Mesoscopic surface folding in EK-181 steel polycrystals under uniaxial tension

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The work is experimental and theoretical study of folded structures formed on free surfaces of polycrystalline materials under uniaxial tension. General mechanisms by which the folded deformation relief develops are demonstrated with the example of EK-181 steel. Numerical simulation shows that the polycrystalline structure of the material can be a condition responsible for local curvature of its initially flat surface and hence for periodic distribution of normal tensile and compressive stresses.

Keywords: deformation relief, numerical simulation, three-dimensional models, stress-strain state, EK-181 steel

DOI: 10.1134/S1029959912010109

1. Introduction

Analysis of the deformation relief arising on the surface of solids under loading gives significant information on the basic regularities and mechanisms of their plastic deformation. In single-crystal materials, the deformation relief appears, as a rule, as numerous slip traces due to displacement of one part of a crystal relative to the other along certain crystallographic planes [1]. In polycrystals, the surface morphology changes due to different strain values of surface grains in a direction normal to free surfaces [2–6]. This shows up as individual rotation of surface grains or their collective deformation, resulting in various band or folded structures. According to [2], surface grains with cubic texture, being "softer" due to high crystallographic symmetry and low Taylor factor, are elongated and sank in under tension, forming dimples on free surfaces. At the same time, "stronger" grains (highest anisotropy and maximum Taylor factor is characteristic of grains with $\{110\}\langle 001\rangle$ edge texture) are extruded in a direction perpendicular to free surfaces. In general, the formation of a deformation relief in polycrystals is a rather intricate process and depends largely on the size of grains, state of grain boundaries, texture of material, loading conditions, etc.

At present, there is no general consensus about the influence of folded surface structures on deformation in the material bulk. On the one hand, it is deemed that extruded surface grains are less sensitive to deformation incompatibility during the interaction with adjacent grains and, hence, are less deformed than the material bulk (i.e., surface grains have a smaller number of active slip systems) [6]. On the other hand, the authors of [7, 8] are of the opinion that a surface layer features increased defect density and, hence, can be a barrier for egress of dislocations emitted by internal sources to the surface. According to the assumption made in [9], the apexes of surface folds are sites at which powerful stress microconcentrators arise due to severe lattice curvature; under loading, these microconcentrators generate dislocations that move along slip planes into the material bulk, thus providing its plastic flow.

The main regularities of surface folding under loading in commercially pure titanium, zirconium alloys and low-carbon and high-strength steels are described in detail in [10–13]. In different materials and various loading conditions, the folded relief can appear as ridges, double and single spirals, and periodic distribution of extrusion and intrusion regions (Fig. 1). Experiments show that despite

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the great variety of shapes and patterns of development, all deformation reliefs have common features: relief folds are independent of crystallographic orientation of grains, evolve over the entire surface of a deformed solid, and have no apparent correlation with microscopic structure of material.

By now, the mechanisms and factors responsible for the emergence and evolution of folded structures on the surface of loaded materials are still a point open to question. Evidently, the formation of periodic deformation folds covering abundant surface grains goes beyond traditional approaches of dislocation theory. Macromechanics, which treats of homogeneous isotropic media, also fails to explain the formation of folded structures on initially flat free surfaces of specimens under uniaxial tension. It is obvious that the origination of specific nonlinear modes of localized deformation and their associated shear and rotation of individual fragments, collective motion of grain conglomerates, etc. reflects a multiscale character of plastic deformation of solids. Correct description of this multiscale process requires combined approaches of physical mesomechanics and nonequilibrium thermodynamics [14].

For fairness, it should be noted that experimental studies often provide only indirect information on consistent evolution of the stress-strain state on the surface and in the volume of materials. Besides, the processes occurring in real systems depend on a whole complex of factors, and their individual contribution is rather hard and at times impossible to distinguish. In this context, a valuable tool of research, in addition to experimental techniques, is mathematical simulation. Solving mechanical problems of structured media in the three-dimensional statement makes it possible to explicitly study the formation mechanisms of surface folds and to trace the interrelation of deformation processes on the surface and in the volume of model materials.

The present work is experimental and theoretical study of the formation and evolution of a mesoscopic deformation relief on a free surface of polycrystals under uniaxial loading. The material chosen for experimental research is EK-181 high-chromium ferritic-martensitic steel [15] that reveals clearly defined patterns of surface folding under loading. The microstructure and phase composition of EK-181 steel, preparation of specimens, and loading conditions are described in detail in [12, 16].

2. Experimental study of the evolution of folded structures on the surface of EK-181 steel under uniaxial tension

Examination with scanning tunnel microscopy, atomic force microscopy and scanning electron microscopy demonstrates that under loading, the surface of EK-181 ferritic-martensitic steel reveals folds of various shapes, size and orientation [12, 17]. Figure 2 shows images and profilograms of the specimen surface at different stages of uniaxial tension. At low degrees of plastic strain ($\varepsilon = 0.5$ %), the folds are mainly oriented perpendicular to the loading axis; however, they can also intersect creating an interlacement effect (Fig. 2(*a*)). The lateral dimension of the folds is ~5 μm and their height is no greater than 20 nm (Fig. 2(*b*)). Note that early in the loading, folded structures are found only in local regions of the specimen surface.

Increasing the strain degree ($\varepsilon = 1.5$ %) gives rise to new much higher deformation folds on the surface (Figs. 2(*c–f*)). The folds are discontinuous as before: a small surface portion reveals several systems of folds of varying orientation and shape. So, straight, zigzag and interlacing folds can be distinguished in Fig. 2(*c*). Under further loading, the entire specimen surface is covered with interlacing folds much larger not only in height but in width as well (Fig. 3(*c*)). At the prefracture stage of the specimens, the lateral dimension of the folds increases to 10–20 μm and their height reaches several micrometers.

