the limit TC and limit stresses.

We will designate the main directions and main values of tensors ϵ' and σ_0 by e_k , ϵ_k , and r_k , σ_k ($k = 1, 2, 3$) (we will assume that e_k coincide with the directions of t elasticity of phase "+" (Fig. 1):

$$r_k = O \cdot e_k; \quad O \cdot O^T = E \quad (12)$$

(O is the tensor of rotation coupling trihedrons r_k and e_k ; E is a unit tensor, " t " is a transposition symbol). Tensor of rotation O and normal vector n which provide for minimum $A(\sigma_0) = 1/2(\sigma_0 \cdot B^- \cdot \sigma_0)$ with additional conditions (10) and (12) and

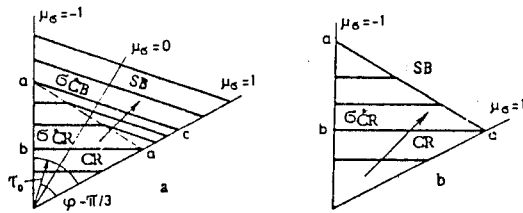


Fig. 3. Deviatoric sections of the boundary surface of appearance of CR and SB: a) $v > 0$; b) $v = 0$. The direction of the decrease in σ_0 is indicated by the arrow.

$$n \cdot n = 1 \quad (13)$$

are determined by solution of the problem of an arbitrary extreme.

We will subsequently assume that the material of phase "-" is isotropic. Then the problem of determining vectors n and e_k in basis r_h is equivalent to the problem of finding n and r_h in basis e_k . Variation of the principal directions of tensor σ_0 by virtue of (12) generates the variations

$$\delta\sigma_0 = \sigma_0 \cdot \Omega - \Omega \cdot \sigma_0; \quad \delta m_0 = B_1 \cdot \delta\sigma_0, \quad (14)$$

where $\Omega = O \cdot \delta O^T$ is an arbitrary skew-symmetric tensor. Extreme $A(\sigma_0)$ in conditions (10) and (13) and in consideration of (14) is determined by the relations

$$\sum_k (\epsilon_k^0 + \alpha m_{kk}) \delta\sigma_k = 0 \quad (\epsilon^0 = B^{-1} \cdot \sigma_0; \quad m_{kk} = r_k \cdot m \cdot r_k);$$

$$m_0 \cdot \delta S^+(n) \cdot m_0 + 4(\beta/\alpha) n \cdot \delta n = 0; \quad (15)$$

$$m \cdot \sigma_0 = \sigma_0 \cdot m. \quad (16)$$

Relations (10), (13), (15), and (16) in consideration of (8) form a system of eight equations with seven unknowns: vector n , orthogonal tensor O , and ratio of Lagrangian multipliers β/α . The "excess" Eq. (10) determines the boundary area of the appearance of equilibrium layers in the space of principal stresses σ_k . The characteristic property of a boundary equilibrium layer of a new phase, the alignment of tensor m to the external stress tensor: $m_{kk} = m_k$, follows from (16). Equations $\epsilon_k^0 + \alpha m_k = 0$ determine parameter α and the point on the boundary surface where the elastic energy density of phase "-" is least among the boundary configurations. Tensors m and ϵ^0 are similar at this point.

5. We will now examine the boundary equilibrium layers in deformation phase transitions, neglecting the change in the moduli of elasticity ($B_i = 0$). Then the phase deformation tensor is coaxial to the external stress tensor, and the normal vector, determined with Eqs. (13) and (15), minimizes the degree of metastability:

$$\psi = -1/2 \epsilon^T \cdot S(n) \cdot \epsilon^T, \quad (17)$$

and the boundary surface equation becomes

$$\sum_k \sigma_k \epsilon_k = \gamma + \psi^*; \quad \psi^* = \min_n \psi \quad (\epsilon_1 > \epsilon_2 > \epsilon_3, \sigma_1 > \sigma_2 > \sigma_3). \quad (18)$$

Since for an isotropic medium

$$C^{-1} = \lambda E E + 2\mu I; \quad K(n) = \frac{1}{\mu} (n E n)^2 - \frac{\lambda + \mu}{\mu(\lambda + 2\mu)} n n n n,$$

where λ and μ are Lamé coefficients [27], we find that the direction of the normal to the boundary layer is determined by a parameter of the phase deformation "type" $\alpha_{13} = (\epsilon_1 + \nu \epsilon_2) / (\epsilon_1 - \epsilon_3)$ ($\epsilon_1 > \epsilon_2 \geq \epsilon_3$). If $\alpha_{13} > 0$, then $n_1^2 = 1$ and the layer is perpendicular to the direction of the largest principal stress. If $\alpha_{13} \leq 1$, then $n_1^2 = \alpha_{13}$, and $n_2 = 0$.

