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NONLINEAR NECK FORMATION IN ZIRCONIUM ALLOYS

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The macrolocalization of plastic strain in samples of zirconium alloys with hexagonal close-packed structure under uniaxial tension was studied by laser speckle interferometry and surface profiling. The occurrence of oscillatory instability in the parabolic stage of plastic flow of zirconium alloys was found to be due to a local nonuniform change of the sample shape. The kinetics of process was shown to be determined by oscillatory changes in the contraction and elongation strains at the macrolocalization site in the hardening-softening regime.

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

Introduction. The currently available experimental information on the strain macrolocalization as an obligatory component of plastic flow at all its stages [1] demonstrate the need to take into account this phenomenon in estimating the ability of materials to undergo stable plastic deformation. Previous studies [2, 3] using laser speckle interferometry have found the features of strain macrolocalization due to the oscillatory instability of plastic flow in the parabolic stage of strain hardening of zirconium alloys. It has been shown that, for a value of the parabolic index $n < 0.5$, there are periodic accumulation of local elongation strain and oscillatory changes in the localization rate of longitudinal strains in the hardening-softening regime at a number of sites of stable macrolocalization, one of which is then transformed to a neck.

Some authors (see, for example, [4–6]) associate the instability of plastic flow at the macroscopic level with the beginning of a nonuniform local change of the sample shape. According to the model of a critical nucleus of strain oscillation (localization) proposed in [6], the general mechanism of the development of instability is due to the supercritical growth of the nucleus, resulting in a local change in the sample geometry.

In the present work, the strain macrolocalization was studied experimentally by independent methods of laser speckle interferometry and sample surface profiling during extension in order to determine the causes of plastic flow instability in zirconium alloys the parabolic stage of strain hardening.

1. Materials and Technique of Experiment. The strain macrolocalization of É125 and zircalloy-2 zirconium alloys with hexagonal close-packed structure (HCP alloys) was studied. The samples having the shape of a bilateral blade of dimensions $46.0\times 9.8\times 1.7$ mm were subjected to uniaxial tension on an Instron-1185 test machine at a strain rate of $3.6\cdot 10^{-5}$ sec^{-1} under a scheme corresponding to a plane stress–strain state. Simultaneously with recording the strain diagram by speckle interferometry, we recorded the field of displacement vectors of points on the sample surface [1]. In addition, the local total elongation strain was determined by summation of the plastic distortion tensor components ε_{xx} and ε_{yy} on the area occupied by the localization site, and the local strain increments $\Delta\varepsilon_{xx}$ and $\Delta\varepsilon_{yy}$ at this the site were determined as the difference of the local total strains $\varepsilon^{\rm c}_{xx}$ and $\varepsilon^{\rm c}_{yy}$ in each 0.2% of the total strain was determined. The kinetics of local plastic flow both in the sample as a whole and at the strain localization sites was studied using the method of reference points with photo recording of the sample during the tests [7, 8]. Profilograms of the sample size variation during extension were constructed be means of laser contactless surface profiling on a MICRO MEASURE 3D station. The distance between the reference

