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MACROSCOPIC CORRELATION OF ELEMENTARY DEFORMATION EVENTS IN A LOW-STABILITY CRYSTAL LATTICE OF FCC-METALS

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Based on an analysis of stepwise deformation and acoustic emission data, a conclusion is made concerning the active role of acoustic emission in activation and, above all – in synchronization of elementary events of deformation on a macroscopic scale. The macroscopic scale is controlled by the wave nature of synchronization of the elementary deformation events in the stress field, which form a low-stability state of the crystal lattice of a deformed material. The principal role belongs to interference of the acoustic signal wave packages, resulting in macroscopic distribution of critical vibrational displacements in a low-stability crystal medium.

Keywords: low-stability state, deformation, acoustic emission.

INTRODUCTION

A special state of the crystal lattice, generally referred to as low stability, could be related to the state of an atomic ensemble in the field of mechanical stresses and thermal fluctuations, whose combined action provides overcoming the potential barrier of bond breaking [1, 2]. There is a wide range of phenomena associated with breaking of interatomic bonds. Here belong such processes as diffusion, crack formation, plastic deformation, etc. An elementary event of bond breaking, e.g., in the case of plastic deformation, is possible under conditions of a combined action of mechanical stresses and energy fluctuation, localized within a limited ensemble of interacting atoms [2]. A simulation study of such fluctuations in an atomic system revealed that a significant energy fluctuation can correspond to a quite stable dynamic state of the lattice, which results from interference (of phonon interaction) [3].

Until today, acoustic emission and its role in plastic deformation processes has not been included into consideration in such studies. It was found out in [1, 4] that under conditions of thermomechanical treatment during the entire heating process there is strain accumulation accompanied by acoustic emission. There are two common scenarios of strain accumulation (monotonous and stepwise) and two types of manifestation of acoustic emission – continuous and pulsed (discrete). It was shown that the acoustic signal amplitude could characterize the correlation between elementary emitters in their ensemble, in other words, in an ensemble of elementary deformation events.

Within the framework an acoustic autoemission model [5], the presence of stepwise deformation and discrete acoustic emission evidence of the spatial-temporal ordering of defect motion in a crystal. In this case, the crystal represents a self-oscillatory system, which is characterized by excitation of oscillations, and the macroscopic processes occur in a cooperative, self-consistent mode, favoring synchronization of oscillations and excitation of quasi-periodic relaxation oscillations.

Mode synchronization and self-synchronization is, in fact, an interference of stress waves with different frequencies. These processes are underlain by a correlation of elementary emitters in a non-equilibrium (active)

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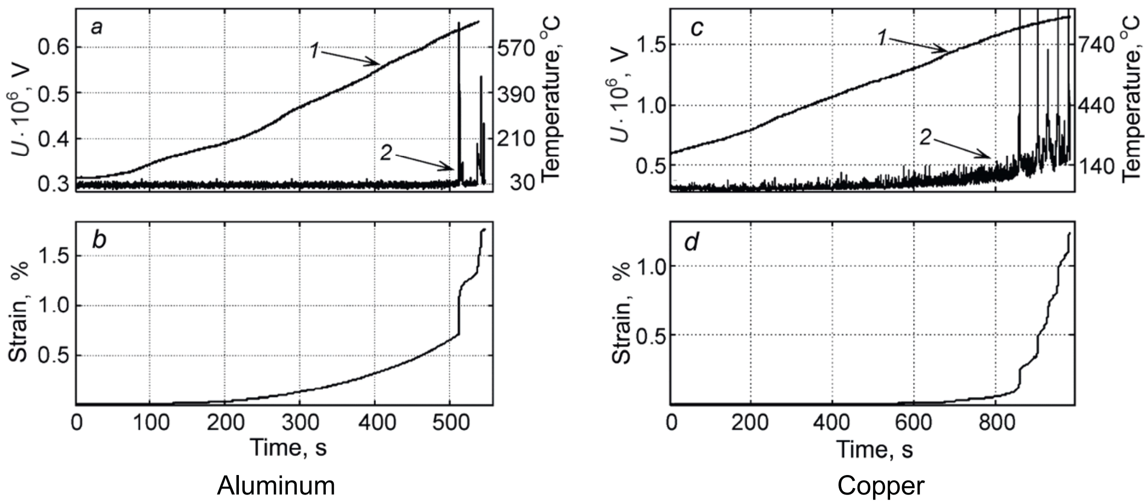

Fig. 1. Monotonous and stepwise strain accumulation (*b*, *d*) and high-temperature acoustic emission pulses (*a*, *c*) under mechanical stress in the neighborhood of low-stability states near the yield stress in a non-isometric thermomechanical cycle for aluminum and copper: temperature per cycle (curve *1*) and r.m.s. acoustic emission voltage (curve *2*).

medium, which result in the formation of short compressive and tensile pulses, whose duration is the shorter, the larger the number of waves with differing frequencies involved in this process [6].

