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HIGH-TEMPERATURE PLASTIC DEFORMATION AND ACOUSTIC EMISSION OF ALUMINUM IN A LOW-STABILITY STATE

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It is found out that under conditions of high-temperature mechanical loading of aluminum in a low-stability state, deformation is manifested as discrete macroscopic changes. An analysis of the activation energy of the temperature-dependent deformation and acoustic emission demonstrates that the period of deformation buildup is accompanied by the diffusion-controlled processes, giving rise to a stepwise accumulation of deformation and quasi-periodic transmission of high-amplitude acoustic-emission signals. The activation volume of an elementary deformation event is increasing exponentially with temperature, indicating an increased scale level of cooperative atomic displacements and formation of a local low-stability state or crystal-lattice instability. The macroscopic manifestation of the sharp deformation change (jump) serves as an evidence of correlation between the elementary events of deformation.

Keywords: condensed state of matter, low-stability state, structure, deformation, structural rearrangement.

INTRODUCTION

Low-stability state of metallic materials is generally due to a specific state of the atomic subsystem of the alloys undergoing, say, martensitic transformations. Traditionally these states are associated with anomalously low elasticity moduli, which results from softening of the phonon modes in the vicinity of a martensitic transition, e.g., a $B2 \rightarrow B19'$ transition in nickel titanium [1]. The presence of soft shear modes along {110} <110> results in shear instability of the $B2$-phase lattice and reduced stress of the martensitic shear, e.g., in Au–Cd [1, 2]. In this case, the cooperative rearrangement of the crystal lattice does not require any breaking of interatomic bonds. There is, however, a wide range of phenomena whose realization requires that atomic bonding should be broken: diffusion processes, crack formation, plastic deformation, etc. In these processes, a special state of the system, referred to as a low-stability state, could be associated with the state of an atomic ensemble in the field of mechanical stresses and thermal fluctuations, whose combined action allows the system to overcome the potential [3, 4]. Simulation of such fluctuations in the atomic system made it possible to find out that strong fluctuation of atomic energy could be a comparatively stable dynamic state [11, 12]. An external mechanical loading of metals (such as copper, nickel, or aluminum) is accompanied by an increased concentration of collective dynamic displacements and variations of the activation enthalpy of diffusion processes [11–13].

In the presence of mechanical stress and temperature, the average time of an anticipated elementary event of breaking of the bond depends on the effective value of the potential barrier that is overcome via thermal fluctuations [4, 14, 15]. In so doing, the effective threshold of activation might be considerably reduced (down to zero), thus characterizing a specific state of the atomic ensemble. In this state of the crystal lattice, plastic flow is associated with this peculiar low-stability state also involving a local loss of shear stability in the active zone of stress concentrators. [3], in which case the motion of the dislocation segment occurs via an over-the-barrier athermic pathway.

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Today, it is common knowledge that plastic flow, especially large plastic deformations, cannot be described as an additive contribution from individual dislocations [16]. Under the conditions of a low-stability state of the crystal structure with respect to external actions, interaction of structure defects acquires a governing role in the structure evolution. The experiments on deformation of metals demonstrate [17], that along the direction of tension one observes propagation of the deformation foci, wherein plastic flow is localized.

Localization of the low-stability (or unstable) state of the crystal lattice under conditions of plastic deformation for a classical three-stage plot of mechanical stress versus relative strain is generally associated with the process of self-organization of dislocations, which is manifested in the formation of slip lines and bands [18, 19]. This implies that the deformation behavior of materials indicates the formation of a weak local stability (or instability) of the atomic system under conditions of mechanical loading, which is in a special way (as a hierarchically interconnected correlated events) manifested in different stages of plastic deformation. Acoustic emission accompanying structure evolution mirrors the processes of self-organization and serves a characteristic of low stability (or instability) and elementary processes in the atomic subsystem under conditions of external impact. The discrete-step deformation and the respective acoustic pulses illustrate the spatial-temporal order of defect motion [20]. Discrete macroscopic deformation changes and maximal acoustic emission signals observed during high-temperature deformation of aluminum [21, 22] have to be analyzed from a perspective of low stability (or stability loss) of the crystal lattice and correlation of the elementary deformation events in the region of plastic flow localization. In this work we report the data of our experiment and the results of an analysis of activation parameters of plastic deformation primarily via an investigation of the acoustic and deformation effects in aluminum at high temperatures.

