Journal of Applied Mechanics and Technical Physics, Vol. 47, No. 3, pp. 426–432, 2006

PLASTIC FLOW INSTABILITY AT THE NECKING STAGE IN ZIRCONIUM ALLOYS

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UDC 660.539.382.2

Regular features in plastic-strain macrolocalization are examined at the parabolic stage of strain hardening in the É635 *and Zircaloy-2 zirconium alloys. Instability of the plastic flow is observed, which is manifested as a periodic variation of space–time distributions of local strain as revealed by means of speckle interferometry. The data obtained are discussed within the framework of a synergetic model for the plastic flow evolution at the final stage.*

Key words: *zirconium alloys, strain, localization, instability, fracture.*

Introduction. Macrolocalization is known to accompany the plastic flow at all stages of the process [1, 2]. It has been found that both wave and stationary space–time patterns of plastic-strain localization can be observed during the deformation of single-crystal and polycrystalline samples. Emergence of either pattern is governed by the strain-hardening law acting at the corresponding stage of deformation [1, 2].

In the present work, we examine the regular features of development of plastic strain localization at the parabolic stage of the plastic flow and at the prefracture stage in samples of the commercial zirconium alloys É635 (an alloy contains by weight 1% Nb; 1.3% Sn; 0.4% Fe; rest Zr) and Zircaloy-2 (an alloy contains by weight 1.2% Sn; 0.5% Fe–Ni–Cr; rest Zr) traditionally used in manufacturing fuel-cell tubes for nuclear reactors [3].

It was found previously that the flow curves of zirconium alloys immediately above the yield point can be fitted with parabolas $\sigma \sim \varepsilon^n$, where n is the parabolicity factor [4–6]. We will call this deformation stage the parabolic stage. The parabolic stage displays an intricate behavior and the corresponding strain curve can be divided into several segments approximated by parabolas with decreasing parabolicity factors running through the values form 0.1 to 0.7. The minimum value of n refers to the beginning of formation of a visible macroscopic neck. Of special interest here is the related evolution of the space–time patterns of plastic-strain localization [4–6]. For instance, a stable stationary strain localization pattern with a constant spatial period λ is typical only of strain patterns with parabolicity factors $n \geqslant 0.5$ in the law $\sigma \sim \varepsilon^n$. A typical feature of segments with $n < 0.5$ in the parabolic strain curve is the motion of localized strain nuclei with a varying spatial period, which is accompanied by periodic strain accumulation at a localized nucleus that transforms to a neck by the end of the parabolic stage.

Physical reasons for the observed evolution of localization at the final stage of the plastic flow in zirconium alloys remain unclear; therefore, strain-localization features resulting in the loss of stability of the plastic flow and in subsequent fracture call for a further study. The knowledge of the specific features of generation and development of plastic-strain localization finally resulting in fracture under plastic deformation is of considerable practical significance, in particular, in estimating the technological plasticity margin of zirconium alloys heavily strained in production of finished articles [3].

1. Materials and Experimental Procedure. We examined recrystallized samples of the É635 and Zircaloy-2 alloys. The É635 alloy consisted of α-Zr grains (the mean grain size was about 4 μm) with dispersed inclusions of Fe_2Zr, Nb_2Zr, and Zr_3Fe intermetallides inside the grains and on their boundaries (the mean size

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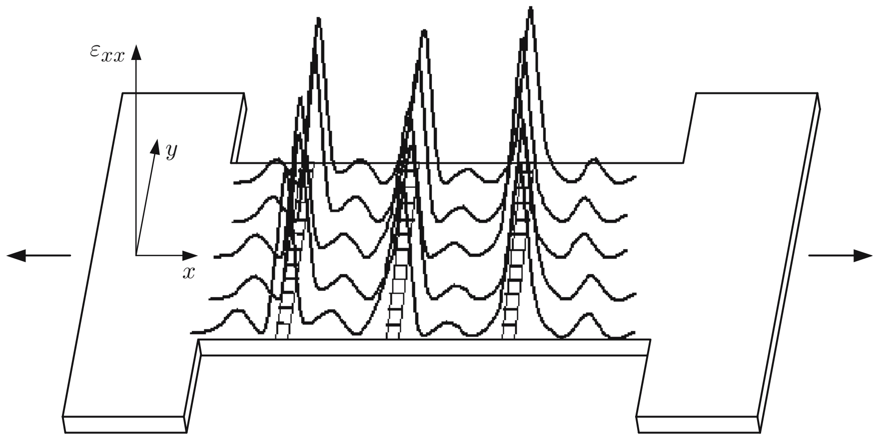

