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THE VELOCITY OF ULTRASOUND IN LOW-CARBON STEEL DEFORMED AT THE LOW YIELD LIMIT

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The variation of a thin structure upon deformation of low-carbon steel at the yield limit is analyzed. The character of the interrelationship between the stage nature of a plastic flow of low-carbon steel and the velocity of ultrasound in it is established. It is shown that the velocity of ultrasound is a parameter for obtaining additional data on the development of plastic flow. The structural changes that exert an effect on the velocity of ultrasound in the deformation that corresponds to the yield site are studied.

1. Formulation of the Problem. The heterogeneity of plastic flow and deformation localizations have recently been studied intensely. The known example of inhomogeneous flow is propagation of the Chernov–Lüders band upon loading of a material with a distinct yield limit. In this case, the object subjected to loading has a mobile narrow boundary, which divides two zones in which the material is in different states. The motion of the Chernov–Lüders band causes an increase in the volume of the plastically deformed region at constant stress; on the expansion diagram, the yield site corresponds to this increase. Zuev [1] interpreted the propagation of the Chernov–Lüders band as the development of one type of dissipative structures in the deformed material, the so-called autowave of switching [2]. Since the autowaves can generate only in an active medium whose properties change upon deformation [2], the data on the change of the material characteristics as the Chernov–Lüders band develops on the yield site are of great interest. This study is devoted to clarification of the indicated circumstances.

2. Material and Techniques of Research. The studies were performed on flat samples of 09G2S low-carbon steel (0.09% carbon, 2% manganese, and 1% silicon) with a 50×10-mm working section; the specimens were cut from a hot-rolled sheet of thickness 3 mm. To remove the internal stresses, the samples were preannealed in vacuum at 950°C for 2 h. The average size of a grain after treatment was approximately 13 μm. The samples were stretched on an Instron-1185 test device with a velocity of $3.3 \cdot 10^{-3}$ mm/sec ($d\varepsilon/dt = 6.6 \cdot 10^{-5}$ sec^{-1}). In these conditions, a "tooth" and a yield site were observed on the flow curve.

The character of deformation localization was studied by the technique of two-exposure speckle interferometry. An ALMEX automated laser measuring complex developed for these purposes at the Institute of Strength and Materials Science Physics of the Siberian Division of the Russian Academy of Sciences allows one to obtain the field of displacement vectors, calculate the plastic-distortion tensor components, and construct their distributions over the entire surface of the sample at any stage of deformation.

Additional information on the behavior of the deformed material at the stage of yield site was gained by simultaneous recording of small changes in the velocity of ultrasound (VU) in a sample, measured by an ISP-12 device [3] by the method of autocirculating the pulses of Rayleigh waves with a carrier frequency of 2 MHz and of recording the deformation diagram. The measuring head of the device with two piezotransducers was installed at the rear side of the stretched sample; this made it possible to record the field of displacement vectors and the data on the VU value, together with recording of the deformation diagram.

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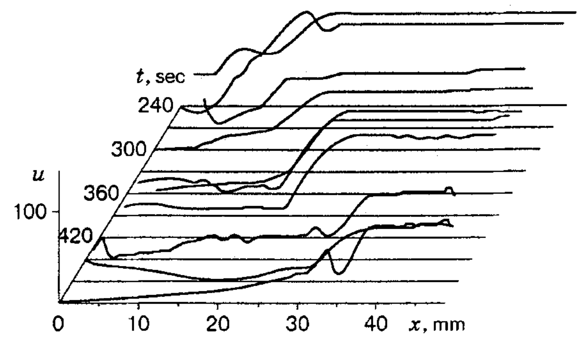

