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MASS TRANSFER BY A DILATATION FIELD OF INCOMPLETE SHEAR

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The concept of an incomplete shear model is developed to explain observations on shear deformation under the pressure of thin layers.

Observation Results. In the experiments of [1–6], specimens in the form of thin layers of a single metal or three layers of two alternate metals (sandwiches) were pressed between flat punches and deformed by rotation of one of the punches. The main results of the observations are as follows. Plastic deformation (PD) in the sandwiches starts in soft metal in which high-pressure regions form. The regions are hardened, and, as a result, move translationally and rotationally as a unit, scratch, fold harder metal, and involve it in plastic motion.

When the relative shear velocity is 1 $\sec^{-1}$, the regions are strengthened and grow self-acceleratedly, spread over the thickness of the specimen, compete with one another, and being arranged in an ordered fashion, form a mesoscopic dissipative structure of a new type in PD theory, i.e., a structure with nonuniform pressure and density. When the relative shear velocity is 10^{-2} $\sec^{-1}$, small regions grow and then relax. Scratching is observed when the shearing strengths of the metals differ by a factor of 5. In this case, scratching begins as soon as deformation commences. Therefore, hardening can be significant and does not require high degrees of PD. The relaxation time for high-pressure regions is a few tens of seconds. The formation of these regions is promoted by nonuniform shear displacements, that is, incomplete plastic shears and nonuniform slips along the contact planes. The nonuniform-pressure structures determine plastic processes in thin layers, and, at elevated PD velocities, also in thick layers and in specimens of any shape, as follows from analysis of [5].

The goal of this paper is to develop theoretical concepts to explain the formation of regions (the ρ-regions) whose density differs from the average, the self-accelerated growth, the strong hardening, the small relaxation time of high-pressure regions, and the similarity of the effects occurring in PD and in friction [1–6].

Two traditional approaches are used to describe PD. 1) In mechanics, a system of equations is written that must predict the effects observed in experiments. 2) In physics, one chooses typical structural elements, calculates the stress fields for these elements (for example, by solution of an elastic problem for an edge dislocation outside its core [7]), and analyzes, using these fields, situations that arise in the course of PD. The second approach is used herein.

Models of Edge Dislocation. The models of a lattice edge dislocation can be divided into two groups according to the form of the displacement-distribution function in the plane of shear $\mathbf{u}(x, y = 0)$. The first group includes stationary-dislocation models (e.g., the Peierls–Nabarro model) with the function $u_x(x)$ that is symmetric about the plane $x = 0$ which passes through the dislocation line. This function satisfies the boundary conditions [7]

$$u_x^+(\infty) = -u_x^+(-\infty) = -b/4, \quad u_x^-(\infty) = -u_x^-(-\infty) = b/4, \tag{1}$$

where u_x^+ and u_x^- are the components of displacement of atomic planes that lie above and below the plane of shear; and b is the displacement vector. The extraplane is located above the plane of shear. The second

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group includes moving-dislocation models (the Frenkel–Kontorova model and the Kosevich model) with an asymmetric function $u_x(x)$ that satisfies, as, e.g., in [8], the boundary conditions

$$u_x^+(\infty) = 0, \quad u_x^+(-\infty) = b, \quad u_x^-(\infty) = u_x^-(-\infty) = 0. \tag{2}$$

An elastic field is found for the first model. The field is symmetric about the plane $x = 0$. The moving-dislocation models are one-dimensional, and an elastic field is not found. In these models, external stresses affect dislocations. According to [7], an elastic field satisfying (1) is also conserved for dislocations in the field of external stresses.

It is, however, obvious that an elastic-dislocation field inherits the symmetry of the boundary conditions and therefore must change under external stresses. After unloading, an asymmetric elastic field becomes a symmetric field in which the forces acting between the atomic planes separated by the plane of shear are in equilibrium. The effects described in [1–6] manifest themselves immediately in the process of plastic deformation and are therefore determined by asymmetric fields.