Tensors $[\sigma]$, σ^+ , and σ_0 are coaxial. If $\alpha_{13} > 0$, then

$$[\sigma_2] = -2\mu(\epsilon_3 + \nu\epsilon_2)/(1-\nu); \quad [\sigma_3] = -2\mu(\epsilon_2 + \nu\epsilon_3)/(1-\nu).$$

If $\alpha_{13} < 1$, then $[\sigma_2] = -E\epsilon_2$, and the largest and smallest principal values of the stress tensor are continuous (E : Young's modulus).

The tensors formed by Kronecker deltas and the unit vector are represented as a linear combination of tensors T^i ($i = 1-6$) [28]. Using basis T^i , it is easy to show that

$$S(n) = -2\mu(T^2 + \kappa T^4) \quad [\kappa = (1+\nu)/(1-\nu)];$$

$$-\frac{1}{2\mu} q \cdot S(n) \cdot q = \kappa(q_{11} + q_{\tau\tau})^2 + (q_{11} - q_{\tau\tau})^2 + 4q_{1\tau}^2; \quad (19)$$

where symmetric tensor q is represented in basis set n , t , τ .

It was shown above that $\psi \geq 0$. It follows from (17) and (19) that in a deformation phase transition, the appearance of a layer with zero metastability is only possible when one or two principal values of tensors ϵ^l are equal to zero, and the nonzero principal values have different signs (plane deformation). These layers are subsequently compared with CR and SB. Then

$$n_1^2 = \alpha_{13} = (2-\nu)^{-1}; \quad n_2 = 0 \quad [v = (\epsilon_1 + \epsilon_3)/\epsilon_1]; \quad (20) \quad [\sigma] = 0, \quad (21)$$

and the boundary surface of (18) is determined by the equation

$$\sigma_1 - \sigma_3(1-\nu) = \Gamma \quad (\Gamma = \gamma/\epsilon_1). \quad (22)$$

We note that the boundary layer with plane phase deformation corresponds to the shear plane (accompanied by expansion) with a vector of discontinuity of motions in the plane e_1, e_3 .

Since the change in the Gibbs energy of the boundary region on passage of the equilibrium layer of the new phase through it is determined by the following equality due to the imperturbability of stresses outside of the layer and (3)

$$\Delta G = \rho_0 V [g^+(\sigma^+) - g^-(\sigma_0)] = -\rho_0 V \epsilon_0 \cdot [\sigma],$$

where V is the part of the layer which intersects the region, then by virtue of (21), the appearance of a boundary layer with plane phase deformation does not cause any change in the Gibbs energy of the substance.

6. The appearance of SB in the approximation of a deformation phase transition is determined according to (22) by the largest and smallest values of the stress tensor and the expansion effect of the structural transformations. For CR ($\epsilon_1 > 0$, $\epsilon_2 = \epsilon_3 = 0$), the criterion of the greatest tensile stress follows from (22)

$$\sigma_1 = \Gamma' \quad [\Gamma' = (\gamma/\epsilon_1)CR]. \quad (23)$$

The layer is perpendicular to the direction of the effect of this stress. The controlling role of the greatest stresses in the case of CR is confirmed by the experimental data in [29, 30].

In extension with stresses σ in conditions of the effect of hydrostatic pressure p , the limiting state is attained when

$$\sigma = \begin{cases} \Gamma' + p; & p < p_* = (\Gamma - \Gamma')/(1-\nu) \quad \text{for CR;} \\ \Gamma + \nu p; & p > p_* \quad \text{for SB;} \end{cases}$$

(p_* determines the brittleness-plasticity transition as a function of the parameters of the transformations). These dependences, like those illustrated in Fig. 2, are in agreement with the experimental data in [20, 31] (see also [14]).