Fig. 1. Schematic illustrating the determination of local strains in plastic-flow nuclei of tensile samples (the nuclei are shown as shaded areas).

of inclusions was 0.08 μm). Zircaloy-2 alloy consisted of recrystallized α-Zr grains (approximately 6 μm) with bulk-dispersed Zr(Fe,Cr)$_2$, Zr$_2$(Fe,Ni), and Zr$_2$(Fe,Cr) intermetallic inclusions approximately 0.15 μm in size.

Flat samples with working-section dimensions of $42 \times 5 \times 2$ mm were extended on an Instron-1185 machine with the rate of displacement of the moving clamp equal to 0.1 mm/min ($\dot{\varepsilon} = 4 \cdot 10^{-5}$ sec^{-1}). The field $\boldsymbol{r}(x, y)$ of point displacement vectors on the sample surface was registered simultaneously with recording stress-strain curves by speckle interferometry [1, 2]. Numerically differentiating this field, we were able to obtain all plastic-distortion tensor components $\beta_{i,j} = \nabla \boldsymbol{r}$. Below, we give distributions of only one component, local strain $\varepsilon_{xx} = \partial u/\partial x$ (u is the projection of the vector $\boldsymbol{r}$ onto the tension axis x).

To reveal the evolution behavior of the space–time distribution of strain in the samples, speckle interferometry was used to examine the local strain in macrolocalization nuclei in the course of the plastic flow. Both the integral local tensile strain obtained by summation of the plastic-distortion tensor components ε_{xx} over the area occupied by a nucleus (Fig. 1) and the local-strain increment $\Delta\varepsilon_{xx}$ in this nucleus were determined. Summation of ε_{xx} at the parabolic loading stage allowed us to identify zones with intense strain localization. In these zones, the local-strain increment $\Delta\varepsilon_{xx}$ was found as the difference between the integral values of ε_{xx} recorded with an interval of 0.2% of the total stain.

A quantitative characteristic of the plastic-flow macrolocalization pattern is the spatial period of strain localization λ, which is the distance between the neighboring strain-localization nuclei. For this distance to be determined more accurately, the spectral analysis of the observed distributions of the plastic-distortion tensor components ε_{xx} was employed.

2. Results and Discussion. The use of $\ln(s - s_e)$–$\ln e$ plots allowed us to identify several straight-line segments with constantly decreasing parabolicity factors n in each parabolic strain curve (Fig. 2). The plastic-flow curve ends with a portion where n tends to zero, corresponding to the stage at which a visible neck (not shown in Fig. 2) is developed in the sample.

The evolution of strain localization at the parabolic stage on the strain curve in zirconium alloys has the following specific feature previously established in [4–6]: for $n \geqslant 0.5$, the system of plastic-strain localization nuclei is stationary, whereas these nuclei start moving at $n < 0.5$, and this motion continues until the parabolic stage is over.

A careful study of the quantitative characteristics of space–time macrolocalization patterns at the parabolic stage of the plastic flow in the alloys considered revealed the following feature: the spatial period λ of local strain nonuniformities depends on the parabolicity factor n. For instance, at the deformation stage corresponding to the segments with $n \geqslant 0.5$ in the parabolic curve, the value of λ remains unchanged. The latter observation complies with previous studies in which the strain-localization period was measured in single-crystal and polycrystalline materials at the parabolic stage of the loading curves [1, 2]. Nonetheless, the spatial period does not remain constant at deformation stages of the examined alloy corresponding to segments with $n < 0.5$ in the parabolic