EXPERIMENTAL PROCEDURE

Given the mechanical stress and temperature [4, 14], the average expectation time of an elementary event of breaking the bond would depend on the effective potential-barrier value $U(\sigma) = = U_0 - \gamma\sigma$, which is overcome in a thermo-fluctuation fashion

$$\tau(\sigma, T) = \tau \exp[U(\sigma) / kT]. \tag{1}$$

Quantity U_0 for every metal is a constant, while parameter γ may vary in a wide range, and by a few orders of magnitude exceed the atomic volume [15]. Summand $\gamma\sigma$ represents work of the external forces localized on a small atomic ensemble; it may vary in a wide range as well. The effective activation threshold $U(\sigma)$ may significantly decrease down to zero, characterizing a specific over-the-barrier state of the atomic ensemble. Plastic flow in this state of the crystal lattice is associated with a poor local stability (or stability loss) with respect to the shear in the zone of active stress concentrators [3], in the case where motion of the dislocation segment occurs in an over-the-barrier athermic fashion.

The material under study is technical grade aluminum, and the experiment consisted in thermomechanical cycling of the specimens by varying the temperature under conditions of constant mechanical shear stress or stress variation at room temperature. The temperature was varied cyclically from room temperature to aluminum melting temperature, and the cyclic variation of mechanical stress was performed up to the values covering its yield stress. The parameters measured in the experiment were as follows: temperature, accumulated deformation, r.m.s. acoustic emission and mechanical stress. The experimental setup, whose special feature is loading of the specimen using a mobile grip, was described in [21].

EXPERIMENTAL RESULTS

The experimental data on strain build-up in the course of specimen heating to 640°C under conditions of mechanical loading are presented in Figs. 1 and 2. Stress accumulation in the annealed specimen at a stress value of 65 MPa (Fig. 1) begins starting from about 170°C, with strain value monotonously increasing from 0.35% during

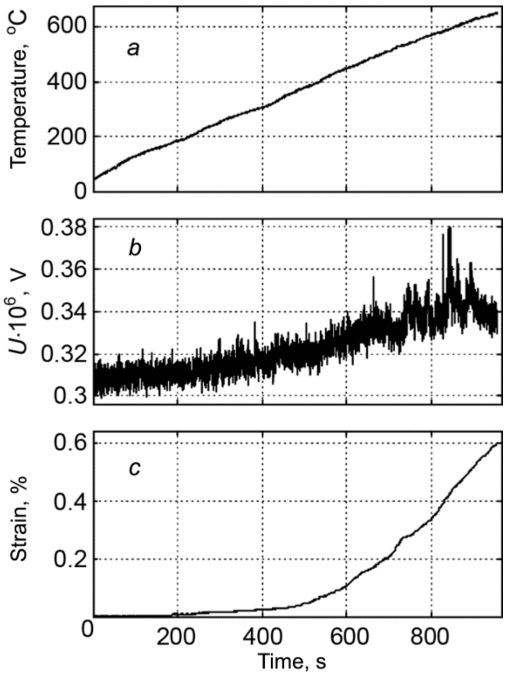

Fig. 1

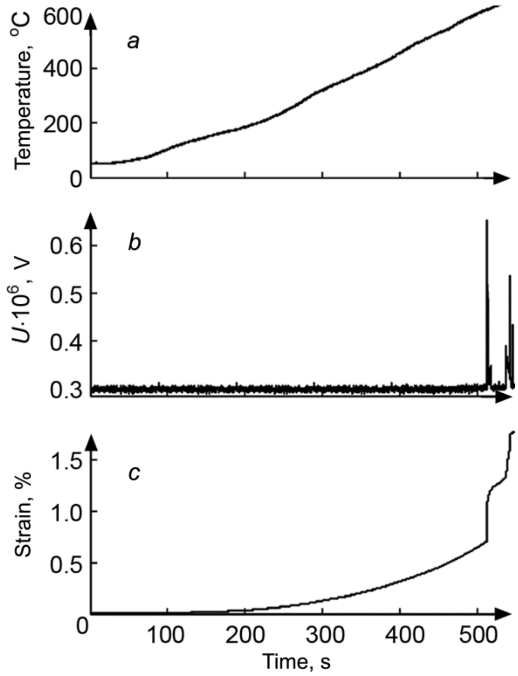

Fig. 2

Fig. 1. Temperature variation (*a*), monotonous behavior of acoustic emission (*b*) and monotonous strain accumulation (*c*) during heating under loading conditions (σ = 6.5 MPa).