Criteria (22) and (23) can be represented as

$$\tau_0 \left[1 - \frac{1}{6}(3 + \mu_\sigma)\nu \right] = \frac{1}{3\sqrt{2}}(\Gamma - \nu\sigma_0)\sqrt{3 + \mu_\sigma^2} \quad \text{for SB;} \quad (24)$$

$$\tau_0 = \sqrt{2}(\Gamma' - \sigma_0)\sqrt{3 + \mu_\sigma^2}/(3 - \mu_\sigma) \quad \text{for CR,}$$

Tensors $[\sigma]$, σ^+ , and σ_0 are coaxial. If $\alpha_{13} > 0$, then

$$[\sigma_2] = -2\mu(\epsilon_3 + \nu\epsilon_2)/(1-\nu); \quad [\sigma_3] = -2\mu(\epsilon_2 + \nu\epsilon_3)/(1-\nu).$$

If $\alpha_{13} < 1$, then $[\sigma_2] = -E\epsilon_2$, and the largest and smallest principal values of the stress tensor are continuous (E : Young's modulus).

The tensors formed by Kronecker deltas and the unit vector are represented as a linear combination of tensors T^i ($i = 1-6$) [28]. Using basis T^i , it is easy to show that

$$S(n) = -2\mu(T^2 + \kappa T^4) \quad [\kappa = (1+\nu)/(1-\nu)];$$

$$-\frac{1}{2\mu} q \cdot S(n) \cdot q = \kappa(q_{11} + q_{33})^2 + (q_{11} - q_{33})^2 + 4q_{12}^2; \quad (19)$$

where symmetric tensor q is represented in basis set n , t , τ .

It was shown above that $\psi \geq 0$. It follows from (17) and (19) that in a deformation phase transition, the appearance of a layer with zero metastability is only possible when one or two principal values of tensors ϵ^i are equal to zero, and the nonzero principal values have different signs (plane deformation). These layers are subsequently compared with CR and SB. Then

$$n_1^2 = \alpha_{13} = (2-\nu)^{-1}; \quad n_2 = 0 \quad [v = (\epsilon_1 + \epsilon_3)/\epsilon_1]; \quad (20) \quad [\sigma] = 0, \quad (21)$$

and the boundary surface of (18) is determined by the equation

$$\sigma_1 - \sigma_3(1-\nu) = \Gamma \quad (\Gamma = \gamma/\epsilon_1). \quad (22)$$

We note that the boundary layer with plane phase deformation corresponds to the shear plane (accompanied by expansion) with a vector of discontinuity of motions in the plane e_1 , e_3 .

Since the change in the Gibbs energy of the boundary region on passage of the equilibrium layer of the new phase through it is determined by the following equality due to the imperturbability of stresses outside of the layer and (3)

$$\Delta G = \rho_0 V [g^+(\sigma^+) - g^-(\sigma_0)] = -\rho_0 V \epsilon_0 \cdot [\sigma],$$

where V is the part of the layer which intersects the region, then by virtue of (21), the appearance of a boundary layer with plane phase deformation does not cause any change in the Gibbs energy of the substance.

6. The appearance of SB in the approximation of a deformation phase transition is determined according to (22) by the largest and smallest values of the stress tensor and the expansion effect of the structural transformations. For CR ($\epsilon_1 > 0$, $\epsilon_2 = \epsilon_3 = 0$), the criterion of the greatest tensile stress follows from (22)

$$\sigma_1 = \Gamma' \quad [\Gamma' = (\gamma/\epsilon_1)CR]. \quad (23)$$

The layer is perpendicular to the direction of the effect of this stress. The controlling role of the greatest stresses in the case of CR is confirmed by the experimental data in [29, 30].

In extension with stresses σ in conditions of the effect of hydrostatic pressure p , the limiting state is attained when

$$\sigma = \begin{cases} \Gamma' + p; & p < p_* = (\Gamma - \Gamma')/(1-\nu) \quad \text{for CR;} \\ \Gamma + \nu p; & p > p_* \quad \text{for SB;} \end{cases}$$

(p_* determines the brittleness-plasticity transition as a function of the parameters of the transformations). These dependences, like those illustrated in Fig. 2, are in agreement with the experimental data in [20, 31] (see also [14]).

Criteria (22) and (23) can be represented as

$$\tau_0 \left[1 - \frac{1}{6}(3 + \mu_\sigma)\nu \right] = \frac{1}{3\sqrt{2}}(\Gamma - \nu\sigma_0)\sqrt{3 + \mu_\sigma^2} \quad \text{for SB;} \quad (24)$$

$$\tau_0 = \sqrt{2}(\Gamma' - \sigma_0)\sqrt{3 + \mu_\sigma^2}/(3 - \mu_\sigma) \quad \text{for CR,}$$

where σ_0 is the hydrostatic component of the stress tensor; τ_0 is the octahedral tangential stress; the Lode-Nadi parameter $\mu_0 = (2\sigma_2 - \sigma_1 - \sigma_3)/(\sigma_1 - \sigma_3)$ determines the type of stressed state. The mutual effect of the hydrostatic component of the stress tensor and the type of stressed state in the approximation of a deformation phase transition according to (24) is determined by the expansion effect of the mechanism of deformation.