Fig. 1

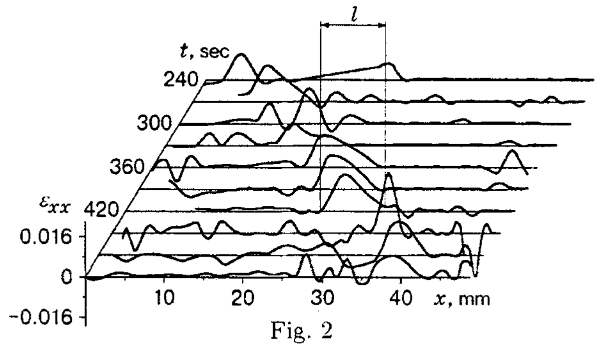

Fig. 2

The deformation-microstructure (the dimensions of the blocks in the zones on both sides of the Chernov–Lüders-band front) characteristics were determined by an x-ray method on a DRON-3 diffractometer in monochromatized Fe radiation. The behavior of the structural elements of the material was studied immediately during loading on the yield site by the method of x-ray topography. To do this, the recording was performed with a URS-002 device in the polychromatic radiation of a tube with a copper anode.

3. Experimental Results. Ordered distributions of the distortion-tensor components appear in a plastic flow of a polycrystalline material. The heterogeneity of plastic flow can be manifested in the form of displacing solitary fronts or their groups [4, 5], so that the material is stratified into active-deformation zones and zones not involved in the process. The solitary plastic-deformation front (Chernov–Lüders-band front) moves along the sample on the yield site when the deformation hardening coefficient is $\theta = d\sigma/d\varepsilon = 0$. The characteristic stepwise dependence of the longitudinal displacement-vector component $u = r\cos\alpha$ (α is the angle between the expansion axis and the displacement sector $\boldsymbol{r}$) on the x coordinate, which is observed in this case, is shown in Fig. 1. In most cases, the localization spot originated near the clamp of the test device, and then its front gradually moved along the sample at a stress equal to the low yield limit. The acts of dislocation sliding upon polycrystal expansion occur precisely in the Chernov–Lüders-band front [6], whereas there are no dislocation phenomena in the other part of the sample.

Figure 2 shows the pattern of local elongations $\varepsilon_{xx} = du/dx$ for this case. Obviously, the sample is extended only in the zone where the maxima of this quantity are observed. The maxima of the shear ε_{xy} and rotational ω_z components of the plastic-distortion tensor $\beta = \nabla \boldsymbol{r}$ also correspond to the maxima of local elongations ε_{xx}. The growth of general deformations leads to the plastically deformed area becoming extended, and the spot of active deformation moves in a self-similar manner along the sample with the velocity $V_a \approx 10^{-4}$ m/sec; in this case, it is a factor of 1.5 greater than the velocity of motion of the mobile clamp of the loading unit. The moment at which the Chernov–Lüders-band front reaches the moving clamp is fixed exactly from a pattern similar to that given in Fig. 2 and corresponds to the termination of the yield-site stage and the onset of the parabolic ($\sigma \sim \varepsilon^{1/2}$) deformation-hardening stage of steel. Thus, it follows from Figs. 1 and 2 that the deformation on the yield site is located at the Chernov–Lüders-band front.

In VU measurements at this stage of plastic flow, the dependence $V_s(\varepsilon)$ for $\sigma = \text{const}$ was found to have a trapezoidal shape (points in Fig. 3 refer to experimental data). Immediately after the yield "tooth," in reaching the lower yield limit the VU increases and then remains constant; it decreases again in the transition from the yield-site stage to the parabolic law of deformation hardening (Fig. 4).

4. Discussion of Results. The above-described dependence of V_s on deformation at a stress equal to the lower yield limit can be explained as follows. Since the portion of the deformed material of the part of the sample located between the converters of the measuring device increases as the band front propagates, it follows from the shape of the dependence $V_s(\varepsilon)$ that the changes in VU are initiated by the processes occurring in the band front, i.e., by dislocation shears properly [6]. Here the total increase in the volume of the deformed material does not play a significant part. The smooth increase in VU at the beginning of the