These waves serve characteristics of the stressed state in the vicinity of structure defects under external impact. Fracture in this case represents breaking of the most stressed bonds not only as a result of thermal but also acoustic fluctuations (autoacoustic fluctuations, according to [6]). Similar ideas are expressed in [7, 8], though the data reported imply that those works discuss a particular case of focusing autoacoustic emission in a deformed medium.

The experiments on detection of strain localization under conditions of deformation of single and polycrystals of aluminum and other metals have demonstrated [9] that in the course of plastic deformation, depending on its stage, one or more deformation foci propagate along the axis of tension, in which plastic flow is localized, which evidences of a spatial and temporal correlation of the elementary events of deformation. This strain localization results from the focusing of acoustic emission pulses and the formation of a new deformation focus [7, 8]. Localization of the crystal lattice instability under plastic deformation of crystals for the case of a three-stage dependence of relative elongation on mechanical stress is related to the process of self-organization of dislocations [10].

The purpose of this work is to analyze the role of acoustic emission in localization of plastic deformation of a metallic system in its low-stability state. We are going to address macroscopic deformation jumps and anomalously high acoustic emission signal amplitudes observed in aluminum under conditions of its high-temperature deformation [11, 12] as a result of a loss of crystal lattice stability in a low-stability state of the system and correlation of elementary events of deformation in the region of plastic flow localization under the action of static and dynamic (acoustic) forces.

STRAIN ACCUMULATION AT HIGH TEMPERATURES

Under conditions of high-temperature loading of fcc-metals (e.g., copper or aluminum) there are two typical scenarios of strain accumulation: monotonous at the loads lower than 0.5 yield stress and stepwise at the loads higher than 0.5 yield stress. As shown in Fig. 1*a*, *b*, the monotonous strain accumulation is eventually small (~0.5%), while the stepwise stage represents macroscopic events with up to 0.5% strain at the load ~19 MPa. On the other hand, in copper (Fig. 1*c*, *d*) the value of stepwise strain is found to be ~0.25% at the load ~40 MPa.

It should be noted that monotonous strain accumulation is observed at all test temperatures, with the monotonous strain accumulation at low-temperature being characteristic for all load values and deformation jumps and monotonous sections alternating at high temperatures. Thus, strain accumulation in the high-temperature interval of low-stability states represents a certain quasi-periodic sequence of macroscopic deformation jumps.

The high-temperature strain accumulation is accompanied by generation of acoustic emission signals representing a combination of low-amplitude and high-amplitude pulses. The former are generated in the course of monotonous strain accumulation and the latter during the stepwise strain accumulation stage; note that in copper the pulse height of single acoustic signals is about twice higher than that in aluminum.

AN ACOUSTIC CRITERION OF CORRELATION OF ELEMENTARY DEFORMATION EVENTS UNDER HIGH-TEMPERATURE STRAINING

High-amplitude acoustic emission signals related to the macroscopic deformation jumps exhibit a quasi-periodic behavior as do the deformation jumps themselves. Without doubt, high-amplitude acoustic emission signals in aluminum and copper evidence of a correlation within the system of elementary deformation events under conditions of low-stability and instability of the deformed metal. A structure indication of the correlation effect is the formation of strain bands accompanied by high-amplitude acoustic emission signals [13]. The macroscopic character of deformation jumps suggests that the correlation effect can involve the entire dislocation ensemble on a scale larger than just a single strain band.

An increase in temperature is accompanied by an exponential growth of the activation volume [4], which is indicative of a considerable increase in the scale of cooperative atomic displacements controlling the elementary event of deformation. On the other hand, this suggests an increase in the elementary volume (activation volume), wherein the local low stability (and, eventually, local instability) of the crystal lattice is manifested. A comparison of the exponential growth of the activation volume and the behavior of the stepwise strain accumulation reveals an increased correlation between the elementary deformation events.

It was shown earlier [1, 4] that the acoustic signal pulse height (specifically, squared amplitude) could serve a measure of correlation of elementary deformation events, due to the fact that outcropping of the dislocation segments of the same slip system onto the surface generates a system of coherent acoustic waves, whose interference forms a single acoustic signal of an anomalously large amplitude.

Operation of a single slip system suggests a certain elementary volume that can be termed as a correlation volume. Due to the macroscopic nature of the deformation jump, we obtain a macroscopic value of the correlation volume that represents a combination of unit volumes associated with strain bands. The macroscopic correlation volume involves only those strain bands that form a coherent ensemble of acoustic emitters, whose interference forms a unit acoustic signal.

LOW-STABILITY STATE OF CRYSTAL LATTICE AND WAVE SYNCHRONIZATION OF ELEMENTARY DEFORMATION EVENTS

The analysis performed suggests that the macroscopic volume of potential elementary sources of acoustic emission would become, as in [5, 6], a synchronized ensemble of emitters. It is evident that this synchronization would be realized in a wave-like fashion. An acoustic emission signal generated in the course of formation of a single strain band propagates from its source as a wave package, whose oscillation phase determines the sign of displacements of atoms from their equilibrium positions. These periodic displacements overlap the static atomic displacements due to a static field of stresses localized on structure inhomogeneities.

