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Kinetics of deformation fronts during serrated Lüders deformation in α-iron at high temperature

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Abstract. At room temperature, the deformation of most bcc metals, which contain a small amount of interstitial elements, is accompanied by the formation of a Lüders band and its monotonic propagation over the tensile yield area. Within the framework of the autowave concept, front of the Lüders band is a switching autowave, which realizes the transition from a metastable elastically deformable state to a stable plastically deformable state. However, in the temperature range of blue brittleness of mild steels of 423 – 510 K, when the interaction of atoms of the dissolved substance with mobile dislocations takes place, propagation of the Lüders band is accompanied by a discrete flow. The patterns of propagation of the Chernov-Lüders fronts in ARMCO iron in the temperature range from 296 to 503 K and strain rates from $6.67 \cdot 10^{-6}$ to $3.7 \cdot 10^{-2}$ s^{-1} are considered in this paper. It was established that under these conditions both monotonic and discrete kinetics of front movement can be realized. Regardless of the movement nature, the Lüders deformation and width of the front remain unchanged throughout the entire process. The local strain rate at the front depends on magnitude of the effective stress, and with monotonic kinetics it increases with stress according to an exponential law, and with discrete kinetics it increases according to a linear law. This difference is due to different autowave modes that are formed in this case. The autowave of localized plasticity switching corresponds to monotonic kinetics, and the autowave of excitation – to discrete kinetics.

Keywords: Chernov-Lüders deformation, deformation front, local strain rate, autowave, localized plasticity

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Особенности кинетики деформационных фронтов при скачкообразной деформации Людерса в α-железе при повышенной температуре

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Аннотация. При комнатной температуре деформация большинства ОЦК-металлов, которые содержат небольшое количество элементов внедрения, сопровождается образованием полосы Людерса и ее монотонным распространением на площадке текучести при растяжении. В рамках автоволновой концепции фронт полосы Людерса является автоволной переключения, которая реализует переход из метастабильного упруго деформируемого в стабильное пластически деформируемое состояние. Однако в температурном интервале синеломкости мягких сталей 423 – 510 К, когда имеет место взаимодействие атомов растворенного вещества с подвижными дислокациями, распространение полосы Людерса сопровождается прерывистым течением. В настоящей работе рассмотрены закономерности распространения фронтов Чернова-Людерса в АРМКО-железе в интервале температур от 296 до 503 К и скоростей деформирования от $6{,}67 \cdot 10^{-6}$ до $3{,}7 \cdot 10^{-2}$ с$^{-1}$. Установлено, что в этих условиях может реализовываться как монотонная, так и дискретная кинетика движения фронтов.

Независимо от характера движения, деформация Людерса и ширина фронта в течение всего процесса остаются неизменными. Локальная скорость деформации на фронте зависит от величины действующего напряжения, причем при монотонной кинетике она возрастает с напряжением по степенному закону, а при дискретной – по линейному закону. Данное различие обусловлено разными автоволновыми модами, которые при этом формируются. Монотонной кинетике соответствует автоволна переключения локализованной пластичности, а дискретной – автоволна возбуждения.

Ключевые слова: деформация Чернова-Людерса, фронты локализованной деформации, локальная скорость деформации, автоволны, локализованная пластичность

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Introduction

At room temperature, deformation of most BCC metals containing small amounts of interstitial elements is accompanied by the formation of a Chernov–Lüders band, which propagates monotonically across the yield plateau during tension [1 – 4]. The propagation behavior of the Lüders band can vary depending on grain size, temperature, applied stress, and strain rate. The band expands uniformly across the yield plateau, with all deformation concentrated at its boundaries, or deformation fronts, at any given moment. The velocities of front movement are proportional to the velocity imposed by the loading device. According to the autowave concept [5 – 7], the Chernov–Lüders band front represents an autowave switch that transitions from a metastable elastically deformable state to a stable plastically deformable state [8; 9]. However, within the blue brittleness temperature range for mild steels (423 – 510 K) [10 – 12], where dislocation movement is influenced by dynamic strain aging, the propagation of the Lüders band is characterized by discrete flow. In [13], it was established that within the temperature range of 393 – 503 K in ARMCO iron, the stationary kinetics of Lüders front movement is replaced by serrated behavior. The temperature at which Lüders deformation becomes serrated increases with increasing deformation rate. On the serrated yield plateau, the discretely propagating Lüders band front represents an autowave of localized plasticity excitation. Notably, front movement in this case only occurs during the stress relaxation process associated with serration. This raises a question about the nature of dependence of the local deformation rate in front region on the applied stress during the serrated process.

