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

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A discrete pattern of the low-frequency acoustic emission spectrum under conditions of high-temperature plastic deformation of aluminum is analyzed. It is attributed to re-distribution of vibrational energy of the primary acoustic signal over resonant vibrations of standing waves of the resonators. In a low-stability crystal medium, standing-wave oscillations initiate elementary deformation displacements in a certain material volume. The linear dimensions of this volume are related to the length of the standing wave, thus determining the macroscopic scale of correlation. The correlated deformation displacements in turn generate acoustic signals, whose interference results in the formation of a single acoustic signal of abnormally high amplitude. In a low-stability state of the crystal lattice, activation of the elementary plastic shears could result from a combined action of static forces, thermal fluctuations and dynamic forces of standing acoustic waves.

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

INTRODUCTION

A large body of information has been accumulated by now, concerning a specific deformation behavior of condensed systems in a low-stability state (e.g., [1–8]), in particular: localized strain [9], stepwise deformation effects [10], high-temperature deformation jumps and high-amplitude acoustic signals [7]. An analysis of these data allows us to treat acoustic emission as a factor of correlation of elementary deformation events in low-stability condensed systems during plastic deformation, activating elementary plastic shears along with mechanical stresses and thermal fluctuations. The phenomenon of acoustic emission, which accompanies a large number of processes, can no longer be perceived as a passive acoustic effect.

Within the framework a model of acoustic autoemission, certain postulates have been formulated on its active role in the processes of deformation and fracture of crystals [11]. According to the model [12], the presence of stepwise deformation and discrete acoustic emission suggest a 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. 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) 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 interference

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[13]. This implies that fracture represents breaking of the most stressed bonds by not only thermal but also acoustic fluctuations [13]. In this work we assume the concept of an active role of acoustic emission in the processes of plastic deformation of a low-stability crystalline medium to be quite relevant. This would allow us to consistently interpret the principal effects observed in the course of plastic flow. In particular, this concerns strain localization at the macroscopic level and association of plastic shears not only with thermal fluctuations but also with localized acoustic vibrations.

The objective of this work is to perform a comparative analysis of acoustic emission and strain accumulation during heating of FCC-metals under mechanical stresses.

LOW-STABILITY STATE AND ACOUSTIC FACTOR OF CORRELATION

A special state of crystal lattice, which is referred to as a low-stability state [1–8] and is related to the state of an atomic ensemble in the field of mechanical stresses and thermal fluctuations, whose combined action allows overcoming the potential barrier of breaking bonds [7, 14], shall be added with a factor associated with acoustic emission.

Under the conditions of mechanical stresses and temperature [14, 15], the average waiting time for an elementary bond rupture depends on the effective value of the potential barrier, which is overcome via thermal fluctuations. The value of the barrier is decreased by the work of external forces, $\gamma\sigma$, localized on a small atomic ensemble, and thus can vary in a wide range. Here σ is the mechanical stress and γ is a certain parameter. The effective activation threshold could therefore decrease down to zero, thus corresponding to a special state of the atomic ensemble weakly stable to an external action (close to the over-the-barrier motion). Plastic flow in this state of the crystal lattice is associated with local low stability (or stability loss) with respect to a shear acting in the stress-concentrator zone [7], where the dislocation segment motion occurs in an over-the-barrier athermic manner.

Localization of low-stability (or unstable) state of crystal structure during plastic deformation is generally associated with self-organization of dislocations, which results in the formation of slip lines and bands [16, 17]. Note that acoustic emission accompanying structure evolution indicates low-stability (or instability) and elementary processes in the atomic subsystem under external forcing [18].

The above considerations suggest that the macroscopic volume of potential acoustic-emission sources would also [12, 13] get synchronized (or correlated) by an ensemble of emitters. It is evident that such synchronization could be achieved using wave propagation as follows. An acoustic emission signal produced during the formation of a single strain band propagates as a wave packet, within which the oscillation phase controls the direction (specifically, sign) of displacement of atoms from their equilibrium positions. Naturally, these displacements overlap with static atomic displacements due to a static stress field.