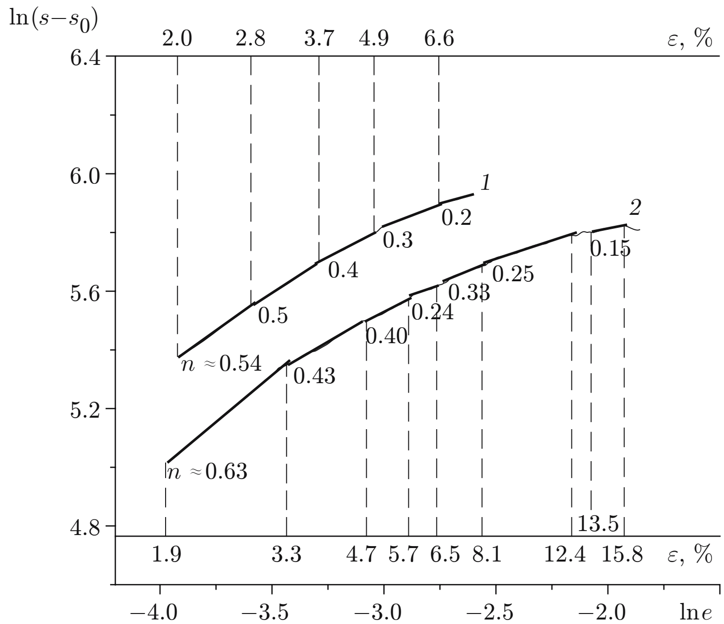

Fig. 2. Logarithmic plot of plastic-flow curves for the É635 alloy (1) and Zircaloy-2 alloy (2).

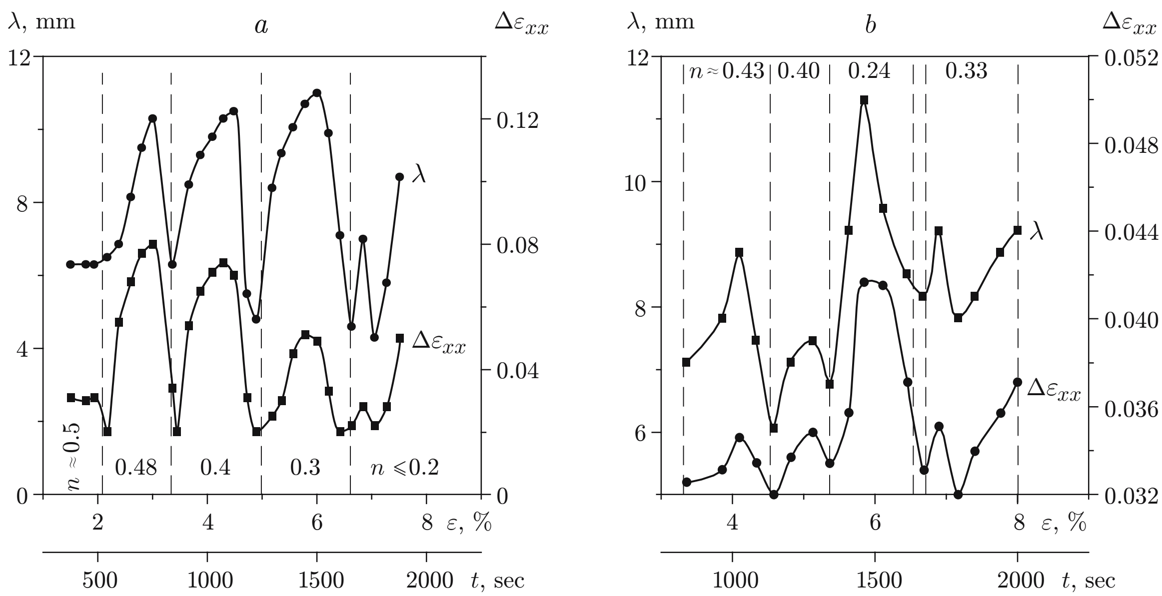

Fig. 3. Spatial period of strain localization λ and local tensile strain increment $\Delta\varepsilon_{xx}$ in the neighborhood of a prefracture site versus the total strain in the É635 alloy (a) and Zircaloy-2 alloy (b).

curve. An analysis of plastic-strain localization patterns corresponding to parabolic segments with parabolicity factors ranging in the interval from 0.5 to 0.1 showed that the value of λ displays periodic changes as the deformation is developed. Figure 3 shows the spatial period of localization λ and the value of $\Delta\varepsilon_{xx}$ at the parabolic stage versus the total strain in the alloys. It should be noted that the period of variation of λ correlates with the duration of stages corresponding to individual segments in the parabolic curve (see Fig. 2).