This study is dedicated to establishing the kinetic regularities of deformation front propagation during serrated Lüders deformation in α-iron at elevated temperatures.

Materials and methods

The material used for the study was ARMCO iron with the following composition (wt. %): C 0.025; Si 0.05; Cu 0.05; Mn 0.035; S 0.025; P 0.015; Fe – remainder. Test samples in the form of double-sided blades were laser-cut from hot-rolled sheet with a thickness of 1.5 mm. The working area of the sample was 50×10 mm. To standardize the stress and structural states before testing, the samples were annealed in a vacuum according to the following regime: 1233 K for 1 h, followed by cooling with the furnace to room temperature.

The prepared samples were subjected to uniaxial tension using an LFM-125 testing machine at speeds ranging from 0.02 to 10 mm/min. Tests were conducted at temperatures ranging from 296 to 503 K. The STE-12H furnace (Walter + Bai) with independent temperature control in three zones was used. The sample temperature was measured using three thermocouples installed along the sample axis at a distance of 20 mm from each other.

Analysis of the kinetics of Lüders deformation fronts was performed using digital image correlation [14; 15] and digital statistical speckle photography [16; 17]. To form the speckle structure, the sample was illuminated with coherent light from a semiconductor laser (635 nm, 15.0 mW). The sample images were captured using a Point Grey FL3-GE-50S5MC digital video camera with a resolution of 2448×2048 pixels at a frame rate of 2 to 25 fps, depending on the stretching speed. Chronograms [18] were constructed from the obtained data arrays, which allowed for the identification of Lüders band nucleation regions and determination of the kinetic characteristics of their fronts.

Results and discussion

Fig. 1 shows the yield plateaus of the stress-strain curves of ARMCO iron obtained at room temperature and elevated temperatures. At room temperature, the strain curve exhibits a typical tooth and smooth yield plateau characteristic of low-carbon steels. At a test temperature of 423 K and a deformation rate of $6.67 \cdot 10^{-5}$ s^{-1}, periodic stress jumps occur on the yield plateau.

It is known that at temperatures below 393 K, ARMCO iron exhibits normal strain rate sensitivity, meaning that

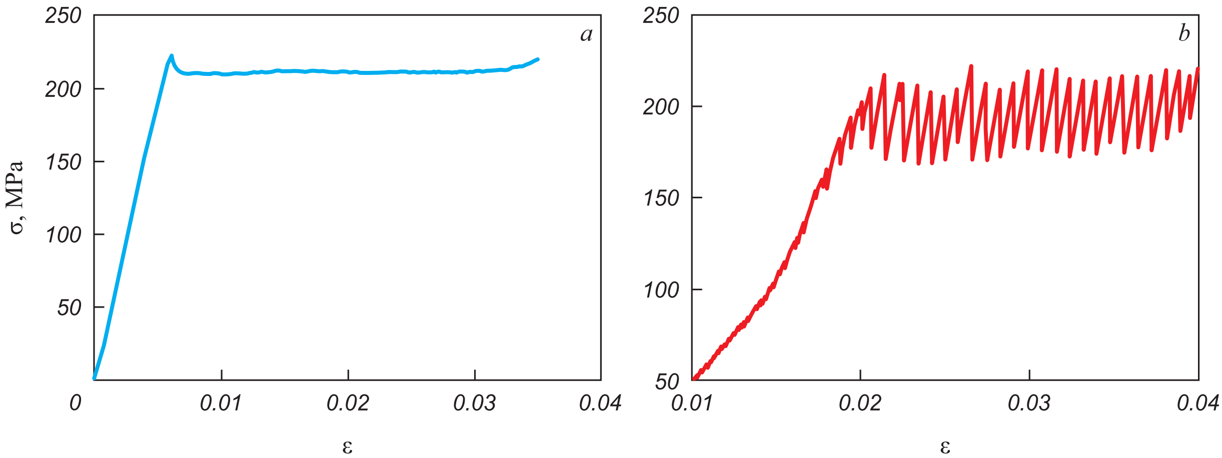

Fig. 1. Yield plateau in α-iron samples at $T = 295$ K, $\dot{\varepsilon} = 6.67 \cdot 10^{-5}$ s^{-1} (*a*) and $T = 423$ K, $\dot{\varepsilon} = 6.67 \cdot 10^{-5}$ s^{-1} (*b*)