A special mention should be made that a local low-stability state of the crystal lattice is a decisive factor in the wave synchronization of a system of elementary deformation events. Under this condition, an oscillatory shift of an acoustic wave is sufficient to activate dislocation slip, which is in fact over-the-barrier, athermic sliding.

This implies that in the expression for the bond-rupture waiting time [7, 14], in addition to the static-force work function U_0, we have to include the dynamic-force work function U_d as follows:

$$\tau(\sigma, T) = \tau \exp[(U_0 - \gamma\sigma - U_\mathrm{d})/kT],$$

where σ is the mechanical stress, γ is a certain parameter, and $\gamma\sigma$ is the external-force work function.

Thus, the effective activation threshold is decreased due to thermal fluctuations and work of the static and dynamic forces of the acoustic wave localized on the structural element. The dynamic-force work of the acoustic pulse exerts a perturbing action on the ensemble of slip systems, whose activation would depend on the oscillation phase in the wave packet.

In the case of a high-temperature deformation of FCC-metals, there were two scenarios of strain accumulation: monotonous and stepwise. It should be noted that the stepwise deformations (jumps) represent macroscopic deformation events followed by high-amplitude acoustic emission signals [7]. It follows that under thermomechanical conditions, the loss of crystal-lattice stability at the macroscopic scale is manifested as deformation jumps and high-amplitude acoustic

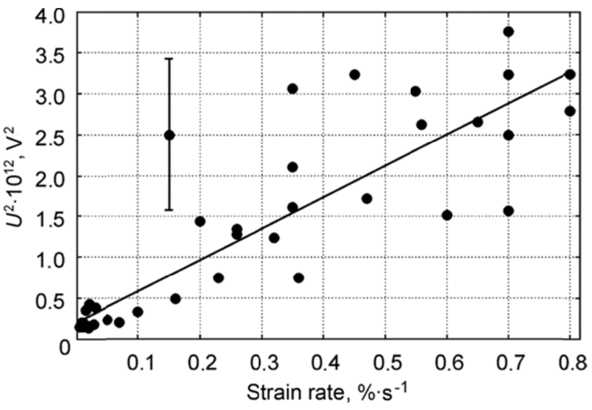

Fig. 1

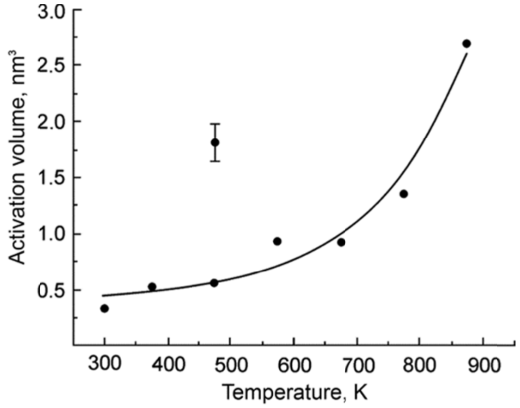

Fig. 2

Fig. 1. Squared acoustic signal amplitude versus strain rate of aluminum within a stepwise deformation stage. A linear approximation of the curve was performed with the correlation coefficient 0.9.

Fig. 2. Activation volume of an elementary deformation event versus temperature of a thermomechanical cycle.

emission signals. An elementary deformation event at high temperature is the formation of a strain band by a large number of dislocations outcropping onto a free or grain-boundary surface [18, 19].

An ensemble of dislocations forming the strain band can represent a dynamic system [20], whose collective behavior is related to coherent sliding of large dislocation groups. An analysis of the deformation jumps in aluminum (and copper) (Fig. 1) has demonstrated that the acoustic emission power *W* during formation of a strain band is directly proportional to the strain rate ($d\varepsilon/dt$) [7, 20].