The diverse folded relief formed on the surface of the EK-181 steel specimens under loading owes to a complex stress-strain state induced by the material heterogeneity. Electron backscatter diffraction analysis shows that the grain

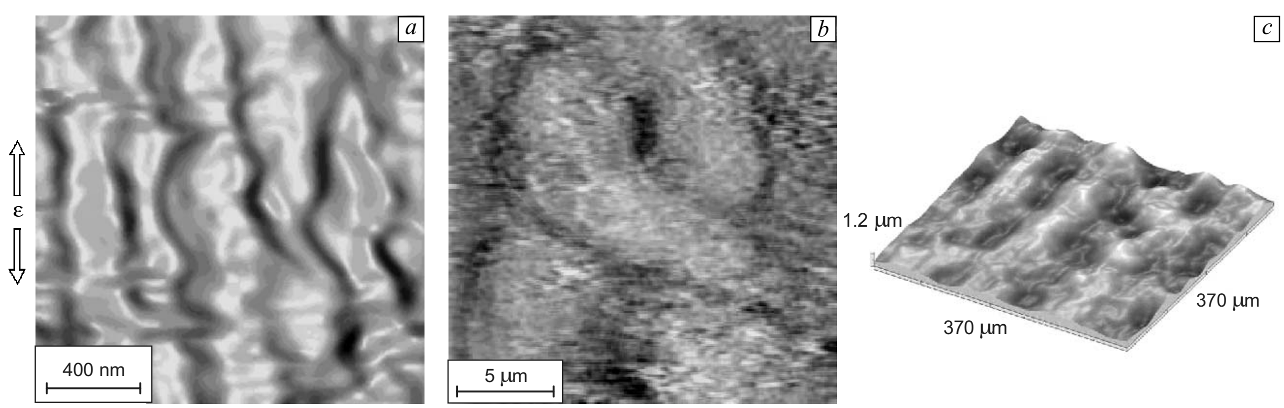

Fig. 1. Images of the surface of St3 low-carbon steel [10] (*a*), VT1-0 commercial titanium [11] (*b*), and E125 zirconium alloy [13] (*c*) in the rolled state (*a*, *b*) or subjected to preliminary ultrasonic impact treatment (*c*); tension, $\varepsilon = 2$ (*a*), 4 (*b*) and 20 % (*c*)

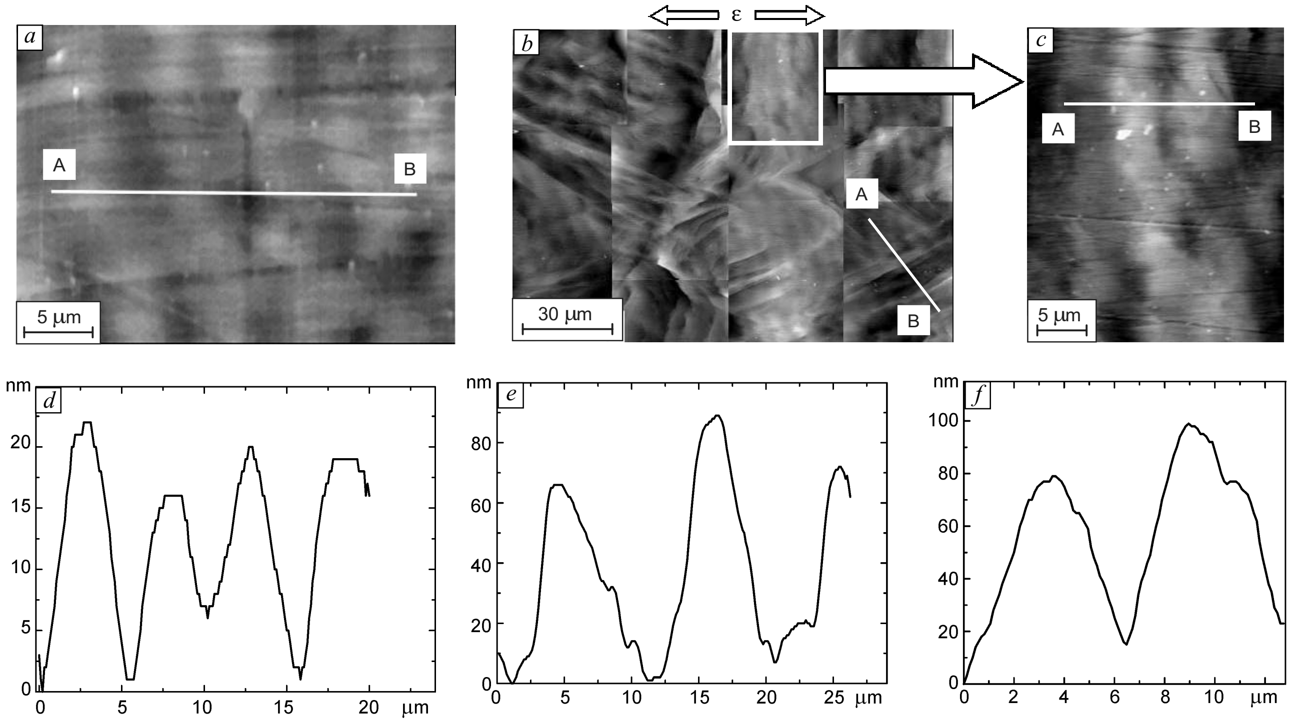

Fig. 2. Images (*a–c*) and profilograms *AB* (*d–f*) of the surface of the EK-181 steel specimens; tension, T = 20 °C, ε = 0.5 (*a*, *d*) and 1.5 % (*b*, *c*, *e*, *f*)

structure of EK-181 sheet steel (6 mm thick) resulting from rolling, quenching and subsequent ageing is very inhomogeneous in thickness (Fig. 4). The surface grains are elongated in the rolling direction, and their longitudinal and lateral dimensions are 50 and 10 µm, respectively (Fig. 4(*a*, *c*)). At a depth of 3 mm (at the plate middle), the equiaxial shape of grains survive and their size is no greater 5 µm. Note that quenching and ageing of EK-181 steel produces a fragmented packet martensite structure and grain-subgrain α-phase structure in the steel [16]. However, the electron backscatter diffraction method allows detection of only large ferrite grains and fails to detect the martensite structure.