Рис. 1. Площадка текучести образцов α-железа при $T = 295$ К, $\dot{\varepsilon} = 6{,}67 \cdot 10^{-5}$ с$^{-1}$ (*a*) и $T = 423$ К, $\dot{\varepsilon} = 6{,}67 \cdot 10^{-5}$ с$^{-1}$ (*b*)

the yield stress on the yield plateau (lower yield strength $\sigma_y^{(l)}$) increases with increasing deformation rate and decrease with increasing temperature [19]. As shown in Fig. 2, *a*, at room temperature, the lower yield strength increases non-linearly with increasing deformation rate.

Studies in the temperature region of the serrated development of the Lueders strain have shown that with increasing deformation rate, the amplitude of stress jumps decreases, while the stress level $\sigma_y^{(l)}$ at which the drop occurs remains constant (Fig. 2, *b*). Thus, in the temperature range of serrated flow, the strain rate sensitivity of the lower yield strength is absent. At the same time, the stress at the onset of the jump (upper yield strength $\sigma_y^{(u)}$) monotonically decreases with increasing deformation rate.

Studies on the nature of deformation localization using digital statistical speckle photography identified that fronts of localized plastic deformation form and move both on the smooth (Fig. 3, *a*) and serrated (Fig. 3, *b*) yield plateaus. However, in the former case, the front moves monotonically at a constant velocity V_f, while in the latter case, it moves discretely, only during the stress drop in the serration process.

Based on the fact that the deformation front passes through the entire length of the sample L during the observed yield plateau Δt, then $L = V_f \Delta t$. During this time, the sample undergoes elongation expressed as $\Delta L = V_d \Delta t$ (where V_d is the deformation rate set by the loading device). Therefore, the deformation acquired by the sample on the yield plateau can be represented as

$$\varepsilon_L = \frac{\Delta L}{L} = \frac{V_d}{V_f}. \tag{1}$$

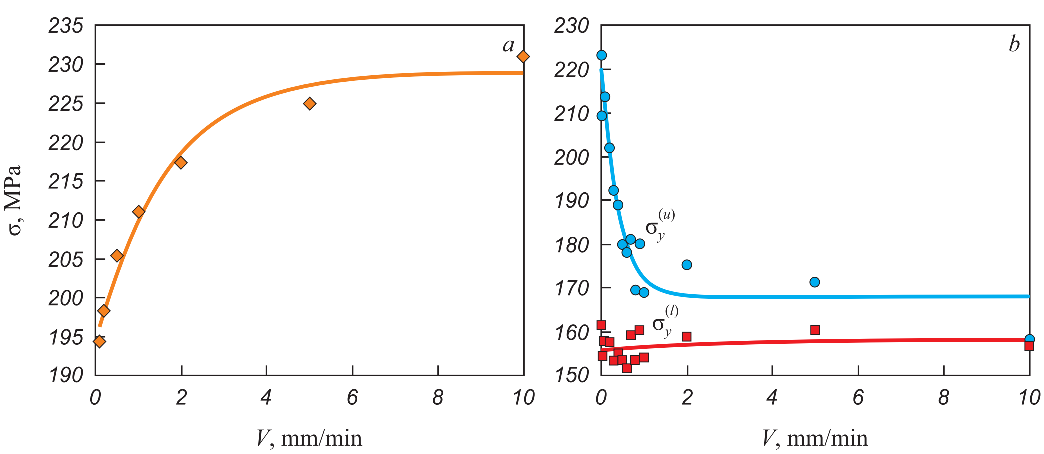

Fig. 2. Strain rate dependence of the lower yield strength at $T = 295$ K (*a*) and strain rate dependence of the lower (■) and upper (●) yield strength at $T = 423$ K (*b*)