Moving-dislocation models are developed to describe the mass transfer under shear mechanisms of plastic deformation [8]. Let us consider the features of this process. We use the continuity equation

$$\int_S (\mathbf{u}, \mathbf{n}dS) = -\Delta V, \tag{3}$$

where S is a closed surface; $\mathbf{n}$ is the internal normal to S; and ΔV is the dilatation of the volume V bounded by the surface S. Boundary conditions (1) and (2) are limiting. They restrict a series of transient conditions for transition from (1) to (2), which correspond to the growth of external stresses responsible for shear. The transient conditions transform (1) into (2) and lead to motion of dislocations. Let surfaces S_1 and S_2 be symmetric about the plane of shear and closed by a part of the plane of shear that contains the dislocation line. It follows from (2) and (3) that for the transient boundary conditions $\Delta V_1 \neq 0$, $\Delta V_2 \neq 0$, and $|\Delta V_1| \neq |\Delta V_2|$. The latter inequality is especially pronounced in the case of a moving dislocation, since (2) implies that $\Delta V_2 = 0$. Note that the boundary conditions for transition from (1) to (2) do not exhaust all possible boundary conditions. For example, $\Delta V_1 = -\Delta V_2$ in the external-stress field of pure shear (see below). According to (3), the greater $\partial u_x/\partial x$, the greater $|\Delta V|$ and $|\Delta\rho/\rho|$, because $\Delta\rho/\rho = -\Delta V/V$ when $m = \rho V = \text{const}$. Thus, ρ-regions exist near a moving dislocation. They contain excessive or deficient mass. The regions accompany the motion of dislocations and transfer the mass they concentrate.

Let us define an incomplete shear exclusively in terms of displacements: in the shearing area the shear displacements are greater than in the rest of the plane of shear. Then we can ignore the following: how the surfaces separated by the shear layer interact, what the interatomic correspondence is, what processes develop, and which state (elastic or plastic) is attained in the plane of shear. In addition, nonuniform slippage along the contact between solids can be regarded as one shear mechanism of mass transfer for which the result of analysis of (3) and of the boundary conditions are valid if one substitutes the term "incomplete slippage" for "incomplete shear" and the term "the edge of the slippage region" for "dislocation." Thus, PD and friction are shear mass-transfer processes. Friction only differs in that there is an additional plane of preferential shear displacement, namely, the contact plane. Finally, the ρ-regions observed in [1–6] form at the expense of mass redistribution by nonuniform shear displacements, i.e., incomplete shears under PD and incomplete slips under friction.

The strain state in the plane with nonuniform shear displacements can be perfectly elastic if, for example, the shear modulus is not the same in different regions of the plane and if displacements do not exceed the elastic limits in these regions. The state can be mixed, i.e., elastic, in regions with high shearing strength and plastic in regions with low shearing strength. It can also be completely plastic. However, in the latter case, using the state that is formed after removal of the external load as the initial reference point for shears, one can regarded the completely plastic state as one of the two states mentioned above.

As a typical structural element we assume a scheme of incomplete shear in which the displacements in the plane of shear or friction are small and supposedly elastic, except for a local region in which the displacements are large.

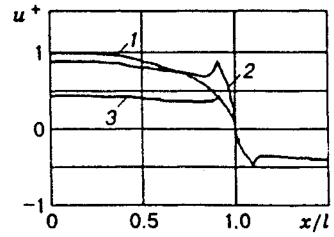

Fig. 1

Model of Incomplete Shear in a Continuum. To construct a plane model of the stress field of incomplete shear, one can use solutions of two elastic problems [9] (they will be referred to as problem I and problem II). In problem I, the field is obtained by superposition of two stress states. The first state corresponds to pure shear with tangential stresses τ_∞ of a plane without a cut. The second state is obtained by applying uniform tangential stresses τ to the edges of a cut that is parallel to the τ_∞ direction. The uniform stresses have the same direction as the displacements of the cut edges and compensate the stresses τ_∞ which act on each edge of the cut from the other edge:

$$\tau_\infty + \tau = 0. \tag{4}$$

The final state can be regarded as a result of shear of a plane with a cut whose edges do not interact. In problem II, only the second stress state is considered, because pure shear does not create a dilatation field.