There are several factors that can be responsible for the formation of the folded relief on the surface of the examined specimens. First, early in the loading of the EK-181 steel specimens, large surface grains characterized by lower yield strength experience plastic deformation, whereas finer grains in the volume are deformed elastically. Under unloading, this can cause folding of the plastically deformed surface layer at the expense of the elastically deformed specimen volume, with the folds being oriented perpendicular to the loading axis (Fig. 2(*a*)).

The heterogeneity of the material can also be the cause for the formation of deformation folds. If the surface layer and material volume have different textures and different elastoplastic characteristics (e.g., Poisson's ratio), the specimen volume under uniaxial tension is capable of compressing its surface layer in a direction perpendicular to the loading axis (Fig. 1(*a*)). The width of folds, as a rule, is limited to one or several grains, and only their height increases with increasing the strain degree. By and large, surface folds can assume any orientation due to the highly heterogeneous grain structure.

Finally, on the surface of the loaded specimen a ridge can be formed as intersecting or interlacing folds whose width and height increases steadily with an increase in strain degree. Notice that interlacement of folds is characteristic of the specimens deformed at room or increased tempera-

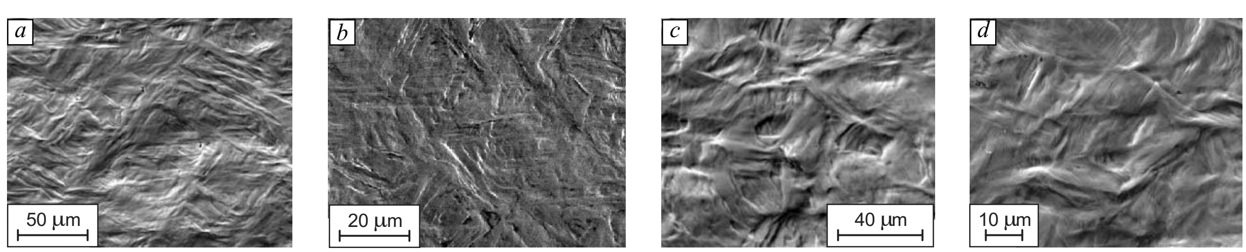

Fig. 3. Images of the surface of the EK-181 steel specimens; tension at T = –196 (*a*), –50 (*b*), 20 (*c*), and 250 °C (*d*), ε = 14 (*a*), 13 (*b*), 14 (*c*) and 15 % (*d*)

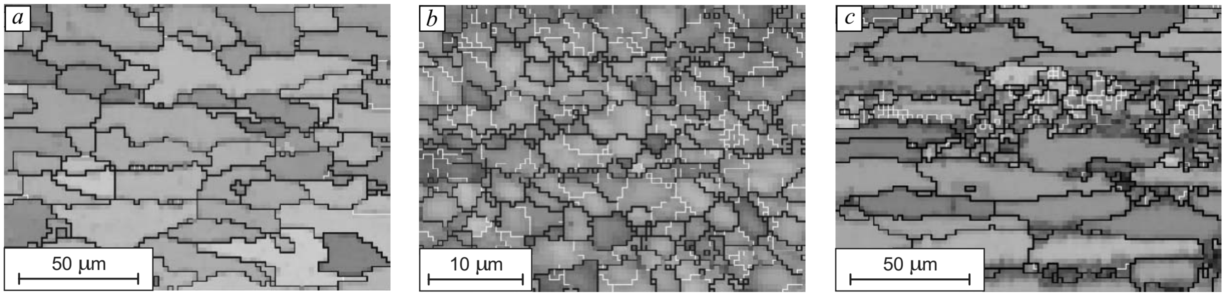

Fig. 4. Grain misorientation maps taken on the lateral face of a rolled sheet of EK-181 steel near the front (*a*) and back surfaces (*c*), and at the sheet centre (*b*)

tures (Fig. 3(*c*, *d*)). In tension at low temperatures, folds are normally rectangular and oriented at 45° to the loading axis (Fig. 3(*a*, *b*)). A condition for similar folding can be the propagation of localized shear bands in the specimen in the directions of maximum tangential stresses. It is the surface grains through which a shear band passes that rotate, being squeezed out or inward, and result in a fold. Note that rotation and elongation of grains is characteristic of adiabatic shear bands propagating in a material under shock loading [18].

The interlacement of folds at increased test temperatures can be governed by zigzag propagation of shear bands in surface layers of the EK-181 steel specimens. Earlier the authors of [19], based on electron microscopy study of ultrafine-grained copper, put forward the mechanism of discrete and quasiperiodic propagation of mesobands of localized deformation as evidence for wavy plastic flow of a deformed solid. It was shown that each period of localized shear comprises a translational mode (of relaxation nature) and rotational mode (a region of elastoplastic rotations with high lattice curvature and high local internal stress arises at the head of a mesoband). The stress concentrator arising at the mesoband head generates a new mesoband whish has noncrystallographic orientation and propagates in the direction of maximum tangential stress. To hold to the loaded specimen axis, the mesoband has to steadily change its direction of motion for a conjugate one.

According to [20], any shear in a deformed solid can propagate only as local structural transformation in a hydrostatic tension zone. The formation of hydrostatic tension zones in EK-181 steel under uniaxial tension can be due to the interface between surface and volume grains that experience stress and strain of differing degree. Local curvature gives rise to stresses normal to the loading axis at the interface between surface and volume grains [21]. As shown below, the normal stresses (σ_{22} and σ_{33}) vary steadily along the interface, assuming alternately positive and negative values and rendering the interface a “chessboard” pattern [22].

The difference in strains in a surface layer and material volume shows up most vividly in delamination of a 37CrNi3MoVN steel specimen on rolling [23]. It is seen in Fig. 5 that the delamination surface is corrugated being representative of periodic distribution of normal tensile and compressive stresses arising in the material under severe deformation.

