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Luders Deformation of Low-Carbon Steel

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Abstract—The development of Chernov—Luders bands on elastoplastic transition in low-carbon steel is investigated. The main factors responsible for the creation and development of the bands are identified. The kinetics of the mobile band boundaries (fronts) is of particular interest. The characteristic speeds are determined. The nucleation rate of Chernov—Luders bands exceeds their expansion rate by more than an order of magnitude. The simultaneous development of more than one band, with the appearance of several moving fronts, is considered. In all cases, the fronts of the Chernov—Luders bands move at matched speeds, so that, at any time, the generalized expansion rate of the deformation zone is constant. The influence of the strain rate on the kinetics of the band fronts is analyzed. Both the generalized expansion rate of the deformed zone and the speeds of individual fronts increase with increase in the loading rate. This is a nonlinear dependence (a power law). The fronts of the Chernov—Luders bands are complex in structure. Different sections of the front may move at nonuniform speeds, so that the front is locally distorted and split. Ahead of the front, in the undeformed sample, precursors whose configuration resembles that of the incipient Chernov—Luders bands may be observed. When they meet, the fronts of adjacent bands cancel out. Annihilation of the band fronts is a complex process, characterized by the formation of precursors and secondary diffuse Chernov—Luders bands. These findings indicate that the simplified concept of the Chernov—Luders bands as a deformed region in a loaded sample, as the front of a band, or as the boundary between deformed and undeformed zones must be revised. A microscopic theory of Luders deformation is based on the cascade growth in density of mobile dislocations on account of their breakaway from the points of attachment and their subsequent multiplication, which occurs instantaneously at the upper yield point within the crystallite (grain). At the same time, the formation of a mobile macroscopic strain front calls for the transfer of plastic deformation by adjacent grains, without strengthening. In other words, grain-boundary accommodation is required. The results obtained suggest that the Chernov—Luders band is such an accommodation zone, and so it has a complex structure.

Keywords: low-carbon steel, elastoplastic transition, unstable plastic flow, Chernov—Luders bands
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Many materials operate below the yield point but in the region of microplastic deformation. The microplastic strain is determined by the upper limit of the working stress with specified dimensional stability of the components and also by characteristics such as the stress relaxation, mechanical hysteresis, and cyclic stability of the structural materials. Thus, on the basis of data regarding microplastic deformation, we may select the optimal machining conditions for materials and specify the optimal operating conditions for machines and structures. Therefore, with increase in the requirements on the reliability, long-term strength, and fatigue strength of machines and structures, physical research on the elastoplastic transition, microplasticity, and the yield point becomes more important.

In the most complete study on this topic, research gathered over half a century is outlined in sections devoted to elastoplastic transition, the physics of the upper and lower yield points, and the Chernov—Luders bands [1]. Previously, traditional experimental methods had been employed: mechanical tests of various types; studies of inelastic behavior on the basis of internal friction and mechanical hysteresis; and investigation of creep and stress relaxation [2, 3]. Structural research consists mainly of electron-microscopic studies. However, electron-microscopic results on the Chernov–Luders bands are purely illustrative and do not provide quantitative information.

At the same time, the elastoplastic transition must be regarded as a multifaceted problem, which raises a whole series of unresolved questions. Currently, the latest digital methods are used to study the elastoplastic transition at the meso and macro level, so as to understand the relevant phenomenology and to obtain quantitative information characteristics [4–7].

At the microplastic stage, deformation occurs in individual microvolumes (independent grains in polycrystals), according to the traditional models [8–10]. Then groups of grains with correlated plastic deformation appear. Such regions act as nuclei of Chernov–Luders bands, which must grow over the whole cross section of the sample before macroscopic plastic deformation begins [11]. However, this model cannot answer the key questions: that is, it cannot determine what is responsible for the formation of the groups of grains where microplastic deformation develops cooperatively; whether the moment of band formation may be regarded as the onset of uniform plastic deformation; what occurs at the front of the propagating Chernov–Luders bands; and what factors affect the speed and orientation of the band front. These questions are considered in the present work.