Fig. 2. Temperature variation (*a*) and acoustic emission pulses (*b*), correlating with the stepwise strain accumulation (*c*) during heating under loading (σ = 18.7 MPa).

heating to 640°C. At the stress value 18.7 MPa (Fig. 2) this monotonous behavior is accompanied by stepwise changes. These data imply that strain is monotonously accumulated during thermal cycles under mechanical stresses (up to a half of the yield stress). The monotonous behavior of deformation correlates with that of acoustic emission. In the case where stress values exceed that of the yield stress, the monotonous behavior of deformation is broken, followed by sharp deformation changes and unit-step-input acoustic signals. For the load values near the yield stress, every loading cycle is accompanied by anomalously large (up to 0.5%) discrete changes in deformation, which correlate with the high-amplitude acoustic signals as powerful as 1μW. For the loads higher than the yield stress, the cycles with monotonous and non-monotonous strain accumulation, which are accompanied by monotonous or non-monotonous behavior of acoustic emission, respectively, are periodically repeated.

Acoustic emission pulses, which correlate with non-monotonous behavior of strain concentration, are also observed under conditions of isothermal loading (Fig. 3) (inserts in Fig. 3*b*, *d* show well-reserved deformation jumps).

A repetition of the isothermal cycle gives rise to a monotonous section of strain accumulation up to the temperature about 400°C; the deformation jumps are localized in the temperature interval higher than 400°C. The acoustic emission pulses are also localized in this interval.

ACTIVATION PARAMETERS OF HIGH-TEMPERATURE DEFORMATION

Activation parameters play an important role in the description of high-temperature emission. In order to determine these parameters in the case of broken atomic bonding we have to treat any kinetic process [4] as depending

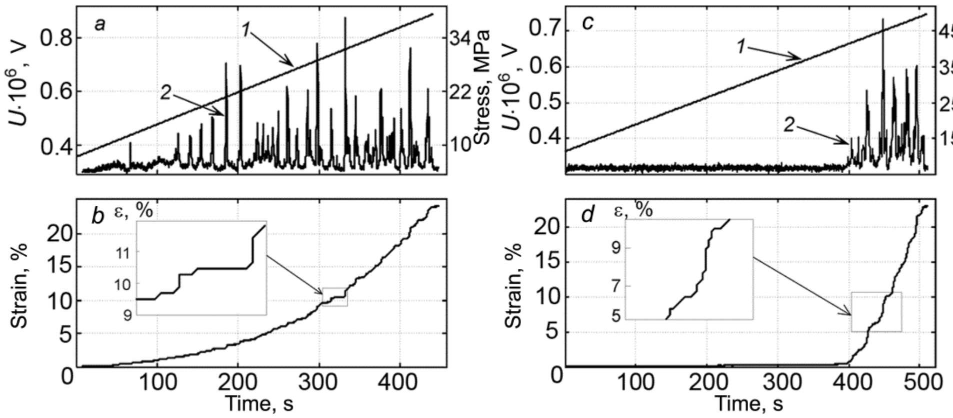

Fig. 3. Pulsed behavior of acoustic emission (*a*, *c*) under conditions of macroscopic monotonous strain accumulation (*b*, *d*) in an isothermal thermomechanical cycle. Temperature – 100°C. The inserts illustrate non-monotonous nature of strain accumulation in an isothermal cycle: loading curve (*1*) and time dependence of the r.m.s. acoustic emission voltage (*2*).

on temperature or mechanical stress. For instance, strain rate variation as a function of temperature or mechanical stress [23, 24]

$$\frac{d\varepsilon}{dt} = \frac{d\varepsilon_0}{dt}\exp\left(-\frac{\Delta H_0 - \sigma b \Delta B}{RT}\right). \tag{2}$$

Here $d\varepsilon/dt$ is the strain rate, $d\varepsilon_0/dt$ is the pre-exponential factor, ΔH_0 is the true activation enthalpy, σ is the mechanical stress localized on a small atomic fragment volume of $b\Delta B$, b is the Burgers vector, ΔB is the area of activation (the area occupied by the dislocation fragment in the course of displacement by the Burgers vector). According to (2), in order to determine the effective activation energy we have to register the rate of strain accumulation as a function of temperature under constant mechanical stress, while to determine the activation volume – the rate of strain accumulation as a function of mechanical stress at constant temperature.