It is reasonable to expect that intensive development of interlacing folds in response to propagation of shear bands in surface grains is bound to proceed in high-strength materials (in which microscale deformation is hindered). It was shown that intermediate ultrasonic treatment of EK-181 steel between quenching and ageing leads to refinement of ferrite surface grains and results in a nanocrystalline grain structure of the α-phase in martensite crystals [12]. Subsequent tension of the EK-181 steel specimens with a nanostructured surface layer greatly increases the width of spiral folds and, hence, the number of surface grains that simultaneously experience extrusion or intrusion. As can be seen in Fig. 6, the folds consist of abundant extruded grains and the fold width at the stage of developed plastic flow reaches 60 μm.

Ultrasonic treatment changes not only the hardness of a surface layer but its thickness as well. These two factors affect the width of deformation folds in the examined EK-181 steel specimens (Fig. 7). The preliminary deformation of surface grains provides more intensive extrusion of folds, while the thickness of the hardened layer determines the periodic distribution of normal tensile stress and, hence, the fold spacing. The size of extruded folds increases steadily with increasing the strain degree of the loaded specimen (Fig. 7(*b*)). Apparently, continuous work hardening of

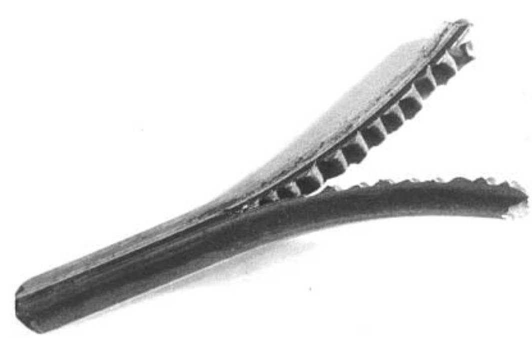

Fig. 5. Specimen of 37CrNi3MoVN steel failed on rolling [23]

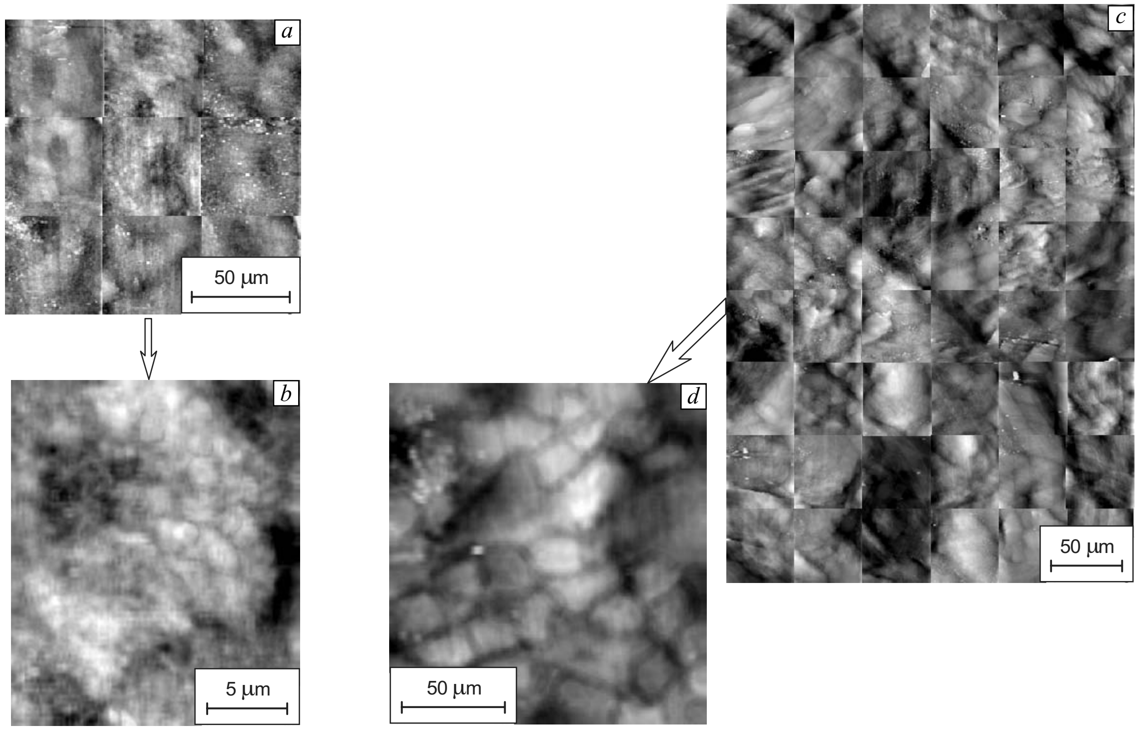

Fig. 6. Images of the surface of the EK-181 steel specimens subjected to ultrasonic treatment; tension: ε = 2 (*a*, *b*) and 8 % (*c*, *d*) [12]

the material speeds up the propagation of localized shear bands and thus governs the growth of deformation folds. Note that the linear dependence of the fold dimensions on the hardness of the hardened layer is observed both in uniaxial tension and in compression.

3. Simulation of the formation of a deformation relief on the surface of three-dimensional polycrystals

Mesoscale deformation in polycrystalline materials was simulated using the approach of mechanics of structured media that implies explicit account of the internal structure of material through the coordinate dependence of its physical and mechanical properties (density, yield strength, elastic moduli, etc.). For numerical realization of the approach, points corresponding to different structural elements in a discrete computational domain were assigned appropriate physical and mechanical properties. Discretization of the computational grid was such that interfaces coincided with nodes of the computational grid. With this discretization, equations of continuum mechanics [24] are applicable in the same way as they are applied to a homogeneous medium, except that constitutive relations and/or mechanical properties on different sides of the interfaces are different. The mathematical statement of a three-dimensional dynamic problem is described in detail in [24, 25].