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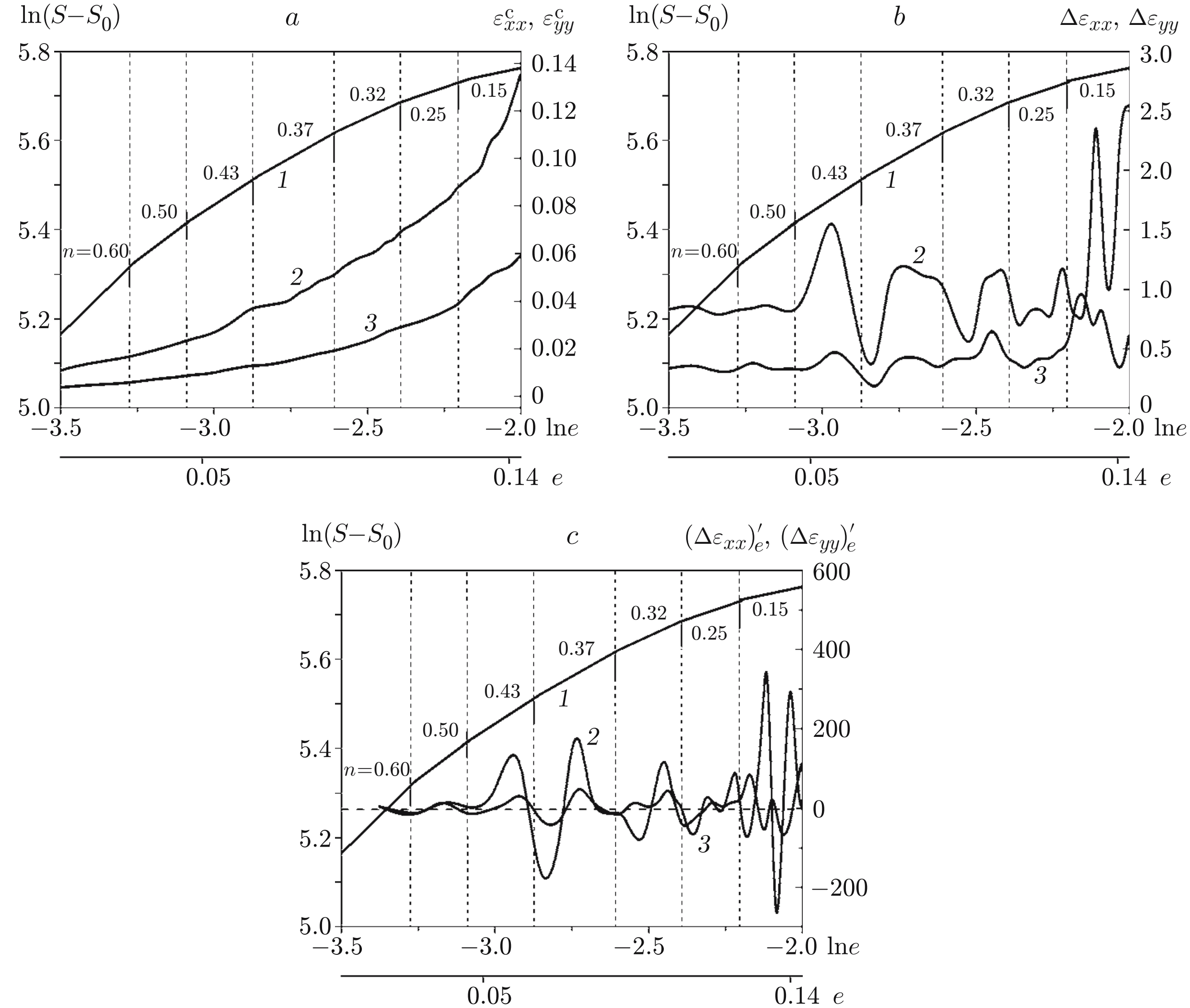

Fig. 1. Accumulation of local contraction and elongation strains in the neck formed in the parabolic stage of the strain curve (curves 1) for zircalloy-2 alloy: (a) local total elongation ε^{c}_{xx} (curve 2) and contraction ε^{c}_{yy} strains (curve 3); (b) local strain increments $\Delta\varepsilon xx$ (curve 2) and neck formation $\Delta\varepsilon_{yy}$ (curve 3); (c) rates of local strain increments $(\Delta\varepsilon_{xx})'_e$ (curve 2) and $(\Delta\varepsilon_{yy})'_e$ (curve 3).

points along the extension axis was measured by the method proposed in [8]. True strain was calculated by the formula $e = \ln(l/l_0)$, which provided quantitative estimates of the evolution of local strain rates in the longitudinal and transverse directions in the final stage of deformation up to necking.

2. Results of Experiments and Discussion. It has been found [9] that the parabolic segment of the strain curve of HCP zirconium alloys is difficult to analyze, and, in the logarithmic coordinates $\ln(S - S_0)$–$\ln e$, it can be divided into a number of straight-line segments with discretely decreasing parabolic index n. The formation of segments with $n < 0.5$ is due to the macrolocalization of plastic flow. Using laser speckle interferometry, the sites of stable strain macrolocalization were found and the nature of the successive accumulation of the total local elongation strain in them ε^{c}_{xx} [2, 3] was studied.