Let us analyze the parameters of activation of high-temperature deformation of aluminum, assuming that the squared r.m.s. acoustic emission voltage (parameter J) during deformation also obeys the exponential law [21]

$$\frac{dJ}{dt} \approx \frac{dJ_0}{dt}\exp\left(-\frac{\Delta H_0}{RT}\right)\exp\left(\frac{\sigma b \Delta B}{RT}\right). \tag{3}$$

If the acoustic signal duration is t, and the r.m.s. stress is U, the value of J can be calculated as $J = \Sigma U^2_i\, \Delta t_i$, where Δt_i is a small time interval within which the r.m.s. stress is assumed to be constant.

Representing the experimental data in the ($\ln U^2 - 10^3/T$) or ($\ln U^2 - \sigma$) coordinates, let us determine the parameters of deformation-process activation. It is evident in Fig. 4 that the experimental data lay along the straight line. This allows us to find the activation parameters to a satisfactory accuracy.

Note that there are two linear sections in the ($\ln U^2 - 10^3/T$) plot, which differentiate two processes controlling strain accumulation and generation of acoustic emission signals. On the other hand, there is one linear section in the ($\ln U^2 - \sigma$) curve, which illustrates the activation-volume constancy at the temperatures of the isothermal thermomechanical cycle.

Let us have a closer look at the effective activation energy and activation volume of the high-temperature deformation of aluminum.

Effective activation energy. The generalized data on the dependence of effective activation energy of high-temperature deformation of aluminum (high-temperature section in Fig. 4a) on mechanical stress presented in Fig. 5

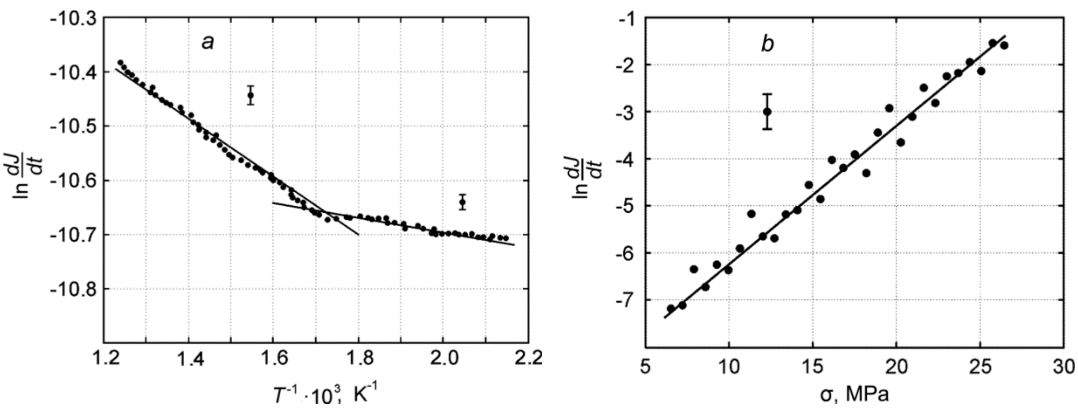

Fig. 4. Experimental acoustic-emission data in one thermomechanical cycle: for determination of activation energy (*a*) and activation volume (*b*).

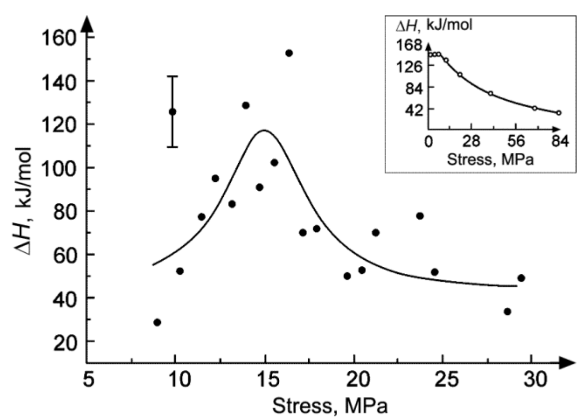

Fig. 5. Effective deformation-activation energy vs. mechanical stress.

