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FORMATION OF PERIODIC MESOBAND STRUCTURES IN THE TENSION OF POLYCRYSTALS WITH LONG BOUNDARIES

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A study is made of how the mechanism of plastic deformation of polycrystalline low-carbon steel is affected by large-scale interface in the form of long localized regions of remelted material extending in the transverse direction. It is shown theoretically and experimentally that oscillating stress mesoconcentrators develop in the neighborhood of such interfaces and that relaxation of these concentrators results in the formation of periodic mesoband structures in deformable polycrystals.

Introduction. The periodic character of the spatial distribution of the elements of dissipative structures in solids is one of the basic phenomena associated with formation of the structure of those solids during plastic deformation. In accordance with the postulates of the physical mesomechanics of materials, plastic deformation is essentially a relaxation process in which flows of strain-induced defects are formed and, in the presence of a nonuniform stress state, propagate only within local regions around stress concentrators [1]. It follows that precisely the spatial ordering of the stress concentrators causes the formation of periodic defect structures during the plastic flow of crystalline solids.

Grinyaev and Panin [2] showed theoretically that the contact stresses at the grain boundaries of an elastically loaded polycrystal are of an oscillating nature owing to the rigid joining of crystallites with different elastic moduli along the common boundaries. This finding made it possible [3] to link the oscillations with the discrete character of slip processes at the interfaces and to determine that stress concentrators initiate plastic shear. As regards the individual structural elements of the polycrystal, the discrete nature of the slip lines can be attributed to oscillations of the elastic stresses at the boundaries of the grains undergoing deformation. The crystalline lattice becomes unstable against shear in local regions around the concentrators, and flows of dislocations are formed and move in certain crystallographic directions.

In accordance with the principle of scale invariance in a solid undergoing deformation [1], the defect structures should also exhibit periodicity at higher (mesoscopic) structural levels of deformation. To observe this effect, it is necessary to determine the conditions under which oscillating stress mesoconcentrators are formed in the specimen and relaxational flows of strain-induced mesoscopic defects are formed and propagate in the neighborhood of those concentrators.

It is very difficult to study this problem on the basis of the standard mechanical tests, since plastic flow develops simultaneously at all scale levels in a specimen undergoing deformation. The stress mesoconcentrators must be introduced into the specimen at the beginning of the test, so that they can play the determining role in the development of plastic deformation. The mesoconcentrators can be introduced by forming long artificial interfaces into the specimen being deformed.

In this investigation, large-scale interfaces in polycrystalline specimens were modeled by a lengthy narrow region of remelted material extending across the specimen. The region was formed by exposing the specimen to a high-energy arc discharge. The resulting state of the material is characterized by a distinct

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gradation of the structure involving the formation of "basic metal–heat-affected zone (HAZ)–remelted zone" regions. The loading of such specimens by an external mechanical field should lead to the creation of oscillating contact stresses of a high scale level at the boundaries of the differently deformed zones. The subsequent relaxation of these stresses results in the formation of periodic mesoscopic band structures in the regions of the metal adjacent to the interfaces.

Material and Method of Investigation. The formation and evolution of mesoscopic band structures on the surface of metallic specimens with the dimensions of 75 × 5 × 1 mm were studied by subjecting the polycrystals to static tension at the rate 2–4 mm/h at a temperature of 293 K. Long regions of remelted material with a width of about 2.5 mm were formed perpendicular to the specimen axis in polycrystals of low-carbon steel St. 10. The average grain size in the steel was 15 μm. The specimen surface to be analyzed was mechanically polished beforehand. An optical-television measurement system [4] was used to record and analyze images of the surface and study the evolution of the mesosubstructure of the polycrystals during deformation. The results obtained by using special programs to analyze two successive images were used to construct the field of the displacement vectors of mesovolumes of the specimens and calculate the distribution of the local components of the plastic strain tensor: the longitudinal component ε_{xx}, the shear component ε_{xy}, and the rotational component ω_z.