In the present work, to determine the effect of transverse stresses on the occurrence of oscillatory instability of plastic flow (for $n < 0.5$), we studies the evolution of the distribution of the local contraction component ε_{yy} both in the test sample as a whole and at the stable localization sites. The accumulation of the total strains of local elongation and local contraction at the stable localization sites during deformation up to the beginning of necking were examined.

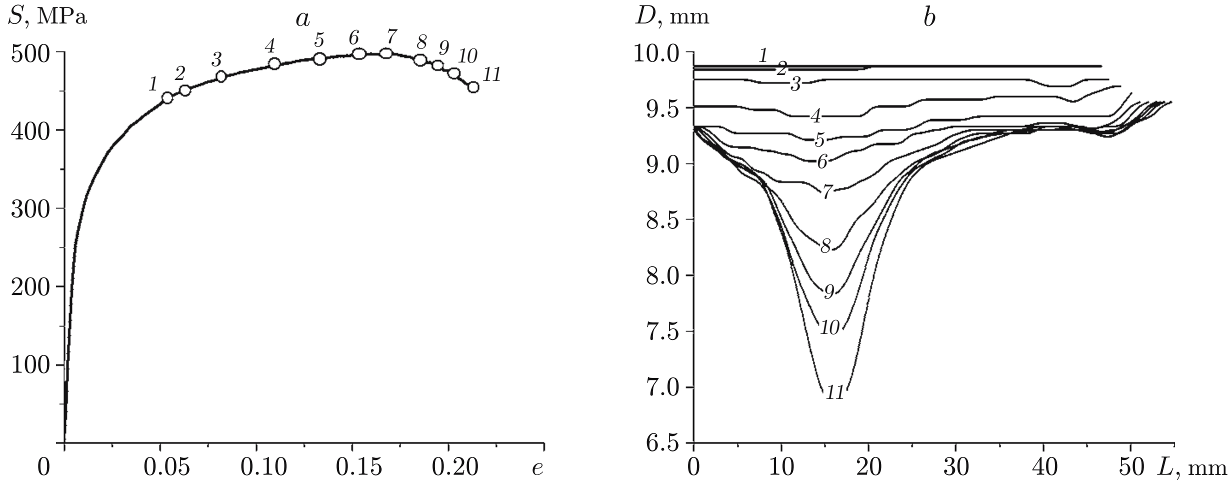

Fig. 2. Tensile strain curve (a) and profilograms (b) of an É125 alloy sample: 1–11 are the numbers of the points at which photographing of the sample was performed.

Figure 1a gives curves of the quantities $\varepsilon^{\rm c}_{xx}$ and $\varepsilon^{\rm c}_{yy}$ versus total strain e in the region of the localization site which is subsequently transformed to a neck for an zircalloy-2 alloy. In addition, Fig. 1a gives a tensile strain curve of the sample in the logarithmic coordinates $\ln(S - S_0)$–$\ln e$. It is evident that the rate of accumulation of the local elongation strain at the localization site is approximately twice the rate of accumulation of the local contraction strain. At the beginning of the stage of parabolic strain hardening at $n > 0.5$, the rate of change of both quantities is constant, and at $n < 0.5$, the sizes of the area of localization of both elongation and contraction strains at the site decrease sharply and then continue to decrease until the maximum load is reached. A feature of the curves is that the accumulation of local total elongation and contraction strains occurs nonuniformly.