imply that it would have a maximum. This form confirms the occurrence of two elementary processes controlling strain accumulation and generation of acoustic signals in the course of high-temperature mechanical loading. From among these processes, we have to single out diffusion-controlled dislocation creep and temperature-activated grain-boundary processes. An insert in Fig. 5 illustrates the dependence of effective activation threshold on stress in a classical representation [25]. It should be noted that in both cases the activation threshold begins to decrease from approximately 15 MPa. In the case under study, an increase in the effective activation threshold begins from approximately 30 kJ/mol (~0.27 eV), the maximum value of the activation threshold being ~160 kJ/mol (~1.5 eV). This might indicate a change in the role and behaviour of diffusion from controlling the dislocation creep (predominantly along grain boundaries) to diffusion mainly occurring in the bulk of the crystallite.

A decrease in the activation energy within the range of stresses between 15–30 MPa down to 40–60 kJ/mol (0.36– 0.55 eV) is assumed to indicate the prevailing type of mass transfer along grain boundaries. In the latter case, diffusion controls strain accumulation due to grain-boundary processes only, where grain-boundary sliding belongs, which occurs via grain-boundary dislocation glide [26]. The grain-boundary sliding proceeds until there is a buildup of grain-boundary dislocations at the triple joints, whose Burgers sum vector would be equal to the Burgers vector of a completed (lattice) dislocation. In this case, a lattice dislocation is initiated, which runs across the crystallite and is absorbed by the adjacent boundary. This process terminates when enough dislocations have build up in the crystallite structure, whose elastic fields suppress nucleation of new dislocations. At high temperatures, it is the processes of

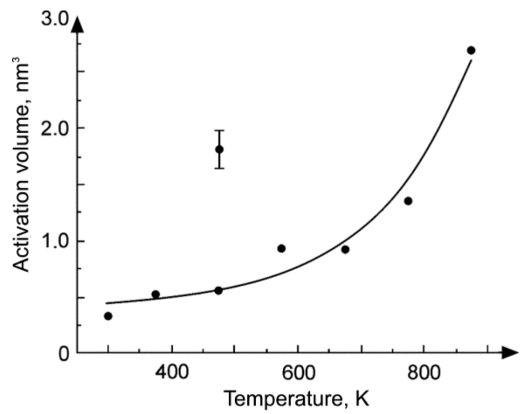

Fig. 6. Activation volume of an elementary deformation event versus the temperature of a thermomechanical cycle.

diffusion-controlled recrystallization which tend to prevail. The process of strain accumulation acquires a quasi-periodic character and is accompanied by quasi-periodic acoustic emission.

Activation volume. Let us discuss the temperature dependence of the activation volume of a unit event of the strain accumulation process (Fig. 6). Based on these data, we can assume that the temperature curve of the activation volume would be exponential. This dependence can be approximated by an exponential function given by

$$y = y_0 + A\exp(T/T_k), \quad (4)$$

where $y_0 = 0.47 \pm 0.12$, $A = 0.0027 \pm 0.004$ is the constant factor, and $T_k = 130 \pm 29$. The correlation coefficient is equal to 0.986, which is close to unity. The dimensionality of quantities A and y_0 coincides with that of volume. The value of y_0 is by an order of magnitude larger than that of the atomic volume, which for solids [15, 27] is close to 0.01 nm^3. It is evident that it is the temperatures, T and T_k, which determine thermal energy kT (k – Boltzmann constant) of the atomic system. For $T = T_k$, the addend $A\exp(T/T_k)$ takes on a value of 0.0073 nm^3, which is close to that of the atomic volume of aluminum 0.0165 nm^3 [4, 27]. The value of the activation volume 0.0182 nm^3 derived using Eq. (4) is close to that obtained for the atomic volume (taking into account the error $A = 0.0027 \pm 0.004$). Thus, temperature T_k determines a certain lowest energy kT_k, whose fluctuation ensures a minimum increment in the activation volume, equal in its value to that of the atomic volume. Temperature $T_k = 130 \pm 29$ coincides with the Debye temperature for aluminum. This coincidence might indicate that the loss of stability of the atomic subsystem in the form of a unit event with a single atom would require excitation of the crystal vibration modes.

The exponential growth of the activation volume in the case of increasing temperature indicates a significant increase in the cooperative atomic displacements controlling the unit event of deformation. On the other hand, it confirms the growth of the unit volume (activation volume), in which a weak local stability of the crystal lattice is maintained (until a local instability develops there). A comparison of the increase in the activation volume and stepwise behavior of strain accumulation indicate an increased correlation of the elementary deformation events.