We study high-quality 08пс low-carbon steel. Plane samples of dog-bone type are cut from hot-rolled sheet. The working section, which measures 50 × 10 × 3 mm, is ground and subjected to deep etching in 12% alcoholic nitric-acid solution. This is necessary since visualization of the Chernov–Luders band fronts requires a diffusely reflecting working surface. In the last stage of sample preparation, they are annealed at 1173 K in vacuum. After annealing, the ferrite/pearlite ratio in the sample structure is 9 : 1. The mean size of the ferrite grain is about μm.

The samples undergo uniaxial extension on a Walter_BAI LFM-125 machine at room temperature. The mobile clamp moves at speeds in the range 0.0125–0.4 mm/min. In such conditions, the loading diagram of the steel has a yield area extending over 3% strain (Fig. 1). The yield spike may be clearly expressed ($\Delta\sigma \approx 10$ MPa; Fig. 1, curve *1*); weakly expressed ($\Delta\sigma \approx 3$ MPa; Fig. 1, curve *3*); or absent (Fig. 1, curve *2*). However, in all cases, Chernov–Luders bands propagate within the yield area.

Statistical speckle photography is used for visualization and analysis of the zones where plastic deformation is localized [12]. This method is based on traditional double-exposure speckle photography, with recording of the image on photographic paper [13]. The object is illuminated by coherent light from a 635-nm semiconductor laser (laser power 15 mW). The images of the deforming sample are recorded by means of a PixeLINK PL-B781 digital camera (6 MPix). The speckle images recorded at 10 frame/s are digitized and stored in sequence. For a point of the digitized image, a sample consisting of a series of measurements is formed; this sample will represent the time dependence of the level of illumination. Then, for each sample, the dispersion and mathematical expectation are calculated. The ratio of the dispersion and mathematical expectation is used to map the zones of localized deformation. By this method, the regions where deformation of the material is localized in the case of specified overall elongation of the sample may be recorded practically in situ. Each material will be characterized by a microplastic stage, according to the data in [1, 7, 11]. Therefore, recording of the regions where deformation of the material is localized does not begin until after the limit of proportionality has been reached (shown by a marker in Fig. 1).

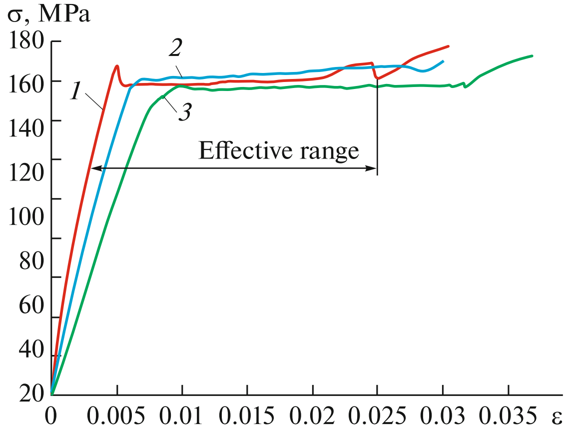

Fig. 1. Typical deformation curves of low-carbon steel samples when the machine's mobile clamp moves at $V_{\text{mach}} = 0.2$ mm/min.

In ferrocarbon alloys, the upper yield point is assumed to be the stress required to detach dislocations from the atmosphere of interstitial impurities (primarily carbon), according to Cottrell theory [8, 14]. Subsequently, these dislocations move freely, and so the deforming stress at first falls and then remains constant until the whole sample is deformed by the localized strain band—that is, the Chernov–Luders band.