Results and Discussion. In studying the behavior of a loaded solid at a mesoscale level (complex ensembles of defects), it is necessary to consider the energy of the cores of the defects. In a continuum description, this energy is represented as a system of interacting elementary excitations. This system can in turn be replaced by a physically adequate field of defects characterized by two quantities: the tensor of the density of defects α and the tensor of defect field density j. The gage theory makes it possible to obtain dynamic field equations in these quantities [5–7]. We shall examine an equation that allows us to qualitatively analyze the defect density function α under static conditions:

$$S_1 \nabla \times \alpha = -\sigma_1 - \sigma_2 + \gamma k T \delta, \tag{1}$$

where S_1 is a constant of the theory and corresponds to the linear energy of a defect, σ_1 are the material stresses due to the defects, σ_2 is the stresses from external forces, which we set equal to zero, k and γ are the compressive bulk modulus and the coefficient of thermal expansion, respectively, and T is an absolute temperature. The stresses σ_1 can be expressed through the tensor of the flux density of a pulse with the opposite sign:

$$\sigma_1 = S_1(\alpha.\alpha - \alpha^2 \delta/2). \tag{2}$$

As in relation (1), in relation (2) the letter δ represents a unit tensor, and $\alpha.\alpha$ denotes that scalar convolution is performed over the second indices. Substitution of (2) into (1) gives

$$\nabla \times \alpha = (\alpha^2 \delta/2 - \alpha.\alpha) + \gamma k T \delta. \tag{3}$$

We assume that the material contains one system of defects (such as α_{zx}) that depends only on the coordinate y. In this case, the line of each defect is directed along z, while the discontinuity of the displacements is directed along x. We find from Eq. (3) that

$$-\frac{\partial \alpha_{zx}}{\partial y} = \frac{\alpha_{zx}^2}{2} + \frac{\gamma k T}{S_1}. \tag{4}$$

Equation (4) has the solution $1/\alpha_{zx} = y/2$ for $T = 0$. Figure 1a shows the defect density function α_{zx} along the y axis in this case. It is clear that the material has a boundary for $y = 0$ on different sides of which the defects have opposite displacement discontinuities, and the defects are localized near the boundary.

For $T \neq 0$, the solution of the equation changes considerably and takes the form

$$-\alpha_{zx} = (2\gamma k T/S_1)^{1/2} \tan[(\gamma k T/2S_1)^{1/2} y]. \tag{5}$$

The distribution of α_{zx} along the y axis is shown in Fig. 1b. In this case, the material along the y axis is

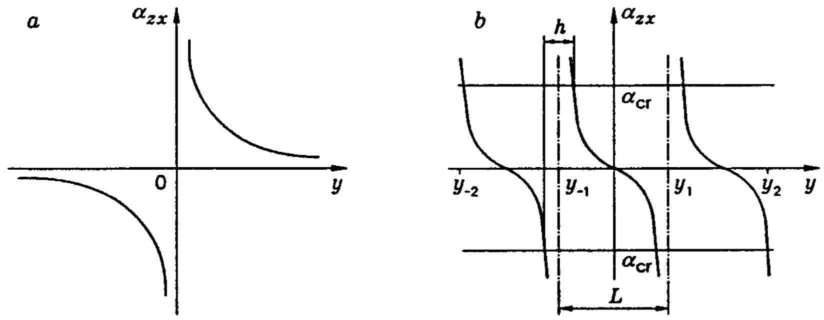

Fig. 1. Distribution of the defect density α_{zx} along the y axis at $T = 0$ (a) and $T \neq 0$ (b).