Рис. 2. Скоростная зависимость нижнего предела текучести при $T = 295$ К (*a*) и скоростная зависимость нижнего (■) и верхнего (●) предела текучести при $T = 423$ К (*b*)

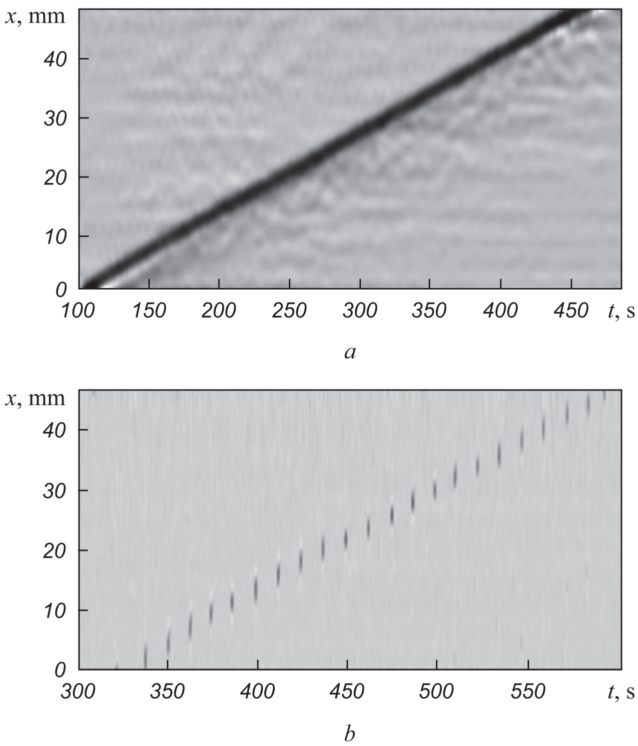

Fig. 3. Chronograms of deformation fronts movement on yield plateaus at strain rate of $6.67\cdot10^{-5}$ s^{-1} and temperatures 293 K (*a*) and 423 K (*b*)

Рис. 3. Хронограммы движения деформационных фронтов на площадках текучести при скорости растяжения $6{,}67\cdot10^{-5}$ $с^{-1}$ и температурах 293 K (*a*) и 423 K (*b*)

From this, it follows that the front velocity and deformation rate are interrelated by the equation $V_d = \varepsilon_L V_f$. If this relationship is normalized by the front width δ, then the relative deformation velocity is expressed as

$$\dot{\varepsilon} = \frac{V_d}{\delta} = \varepsilon_L \frac{V_f}{\delta} = \frac{\varepsilon_L}{t_f}, \qquad (2)$$

where t_f is the time of front motion during a jump at a certain velocity V_f.

Thus, the relative deformation velocity $\dot{\varepsilon}$ and front velocity V_f must be linearly related if the deformation ε_L at any given time is constant and concentrated at the front. Furthermore, for this equation to hold, the width of the deformation front δ during motion must also remain constant.

To test the first postulate of ε_L constancy, measurements of marker displacements on the surface of the sample were conducted during deformation on a serrated yield plateau. Markers were applied to the surface of the sample in three rows, spaced 100 μm apart, using a PMT-3M microhardness tester. Two series of images of these markers were then taken before and after deformation using a NEOPHOT-21 optical microscope. Measurements of the distance between the centers of two adjacent markers before deformation (l) and after deformation (l_1) allowed for the determination of the displacement of each marker $\Delta l = l_1 - l$, thus obtaining the displacement field $\Delta l(x)$ (where x is the marker coordinate). By numerically differentiating this field, the local deformation at each point was calculated as $\varepsilon_L = \Delta l / l$. Fig. 4 shows the distribution of ε_L along the length of the sample. The application of the hypothesis of a normally distributed population [20] showed that changes in ε_L are random in nature, with the magnitude being considered constant and its average value being $\varepsilon_L = 0.0184 \pm 0.0003$.