As shown by experiments, however, the nucleation of Chernov–Luders bands occurs immediately beyond the limit of proportionality at stresses considerably below the upper yield point [15, 16]. If the sample's strain curve has a sharp yield spike (Fig. 1, curve *1*), the nucleation of Chernov–Luders bands begins with the formation of a wedge of deformed material in the center of the sample. This wedge expands until it reaches the opposite edge of the sample (Fig. 2). The speed of the band front is $(0.4–1.2) \times 10^{-3}$ m/s at this stage. The growth of the wedge-shaped band extends

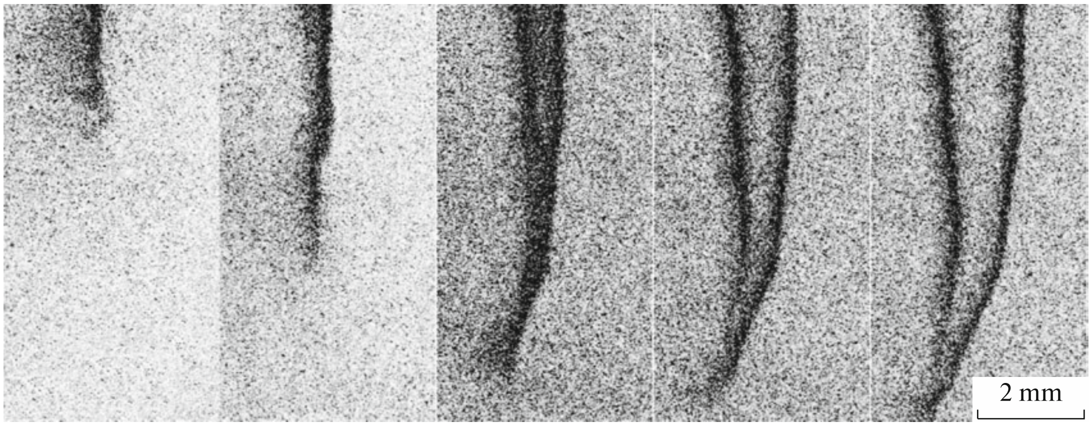

Fig. 2. Nucleation of a Chernov–Luders band: the interval between images is 3 s.

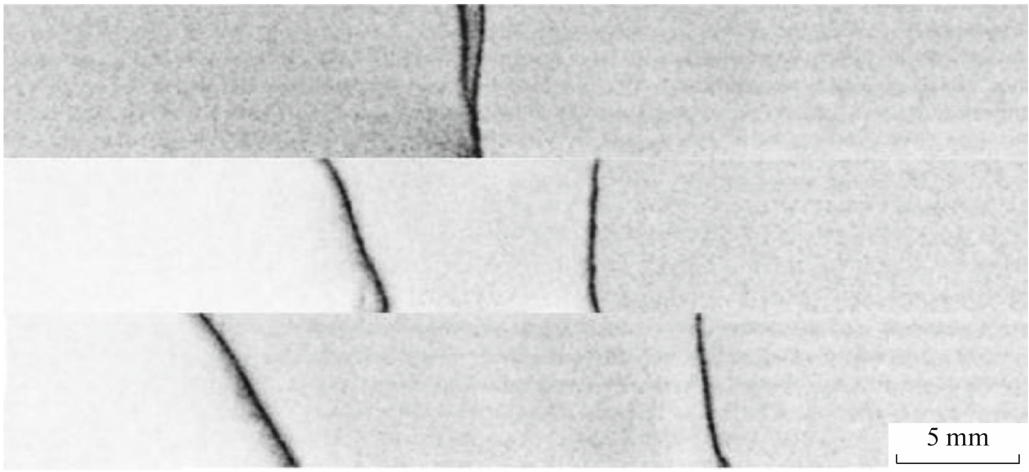

Fig. 3. Expansion of the Chernov–Luders band from a single nucleus: the interval between images is 60 s.

over both the ascending and descending branches of the yield spike. The lower yield point corresponds to the moment at which the nucleus covers the whole sample cross section. That ends the formation of the Chernov–Luders band and begins its expansion. The band fronts move in opposite directions (Fig. 3). Both fronts move at the same speed: (0.07–0.08) × 10^{-3} m/s. The inclination of the fronts to the axis of extension varies from 60° at the instant of formation to 90° before stopping.