The investigation of the kinetics of strain localization at the stable macrolocalization sites showed that the dependences of the local strain increments $\Delta\varepsilon_{xx}$ and $\Delta\varepsilon_{yy}$ (Fig. 1b) and the increment (or acceleration) rates of local elongations $(\Delta\varepsilon_{xx})'_e$ and contractions $(\Delta\varepsilon_{yy})'_e$ (Fig. 1c) on the total strain e are nonlinear at these sites. The oscillatory change in the localization rate occurs in the hardening-softening regime. In Fig. 1 it is evident that, using the high-sensitivity speckle interferometry method, the beginning of the periodic accumulation of local elongation and contraction strains at the localization sites can be recorded even on the segments of the parabolic curve with $n \geqslant 0.5$. However, a sharp increase in the local strain increment and localization rate occurs as the parabolic index decreases to values $n < 0.5$. As the total strain increases, the amplitudes of oscillations of these localization parameters increase and become maximal when the maximum load is reached. Obviously, the continuous periodic accumulation of strains at the localization sites in both the longitudinal and transverse directions should lead to a local change in the sample shape.

Profiling of the sample being deformed showed that the deformation in three directions (transverse, longitudinal, and normal to the sample surface) develops nonuniformly. Strain macrolocalization is most pronounced in the profilograms showing a change in the shape of the lateral surface of the sample along its working part. Figure 2 gives profilograms for an É125 alloy sample (L and D are the length and width of the sample, respectively). The points on the strain curve correspond to the moments the profilograms were taken. It is evident that, at $e > 5\%$, there are two macrolocalization sites on the surface at which the sample geometry begins to change. With time, one of the sites ceases to increase, whereas the other grows more rapidly and then transforms to a neck (see Fig. 2). A similar picture of the evolution of the strain localization due to a sample shape change was obtained for the deformation along the normal to the sample surface, but, in this case, the surface shape changed less significantly. The picture of the evolution of the local longitudinal strain distribution was obtained from measurements of the distance between the reference points along the extension axis. It was found that strain macrolocalization caused a local change in the sample surface geometry even at $e > 5\%$.

A comparison of the obtained profilograms with the strain curve show that the sudden local nonuniform change in the sample geometry due to a local change in the surface curvature and a local increase in the surface