Complex potentials [9] for the stress-tensor and displacement-vector components for problem I can be obtained by adding the potentials for uniform extension of a plane with a cut by stress σ directed at an angle of $\pi/4$ to the cut line and the potentials for uniform extension by stress $-\sigma$ directed at $3\pi/4$ to the cut line. Here $\tau_\infty = \sigma$. The general form of these potentials is given in [9]. Problem II is also solved in [9]. The difference in the displacements determined from the potentials of problems I and II corresponds to the rotation of a plane as a unit under pure shear in problem I. The dilatation fields are the same. The potentials of problem II are used in the calculations:

$$\varphi(\zeta) = \frac{i\tau l}{2\zeta}, \quad \psi(\zeta) = \frac{i\tau l}{\zeta(\zeta^2 - 1)}, \tag{5}$$

where $\zeta = r\exp(i\theta)$ and $2l$ is the length of the cut. In accordance with [9], we have

$$\sigma_{xx} + \sigma_{yy} = 4\mathrm{Re}\varphi(\zeta); \tag{6}$$

$$2\mu(u_x + u_y) = æ\varphi(\zeta) - [\omega(\zeta)/\omega'(\zeta)]\overline{\varphi'(\zeta)} - \overline{\psi(\zeta)}. \tag{7}$$

Here σ_{xx} and σ_{yy} are normal stresses; μ is the shear modulus; $\omega(\zeta) = 0.5l(\zeta + \zeta^{-1})$ is the mapping function; $æ = 3 - 4\nu$; and ν is Poisson's ratio. After substituting (5) into (6) and (7) and necessary calculations, we obtain

$$P = -\frac{4(1+\nu)\tau}{3}\,\frac{r^2\sin(2\theta)}{r^4 - 2r^2\cos 2\theta + 1}, \tag{8}$$

$$u^+ = \frac{(1-\nu)\tau}{\mu}\sqrt[2]{l^2 - x^2}, \tag{9}$$

where u^+ is the displacement of the upper edge of the cut (curve 1 in Fig. 1); the coordinate origin is in the middle of the cut; $x = l\cos\theta$ (here and below $u = u_x$). Since $u^+(l) = u^+(-l)$, it becomes clear that u^+ characterizes, in essence, the excess of displacements of the cut edge over the elastic displacements at stoppage points $x = \pm l$.

Displacement of the cut edges redistributes the mass near the cut. As a result, two ρ-regions whose dilatations are nonzero and have opposite signs form on each side of the cut line. Figure 2a presents regions in which the relative dilation is greater than $0.15(1 - 2\tau)\tau/\mu$ (the filled regions) or is greater than $(0.15(1 -$

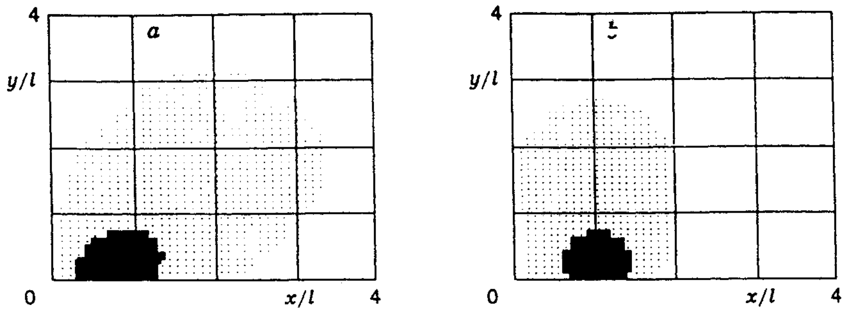

Fig. 2

$2\tau)\tau/\mu)\cdot 10^{-2}$ (the dots). In the regions directed along the displacements of each edge of the cut, the dilatation is negative and the pressure and density are elevated. The largest values of dilatation are localized near the parts of the cut on which the displacements change most rapidly. As τ grows, the deviation from the mean values increases. As l grows, the ρ-regions grow too, and the ρ-regions located on the same side of the cut line move in opposite directions and cause mass transfer. The excessive or deficient mass concentrated in one ρ-region (for example, in the first quadrant in Fig. 2a) can be found as

$$\Delta m = \rho \Delta V = \frac{\rho}{K} \int\limits_{1}^{R} r dr \int\limits_{0}^{\pi/2} P(\omega'(\zeta)\overline{\omega'(\zeta)}) d\theta = \frac{\rho(1-2\nu)\tau}{2\mu} l^2 \ln R, \tag{10}$$

where $(\omega'(\zeta)\overline{\omega'(\zeta)})^{0.5}$ is the change in linear dimensions in conformal mapping, and R is the cut-off radius. The mass transfer associated with the motion of one end of the cut is $2\Delta m$, that is, Δm in each direction. The total mass transfer is $4\Delta m$.