divided into regions whose dimension L is determined as

$$L = \pi(2S_1/\gamma kT)^{1/2}. \quad (6)$$

It is apparent from Eq. (6) that an increase in temperature is accompanied by a decrease in the size of the regions, but an increase in the absolute value of α_{zx} inside the regions because of the presence of the multiplier $(2\gamma kT/S_1)^{1/2}$ in Eq. (5). The boundaries of the regions

$$y(\gamma kT/2S_1)^{1/2} = \pi/2 \pm n\pi \qquad (n = 0, \pm 1, \pm 2, \ldots)$$

are similar to slipbands [8], since the defects have opposite displacement discontinuities on different sides of the boundary. If we assume that the defect density α_{zx} cannot exceed a certain critical value α_{cr}, it becomes possible to qualitatively analyze the width of the boundary (mesoband) h:

$$h = 2(2S_1/\gamma kT)^{1/2} \arctan[(2S_1/\gamma kT)^{1/2}\alpha_{cr}]$$

or

$$h = (2L/\pi)\arctan(L\alpha_{cr}/\pi). \quad (7)$$

Thus, the width of the slipbands h is related to the size of the regions L between them. When $L\alpha_{cr}/\pi > 1$, Eq. (7) can be approximately represented in the form

$$h = (2L/\pi)[\pi/2 - \pi/(L\alpha_{cr}) + \pi^3/(3L^3\alpha_{cr}^3) - \ldots],$$

while when $(L\alpha_{cr}/\pi)^2 < 1$ we obtain $h = 2L/\pi[L\alpha_{cr}/\pi - L^3\alpha_{cr}^3/3 + \ldots]$.

The results presented above show that the elements of the mesoscopic defect structures in a loaded solid undergoing plastic flow can periodically be spatially redistributed.

The results of experimental studies performed on polycrystals with large-scale interfaces agree with the conclusions of the theoretical model. The long region of remelted material that forms across a polycrystalline specimen under load is a severe stress concentrator in the shape of a band. The concentrator itself forms a nonuniform stress state in the specimen and accounts for the development of highly nonuniform plastic strain at the mesolevel. At the beginning of macroscopic deformation (with elongation of the specimen $\varepsilon = 0.01$–0.02), a localized plastic flow develops in the HAZ in the form of a wave of localized plastic deformation before plastic flow even begins in the base metal. The wave is characterized by oscillation of the shear strains ε_{xy} and by rotations ω_z that occur perpendicular to the specimen axis and in synchrony with the shears (Fig. 2). These findings are qualitatively similar to the theoretical results (see Fig. 1b). The character of the wave can be attributed to the fact that each local shear and the coupled rotation, initiated by the stress mesoconcentrator on one side of the HAZ, create an opposing stress mesoconcentrator on the other side of the HAZ (in mechanics, the stresses associated with this concentrator are referred to as image forces). The newly created concentrator is relaxed by the shear strain ε_{xy} and rotation ω_z of the opposite sign. Such relaxation requires satisfaction of the law of conservation of angular momentum. In accordance with the latter, the sum of the rotors of all

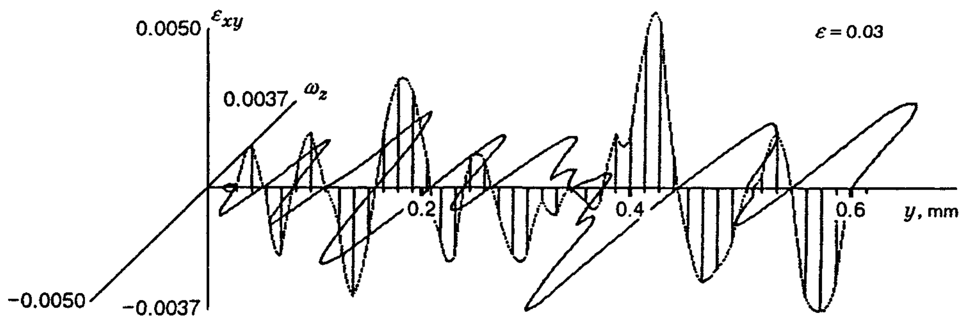

Fig. 2. Distribution of the components of shear ε_{xy} and rotation ω_z in the heat-affected zone along the y axis (perpendicular to the specimen).