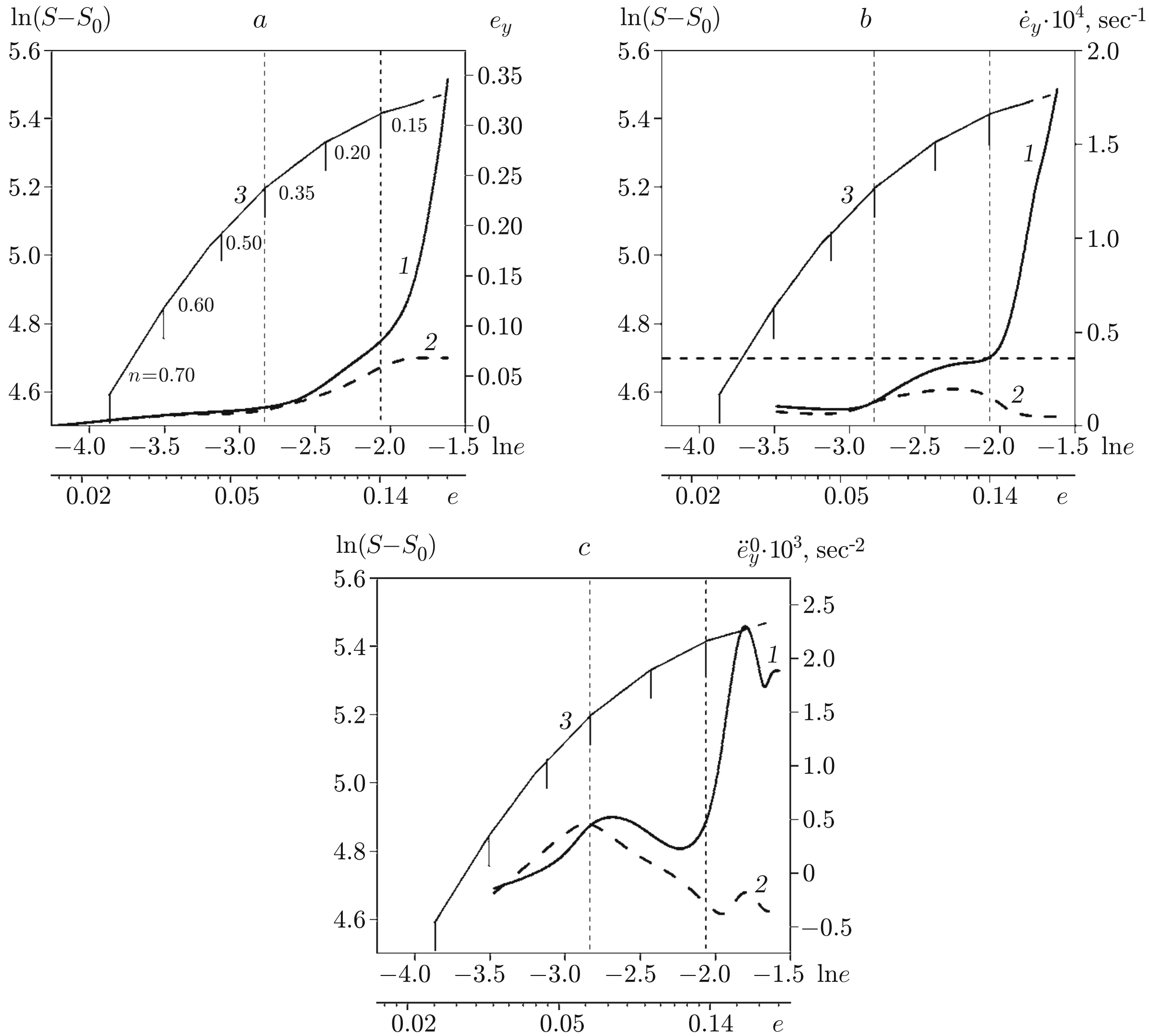

Fig. 3. Evolution of local contraction strain at the active neck (curves 1) and inactive neck (curves 2) in the parabolic stage of the strain curve (curves 3) for an É125 alloy: (a) local contraction strain e_y; (b) local contraction strain rate $\dot{e}_y$; (c) local contraction strain acceleration $\ddot{e}_y$; the horizontal dashed line is the applied strain rate determined by the rate of displacement of the machine grips equal to $3.6 \cdot 10^{-5}$ sec^{-1}.

area occurs on a parabolic segment with a parabolic index $n < 0.5$. This implies that instability of the plastic flow of zirconium alloys on this segment is due to a nonuniform distortion of the sample during neck formation. Thus, it can be assumed that the discrete decrease in the parabolic index beginning from the value $n = 0.5$ is a consequence of the plastic flow macrolocalization of the materials studied.

It is of interest to study the development of localized strain sites in É125 and zircalloy-2 alloys found in the profilograms. Thus, beginning from the parabolic segment with $n < 0.5$, two necks are formed, one of which first develops more rapidly than the other and then lags behind it, i.e., in the initial stage there is a competition of the necks (see Fig. 2). Such sites of localized strain are referred to as an active neck and an inactive neck [4]; the active neck is the one at which the degree of strain localization is higher at the given time. Usually, during extension of zirconium alloy samples, 2–4 inactive necks can be observed [2].

The development of localized strain sites is presented in Fig. 3, which gives curves of the kinetic characteristics of local deformation. Figure 3a shows curves of the local transverse strain and strain rate and acceleration at the