Summation of the local tensile strain values ε_{xx} over the sample at the parabolic stage of loading allowed us to identify three strain-localization zones for which the integral local elongation ε_{xx} exceeded the average value over the sample. The distance between these zones was approximately 0.8 cm for both alloys. As the deformation continued

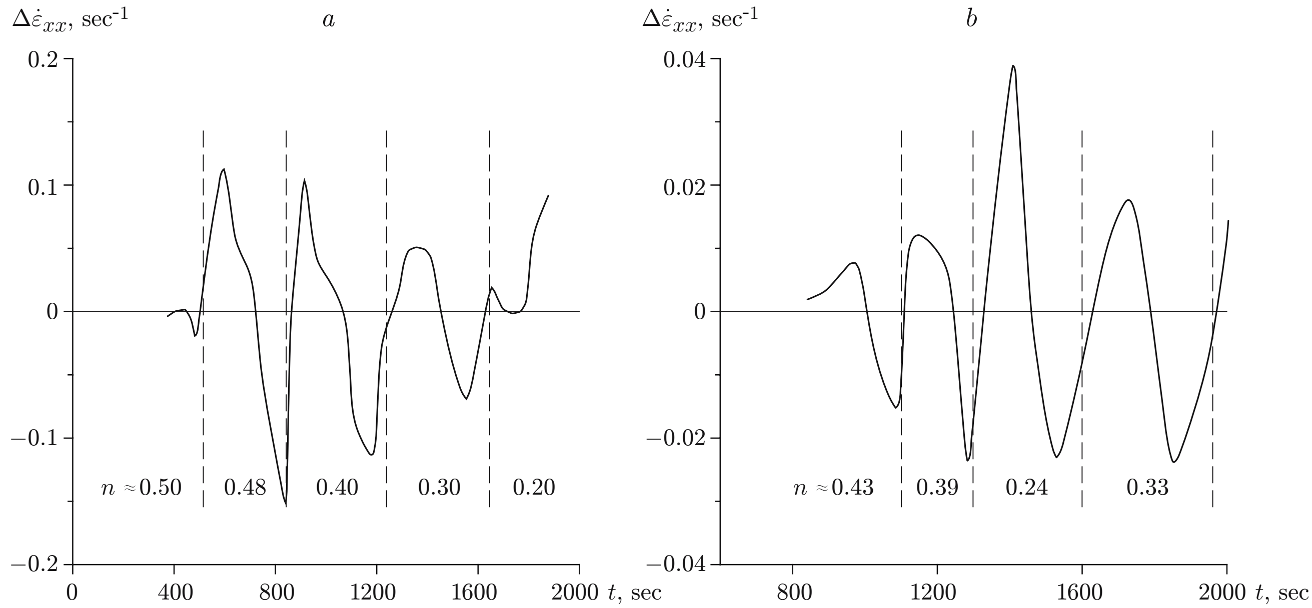

Fig. 4. Distribution of the strain-localization rate $\Delta\dot{\varepsilon}_{xx}$ at the parabolic stage in deformed É635 alloy (a) and Zircaloy-2 alloy (b).

its development, the value of ε_{xx} grew faster in one of the localization nuclei that subsequently transformed to a prefracture site and then to a neck. Such strain-localization evolution, giving rise to several "inactive" necks, one of which subsequently became "active" (stable) with deformation development, was observed in tensile samples of In–Pb alloys [7].

A comparison between the curves of the incremental local elongation $\Delta\varepsilon_{xx}$ and the spatial period of inhomogeneities λ versus the total strain at the parabolic stage revealed the following feature: a periodic increase in λ is accompanied by periodic accumulation of strain in a chosen plastic-flow nucleus. Figure 3 shows the variation $\Delta\varepsilon_{xx}$ for the nucleus from which the neck is formed.

It should be noted that a similar periodic dependence of $\Delta\varepsilon_{xx}$ on the total strain was also observed for two other zones with intense strain localization, but the local elongation increments in these zones at the deformation stages corresponding to parabolas with $n < 0.3$ decreased gradually until one plastic-flow localization nucleus corresponding to the emerging neck was formed.