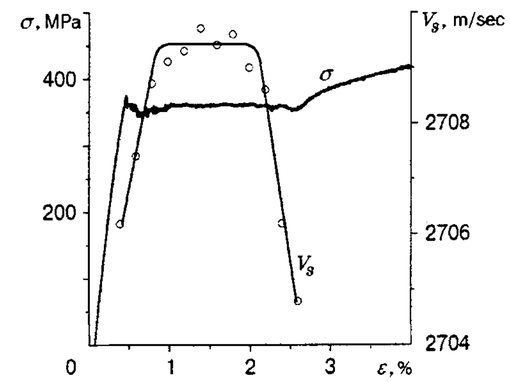

Fig. 3

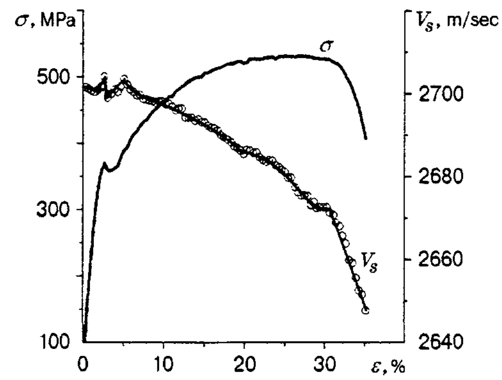

Fig. 4

yield site and the almost symmetric decrease at its end have the following explanation. For the deformation-site width $l \approx 10$ mm (see Fig. 2), this zone passes by one of the ultrasound converters for $t \approx l/V_a \approx 10^2$ sec. Here the deformation increment on the yield site amounts to $\delta\varepsilon \approx (d\varepsilon/dt)t \approx 6 \cdot 10^{-3}$ (approximately 0.6%) (see Fig. 3). The time at which the active zone leaves the working area of the VU meter after the deformation terminates on the yield site is also approximately 10^2 sec. Finally, the motion of the active zone between the converters corresponds to an almost constant value of VU. This means that, measuring the velocity of ultrasound, one can obtain information on the kinetics of motion of the deformation sites in plastic flow. This is supported by the fact that the right branch of the dependence $V_s(\varepsilon)$ in Fig. 3 is steeper than the left branch. As the experimental data show, this is connected with the fact that the width of the deformation-localization zone on the yield site becomes narrower as its end is approached.

According to [3], the VU increases as the internal stresses in materials decrease and vice versa. This phenomenon is associated with the occurrence of double acoustic refraction in the stressed volumes [7] and crystal-lattice defect generation [8], which causes defective elastic moduli. Obviously, the segments of the dependence $V_s(\varepsilon)$ with different signs of the derivative $dV_s/d\varepsilon$ correspond to the increase and decrease in internal stresses in the deformed polycrystal, since the deformation processes at the Chernov–Lüders-band front do not depend on the position of this front [6]. Here the increase in VU corresponds to the decrease in the stress level and vice versa. In the case of a polycrystalline material, the latter can be explained by the fact that, for small degrees of deformation, the stresses relax owing to local rotations of separate volumes of the material [9]. Such rotations were previously registered by the method of x-ray topography during deformation of polycrystalline aluminum [10]. This assumption is supported by the changes in the structural state of materials upon plastic deformation. The method of x-ray diffractometry was employed to establish the changes in the thin structure of a material on the yield site. The measurements were performed ahead of the Chernov–Lüders-band front (plastically nondeformed volume) and behind this front (deformed part of the sample). The displacements of the α–Fe lattice lines and their broadening were not observed. Moreover, the ratio between the integral intensities of the 110 and 200 lines remains constant before and after passage through the Chernov–Lüders band. This means that second-kind distortions do not contribute to the physical broadening of the lines at this stage.

The dimensions of the structural units (blocks) were determined by recording the defocused diffraction lines by the Warren method [11]. In this case, a counter scanned a defocused diffraction line, and reflections with a great number of subreflections were obtained on a diffractogram. The 220 diffraction lines were analyzed before and after passage through the Chernov–Lüders band. On the lines α_1 and α_2, the radiograms contained many subreflections, and the mean dimensions of the blocks were found with the use of the angular position by the Warren method. It was established that before passage through the Chernov–Lüders band, the characteristic dimensions of the blocks are 20–120 nm for an average size of about 70 nm. In the part of the sample through which the deformation front has already passed, the dimensions of the blocks almost double: the average dimension is approximately 120 nm and the maximum dimension is 250 nm. Thus, the block dimensions increase substantially upon passage through the Chernov–Lüders-band front, and their distribution over the sample becomes more regular.