As stated in [17], when using the digital statistical speckle photography method to visualize deformation fronts, the brightness of the front image is proportional to the deformation within it. From this, the average width of the front δ can be determined. Measurements for fronts moving during all jumps (Figs. 1, *b* and 3, *b*) showed that their width is constant and equal to 105 ± 7 μm. Thus, the second postulate of front width constancy is also fulfilled, and equation (2) can be used to investigate the relationship between local deformation rate and stress in the during a jump.

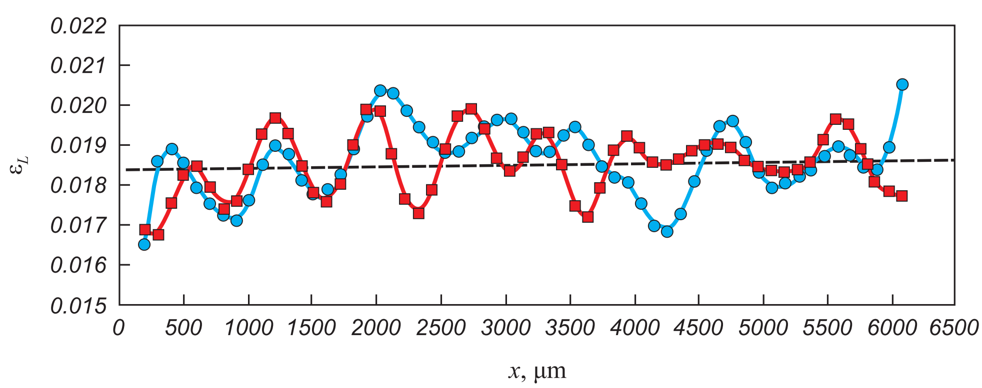

Fig. 4. Dependence of local deformation ε_L on yield plateau on the position of markers *x*

Рис. 4. Зависимость локальной деформации ε_L на площадке текучести от положения маркеров *x*

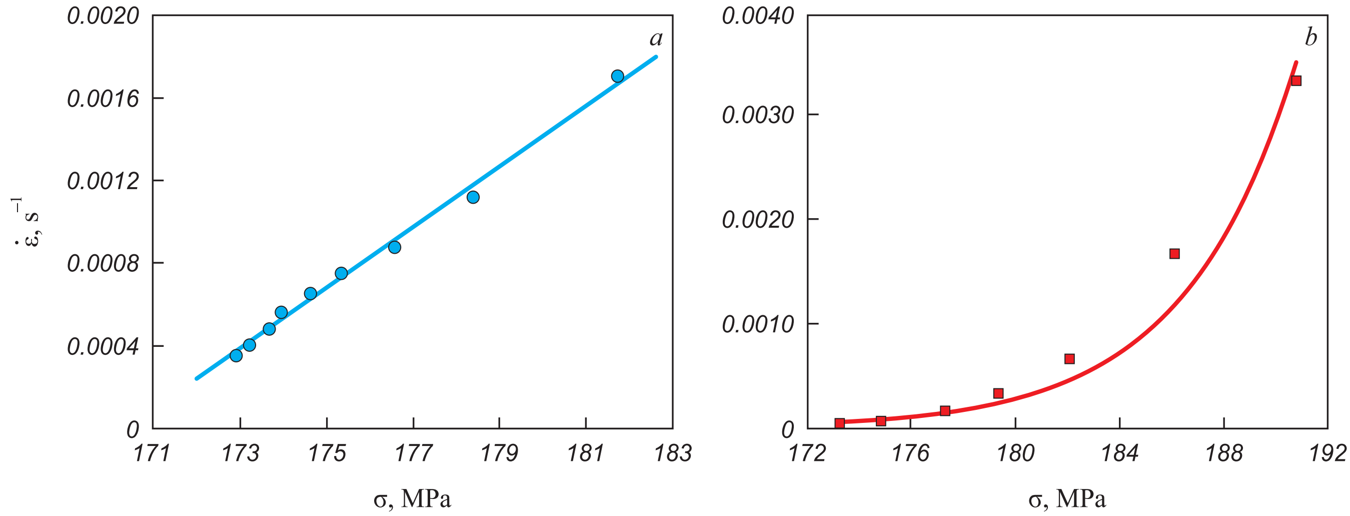

Fig. 5. Change of strain rate during serrated movement of the front (*a*) and change in deformation rate during monotonic movement of the front (*b*)