Figure 4 shows the distribution of the strain-localization rate $\Delta\dot{\varepsilon}_{xx}$ (growth rate of the local strain $\Delta\varepsilon_{xx}$ per time unit in the nucleus under consideration) at the parabolic stage of the plastic flow in É635 and Zircaloy-2 alloys. An oscillatory behavior of the strain-localization rate in the hardening–softening regime is observed here, which can be adequately understood within the framework of deformable continuum mechanics. Indeed, owing to a local increase in the strain rate resulting in more intense local hardening in a localized nucleus, the corresponding growth of stress in the flow at this site is accompanied by retardation of strain localization and, subsequently, by more uniform sample deformation. As a result, a hardening–softening cycle is observed. In our case, this cycle corresponds to one of the segments with $n < 0.5$ in the parabolic curve (see Fig. 4). Such a behavior displayed by the material is typical of superplastic flows [8].

The value of the spatial period of strain localization yields the distance between the neighboring strain-localization nuclei along the tension axis; therefore, the quantity $N = \lambda/L$ (L is the working length of the sample) in the general case is the total number of localization nuclei in the sample. Hence, in addition to λ, the number of strain-localization zones n changes at the parabolic stage of deformation. It can be expected that a decrease in the number of localization nuclei (or an increase in λ) is accompanied by accumulation of the local strain ε_{xx} in these zones. An analysis of the space–time patterns of the distribution of local-elongation components in both alloys allowed us to establish the mechanism of plastic-strain accumulation in the zones with intense localization. A schematic illustrating this process for Zircaloy-2 alloy is shown in Fig. 5 (the arrows show the direction in which the strain-localization nuclei move with varied λ). Figure 5a shows the distributions of local elongations ε_{xx} for