Hence, from a single nucleus, a pair of fronts of the Chernov–Luders bands is always formed. The motion of a single deformation front, which is described by many researcher, in fact corresponds to the nucleation of Chernov–Luders bands at the boundary of the sample's working section. The view that the Chernov–Luders band is always initiated at the clamps in plane samples is not entirely correct. In general, nucleation of the bands is stochastic; the point of nucleation cannot be known in advance, although in fact the bands are predominantly initiated close to one of the clamps (Fig. 1, curve *3*). Then the fronts are in different conditions, and although they move at the sample speed at first, one reaches a fillet where the stress is less, slows, and comes to a halt. The other moves through the working region, where the cross section is constant; the stress corresponds to the yield area. Its speed increases as the speed of the first falls. When the first stops, the velocity of the second has doubled to 0.15 × 10^{-3} m/s.

There are cases in which the bands are initiated at both ends of the sample's working space (Fig. 4a). In that case, there is no yield spike (Fig. 1, curve *2*). As is evident from Fig. 4b, all the fronts of both bands move at correlated speeds. If one front stops, the speed of the other (or others) rises.

By kinetic analysis of the front for all possible combinations of bands and their boundaries, we obtain the relation

$$\sum_{i=1}^{N} \left|V_f^{(i)}\right| = \tilde{V}_f = \text{const}, \qquad (1)$$

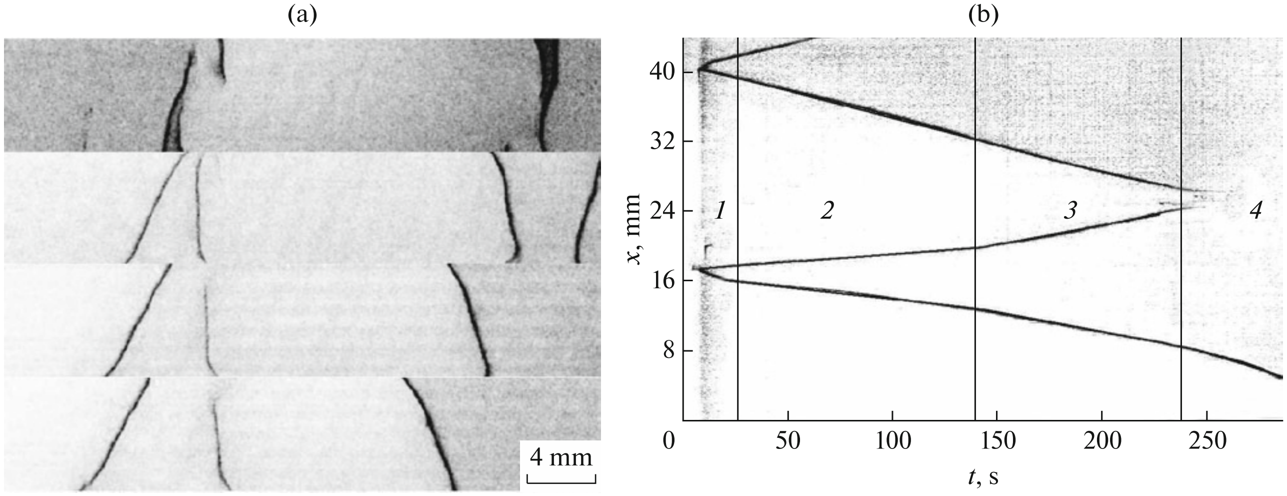

Fig. 4. Motion of the fronts with multiple nucleation of Chernov–Luders bands: (a) successive images (at 40-s intervals); (b) time dependence (the speed of any front corresponds to the slope of the corresponding section of the curve); (*1*) formation of four fronts; (*2*) motion of four fronts with equal speed; (*3*) motion of three fronts; (*4*) annihilation of two fronts and increase in speed of the remaining front.

where $\left|V_f^{(i)}\right|$ is the modulus of the velocity of front i of the Chernov–Luders band; N is the number of fronts moving simultaneously.