X-ray topographic recording by the Shults method [12] of the same segment of the deformed sample allowed one to explain the mechanism of block rotation. At the initial moment, i.e., before passage through the Chernov–Lüders band, blocks with a large angle of disorientation were observed, and there were two lines on a film. On the band itself, the blocks displaced to a new position, and the lines merged. After the observation zone was passed by the Chernov–Lüders band, additional rotation occurred, and the former line was divided into new lines. This three-stage process was completed by the noticeable decrease in the angle of block disorientation with $11'6''$ at the initial moment and up to $6'5''$ after passage through the Chernov–Lüders band.

Conclusions. Thus, plastic deformation at the yield stage markedly increases the angle of disorientation of the substructural units and enlarges their dimensions. This leads to a decrease in the defectness of a material and deformation hardening upon its subsequent deformation. Thus, the phenomena that occur at a stress equal to the lower yield limit change the state of the deformed medium and make the transition of plastic flow possible from the microscopic scale level, where the main role is played by the motion of dislocations at the Chernov–Lüders-band front, to the stage of deformation hardening, at which a system of mesoscale-level deformation sites [13, 14], which forms a stationary dissipative structure (system of fixed deformation centers) [2] characteristic of the parabolic stage of deformation hardening, appears. The development of plastic deformation at this stage is accompanied by a decrease in VU which is close in character to that described in [9]. This is, probably, caused by the accumulation of dislocation-type defects and their ensembles as the general deformation grows [6].

REFERENCES

1. L. B. Zuev, "Formation of plasticity autowaves upon deformation," *Metallofiz. Nov. Tekhnol.*, **16**, No. 10, 31–36 (1994).
2. A. Yu. Loskutov and A. S. Mikhailov, *Introduction to Synergetics* [in Russian], Nauka, Moscow (1990).
3. V. V. Murav'ev, L. B. Zuev, and K. L. Komarov, *Velocity of Sound and the Structure of Steels and Alloys* [in Russian], Nauka, Novosibirsk (1996).
4. L. B. Zuev, V. I. Danilov, and N. V. Kartashova, "Space–time self-organization of plastic deformation of fcc single crystals," *Pis'ma Zh. Éksp. Teor. Fiz.*, **60**, No. 7, 538–540 (1994).
5. L. B. Zuev and V. I. Danilov, "Nature of large-scale correlations in plastic flow," *Fiz. Tverd. Tela*, **39**, No. 8, 1399–1403 (1997).
6. V. I. Trefilov, V. F. Moiseev, and É. P. Pechkovskii, *Deformation Hardening and Fracture of Polycrystalline Metals* [in Russian], Naukova Dumka, Kiev (1987).
7. T. Tokuoka and Yu. Iwashimizu, "Acoustical birefringence of ultrasonic waves in deformed isotropic elastic materials," *Int. J. Solids Struct.*, **4**, No. 3, 383–389 (1968).
8. A. B. Lebedev, S. B. Kustov, and B. K. Kardashev, "Internal friction and the defect of the Young modulus upon deformation of crystals," *Fiz. Tverd. Tela*, **34**, No. 9, 2915–2921 (1992).
9. L. B. Zuev, B. S. Semukhin, and K. I. Bushmeleva, "Velocity of ultrasound and the stage nature of plastic flow of polycrystals," *Pis'ma Zh. Éksp. Teor. Fiz.*, **22**, No. 14, 76–79 (1996).
10. L. B. Zuev, T. M. Poletika, and B. S. Semukhin, "Rotations of the macrovolumes of material upon plastic deformation," *Krystallografiya*, **40**, No. 6, 1071–1073 (1995).
11. B. I. Warren, "X-ray study of deformed metals," in: *Successes of Physic Metals* [Russian translation], Vol. 5, Metallurgizdat, Moscow (1963), pp. 172–237.
12. A. Gunier, *Théorie et Technique de la Radiocrystallographie*, Dunond, Paris (1961).
13. L. B. Zuev and V. I. Danilov, "Plastic deformation modelled as a self-excited wave process at the meso- and macro-level," *Theor. Appl. Fracture Mech.*, **30**, No. 1, 175–184 (1998).
14. L. B. Zuev and V. I. Danilov, "A self-excited wave model of plastic deformation in solids," *Philos. Mag. A*, **79**, No. 1, 43–57 (1999).