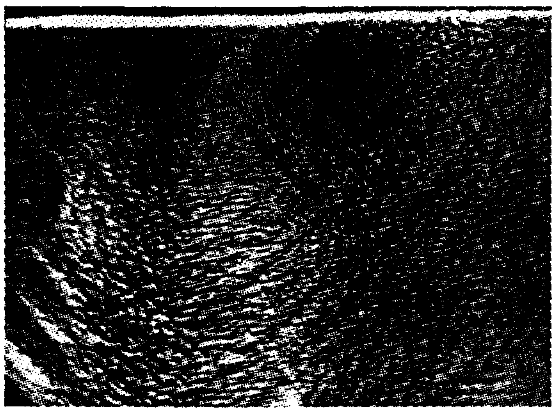

Fig. 3

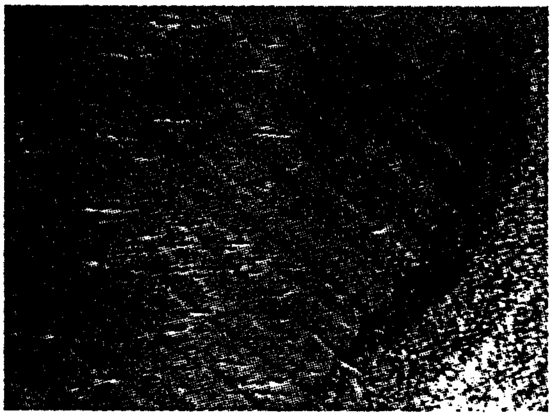

Fig. 4

Fig. 3. Reflection and growth of mesobands from interfaces in the heat-affected zone.

Fig. 4. Nucleation of regular mesobands over a long "heat-affected zone–basic metal" interface and their growth in the basic-metal region.

of the flows of strain-induced defects in the continuity conditions must be equal to zero [1].

Thus, the wave propagation in the HAZ is related to the creation of a series of oscillating stress mesoconcentrators at the boundaries of the HAZ. Their relaxation occurs by the propagation of mesobands on both sides of the interfaces. In the heat-affected zone of the width Δt_1, reflection of the mesobands from the opposing interface (Fig. 3) results in the propagation of a wave of localized plastic strain having the length λ_1. Relaxation of the stress mesoconcentrators in the base metal of the specimen occurs by the propagation of the mesobands depicted in Fig. 4 (magnification of 40, $\varepsilon = 0.03$). The mesobands create image forces on the lateral surfaces of the specimen, and these forces in turn form the conjugate mesobands shown in Fig. 5 (magnification of 110, $\varepsilon = 0.04$). As a result, oscillating mesobands also propagate along the specimen, forming a periodic mesoband structure. The period of this structure, λ_2, is determined by the width of the specimen Δt_2. Since $\Delta t_2 > \Delta t_1$, we have $\lambda_2 > \lambda_1$.

In essence, the oscillating mesobands that propagate through the specimen are the analog of Luders lines. However, in contrast to conventional Luders lines, each band-like mesostructure is formed and grows during the strain-hardening stage, which is associated with the intensive development of localized plastic strain in the HAZ, rather than on the flow site. One feature that mesobands have in common with conventional Luders lines is their connection with stress mesoconcentrators. The mesobands are in fact the primary sources

