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Wave Correlation of Elementary Deformation Events during Plastic Deformation of Metals

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Abstract. The investigations show that the spectral density of acoustic emission signals for monotonic accumulation of deformation is represented by three spectral lines located below 60 kHz and some area of about 90 kHz, while the spectral density of signals for the stepwise pattern is characterized by a significant complication of the spectrum, the emergence of new spectral lines. Acoustic emission reflects self-organization processes characterized by poor stability and elementary processes in the atomic subsystem under external influence.

INTRODUCTION

The phenomenon of acoustic emission accompanied by an extensive range of processes associated with the evolution of the crystalline medium can no longer be seen only as a passive acoustic effect. Experimental data on strain localization [1], abrupt deformation effects [2], high temperature deformation jumps, and high-amplitude acoustic signals [3] allows us to consider acoustic emissions as a factor in the correlation of the elementary deformation events of plastic deformation processes, which activate elementary plastic changes, along with mechanical stresses and thermal fluctuations. In the framework of the model acoustic autoemission [4], certain provisions of the active role of acoustic emission during deformation and fracture of crystals was formulated. According to the model acoustic autoemission, jump-like deformation and acoustic emission discreteness show a spatiotemporal regulation of movement defects in the crystal. In this case, the crystal is a self-oscillating system, which is characterized by vibrational excitation, and microscopic processes are cooperative and self-consistent, thus contributing to the synchronization of the oscillation excitation and relaxation of quasi-periodic oscillations. Synchronization and self-synchronization of radiation modes are actually wave interference voltages with different frequencies.

At the core of these processes is the correlation of elementary radiators in the nonequilibrium (active) medium, which leads to the formation of short pulses of compression and extension whose length is reduced with the increasing number of waves of different frequencies involved in interference [5]. Thus, destruction is a rupture of the most stressed interatomic bonds by means of thermal and acoustic fluctuations (autoacoustic fluctuations in terms of Bovenko) [5]. We believe that the concept of the active role of acoustic emission during plastic deformation of the crystal medium in the low-stability state allows us to prove the main effects during plastic flow, for example, the effect of strain localization on the macroscopic scale as well as the connection of plastic changes with the action not only of thermal fluctuations but also of acoustic vibration localized on these scales.

ACTIVATION ENERGY AND THE LOW-STABILITY STATE OF THE CRYSTAL LATTICE

The special state of the crystal lattice, which is called the low-stability state and associated with the state of the atomic ensemble in the field of mechanical stresses and thermal fluctuations, is a combined effect, which allows

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overcoming the potential barrier of communication gap [3] and is associated with acoustic emission. In the context of the action of mechanical stress and temperature [6]

$$\tau(\sigma, T) = \tau \exp\left[\frac{U(\sigma)}{kT}\right] \tag{1}$$

and it depends on the effective value of the potential barrier

$$U(\sigma) = U_0 - \gamma\sigma. \tag{2}$$

The value U_0 is constant for each metal while the parameter γ can vary widely and is several orders of magnitude superior to the atomic volume [7]. The summand term γσ represents the operation of external forces localized in a small atomic ensemble and can vary widely according to the variation of the parameter γ. Thus, the effective activation threshold $U(\sigma)$ can be significantly reduced to zero, thus describing the particular above-barrier state of the atomic ensemble. In this state, plastic flow of the crystal lattice is due to a weak local stability (or the loss of stability) relative to the shift in the range of stress concentrators [3], when the movement of the dislocation segment through the above-barrier is athermal. Localization of the low-stability (or unstable) state of the crystal structure by plastic deformation is usually associated with the process of self-organization of dislocations, which is manifested in the formation of lines and slip bands [8]. The evolution of the structure of acoustic emission signals reflects self-organization processes characterized by a weak stability (or instability) and elementary processes in the atomic subsystem under external influence [9]. The conclusion that can be drawn from the above analysis is that a macroscopic amount of possible elementary acoustic emission sources should be, as in the papers by Bovenko [4, 5], a synchronized (or correlated) ensemble of emitters. Obviously, such synchronization can be affected by the wave. An acoustic emission signal produced during the formation of a deformation band extends from the source in the form of a wave packet whose oscillation phase determines the sign of displacements of atoms from their equilibrium positions.