With the selected loading speed V_{mach} = 0.2 mm/min, $\tilde{V}_f = 0.16 \times 10^{-3}$ mm/s. It follows from Eq. (1) that the growth rate of the plastically deformed zone in the sample is constant over the yield area. This growth rate must be related to the loading rate. The relation between $\tilde{V}_f$ and V_{mach} may be obtained from the obvious equality of the time for absolute elongation δL of the sample in the yield area and the time for the working part of the sample L to be traversed by the band fronts

$$\frac{L + \delta L}{\tilde{V}_f} = \frac{\delta L}{V_{\text{mach}}}. \tag{2}$$

Since $\delta L \ll L$, it follows from Eq. (2) that

$$\tilde{V}_f \approx \frac{L}{\delta L} V_{\text{mach}} \approx \frac{V_{\text{mach}}}{\varepsilon_{\text{pl}}}, \tag{3}$$

where $\varepsilon_{\text{pl}} = \delta L/L$ is the length of the yield area in strain units.

Usually, $10^{-2} \le \varepsilon_{\text{pl}} \le 3 \times 10^{-2}$. Hence, $\tilde{V}_f = (10\text{–}30)V_{\text{mach}}$. That is in good agreement with [5, 7].

It follows from Eq. (3) that the generalized velocity $\tilde{V}_f$ of the Chernov–Luders band fronts is determined by the growth rate V_{mach}. However, the specific form of this dependence is not obvious. To establish the dependence, we conduct experiments with stepped change in V_{mach}.

The tests begin at a strain rate of 0.4 mm/min. Absolute elongation of 0.2 mm is attained at the yield area. The strain rate is then reduced by half, to 0.2 mm/min. Then, at that strain rate, the sample is again elongated by 0.2 mm, and the strain rate is again reduced by half. The cycle is repeated six times, with a strain rate of 0.0125 mm/min in the last case. (The cycles are denoted by numerals *1*–*6* in Fig. 5). Note that, with decrease in the strain rate, the deforming stress is reduced. In this experiment, two bands are formed at both clamps of the loading device. Therefore, we observe two opposing fronts. We see in Fig. 5 that the speeds of the bands decline synchronously. In the other experiments, the strain rate is increased in stages. Then the deforming stress increases, and the speed of the Chernov–Luders band fronts increases.

In Fig. 6, we show the dependence of the velocity modules of the Chernov–Luders band fronts on the strain rate for five loaded samples. We see that this

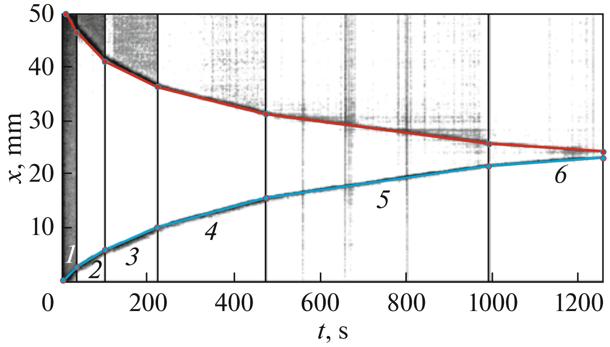

Fig. 5. Time dependence of the Chernov–Luders band fronts in deformation with variable speed of the mobile clamp.