The deviatoric sections of the boundary surface of appearance of CR and SB (with $\sigma_0 = \text{const}$) are shown in Fig. 3 in polar coordinates $r = \tau_0$ and $\varphi = \arctan(\mu_0/\sqrt{3})$ ($\mu_0 = \pm 1$ correspond to uniaxial extension and compression in condition of the effect of hydrostatic pressure). Line aa of the change in the mechanisms of deformation (brittleness-plasticity transitions) and the critical average stress are determined by the relations

$$\tau_0^* = (\Gamma - \nu\Gamma')\sqrt{3 + \mu_0^2}/[3\sqrt{2}(1-\nu)];$$

$$\sigma_0^* = \{3[(2-\nu)\Gamma' - \Gamma] + (\Gamma - \nu\Gamma')\mu_0\}/[6(1-\nu)].$$

When $\sigma_{SB}^* < \sigma_0 < \sigma_{CR}^*$ (rectangle abac), CR or SB arise as a function of the stressed state. Outside of this interval of the hydrostatic components of the stress tensor, only CR or only SB appear. Here

$$\sigma_{SB}^* = [(3-\nu)\Gamma' - 2\Gamma]/[3(1-\nu)]; \quad \sigma_{CR}^* = [(3-2\nu)\Gamma' - \Gamma]/[3(1-\nu)].$$

We note that when certain relations between the parameters of the structural transformations are satisfied (here when $\Gamma > (3-\nu)\Gamma'/2$), CR can appear with negative values of the first invariant of the stress tensor, which is in agreement with the experimental data in [30] and indicates the limitedness of the approaches to the description of CR which use the condition $\sigma_0 > 0$ as a necessary condition (see, e.g., [32]).

Consideration of the change in the moduli of elasticity in orientation transformation results in substitution of the piecewise-linear dependences (18) by more complex quadratic dependences with respect to the stresses according to (10). The direction of propagation of SB will be a function of the change in the moduli of elasticity.

The proposed examination reflects the correlation of the effect of the type of stressed state and the hydrostatic component of the stress tensor, describes the brittleness-plasticity transition as a function of the type of stressed state, and permits plotting the boundary surface of appearance of CR and SB from unified positions in consideration of the change in the mechanisms of deformation and the expansion effect.

We would like to thank A. Ya. Gol'dman and S. K. Kanaun for their assistance in the research.

LITERATURE CITED

1. C. B. Bucknall, High-Impact Plastics [Russian translation], Leningrad (1981).
2. J. A. Sauer, J. Marin, and C. C. Hsio, "Creep and damping properties of polystyrene," J. Appl. Phys., 2, No. 6, 507-517 (1949).
3. B. Maxwell and L. F. Rahm, "Rheological properties of polystyrene below 80°C," Ind. Eng. Chem., 41, 1988-1993 (1949).
4. M. I. Bessonov and E. V. Kuvshinskii, "Cracks in transparent plastics, their growth and structure," Fiz. Tverd. Tela, 1, No. 9, 1441-1447 (1959).
5. M. I. Bessonov and E. V. Kuvshinskii, "Some features of failure of hardened polystyrene," Vysokomolek. Soedin., 1, No. 10, 1561-1569 (1959).
6. M. I. Bessonov and E. V. Kuvshinskii, "Features of the development of failure cracks in solid polymers," Fiz. Tverd. Tela, 3, No. 2, 607-610 (1961).
7. G. Kaush, Failure of Polymers [Russian translation], Moscow (1981).
8. "Crazing in polymers," Adv. Polym. Sci., 52153, 347 (1983).
9. W. Whytney, "Observation of deformation bands in amorphous polymers," J. Appl. Phys., 34, No. 12, 3633-3634 (1963).
10. A. S. Argon, R. D. Andrews, J. A. Godrick, and W. Whitney, "Plastic deformation bands in glassy polystyrene," J. Appl. Phys., 39, No. 3, 1899-1906 (1968).
11. T. E. Brady and G. S. Y. Yeh, "Similarity between craze morphology and shear-band morphology in polystyrene," J. Mater. Sci., 8, No. 5, 1083-1094 (1973).
12. A. M. Donald and E. J. Kramer, "The competition between shear deformation and crazing in glassy polymers," J. Mater. Sci., 17, No. 7, 1871-1879 (1982).