In our numerical study we used model polycrystalline specimens whose mechanical characteristics matched those of high-strength steel. The procedure of generation of three-dimensional polycrystalline structures is reported at length in [21]. Calculations were performed for structures generated on grids of dimensions 300×100×300 (Fig. 8(*a*)) and 100×100×200 (Fig. 8(*b*)) with a step of 5 μm. The ave-

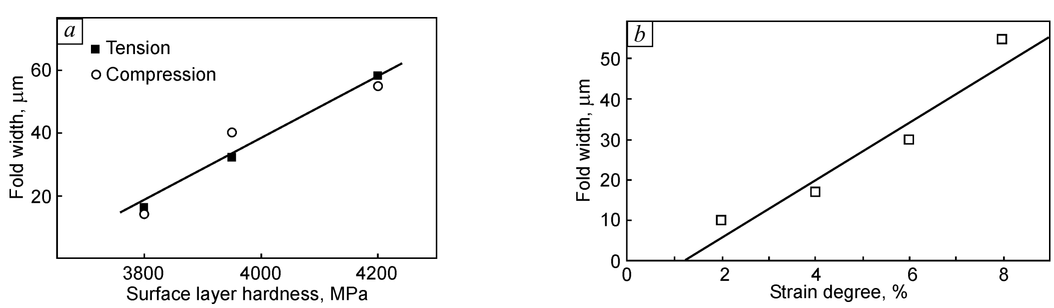

Fig. 7. Dependences of the width of relief folds on the surface of the ultrasonically treated EK-181 steel specimens on the hardened layer hardness (*a*) and strain degree (*b*) [12]

rage grain diameter in the specimens was 70 and 45 μm, respectively. The models of elastoplastic behavior of individual grains take into account grain boundary hardening and work hardening, and also a spread in crystallite elastic moduli within 5 %. Work hardening was allowed for through the dependence of yield stress on accumulated plastic strain. For the *i*-th grain, this dependence has the form:

$$\sigma_0' = \sigma_0^i - 96.3\exp\left(-\frac{\varepsilon_{\text{eq}}^{\text{p}} - 0.025}{0.07529}\right) \text{ [MPa]}, \qquad (1)$$

where σ_0' is the yield stress; $\varepsilon_{\text{eq}}^{\text{p}}$ is the accumulated plastic strain intensity. The value of $\varepsilon_{\text{eq}}^{\text{p}}$ for the *i*-th grain was determined according to the Hall–Petch law:

$$\sigma_0^i = \sigma_{\text{s}} + k_{\text{y}} \big/ \sqrt{D^i}, \qquad (2)$$

where $\sigma_{\text{s}} = 20$ MPa is the yield strength of a Fe single crystal; k_{y} is the grain boundary hardening coefficient; D^i is the diameter of the *i*-th grain.

The system of equations [21, 24, 25] with specified initial and boundary conditions, which determine the loading pattern, was solved numerically by the finite difference method [24] with the use of parallel algorithms.

Let us introduce a coordinate system X_i (i = 1–3) as shown in Fig. 8. Let L_1, L_2 and L_3 be the linear dimensions of the specimen along the corresponding directions. The boundary conditions simulative of tension along the axis X_1 are specified at the surfaces $x_1 = 0$ and $x_1 = L_1$ in the velocity form:

$$U_1\big|_{x_1=0} = -v, \quad U_1\big|_{x_1=L_1} = v, \qquad (3)$$

where x_i is spatial coordinates; $U_i = \dot{x}_i$ are the velocity vector components; and v is the grip velocity. In the directions X_3 and X_2 these surfaces are assigned the free surface conditions:

$$\sigma_{i2}n_2 = \sigma_{i3}n_3 = \sigma_{23} = 0 \qquad (4)$$

or the symmetry conditions:

$$U_2\big|_{x_1=0,L_1} = 0. \qquad (5)$$

Here σ_{ij} are the stress tensor components; n_i are the normal vector components; summation is over repeated indices.

The upper surface $x_2 = L_2$ is the main object of research and is considered to be free of external forces:

$$\sigma_{ij}n_j = 0. \qquad (6)$$

At the opposite surface $x_2 = 0$, the symmetry conditions in the direction X_2 are specified in the velocity form:

$$U_2\big|_{x_2=0} = 0. \qquad (7)$$

The boundary conditions at the lateral surfaces $x_3 = 0$ and $x_3 = L_3$ were varied to study their effect on deformation patterns at the free surface. In the first case, the surfaces were assigned zero displacements in a direction perpendicular to their planes, which modeled macroscale plane deformation; in the second case, the displacements in this direction were taken to be free (of external forces).

The numerical simulation shows that the initially flat free surface of the model polycrystals experiences morphological changes even at the elastic stage of loading. The effect of the grain structure on the formation of a deformation relief was studied through comparing a homogeneous isotropic material and a polycrystalline material loaded under the same conditions to the same strain degree. The surface of the homogeneous isotropic specimen (Fig. 9(*a*)) remains flat, which corresponds to macroscale conditions of uniaxial loading. In the polycrystalline specimen, groups of surface grains (grey grains on the magnified fragment, Fig. 8(*a*)) are involved in joint motion in a direction per-

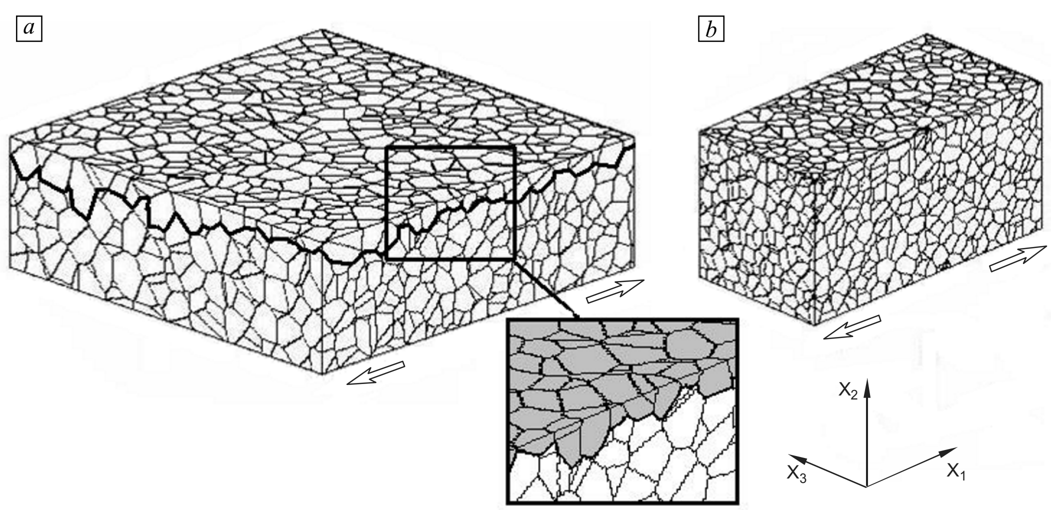

Fig. 8. Model polycrystalline structures generated on 300×100×300 (*a*) and 100×100×200 grids (*b*). Grey grains on the magnified fragment are grains that escape to the surface; a solid line is the interface between them and the underlying grain layer. The tension direction is marked by arrows