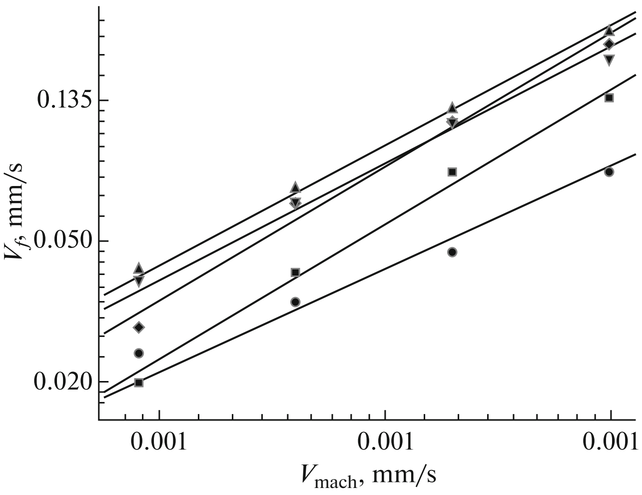

Fig. 6. Dependence of the speed V_f of the Chernov–Luders band fronts on the loading rate V_{mach}: the points correspond to experimental data, and the lines to regression curves.

dependence is nonlinear and corresponds to a power law of the form

$$\tilde{V}_f = KV_{\text{mach}}^n,$$

where K is a numerical coefficient.

This equation may be used for the generalized expansion rate $\tilde{V}_f$ of the deformed region and for the speeds of the individual fronts $\left|V_f^{(i)}\right|$. The exponent n varies from 0.731 to 0.961 in different experiments. This occurs since K is determined by the stress at the yield area, according to [17]. In other words, K depends nonlinearly on V_{mach}. Nevertheless, the mean value $\langle n \rangle = 0.867 \pm 0.095$ is in good agreement with the data of [5]. This may evidently be explained in that description of the kinetics of the Chernov–Luders band fronts must be based not on the mean stress but on its local value in the region corresponding to the front's current position. In particular, within that framework, the variation in speed of the Chernov–Luders band fronts when there are several fronts (as in Fig. 4, for example) may be attributed to redistribution of the local internal stress.

It is important to know the structure of the propagating band front (Fig. 7). The moving front *1* may be split and may be preceded by precursors, which are capable of uniting as another front *2* at a distance of 1.5–2.0 mm. Then both fronts move synchronously in the same direction. Of course, the rear front *1* will then pass through an already-deformed region of the sample.

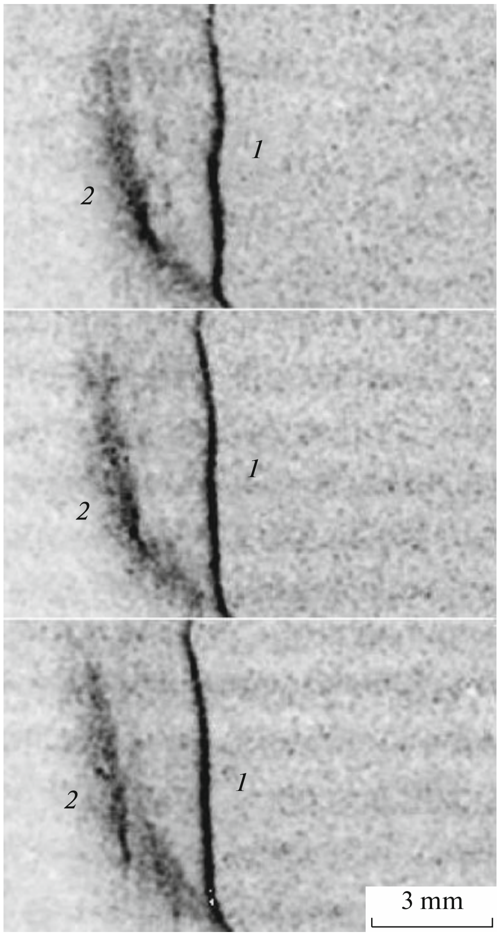

Fig. 7. Chernov–Luders band front (*1*) with precursors (*2*): the interval between images is 5 s.