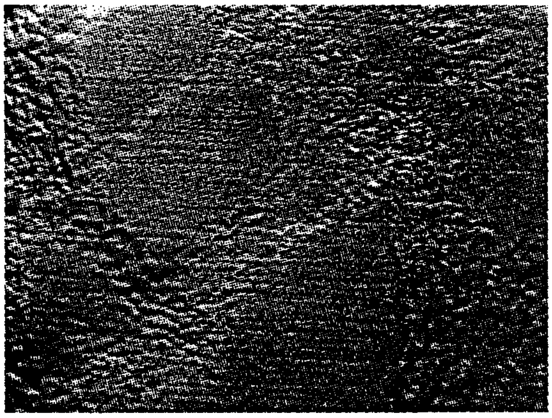

Fig. 5

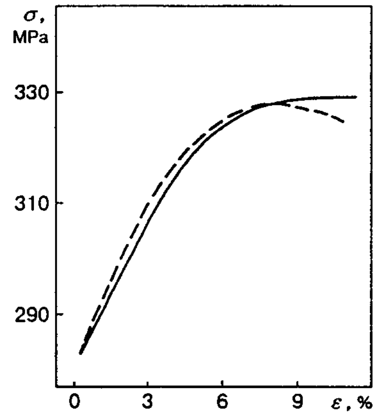

Fig. 6

Fig. 5. Formation of conjugate mesobands in the basic-metal region.

Fig. 6. Dependence of the flow stress σ on plastic strain ε for polycrystals with long interfaces (the dashed curve) and without such interfaces (the solid curve).

of the elastic energy that must be continuously supplied to Luders lines, whose propagation is particularly relaxational in character.

The localized-strain mesobands have certain orientation parameters: the direction of their propagation is independent of the crystallographic orientation of the individual grains of the polycrystal and coincides with the direction of the maximum shear stresses $\tau_{\max}$ (a 45° angle to the axis of the applied load). We recall that the microbands observed by means of a transmission electron microscope in the rolling of cubic body-centered [9] and face-centered [10] crystals were also oriented in conjugate directions of maximum shear stresses. This result is consistent with the results of theoretical studies of a multilevel model of the plasticity of structurally nonuniform media. Those results indicate that slipbands form from the interfaces of fragments [11], and they suggest that the given phenomenon is a feature common to all similar bands.

To explore the kinetic aspects of the mechanism responsible for relaxation of the oscillating elastic stresses at the interfaces, we constructed and analyzed the fields of vectors which characterize the displacements of mesovolumes at different stages in the formation of a periodic band-like mesosubstructure (see Fig. 4). The resulting data indicates that stress mesoconcentrators from the oscillating row successively become involved in the relaxation process. This is manifested experimentally in the sequential discrete character of the formation and evolution of bands of localized plastic strain from the boundaries into the basic metal of the specimen as the degree of deformation increases.

The formation of band-like mesoscopic structures in specimens with large interfaces is an additional channel for the dissipation of elastic energy in loaded polycrystals. An analysis of the displacement field vectors at the stage where the mesoband structure has already been formed shows that the blocks of the mesostructure move as a whole in accordance with the "shear + rotation" scheme. This results in a decrease in the strain-hardening factor $\theta = d\sigma/d\varepsilon$ during the final stage of plastic flow of the specimens $\varepsilon > 0.03$ (the dashed curve in Fig. 6), before necking of the specimen (fracture occurs in the basic-metal region rather than the HAZ due to misorientation of the blocks of the mesosubstructure).

Conclusion. An analysis of the above results confirms that the interfaces in a loaded solid are sources of oscillating contact stresses at all scale levels. Relaxation of these stresses leads to the formation of periodic band-like structures of the corresponding scale: crystallographic slip lines, microbands in which the regions of the crystalline lattice have been reoriented, slipbands, and mesoscopic bands of localized plastic deformation. The formation of band-like mesoscopic structures is an additional channel for dissipation of the elastic energy in a loaded solid. The elements of the band-like mesosubstructures (the bands of localized plastic strain) are nucleated at the interfaces in the vicinity of the stress mesoconcentrators and are of the nature of Luders lines. Their orientation is noncrystallographic in character and is determined by the directions of the maximum shear stresses. These factors illustrate the determining role of interfaces in the mechanisms of deformation of solids.

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