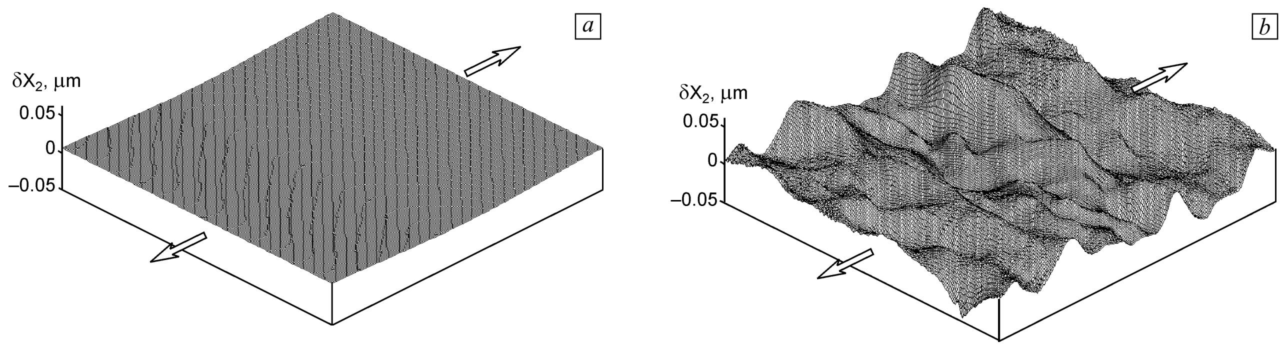

Fig. 9. Free surfaces of the homogeneous (*a*) and polycrystalline (*b*) specimens stretched to 0.22 %

pendicular to the surface planes (Fig. 9(*b*)). The relief folds are periodically distributed extrusion and intrusion regions with respect to the surface plane of the homogeneous specimen.

The orientation and shape of surface folds depend on the stress-strain state, in particular, on the boundary conditions at the lateral surfaces. Early in the plastic flow, the surface of the square specimen (Fig. 8(*a*)), whose lateral faces are free of external forces, reveals folds oriented at an angle of ~45° to the tension axis (Fig. 10(*a*, *b*)). Evidently this orientation angle of folds is related to the direction of maximum tangential stress. If the lateral faces are rigidly fixed, the free surface experiences macroscopic deflection against which the relief of smaller scale becomes hardly distinguishable (Fig. 11(*a*)). However on the relative scale with exclusion of macroscopic strain, the surface reveals clearly defined mesoscopic folds passing over the entire specimen surface perpendicular to the loading axis (Fig. 11(*b*)).

Like with the square plate, the surface of the rectangular bar (Fig. 8(*b*)) with free lateral faces reveals folds oriented in the directions of maximum macroscopic tangential stress. The folds pass throughout the specimen and their superposition results in a zigzag pattern of the folded relief (Fig. 12(*b*, *c*)). Thus, the simultaneous formation of folds of various shapes and orientations observed in the experiments can be explained by the inhomogeneous stress-strain state of the loaded specimen. The fact that adjacent regions of the material are actually under different loading conditions can be associated with their different locations in the specimen and with the presence of hardening phases, textures, liquation bands, etc.

The major contributor to the deformation relief is surface grains that escape to the surface (see the magnified fragment in Fig. 8(*a*)). In our models, the mechanical properties of surface grains were no different from those of the rest material; however, the egress to the free surface automatically provided these grains with much freedom in their

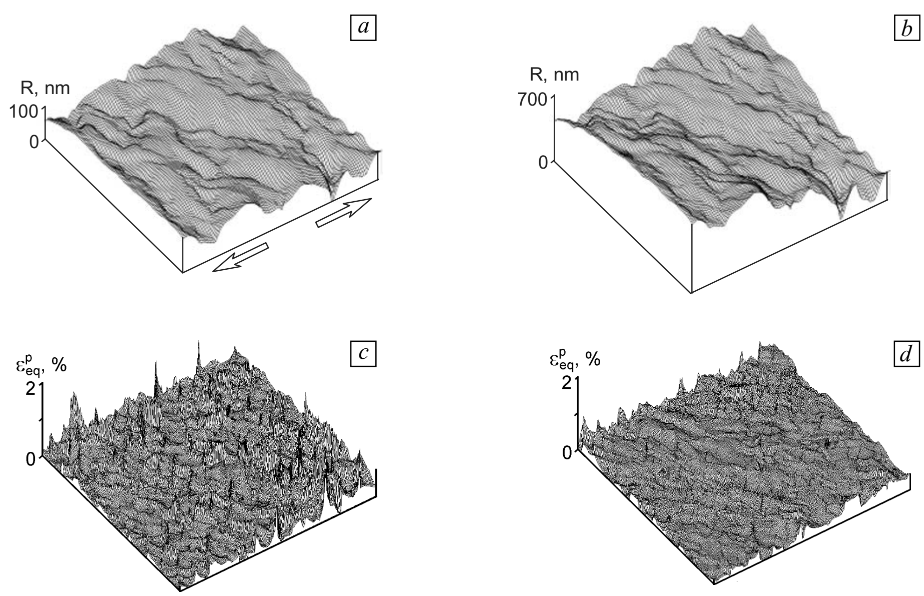

Fig. 10. Relief folds on the surface of the square polycrystal (*a*, *b*) and plastic strain intensity at the surface (*c*) and in the internal section (*d*); tension, ε = 0.2 (*a*) and 0.4 % (*b*–*d*). The lateral surfaces are free from external forces. The tension direction is marked by arrows