Рис. 5. Изменение скорости деформации при скачкообразном движении фронта (*a*) и изменение скорости деформации при монотонном движении фронта (*b*)

Fig. 5, *a* shows this dependence. It can be seen that $\dot{\varepsilon}$ increases linearly with increasing stress. The correlation coefficient of the interpolating relationship is $\rho = 0.99$. On the other hand, in the case of a monotonically moving front, based on the correlation relationship (Fig. 2) and equations (1) and (2), the strain rates at the front can be calculated for each $\sigma_y^{(l)}$ (Fig. 5, *b*). It is evident that it cannot be interpolated by a linear function. In other words, the strain rates in the monotonically moving front and the serrated moving front react differently to changes in the stress state.

The reason for this difference may be the change in the deformation autowave mode from the autowave of switching to the autowave of excitation. In [13], it is shown that the kinetics of Lüders front motion in ARMCO iron is indeed controlled by the effect of dynamic strain aging, i.e., the delay time t_w of mobile dislocations at barriers overcome by thermally activated processes, and the time t_a of carbon impurity deposition on these dislocations. At temperatures below 393 K, when $t_a \gg t_w$, front moves monotonically and represents an autowave of localized plasticity switching. In this case, the local strain rate increases non-linearly with stress according to a parabolic law. The discrete nature of the deformation front movement occurs under temperature-rate conditions where t_w and t_a are comparable. The serrated moving deformation front represents an autowave of localized plasticity excitation. In this case, the local strain rate depends linearly on the applied stress.

Conclusion

The deformation accumulated on the serrated yield plateau in α-iron is constant. Under these conditions, the width of the front is also a constant in the first approximation.

The local strain rate during the monotonic movement of the front (296 – 393 K) increases with stress according to a power law. In the case of serrated Lüders deformation (393 – 503 K), the local strain rate is directly proportional to the applied stress.

The difference in front kinetics is determined by the reaction characteristics of active deformable media to external mechanical action and is controlled by the effect of dynamic strain aging.

References / Список литературы

1. Hall E.O. Yield Point Phenomena in Metals and Alloys. New York: Plenum Press; 1970:296.
2. Seeger A., Frank W. Non Linear Phenomena in Materials Science. New York: Trans. Tech. Publ.; 1988:125–137.
3. Fridel J. Dislocations. Oxford – London – Edinburg – N. Y. – Paris – Frankfurt: Pergamon Press; 1964:576.
4. Cottrell A.H. Dislocation and Plastic Flow in Crystals. New York: Oxford Univ. Press.; 1953:223.
5. Zuev L.B. Using a crystal as a universal generator of localized plastic flow autowaves. *Bulletin of the Russian Academy of Sciences: Physics*. 2014;78(10):957–964. https://doi.org/10.3103/S1062873814100256
6. Zuev L.B., Barannikova S.A., Danilov V.I., Gorbatenko V.V. Plasticity: from crystal lattice to macroscopic phenomena. *Progress in Physics of Metals*. 2021;22(1):3–57. https://doi.org/10.15407/ufm.22.01.003
7. Krinsky V.I. Self-Organization: Autowaves and Structures Far from Equilibrium. Berlin: Springer-Verlag; 1984:270.
8. Danilov V.I., Gorbatenko V.V., Danilova L.V. Kinetics of Lüders deformation as an autowave process. *Izvestiya. Ferrous Metallurgy*. 2022;65(4):261–267. (In Russ.). https://doi.org/10.17073/0368-0797-2022-4-261-267

Данилов В.И., Горбатенко В.В., Данилова Л.В. Кинетика деформации Людерса как автоволнового процесса. *Известия вузов. Черная металлургия*. 2022;65(4):261–267. https://doi.org/10.17073/0368-0797-2022-4-261-267

9. Zuev L.B., Danilov V.I., Danilova L.V. Gorbatenko V.V. Deformable material as a nonlinear active medium. *Izvestiya vuzov. Fizika*. 2022;65(2):89–97. (In Russ.). https://doi.org/10.17223/00213411/65/2/89

   Зуев Л.Б., Данилов В.И., Данилова Л.В. Горбатенко В.В. Деформируемый материал как нелинейная активная среда. *Известия вузов. Физика*. 2022;65(2):89–97. https://doi.org/10.17223/00213411/65/2/89

10. Babich V.K., Gul' Yu.P., Dolzhenkov I.E. Strain aging of steel. Moscow: Metallurgiya; 1972:320. (In Russ.).

    Бабич В.К., Гуль Ю.П., Долженков И.Е. Деформационное старение стали. Москва: Металлургия; 1972:320.