As regards the deformation process under load applied on the external surfaces of the body, application of external tangential stresses to the cut edges in problem I is a formal expedient. For this reason, this method will not be used in the physically reasonable interpretation of (4). From the equilibrium condition

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} = 0 \tag{11}$$

for the square element adjacent to a cut edge with $\Delta x = \Delta y$ (Fig. 3a), we obtain

$$\tau_\infty + (\sigma_2 - \sigma_1) = 0. \tag{12}$$

The tangential stresses τ_∞ of the external field near the cut are balanced by the difference of the normal stresses. If the external load is removed, the stresses $(\sigma_2 - \sigma_1)$ will displace the edges of the cut back in their original position.

Actually, the cut edges interact with any mechanism of displacements. In a continual approximation, the interaction of the edges is determined by the external or internal friction forces. Then, according to (11), we have

$$\tau_\infty + (\sigma_2 - \sigma_1) = [\tau], \tag{13}$$

where $[\tau]$ is the critical shearing resistance along the cut line. Under external friction, $[\tau] \neq 0$ if contracting stresses act along the cut line. These stresses arise when the stress state of the external field differs from pure shear (see above how the dilatation distribution of the elastic field of an edge dislocation becomes antisymmetric about the plane of shear under external load). In this case too, the displacements completely disappear when the stress is removed. It may, however, turn out that $[\tau]$ enhances the uniformity responsible for incomplete shear. Then an increase in the external action will lead to self-accelerated growth of the ρ-regions without growth in l. A ρ-region of strong contraction forms. These regions can perform rotational motions as a unit [1, 2]. Recovery of the original size of ρ-regions (by expanding, for example) along new directions that come into play after rotation will be hindered by the reaction of the ambient medium, which acts as a truss, rather than by external stresses, as according to (12). This defect remains after the load is removed. This is a Somigliana dislocation [10], since it can be obtained by the formation of such dislocations: making a cut, performing a displacement (in the course of rotation of the ρ-region), and "gluing" of the cut edges. The elastic field of the Somigliana dislocation formed has a dilatation component.

If $[\tau]$ is the internal friction, the reversibility under unloading will be partial. The remaining defect is also a Somigliana dislocation. Thus, under internal friction, the mass transferred in the course of development of incomplete shear is packed partially Δm_1 in the stress field of external load and partially Δm_2 in the stress field of the Somigliana dislocations.

The reverse shear along the cut stops when

$$\sigma_2 - \sigma_1 = [\tau], \tag{14}$$

and Δm_2 can be found by substituting $[\tau]$ into (10). Maximum tangential stresses that can be applied to the cut edges have the form

$$\tau_{\max} = g[\tau_c] + (1-g)[\tau], \tag{15}$$

where g is the length of the cut line occupied by restrictors and $[\tau_c]$ is the critical resistance to displacement of the restrictors. The plastic displacements in the incomplete-shear region and, hence, Δm are proportional to $(\tau_{\max} - [\tau])$. Substitution of this quantity, and then $[\tau]$, into (10) according to (14) yields

$$\frac{\Delta m_2}{\Delta m} = \frac{[\tau]}{\tau_{\max} - [\tau]} = \frac{\tau}{g([\tau_c] - [\tau])}, \tag{16}$$

which implies that Δm_2 and $\Delta m_1 = \Delta m - \Delta m_2$ can be commensurate (for example, they can be equal when $g = 0.5$ and $[\tau_c]/[\tau] = 5$).

The stresses $(\sigma_2 - \sigma_1)$ can exceed significantly $[\tau]$. This is perceived as a grqwth of resistance to the shear along the shear systems which are or have been active. This effect explains the multiple increase in the shearing resistance of the local regions of soft metal, which involve the harder metal in plastic motion [1, 2, 6]. Unloading causes elastic and then viscoplastic relaxation of the ρ-regions. The relaxation time of the latter is calculated in [5] and is close to that found in the experiments of [2].