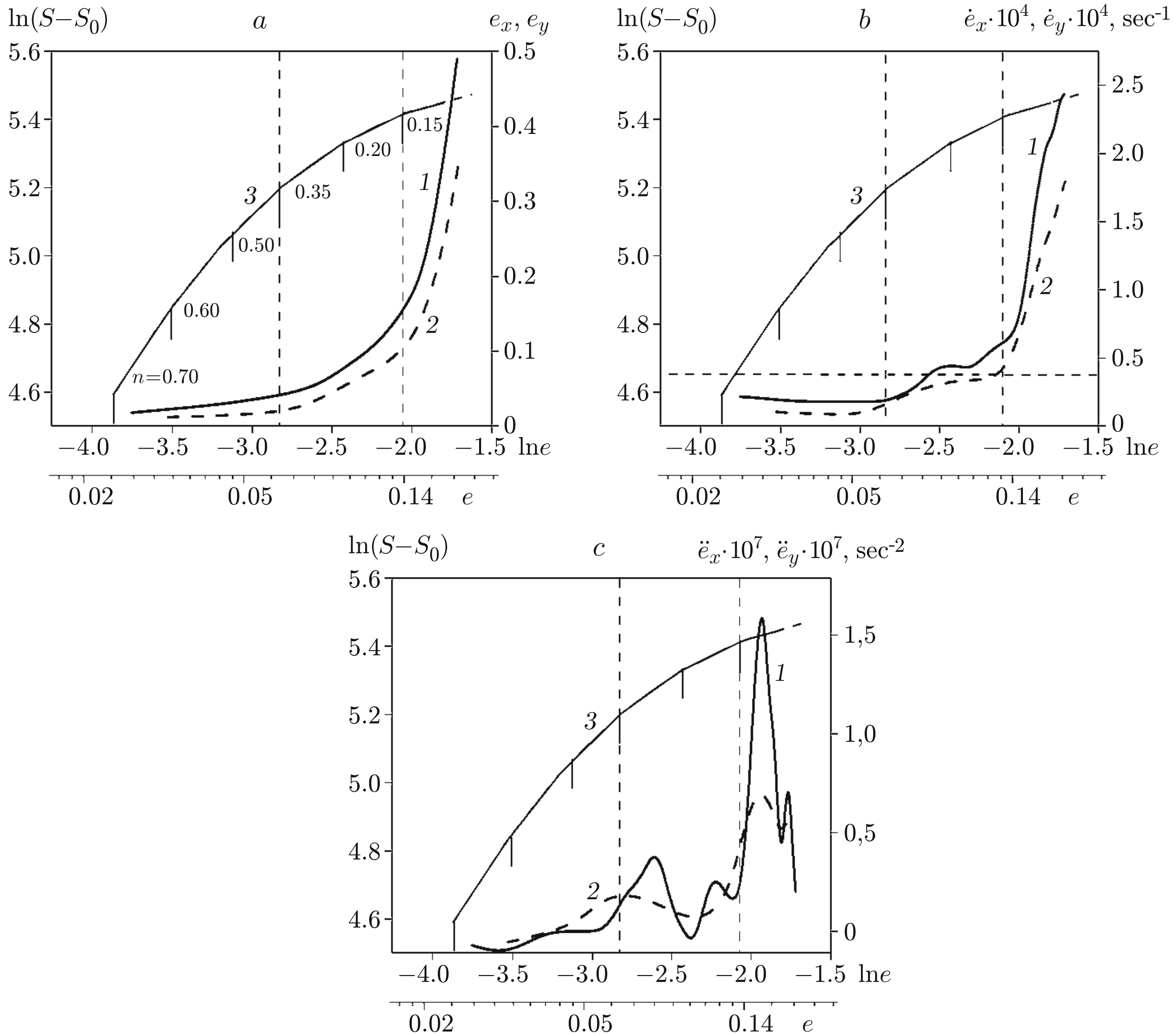

Fig. 4. Change in the local elongation strain (curves 1) and contraction strain (curves 2) in the neck in the parabolic stage of the strain curve (curves 3) for É125 alloy: (a) local strains e_x and e_y; (b) local strain rates $\dot{e}_x$ and $\dot{e}_y$; (c) local strain accelerations $\ddot{e}_x$ and $\ddot{e}_y$.

active and inactive necks versus total strain. It is evident that, from the moment of the occurrence of plastic flow, the strain rate on the segments on which the necks were then formed is lower than the applied strain rate, and after the formation of the sites of local geometrical distortion at $n < 0.5$, it increases. After that, the local contraction strain rate at the inactive neck decreases until one plastic flow macrolocalization site remains, which is an active neck. Before fracture, the strain rate at this neck reaches the maximum value equal to $1.8 \cdot 10^{-4}$ sec^{-1}.