Low-stability state of the crystal lattice is a decisive factor in wave synchronization of the system of elementary deformation events. Without doubt, an external mechanical action (stress field) localized on defects transforms the crystal medium into a state of low stability due to the effective activation threshold ($U_0 - \gamma\sigma$) reduced virtually down to zero. In this state, an oscillatory displacement is sufficient to activate dislocation sliding, i.e., athermic over-the-barrier sliding, in fact.

In other words, it is necessary to include not only the work of static but also dynamic forces into the equation of bond breaking holdover time

$$\tau(\sigma, T) = \tau \exp[(U_0 - \gamma\sigma - Ud) / kT] . \quad (1)$$

Here, quantity U_0 for the metal in question is a constant, while summand $\gamma\sigma$, representing the work of external static forces localized on a small ensemble, could considerably vary due to variation in parameter γ in a wide range and by a few orders of magnitude exceed the atomic volume [6], and Ud is the work function of the acoustic-wave dynamic forces.

Thus, the effective activation threshold is reduced due to thermal fluctuations, the work of static forces localized on the structure element, and due to the work of dynamic forces of the acoustic wave. The work of dynamic forces from the propagating acoustic pulse acts as a perturbation on the combination of slip systems, whose actuation would depend on the phase of oscillations in the acoustic wave package.

WAVE SYNCHRONIZATION OF ELEMENTARY DEFORMATION EVENTS. TRAVELLING WAVE MODE

Oscillatory displacements propagating in a stressed medium of the wave package activate dislocation glide in the slip plane involved into the macroscopic correlation volume. Due to damping, the oscillation amplitude in the wave package is decreased, which results in termination of sliding in this slip system.

On the other hand, the activated slip system forms an acoustic emission signal that would activate the dislocation glide. This, in turn, activates sliding in another slip system, forming a new wave package. Thus, a system of acoustic signals is formed, which is poorly correlated. In an experimental setting (see Fig. 1) this situation corresponds to a monotonous strain accumulation and growth of the r.m.s. acoustic emission voltage with increasing deformation temperature.

SHOCK WAVES IN A LOW-STABILITY CRYSTAL MEDIUM

Shock-wave generation in crystals in the course of evolution of the crystal medium is extensively discussed due to the opportunities offered by computer simulation approaches [15]. We can argue that generation of shock waves is related to the processes of defect structure relaxation in crystals, shock-wave transformation into a longitudinal acoustic wave, and development of relay atomic displacements. In fact, we observe non-linear oscillations excited in a low-stability crystal medium (active medium, in essence).

STANDING WAVE MODE

A completely different situation is observed in the case of a standing acoustic wave, which requires an interference of two counter-propagating waves [16]. In a deformed specimen this is possible in the case where the wave package is reflected from the external boundary, in other words, the specimen represents a sort of a resonator forming a system of incident and scattered waves. At a distance of $\lambda/2$ (λ – the traveling wavelength) from each other in a standing wave there are nodal points without any oscillations. In between two nodal points there are antinodes, where the wave amplitude is maximal and, in an ideal case, equal to a doubled travelling wave height.

A peculiarity of this wave scenario is the fact that oscillations periodically (with period $T/2$, where T is the oscillation period in the travelling wave) die away and the maximum oscillation amplitude is achieved in between these events. It is noteworthy that in every other point of time the oscillation phase in the antinodes is exchanged for π. On the other hand, maximum stress is generated in the nodal points where the phase changes periodically, thus replacing tension by compression.

Due to damping and radiation losses, standing waves can be generated in the case of compensation of the oscillatory energy losses via the work of the entire system of emitters satisfying the resonator criterion. In this case, a standing wave can be represented as a superposition of travelling and reflected waves with differing amplitudes. For a 3D case, the interference pattern represents a system of nodes and antinodes located in the planes parallel to the resonator boundary.

Thus, macroscopic deformation jumps can be related to development of standing waves in a low-stability crystal medium formed by the field of mechanical stresses, whose cooperative action gives rise to synchronization of plastic shears in a scale determined by the wavelength.

SUMMARY

An analysis of the stepwise deformation and acoustic emission has prompted a logical conclusion on an active role of acoustic emission in the activation, and above all – synchronization of elementary deformation events on a macroscopic scale. The macroscopic scale is determined by the wave nature of synchronization of the elementary deformation events in the field of stresses forming a low-stability state of the crystal lattice of the material under deformation. In this setting, the decisive role belongs to interference of the wave packages of acoustic emission signals, giving rise to a macroscopic distribution of critical oscillatory displacements in a low-stability crystal medium.

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