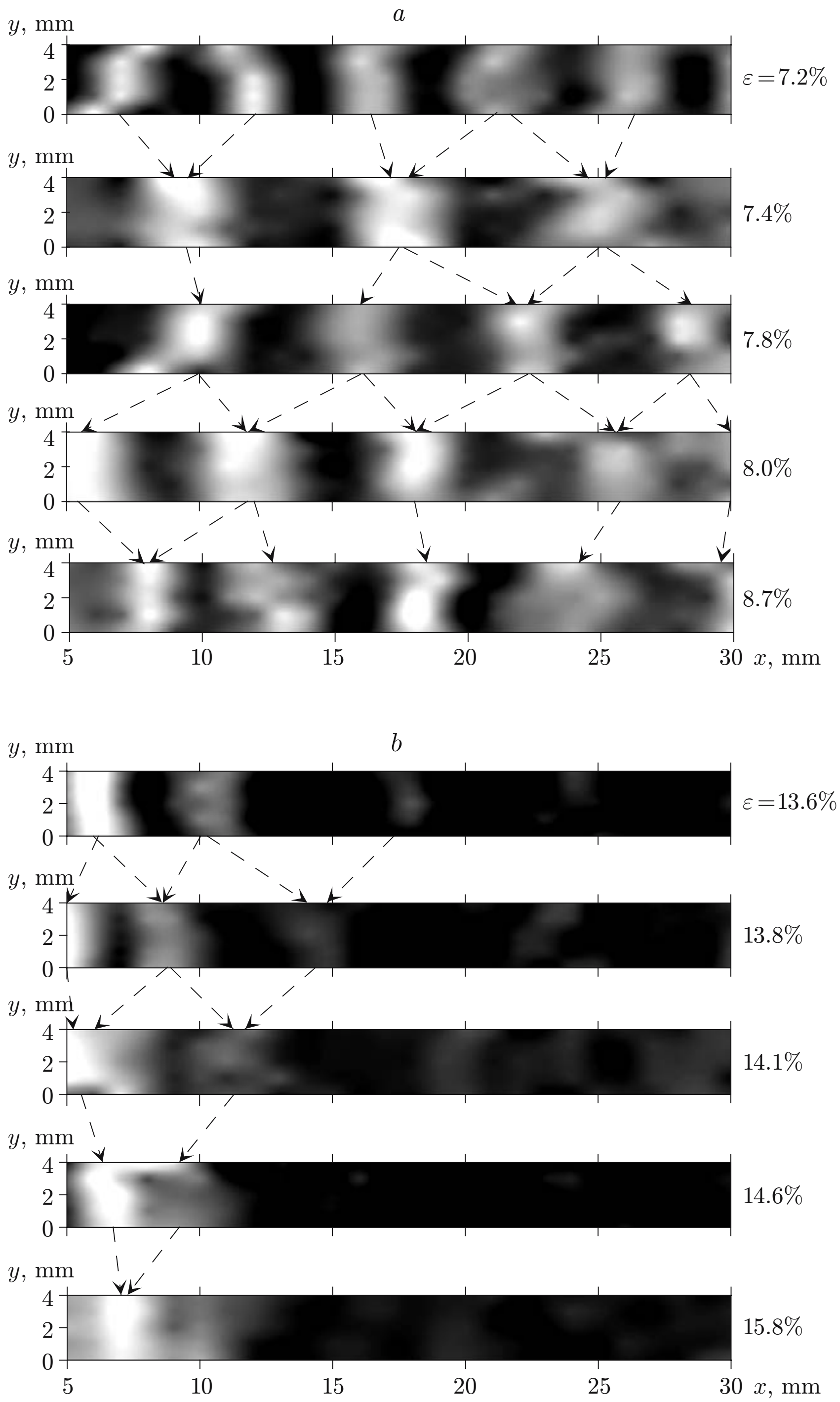

Fig. 5. Evolution of plastic-strain localization patterns in a Zircaloy-2 alloy at the deformation stages corresponding to segments with $n \approx 0.3$ (a) and $n \approx 0.1$ (b) in the parabolic loading curve.

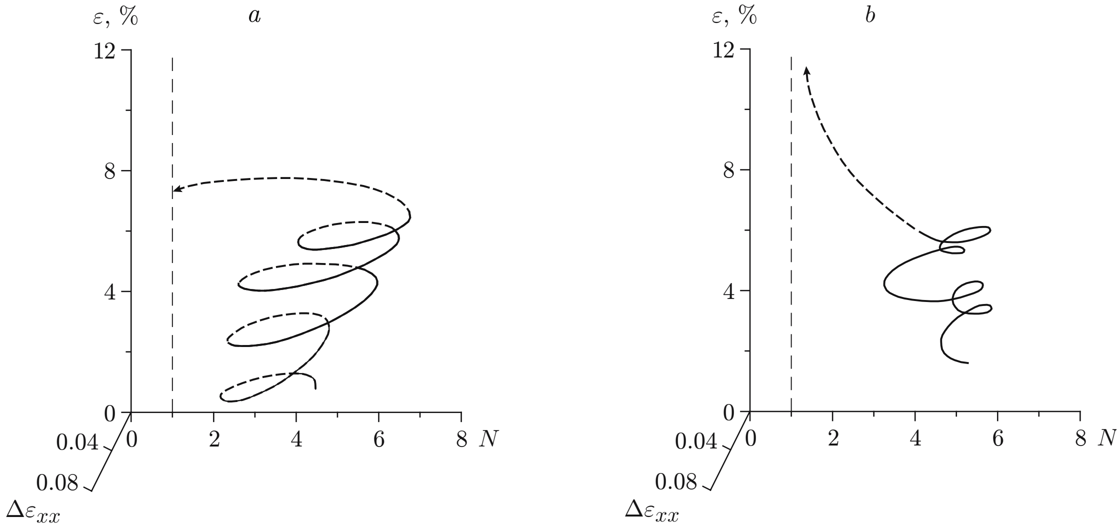

Fig. 6. Phase trajectory for the evolution of strain localization in the É635 alloy (a) and Zircaloy-2 alloy (b) (the dashed curve shows the limiting state of the system with a neck).

different values of the total strain at the deformation stage corresponding to the parabolic curve with $n \approx 0.3$ for one cycle of variation of the spatial period λ (see Fig. 3b). It is seen that an increase in λ is accompanied by merging of strain-localization nuclei, which is responsible for strain accumulation in several localization zones (see Fig. 3b); a decrease in λ results in the formation of additional strain-localization zones of lower intensity. Figure 5b illustrates the evolution of spatial distributions of strain-localization nuclei in the sample at the prefracture stage corresponding to the segment with $n \approx 0.1$ in the parabolic curve. In this figure, one can trace the formation of on strain-localization nucleus is formed, which gives rise to a neck visually seen at this stage.