Model of Incomplete Shear in an Atomic Medium. A more through analysis of the effect of interaction of the cut edges requires allowance for the periodic character of interatomic forces for monolithic solids. If the difference between the complete relative displacements of the opposite edges of the cut near the neighboring parts L_1 and L_2 of the cut line has the form

$$\Delta u = (u^+ - u^-)_{L_1} - (u^+ - u^-)_{L_2} \geqslant a \tag{17}$$

(a is the crystal-lattice parameters on the cut line), an atomic nonius forms such that $(N-1)$ atoms at the lower edge of the cut are placed opposite N atoms at the upper edge in Fig. 3a. The tangential stresses caused by the interatomic interaction of the edges and applied to each of the edges on the left and on the right of the nonius are in opposite directions so as to decrease displacements on the right-hand side and increase displacements on the left-hand side (Fig. 3b). Because of this, the change in displacements becomes localized, and local regions in which the change in displacements is faster as compared with the neighboring regions appear in the curves of $u^+(x)$ and $u^-(x)$ (Fig. 3c). Since ρ-regions are connected with those parts of the cut line in which the displacements vary, local ρ-regions are formed near nonii. If $\Delta u = na$, then n small ρ-regions form in place of one large ρ-region. If there is only one dislocation in the body (not two as in the case of a cut in the model adopted here), then after unloading and reverse displacement of the cut edges the curves of $u^+(x)$ and $u^-(x)$ will take a symmetric form that corresponds to (1) (Fig. 3d).

To model the displacement u_d^+ of the nonius under external stress, it is assumed that

$$u_d^+ = u_1^+ - u_2^+, \tag{18}$$

where $u_{1,2}^+$ are displacements of the form of (9) for $l_1 = l$, $\tau_1 = k_3\tau$ and $l_2 = k_1 l$, $\tau_2 = k_2 k_3 \tau$, respectively. The

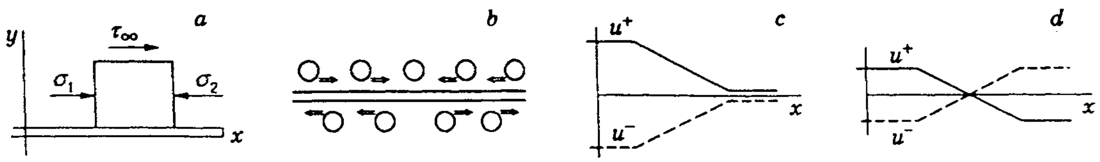

Fig. 3

coefficient k_1 is chosen so that u_d^+ have a form similar to that in Fig. 3c. The coefficient k_2 is found from the condition

$$u_d^+(0) = u_1^+(k_1 l) \tag{19}$$

and k_3 from the condition

$$\Delta m_d = \Delta m. \tag{20}$$

For the chosen $k_1 = 0.9$, the dependence u_d^+ is shown in Fig. 1 (curve 2). Then

$$P_d(x,y) = P_1(l_1, \tau_1; x, y) - P_2(l_2, \tau_2; x, y). \tag{21}$$

To model the displacements u_{rd}^+ near a nonius with out external field (Fig. 3d), it is assumed that

$$u_{rd}^+ = u_{d1}^+ - u_{d2}^+. \tag{22}$$

Here $u_{d1}^+ = 0.5u_d^+(x)$ describes displacements of the cut edge on the left of the nonius ($x < l$), and $u_{d2}^+ = 0.5u_d^+(2 - x)$ displacements on the right-hand side of the nonius ($x > l$). Thus, u_{rd}^+ is obtained as a result of two cuts: the first in the region $(-l, l)$ and the second in the region $(l, 3l)$, the edges being equal in magnitude and opposite in direction. The coefficient 0.5 in the formulas for u_{d1}^+ and u_{d2}^+ shows that, with equality of the length of each cut to the length of displacements u_d^+ in (9), (10), and (22), the stresses τ_1 and τ_2 and Δm decrease by a factor of 2 for each of the cuts. However, since the edges move toward each other, the excessive or deficient mass in the dilatation fields of these displacements is summed up. As a result, we have

$$\Delta m_{rd} = \Delta m_d = \Delta m. \tag{23}$$

The dependence $u_{rd}^+(x)$ is shown in Fig. 1 (curve 3). Figure 2b shows the regions in which the values of relative dilatation are greater than those in Fig. 2a.