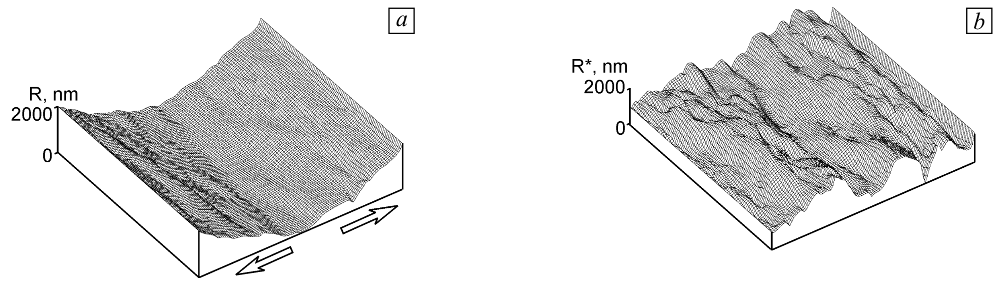

Fig. 11. Relief folds on the surface of the square polycrystal in absolute (*a*) and relative scales (*b*); ε = 0.4 %. The lateral surfaces are rigidly fixed in a direction perpendicular to tension

form change compared to crystallites in the volume. Thus, the grain boundaries between the crystallites escaping to the surface and the underlying layer can be treated as an extended interface between two materials differing in their response to external loading.

Comparison of plastic deformation patterns on the surface and in the volume of polycrystals shows that the maximum plastic strain intensity is reached on the free surface of the specimen (Fig. 10(*c*)). It is in the vicinity of triple grain junctions and grain boundaries escaping to the surface that the most favorable conditions for the origin of plastic shear are realized. This result agrees with the conclusions for polycrystalline aluminum alloys made in [21]. In the general case, the deformation relief does not match the plastic strain intensity distribution (Fig. 10). The highest level of plastic strain is found along grain boundaries, no matter what the loading conditions are. Moreover early in the loading, the plastic strain inside grains is absent or close to zero, i.e., a relief fold is formed through displacement of adjacent grains as a unit relative to each other in the direction of the free surface.

Numerical calculations confirm the experimental data according to which throughout the elastic stage and at the initial stage of plastic flow, only the height of folds increases and their width remains constant. For quantitative comparison of relief formations at different deformation stages, we introduce the roughness parameter [3]:

$$R_a = \frac{1}{L}\int_0^L |z(x)|\,dx, \tag{8}$$

where L is the length of a line along which a profile is taken; $z(x)$ is the height of the profile with respect to the minimum level at the point x. It is seen from Fig. 13 that the strain dependence of the roughness parameter has two linear portions. Initially, the increase in strain degree from 0.2 to 0.4 % causes the surface roughness (corresponding to the fold height) to increase several times. In further loading, the roughness increases by an order of magnitude due to intensive strain localization against which fine relief folds become hardly distinguishable (Fig. 12(*d*, *e*)). Comparison of the dependence of R_a with deformation relief patterns shows that the change of the slope on the curve at ε = 1.2 % corresponds to a qualitative change of the relief in the transition to the stage of developed plastic deformation.

Calculations for polycrystals with different elastoplastic characteristics demonstrate that in more plastic materials, the surface folds are smeared even at the initial stage of plastic deformation. In stronger materials, the stress level at grain boundaries is much higher which leads to displacements of surface grains relative to each other (Fig. 12(*b*, *c*)). In further loading, the surface relief is roughened and

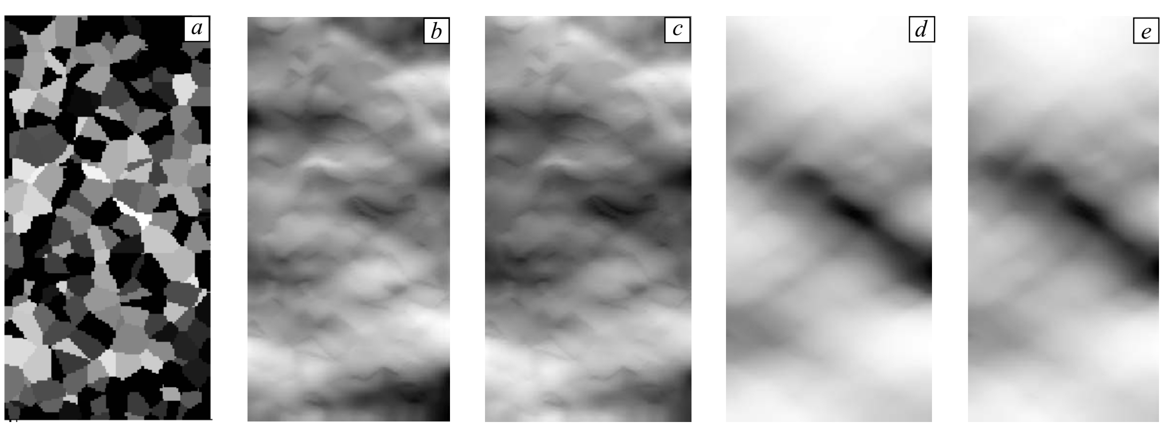

Fig. 12. Surface of the rectangular polycrystal: microstructure (*a*) and deformation relief at different strain degrees: ε = 0.01 (*b*), 0.1 (*c*), 1.1 (*d*) and 8.1 % (*e*). The lateral surfaces are free from external forces

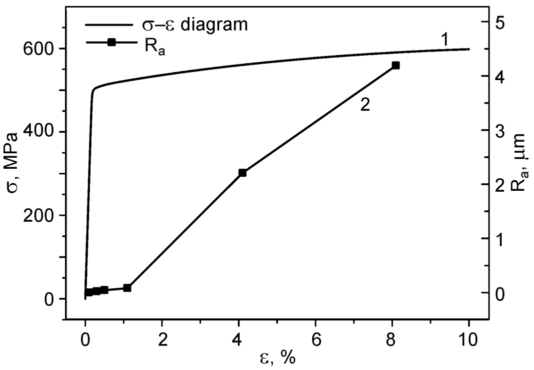

Fig. 13. Loading curve (*1*) and strain dependence of the surface roughness R_a of the model specimen (*2*)