ACOUSTIC EMISSION AND ELEMENTARY EVENTS OF PLASTIC DEFORMATION

An elementary deformation event at elevated temperature is the formation of a strain band that represents outcropping of a large number of dislocations onto the free surface [23, 28]. From the reported data follows that under conditions of thermomechanical action the loss of crystal-lattice stability or low-stability state of the system is manifested in the formation of deformation jumps accompanied by high-amplitude acoustic emission signals. The experiments demonstrate that the shape of the deformation jump significantly influences the acoustic signal amplitude: the lower the tilt angle of the deformation jump, the lower the amplitude. This is accompanied by a considerable

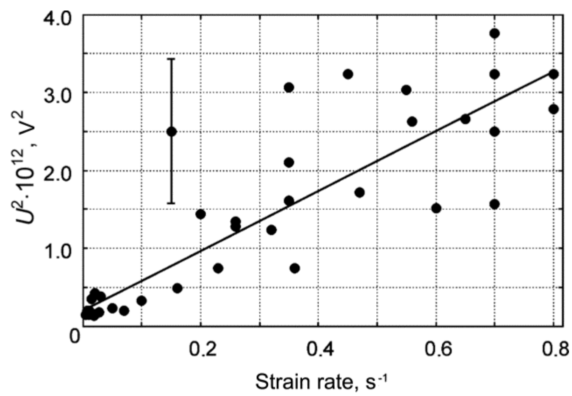

Fig. 7. Squared acoustic signal amplitude versus strain rate in the stepwise section of the curve. The linear approximation of the dependence was performed using a correlation coefficient of 0.9.

broadening of the signal (increased duration of the signal) and even its transformation into a number of separate low-amplitude signals. The slope of the curve of deformation versus time of the process in the stepwise section represents the rate of strain accumulation. Let us discuss the dependence of the acoustic signal amplitude on the strain rate within the stepwise sections of the curve (Fig. 7). The acoustic signal amplitude correlates with the strain rate in the stepwise sections of the curve, indicating the correlation of the acoustic emission signals and the elementary deformation events.

Every abrupt change (jump) of deformation is, according to [29], related to the formation of a strain band, and the dislocation ensemble forming it can be treated as a dynamic system, whose collective behavior is associated with coherent sliding of large groups of dislocations. Thus, this strain band is formed via outcropping of the coherent ensemble onto the specimen's surface, which represents a system of elementary radiating elements. These, in turn, produce an acoustic signal of anomalously high amplitude. When the deformation temperature is increased, these strain bands become larger [28], which corresponds to the increased activation volume. Hence, this increase is also consistent with an increase in the volume of the atomic ensemble undergoing a transition into low-stability state. The macroscopic value of the deformation jump in the experiments under consideration demonstrates that more than one strain band are involved this event. In fact, this situation corresponds to synchronization of the acoustic modes (wave interference) of a certain number of radiators [20, 30]. Thus, the correlation effect in the course of such a macroscopic jump would cover a system of strain bands, and the acoustic signal amplitude might serve a measure of this correlation.

SUMMARY

The acoustic emission detected in the course of plastic deformation serves a reflection of the processes of self-organization within the system of elementary deformation events and is associated with a local atomic ensemble either found in low-stability state or undergoing shear instability. The acoustic emission signals are formed at the macroscopic scale as a result of interference of elementary waves, whose sources are ensembles of dislocations outcropping to the boundary.

At high temperatures, strain accumulation might occur in a non-monotonous manner and represent abrupt deformation changes (jumps) at different scale levels (up to the macroscopic scale), which are followed by acoustic signals whose amplitude correlates with the rate of the deformation increment within the non-monotonous section. The macroscopic deformation jumps indicate a local low-stability of the system or a local loss of stability of the crystal-lattice (of as large as a crystallite). The size of an atomic ensemble, found in a low-stability state or being involved into shear instability, is increasing exponentially, since the activation volume is also increasing with the deformation temperature.

An analysis of the activation energy of the temperature-dependent deformation and acoustic emission demonstrates that concurrently with high-temperature strain accumulation and acoustic emission there are certain diffusion-controlled processes resulting in a quasi-periodic stepwise strain accumulation and quasi-periodic repetition of high-amplitude acoustic emission signals.

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