Thus, it is the outcropping of a dislocation ensemble representing a system of elementary coherent emitters onto the surface, which forms an acoustic signal. The amplitude of this signal is the higher, the higher the rate of strain accumulation. As the deformation temperature is increased, the strain bands become larger in size [21], which correlates with the increased activation volume analyzed in Fig. 2.

The macroscopic value of the deformation jump in the experiments performed is suggestive of the fact that more than one strain band participates in this event. In other words, the correlation effect in the course of a deformation jump would involve a system of strain bands at the macroscopic scale, with the acoustic signal amplitude being a measure of correlation.

SPECTRAL DENSITY OF ACOUSTIC EMISSION SIGNALS

A spectral analysis of the oscillatory process has been performed with the initial signal sampling rate 10 mHz. The resulting spectrum of the oscillatory processes in a specimen – waveguide system suggests that resonant spectral density peaks form even without any acoustic emission source. Figure 3 shows that the acoustic spectrum in such a system is generally characterized by a single peak at the frequency 35.7 kHz and a low-frequency, broadband spectral density background.

An analysis of the acoustic noise of a specimen – waveguide system demonstrates that the spectral density in the absence of acoustic emission signals bears a discrete character. This suggests that the specimen – waveguide system represents a resonant system consisting of a number of resonators distributing the oscillatory energy of noise perturbation over spectral ranges in the form of standing longitudinal and transverse waves. Moreover, an acoustic field is formed in the specimen – waveguide system for any configuration of the latter, which represents a system of resonant

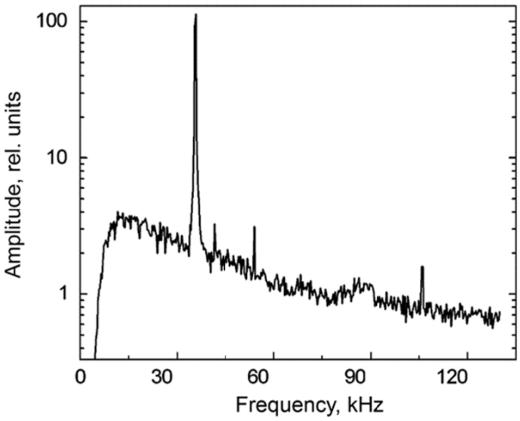

Fig. 3. Spectral density of a specimen – waveguide system.

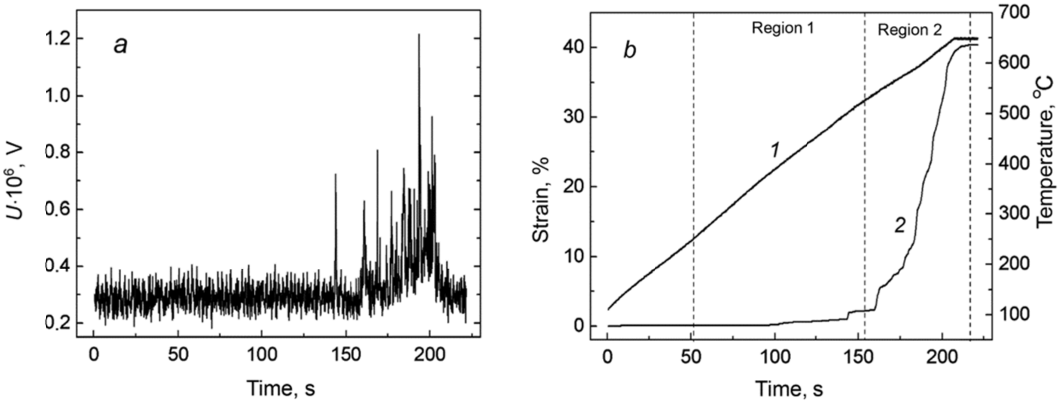

Fig. 4. Acoustic emission (*a*) and strain accumulation (*b*) during heating of aluminum under mechanical loading at 39 MPa: temperature during heating (curve *1*) and monotonous and stepwise strain accumulation (curve *2*).

vibrations in the form of an ensemble of standing longitudinal and transverse waves, wherein the oscillatory energy of the noise is concentrated.