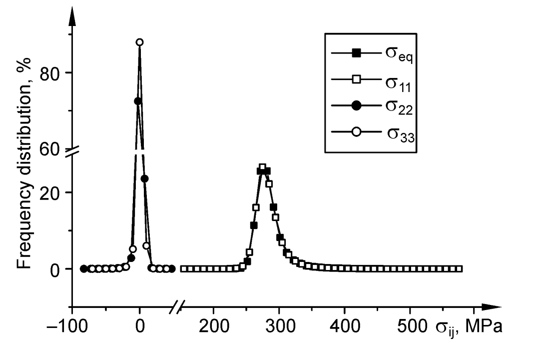

Fig. 14. Frequency distribution of the stress tensor components in the rectangular polycrystalline specimen in tension to ε = 0.1 %

finer folds against its background become hardly distinguishable (Fig. 12(*d*)).

4. Origin of normal tensile and compressive stresses in surface layers of loaded specimens

The internal heterogeneity of the material ensures that in its local regions all stress and strain tensor components assumes nonzero values. By way of illustration, Fig. 14 shows frequency distributions of the stress tensor components σ_{11}, σ_{22} and σ_{33}, and the stress intensity σ_{eq} in the rectangular model polycrystal stretched to 0.1 %. Clearly the largest contribution to the stress-strain state is made by the stress σ_{11} operative in the tension direction. The frequency distributions of the stresses σ_{22} and σ_{33} operative in a direction perpendicular to the tension axis display a symmetric spread about zero which, in total, provides the absence of macroscopic stress and hence ensures macroscopic equilibrium of the specimen.

On the surface of the loaded specimen, the deviation of the stresses σ_{22} and σ_{33} from zero is observed solely in local regions of the material along grain boundaries. However in a near-surface layer of the material (at a depth equal to half the average grain size), periodic alternation of extended narrow regions in which the normal stresses are either positive or negative is found (Fig. 14).

Interestingly, the regions of positive and negative stresses σ_{22} at the elastic loading stage are oriented in the main perpendicular to the loading axis (Fig. 15(*a*)). This pattern changes qualitatively at the stage of developed plastic flow: tensile and compressive stress regions are reoriented at an angle of ~45° to the tension axis and this corresponds to the deflection of areas of maximum tangential stresses (Fig. 15(*b*)). Similar conclusions hold true for the strain tensor components [21].

In terms of macroscopic equilibrium, the alternation of tension and compression regions in plastic flow is not a necessity and can disappear with increasing the strain degree, because plastic strain does not uniquely related to stress (does not produce stress). However, in materials with a high work hardening coefficient, the development of a deformation relief as periodic tension and compression regions is found at the stage of developed plastic flow as well.

5. Conclusion

In the work, we performed theoretical and experimental research in the mechanisms of nucleation and evolution of folded structures on the surface of model polycrystals and specimens of EK-181 ferritic-martensitic steel under uniaxial tension. It is found that in the material, the initially flat surface free of external forces experiences morphological changes beginning with the elastic loading stage. Whole groups of surface grains are involved in joint motion in a direction perpendicular to the surface planes, forming extended regions of extruded and intruded material. The relief folds on the surface can be formed at a varying angle to the tension axis depending on the material structure and loading conditions.

Different mechanisms were proposed for the formation of a folded relief on the surface of loaded polycrystals. It is

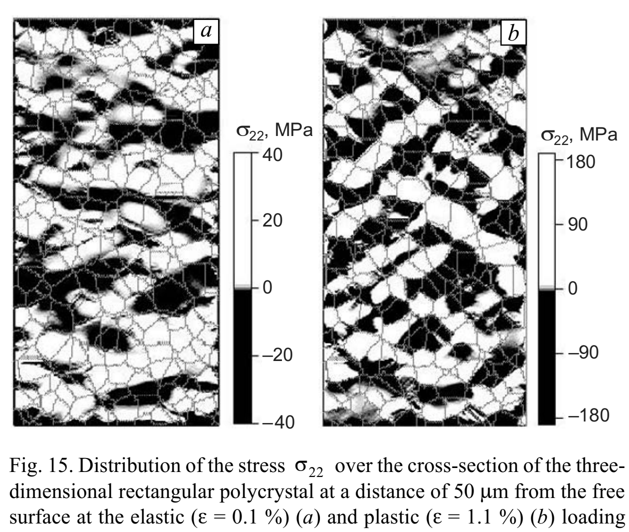

Fig. 15. Distribution of the stress σ_{22} over the cross-section of the three-dimensional rectangular polycrystal at a distance of 50 μm from the free surface at the elastic (ε = 0.1 %) (*a*) and plastic (ε = 1.1 %) (*b*) loading stages

shown that in high-strength materials in which microscale deformation is hindered, interlacing surface folds can arise due to zigzag distribution of mesobands of localized shear in the material. The continuous reorientation of shear bands owes to periodic distribution of normal tensile stress zones at the interface between the surface and volume grains. The surface grains through which shear bands pass are rotated being extruded or intruded and result in folds.

Analysis of the stress state shows that on the mesoscale all stress and strain tensor components, which are bound to be zero on the macroscale under uniaxial loading, assume positive and negative values. The heterogeneous polycrystalline structure of the material gives rise to periodically distributed local compression and tension regions and is a condition for the formation of deformation folds of varying curvature on the specimen surface.

The work was supported by the Presidium of RAS (Fundamental research program No. 11), SB RAS (project III.20.1.1), RFBR (project No. 10-08-00084-a), and President of the Russian Federation (grants MD-6370.2010.1, MD-188.2010.8 and MD-202.2011.8).

The electron backscatter diffraction analysis of the EK-181 steel specimens was performed on the equipment of the Nanotech Shared Use Centre of ISPMS SB RAS. The numerical simulation was performed on a SKIF multiprocessor cluster of Tomsk State University.

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