In Fig. 3c, it is evident that the degree of strain localization at the sites increases nonuniformly: one can see periodic acceleration and deceleration of the process of contraction strain accumulation. An analysis of the strain localization at the active neck in the longitudinal and transverse directions revealed a number of regularities. Figure 4a shows strain curves and local elongation and contraction strain curves, which can be divided into three segments. In the parabolic stage of plastic flow at $n \geqslant 0.5$, there is an insignificant linear increase in the local strain, and beginning from the nonuniform change in the geometrical sample shape, accompanied by a decrease in the parabolic index to values $n < 0.5$, the increase in the local strain becomes nonlinear. The most considerable increase in the degree of strain localization occurs at $n < 0.2$, when geometrical softening of the material begins and a neck is formed at which fracture occurs. Thus, the elongation strain rate of the sample at the neck reaches a value equal to $2.5 \cdot 10^{-4}$ sec^{-1}, which is more than seven times the applied strain rate (Fig. 4b).

The kinetics of strain localization in the active neck is shown in Fig. 4b and c. It is evident that, beginning from the parabolic segment ($n < 0.5$), the kinetic localization parameters $\dot{e}$ and $\ddot{e}$ in the hardening-softening regime behave in an oscillatory manner. A similar pulsating nature of development of local strain has been observed for cylindrical samples of some plastic materials [3]. In the kinetic curves of strain localization (Fig. 4b and c), one can also distinguish three segments: a segment with an almost constant rate of local plastic flow ($n \geqslant 0.5$), a segment of oscillatory hardening-softening ($0.2 < n < 0.5$), and a segment of stable softening ($n < 0.2$), which corresponds to the formation of a macroscopic neck. For extension of plane samples, the development of localization of longitudinal and transverse strains has the following feature. The oscillation of the local contraction strain at the macrolocalization site formed at $0.2 < n < 0.5$ leads in phase the oscillation of the local elongation strain. In the stage of stable softening upon reaching the maximum loading, these oscillations coincide in phase, which is accompanied by a sharp increase in their amplitude and formation of a neck at which fracture occurs. It can be assumed that the observed nonlinear oscillations of local longitudinal and transverse strains at the macrolocalization site are interrelated. Indeed, a gradual increase in the effect of the geometrical factor leads to the beginning of formation of a complex stress state responsible for the occurrence of a hydrostatic stress component [10]. In this case, due to the growth of transverse stresses, there is an increase in the material flow stress in the longitudinal direction [3]. Apparently, an increase in the strain rate in the transverse direction in the localization zone leads to hardening and, as a consequence, to deceleration of the localization of transverse strain, which is accompanied by an increase in the local longitudinal strain rate, hardening, and, ultimately, deceleration of strain localization along the extension axis. The oscillatory process of geometrical hardening-softening at the macrolocalization site in the transverse and longitudinal directions continues until the oscillations coincide in the phase. This moment determines the beginning of formation of a neck at which fracture of the sample occurs. The observed oscillatory instability phenomenon is analogous to the frictional self-oscillations due to complex oscillations of a body in the normal and tangential directions to the friction surface [11]. In this case, the force of resistance to deformation and the rate of extension of the sample are similar to the friction force and sliding rate.

Conclusions. The study leads to the following conclusions.

By using speckle interferometry and surface profiling, it was found that the occurrence of oscillatory instability in the parabolic stage of plastic flow of zirconium alloys is due to the beginning of a local nonuniform change in the sample geometry, which is a precursor of neck formation. This process begins in the parabolic stage at a value of the parabolic index $n < 0.5$ and is accompanied by a gradual decrease in the parabolic index.

Three stages of necking were revealed: the stage of linear increase in the rate of local strains at $n > 0.5$, the stage of local oscillatory hardening-softening of the material determined by the periodically progressing decrease in the transverse section of the sample ($0.2 < n < 0.5$), and the stage of stable softening ($n < 0.2$), at which a macroscopic neck is formed.

The accumulation of local strains at the macrolocalization sites was found to proceed nonlinearly in both the longitudinal and transverse directions; the kinetics of periodic hardening-softening is determined by the oscillatory nature of the maximum transverse and longitudinal strains at the macrolocalization site.

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