Let us analyze the experimental data on acoustic-emission monitoring and strain accumulation in aluminum within the heating temperature interval from room temperature to 600°C at the load 39 MPa (Fig. 4). Strain accumulation occurred in two stages: up to the temperature 500°C its character was monotonous (region 1 in Fig. 4*b*), above 500°C – strain accumulation occurred in a stepwise fashion as a sequence of macroscopic deformation events alternating with sections of monotonous strain accumulation (region 2 in Fig. 4*b*). Comparing Figs. 4*a* and *b*, we can readily notice a cardinal change in the acoustic emission character in the transition from the temperature region 1 to region 2. Naturally, two types of acoustic emission spectra correspond to this strain accumulation character (Fig. 5). Figure 5*a* presents the spectrum of acoustic emission signals characteristic of monotonous strain accumulation and monotonous acoustic emission. The spectral density of signals in the specimen – waveguide system represents a system of discrete lines distributed in the low-frequency range. Note that it appreciably differs from the spectrum of ceramic noise and that of the amplifying stage of the recording system, whose spectral density represents a gradually increasing function with a maximum at about 11 kHz. The spectral density of the acoustic emission signals for the monotonous stage of strain accumulation is represented by three spectral lines below 60 kHz and the presence of a weakly pronounced region near 90 kHz. On the other hand, the spectral density of acoustic emission signals within the stepwise

TABLE 1. Parameters of Acoustic Resonators of a Specimen – Waveguide System for Region 2

Resonator number	Frequency, Hz	L, mm, (P-wave), $k = 1$, $V = 6420$ m/s	L, mm, (S-wave), $k = 1$, $V = 3040$ m/s	L, mm, (S-wave), $k = 1$, $V = 2530$ m/s
1	35700	89.9	42.6	35.4
2	41500	77.3	36.6	30.5
3	44500	72.1	34.2	28.4
4	45800	70.1	33.2	27.6
5	47900	67.0	31.7	26.4
6	49400	65.0	30.8	25.6
7	54000	59.4	28.1	23.4
8	67400	47.6	22.6	18.8
9	86000	37.3	17.7	14.7
10	88500	36.3	17.2	14.3

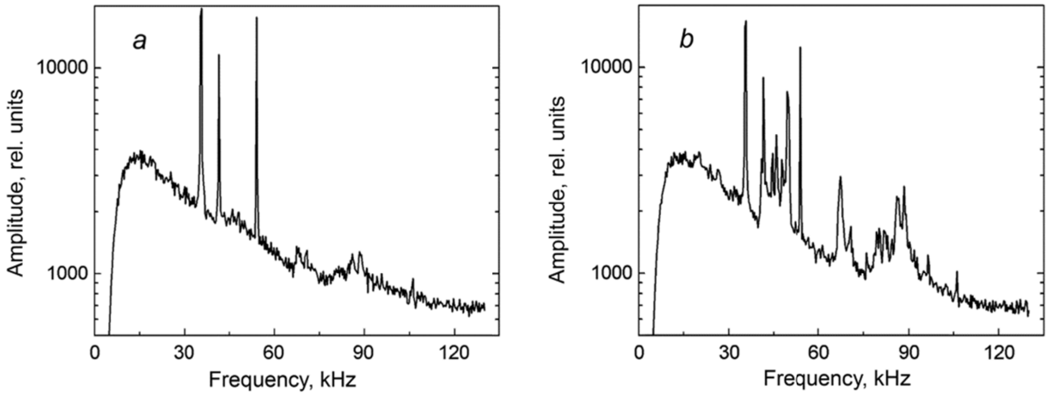

Fig. 5. Acoustic-emission frequency spectrum in the specimen – waveguide system for the monotonous (*a*) and stepwise (*b*) cases of strain accumulation.