Figure 4 shows the relative-dilatation distribution $D = \Delta V/V$ [in units $(1 - 2\nu)\tau/(2\mu)$] for the three models (curve 1 in Fig. 4 for displacements (9), curve 2 for an atomic nonius under external tangential stress, and curve 3 for an atomic nonius without no external stress) along the lines $y = 0.04l$, $0.4l$, and $4l$ (a–c) and also Fig. 2 show that as a nonius forms the ρ-region near the cut line narrows. If there is no external field, the maximum of dilatation at all three levels is located above the nonius. Under the action of a shear field, u_{rd}^+ is transformed into u_d^+. With distance from the cut, the maxima of the regions located on the same side of the cut line move in opposite directions and at $y = 4l$, they practically coincide with the maxima of the displacements by (9). Thus, although the external shear stress does not create a dilatation field, it causes larger displacements of the edges than the displacements along the plane of shear beyond the cut. The displacements of the regions adjacent to the edges are also larger than the displacements of the surrounding material. Because of this, the stress and dilatation fields change. For this reason, the edge-dislocation field under external shear stresses is modeled in the case of displacements u_d^+. In addition, the field of a moving dislocation is also modeled when, according to (13), $\tau_\infty > [\tau]$. Velocities of the dislocation motion are assumed to be small so that dynamic effects can be ignored.

It is assumed in dislocation theory [7] that the external load does not alter the dislocation-stress field, as follows from the Colonetti theorem. In actual fact, the external load disturbs the symmetric distribution of displacements about the plane passing through the atomic extraplane. The source of internal stresses is therefore altered. In this case, it would be incorrect to apply the Colonetti theorem.

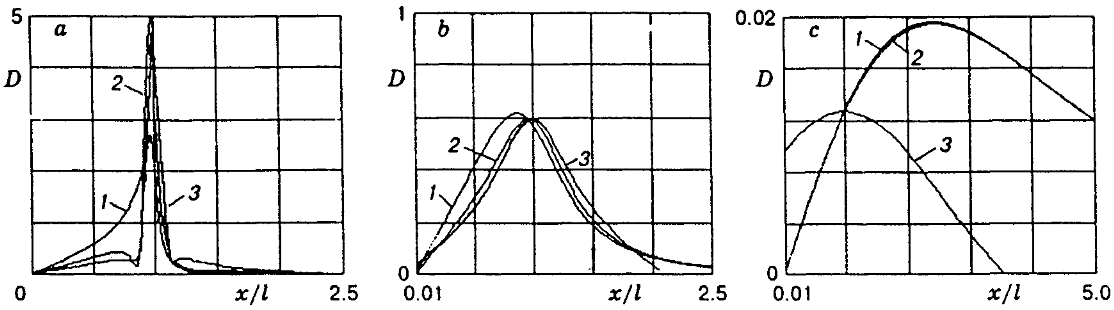

Fig. 4

The conclusion about the formation of ρ-regions under nonuniform distribution of shear displacements over the friction surfaces is close to the hypothesis of Gittus [11], according to which specific Somigliana dislocations form and move over the friction surfaces. Gittus [11] called these dislocations interfaceons. Such defects can be obtained by applying the Somigliana procedure, provided that two conditions are satisfied: displacement of the edges does not disturb the correspondence between shapes of the edges, and gluing of the edges does not prevent reverse shear displacements of the edges under unloading. The concepts developed here make it possible to explain not only the data in [1–6] but also the motion of the material in a boundary layer under friction [12, 13], strong distortions of the silver crystal lattice on the shear surfaces with a relaxation time of 15 sec [14], and the occurrence of high-pressure phases under shear deformation. For example, Tolochko et al. [15] found a Sn-III phase on the shear surfaces in tin. The phase is stable under pressures higher than 9.5 GPa, and disappears in 0.5 sec after shearing. Neverov and Chernov [16] obtained a Si-III phase by shearing thin silicon layers under a pressure of 1 GPa. This phase is known to form under pressures higher than 6.5 GPa.

In this work, incomplete-shear models are used to consider mass transfer under shear plastic deformation and under friction. The state resulting from unloading of the current state is used as a reference point for displacements of the points on the surface of those parts of the body that are separated by the plane of shear. This technique allows one: 1) to exclude from analysis continuous displacements along the plane of shear (complete displacements) by taking into account their effect on body-shape variation and, hence, on the variation of the boundary conditions; 2) to analyze, using the concepts developed, any current state formed in the course of shear plastic deformation or during slippage under friction.

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