11. Liu W., Lian J. Stress-state dependence of dynamic strain aging: Thermal hardening and blue brittleness. *International Journal of Minerals, Metallurgy and Materials*. 2021;28(5):854–866. https://doi.org/10.1007/s12613-021-2250-1
12. Prokhorov A., Vshivkov A., Plekhov O., Kashaev N., Fomin F., Ozerov M., Zherebtsov S. The effect of LSP on the structure evolution and self-heating of ARMCO-iron under cyclic loading. *Metals*. 2021;11(8):119. https://doi.org/10.3390/met11081198
13. Danilov V.I., Orlova D.V., Gorbatenko V.V., Danilova L.V. Effect of temperature on the kinetics of localized plasticity autowaves in Lüders deformation. *Metals*. 2023;13(4):773. https://doi.org/10.3390/met13040773
14. Sutton M.A. Digital Image Correlation for Shape and Deformation Measurements. Springer Handbooks. Boston MA: Springer; 2008:1100.
15. Briers J.D., Webster S. Quasi real-time digital version of single-exposure speckle photography for full-field monitoring of velocity or flow fields. *Optics Communication*. 1995;116(1-3): 36–42. https://doi.org/10.1016/0030-4018(95)00042-7
16. Erbeck R., Merzkirch W. Speckle photographic measurements of turbulence in an air stream with fluctuating temperature. *Experiments in Fluids*. 1988;6(2):89–93. https://doi.org/10.1007/BF00196458
17. Zuev L.B., Gorbatenko V.V., Pavlichev K.V. Elaboration of speckle photography techniques for plastic flow analyses. *Measurement Science and Technology*. 2010;21(5):054014. http://dx.doi.org/10.1088/0957-0233/21/5/054014
18. Sun H.B., Yoshida F., Ohmori M., Ma X. Effect of strain rate on Lüders band propagating velocity and Lüders strain for annealed mild steel under uniaxial tension. *Materials Letters*. 2003;57(29):4535–4539. https://doi.org/10.1016/S0167-577X(03)00358-6
19. Estrin Yu., Kubin L.P. Plastic instabilities: phenomenology and theory. *Materials Science and Engineering: A*. 1991;137: 125–134. https://doi.org/10.1016/0921-5093(91)90326-I
20. Zazhigaev L.S., Kish'yan A.A., Romannikov Yu.I. Methods for Planning and Processing the Results of a Physical Experiment. Moscow: Atomizdat; 1978:232.

    Зажигаев Л.С., Кишьян А.А., Романников Ю.И. Методы планирования и обработки результатов физического эксперимента. Москва: Атомиздат; 1978:232.

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Вклад авторов / Contribution of the Authors

Д. В. Орлова – анализ и обсуждение экспериментальных результатов, написание первичного варианта рукописи.
В. И. Данилов – формирование идеи, утверждение окончательного варианта рукописи.
В. В. Горбатенко – проведение механических испытаний, регистрация эволюции картин локализованной пластичности, анализ и обсуждение хронограмм.
Л. В. Данилова – математическая обработка экспериментальных данных, построение и анализ корреляционных зависимостей.
А. В. Бочкарева – проведение экспериментальных исследований, анализ данных по ширине и скорости деформационного фронта.

D. V. Orlova – analysis and discussion of experimental results, writing the draft version of the manuscript.
V. I. Danilov – formation of the article main concept, revising final version of the manuscript.
V. V. Gorbatenko – carrying out mechanical tests, registration of evolution of localized plasticity patterns, analysis and discussion of chronograms.
L. V. Danilova – mathematical processing of experimental data, construction and analysis of correlation dependencies.
A. V. Bochkareva – conducting experiments, analysis of width and rate of the deformation front.

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