It should be noted that the present results correlate well with the concept of space–time cyclicity of plastic-strain localization, according to which the well-developed plastic deformation is always nonuniform due to alternating hardening and softening processes in local regions inside the material [9, 10]. It is known that interrelated collective effects on the meso- and macrolevels can give rise to an oscillatory regime with periodic variations of the defect structure and mechanical characteristics of materials [11]. Moreover, the study of plastic-flow localization and instability [7, 12] revealed a cyclic behavior of the space–time evolution of local-strain distributions accompanied by the onset of an oscillatory process of the hardening-softening type. According to [12], this process initiates periodically emerging local softening regions in the material, “traveling necks,” originating long before the formation of a stable neck and subsequent fracture in the material.

The present data allow us to conclude that it is the self-consistent periodic variation of the spatial period of strain localization λ and the strain increment $\Delta\varepsilon_{xx}$ in localization nuclei that defines the plastic-flow instability at the parabolic stage in deformed zirconium-alloy samples, which accompanies the formation of one localization nucleus to be developed into a neck.

In the evolution of dissipative structures during the development of deformation [13, 14], synergetic ideas make it possible to explain the observed reconstruction of space–time strain-localization patterns at the parabolic stage of the plastic flow in zirconium alloys. We believe that the transformation of the steady regime established at the stage on the segment with $n \approx 0.5$ in the parabolic curve is indicative of the loss of current-equilibrium stability, resulting in a new periodic regime called a limiting cycle. The periodic dependence $\lambda(t)$ shown in Fig. 3 is typical of the so-called tough loss of stability where the system undergoes a jumplike transition from the stationary to the oscillatory regime [14]. In this case, the development of the strain-localization pattern can be presented as the motion of a representative point along a trajectory in the phase space corresponding to the time evolution of the deformed system. This trajectory yields the geometric relation between the parameters $\Delta\varepsilon_{xx}$ and N for different degrees of plastic strain (different times). Figure 6 shows the phase trajectories for strain localization in the É635 and Zircaloy-2 alloys. It is seen that the phase curve exhibits an unstable limiting cycle after the end of the stage corresponding to the segment with $n \approx 0.5$ in the parabolic curve [13, 14]. As the total strain increases, the system evolves following one of the spiral turns so that the density of strain-localization nuclei N first decreases as the nuclei merge together and then increases.

In the course of such evolution, the strain-localization intensity $\Delta\varepsilon_{xx}$ in the nuclei first increases and then decreases owing to redistribution of local strains among newly generated additional zones, which corresponds to more uniform deformation of the sample. Apparently, one turn of the spiral corresponds to a segment with $n < 0.5$ in the parabolic curve, presenting an individual stage in plastic-flow localization in the alloy. The established oscillatory regime is unstable, because the trajectory leaves the limiting cycle, tending to a point corresponding to one localization nuclei, namely, a neck (see Fig. 6). Stability of the plastic flow over the phase trajectory depends on the strain-hardening character and on the plasticity margin of the material. For instance, for many plastic materials, the strain curve can be approximated by a parabola with a parabolicity factor n tending to 0.5, which ends with an increase in amplitude of one of the stationary nuclei, followed by its subsequent transformation to a neck [1, 2]. Provided that the parabolic curve has at least one segment with $n < 0.5$, one cycle of periodic variation of λ is possible, as was observed, e.g., in silicon iron [15].

Conclusions. The present experimental data concerning the periodic behavior of the spatial period of local strains and their intensities in plastic flows of zirconium alloys allow some common features to be revealed in the evolution of the nonequilibrium system at the final stages of the process.

1. At the parabolic stage of strain hardening with $n < 0.5$, the plastic flow is accompanied by the loss of stability, characterized by periodic variation of the spatial period λ of strain macrolocalization correlating with periodic variation of the local-elongation increment $\Delta\varepsilon_{xx}$ in localization nuclei.

2. The oscillatory regime that characterizes the plastic-flow localization instability at the final stage of deformation can be described by a phase trajectory, which is a limiting cycle whose stability is determined by the capability of the material to plastic deformation.

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