- 1
he
-
as-
na-
3
ed
city
1
2-
B.
id
ie,"
13. C. O'Sell and A. G. Goper, "Plastic bonding in glassy polycarbonate under plane simple shear," *J. Mater. Sci.*, 20, No. 10, 3462-3472 (1985).
 14. A. B. Freidin and A. Ya. Gol'dman, "Appearance of crazing and shear bands as deformation phase transitions in glassy polymers," *Mekh. Kompozitn. Mater.*, No. 5, 771-777 (1984).
 15. R. N. Haward, B. M. Murphy, and E. F. T. White, "Relationship between compressive yield and tensile behaviour in glassy thermoplastics," *J. Polym. Sci. A-2*, 9, No. 5, 801-814 (1971).
 16. K. Friedrich and K. Schäfer, "Über den Einfluss von Scherbändern auf den Bruch in Polystyrok," *Progr. Colloid Polym. Sci.*, 66, 329-340 (1979).
 17. C. C. Chau and G. C. M. Li, "Fracture of shear bands in atactic polystyrene," *J. Mater. Sci.*, 16, No. 7, 1858-1873 (1981).
 18. K. Friedrich and K. Schäfer, "Coarse shear bands and fracture in polystyrene," *J. Mater. Sci. Lett.*, 14, No. 2, 480-483 (1979).
 19. C. S. Hekke and E. J. Kramer, "Crazing and shear deformation in crosslinked polystyrene," *J. Polym. Sci.: Polym. Phys. Ed.*, 22, No. 4, 721-737 (1984).
 20. A. B. Freidin, "The creep boundary surface and appearance of crazing and shear bands in glassy polymers," *Tr. LPI im. M. I. Kalinina*, No. 393, 76-82 (1983).
 21. S. Ya. Frenkel' and G. K. El'yashevich, "A thermodynamic description of the correlation of the structure and rheological properties of condensed polymer systems," in: *Relaxation Phenomena in Polymers [in Russian]*, Leningrad (1972), pp. 234-240.
 22. E. F. Oleinik, S. N. Rudnev, O. B. Salamatina, S. I. Nazarenko, and G. A. Grigoryan, "Two modes of plastic deformation of glassy polymers," *Dokl. Akad. Nauk SSSR*, 286, No. 1, 135-139 (1986).
 23. A. Ya. Malkin, "Types and mechanisms of nonlinearity of the mechanical behavior of polymers," *Vysokomolek. Soedin.*, A29, No. 4, 801-806 (1987).
 24. M. A. Grinfel'd, "Conditions of thermodynamic phase equilibrium of nonlinearly elastic material," *Dokl. Akad. Nauk SSSR*, 251, No. 4, 824-828 (1980).
 25. L. B. Kublanov and A. B. Freidin, "Solid phase nuclei in a deformable material," *Prikl. Mat. Mekh.*, 52, No. 3, 493-501 (1988).
 26. M. A. Grinfel'd, "Construction of a physically linear theory of coherent transitions," *Izv. Akad. Nauk SSSR, Mekh. Tverd. Tela*, No. 5, 79-91 (1986).
 27. I. A. Kunin and E. G. Sosnina, "Concentration of stresses on an ellipsoidal inhomogeneity in an anisotropic elastic medium," *Prikl. Mat. Mekh.*, 37, No. 2, 306-315 (1973).
 28. I. A. Kunin, *Theory of Elastic Media with a Microstructure [in Russian]*, Moscow (1975).
 29. M. E. J. Dekkers and D. Heikens, "The effect of interfacial adhesion on the mechanism for craze formation in polystyrene-glass bead composite," *J. Mater. Sci.*, 18, No. 11, 3281-3287 (1983).
 30. K. Matsushige, S. V. Radcliffe, and E. Baer, "The mechanical behavior of polystyrene under pressure," *J. Mater. Sci.*, 10, No. 4, 833-845 (1975).
 31. M. Kawagoe and M. Kitagawa, "Craze initiation in poly(methylmethacrylate) under biaxial stress," *J. Polym. Sci.: Polym. Phys. Ed.*, 19, No. 9, 1423-1433 (1981).
 32. R. J. Oxberough and P. B. Bowden, "A general critical-strain criterion for crazing in amorphous glassy polymers," *Philos. Mag.*, 28, No. 3, 547-559 (1973).