A similar situation arises when fronts from two Chernov–Luders band fronts meet. They should annihilate, according to current concepts [18, 19] (Fig. 8, fronts *2* and *3*). This process includes the division of the zone between the band fronts into fragments by the formation of secondary diffuse bands, which convert the volume between the primary bands to a deformed state. The primary band fronts continue to move through the already-deformed region of the sample. This process is accompanied by strong fluctuations in the stress at the yield area, as already noted.

On the basis of the results, we conclude that the nucleus of the Chernov–Luders band grows through a sample cross section in the form of a wedge and then the deformational fronts of the band begin to move. Therefore, the dislocational model of the yield spike must be refined.

The Chernov–Luders band fronts have a complex structure. Different sections may move at different speeds, so that the front is locally distorted and splits. Ahead of the front, in the undeformed sample, precursors whose configuration resembles that of the incipient Chernov–Luders bands may be observed. As they expand, the precursors form a new front at a distance of 1.5–2.0 mm from the initial front. Then, both fronts move in the same direction in a coordinated manner.

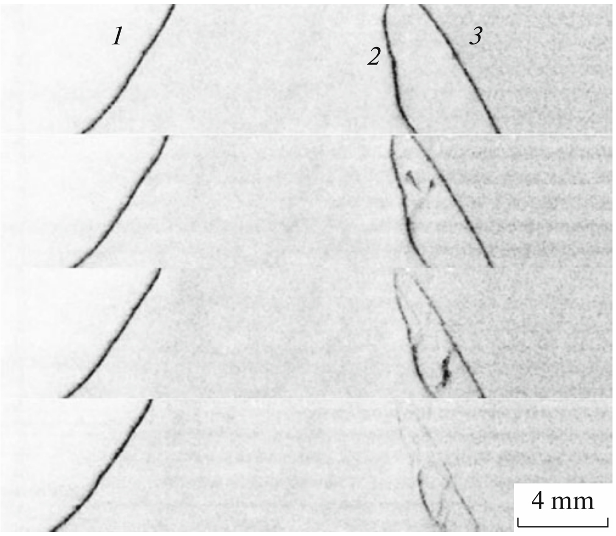

Fig. 8. Annihilation of the mobile fronts of adjacent Chernov–Luders bands: the interval between images is 10 s.

The rear band front passes through a region of the sample that has already been plastically deformed.

These findings indicate that the simplified concept of the Chernov–Luders bands as a deformed region in a loaded sample, as the front of a band, or as the boundary between deformed and undeformed zones must be revised. Cantrell's microscopic theory of Luders deformation must be refined [8, 20]. The theory assumes cascade growth of the mobile dislocations on account of their breakaway from the points of attachment and their subsequent multiplication, which occurs instantaneously at the upper yield point within the crystallite (grain). However, the formation of a mobile macroscopic strain front calls for the transfer of plastic deformation by adjacent grains, without strengthening. In other words, grain-boundary accommodation is required. The results obtained suggest that the Chernov–Luders bands is such an accommodation zone, and so it has a complex structure.

CONCLUSIONS

The nucleation of Chernov–Luders bands occurs in the microplastic section of the deformation curve long before the upper yield point. The yield spike corresponds to growth of the Chernov–Luders band's nucleus across the sample cross section, while the yield region corresponds to motion of the deformation fronts of the Chernov–Luders bands. The growth rate of the nucleus is approximately five times the expansion rate of the Chernov–Luders band, which, in turn, is about 50 times the speed of the machine's mobile clamp.

Regardless of the number of bands formed, the expansion rate of the sample's deformed zone remains constant over the whole yield area. It depends on the loading rate according to a power law; the exponent is less than one.

The annihilation of the fronts of adjacent Chernov–Luders bands is a complex process characterized by the formation of precursors and secondary diffuse Chernov–Luders bands.

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