region is characterized by a considerably more complicated spectral pattern: there are new well-resolved spectral lines, including a few at 90 kHz. Table 1 lists the measured and calculated parameters of the resonators of the specimen – waveguide system for the entire collection of spectral lines, which characterize the process of strain accumulation in aluminum. The geometrical parameters of the resonators were calculated from the standing wave relation $2L = k\lambda$ (λ – wavelength). Of special significance in the specimen – waveguide system is the resonator corresponding to the specimen representing a 30 mm waveguide section. It is manufactured as a stress concentrator on which strain is localized. The data presented in Table 1 suggest that within the longitudinal range, the resonator corresponding to this section appears to form standing waves at the frequencies 67.4, 86 and 88.5 kHz. A most probable excitation of transverse standing waves in this resonator would be in the fundamental mode.

The discrete character of spectral density suggests that the specimen – waveguide system under study represents a resonant configuration consisting of a few resonators. They distribute the oscillatory energy of both the acoustic noise and primary acoustic emitters over the spectral ranges in the form of standing P- and S-waves. This implies that the acoustic spectra in question represent a secondary effect with respect to the primary acoustic signal. The source of acoustic emission is outcropping of an ensemble of dislocations of a single slip-system onto the surface, which form one strain band [16].

The spectral density of acoustic emission signals in the course of monotonous strain accumulation is presented as three resonant peaks. During stepwise strain accumulation, there is a well-resolved spectral-density maximum at the frequency about 90 kHz, which characterizes standing-wave formation in the region of strain localization. It is noteworthy that the spectral density from the region undergoing deformation is quite high for a stable standing wave to form. Thus, in the stepwise stage of strain accumulation, considerable energy of standing-wave oscillations is stored in the resonator representing a strain-localization region.

ACOUSTIC WAVE FACTOR OF SELF-ORGANIZATION OF ELEMENTARY DEFORMATION EVENTS

The concept of low stability of crystal lattice implies that the crystal system in this state is an active medium [13, 22]. In other words, during plastic flow the crystal lattice represents an oscillatory system excited in a standing-wave mode. Activation of an elementary deformation event results both from thermal fluctuations [7, 14] and acoustic vibrations [8]. Since a standing wave has a macroscopic nature, the elementary deformation events are activated at the macroscopic level. This occurs in a certain collection of slip planes favourably oriented with respect to the oscillatory displacements of the standing wave. Under low-stability condition, these oscillatory displacements activate unit shears in the crystal lattice, which represent a correlated macroscopic ensemble of elementary deformation events building a macroscopic deformation jump. A standing acoustic wave thus determines the macroscopic scale of correlation of elementary strain-induced shears. On the other hand, it naturally controls the region of strain localization, which could be presented, according to [23], as an area of a high concentration of acoustic-emission sources. The ensemble of correlated elementary deformation events it its turn forms a single acoustic signal resulting from the interference of a certain number of unit acoustic signals satisfying the coherence condition. As a result, the system appears to be rigidly synchronized both with respect to elementary deformation events and generated acoustic signals.

SUMMARY

Activation of elementary plastic shears in the case of low crystal-lattice stability can occur via a combined action of static forces, thermal fluctuations and dynamic forces of standing acoustic waves.

An analysis of the low-frequency acoustic emission spectrum in the mode of high-temperature plastic deformation of aluminum has shown that its discrete pattern is attributed to re-distribution of the oscillatory energy of the primary acoustic signal over the resonant vibrations of standing acoustic waves of the resonators. In a low-stability medium, oscillations of a standing wave activate elementary deformation shears in a certain volume, whose size is related to the length of the standing-wave determining the scale of macroscopic correlation. The correlated deformation shears generate acoustic signals, whose interference results in a single acoustic signal of anomalously high amplitude.

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