These periodic displacements are superimposed on static displacements of atoms, which are caused by the static stress field. The low-stability state of the crystal lattice is a determining factor for the wave synchronization system of elementary deformation events. In this state, the vibrational displacement of acoustic waves is enough to activate the dislocation slip (athermal barrier slip). In other words, in Eq. (1) for the communication gap timeout we should consider not only static forces but also the dynamic force work U_d [3]

$$\tau(\sigma, T) = \tau \exp\left[\frac{U_0 - \gamma\sigma - U_\mathrm{d}}{kT}\right]. \tag{3}$$

Thus, the effective activation threshold is reduced by thermal fluctuations due to the work of static forces localized at the structural element and also due to the work of dynamic forces of the acoustic wave. Dynamic forces of an acoustic pulse have a disturbing effect on the set of slip systems, operation of which will depend on the phase of oscillation in the acoustic wave packet.

SPECTRAL DENSITY OF ACOUSTIC EMISSION SIGNALS

The spectral analysis of oscillatory processes was carried out with the help of the developed program with the sampling frequency of original signals 10 MHz. The resulting spectrum of oscillatory processes in the specimen-waveguide system shows that resonance peaks of the spectral density are formed even in the absence of the acoustic emission source. In our specimen, the waveguide system of the acoustic noise spectrum is characterized mainly by the single peak at a frequency of 35.7 kHz and the low-frequency broadband background of spectral density. As follows from the analysis of the spectrum of the acoustic noise in the specimen-waveguide system, the discrete nature of the spectral density in the absence of production of the acoustic emission signal indicates that our specimen-waveguide system is a resonant system consisting of multiple resonators distributing vibrational energy of the noise disturbance for the spectral range of longitudinal and transverse standing waves. Moreover, we can conclude that in any specimen-waveguide configuration, the system produces an acoustic field that represents a resonance oscillation system as a set of longitudinal and transverse standing waves, which concentrates vibrational energy of noise. As shown, strain accumulation under high loading of aluminum is carried out in the two ways: in the low temperature region it is monotonic and in the high temperature region it is carried out discontinuously in the sequence of macroscopic deformation acts interspersed with plots of monotonic deformation accumulation.

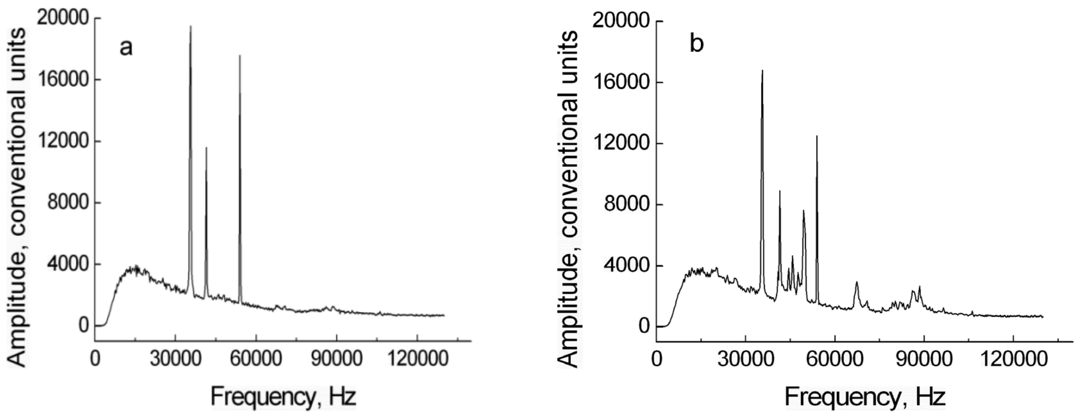

FIGURE 1. Frequency spectrum of acoustic emission of the specimen-waveguide system for the monotonic (a) and stepwise (b) strain accumulation

Such a character of strain accumulation corresponds to two types of acoustic emission spectra (Figs. 1a and 1b). Figure 1a shows the spectrum of acoustic emission signals characteristic of monotonic and repetitive strain accumulation of acoustic emission. Figure 1b shows the spectrum of acoustic emission signals for abrupt accumulation of deformation and acoustic emission pulses. According to those in Figs. 1a and 1b, the spectral density of acoustic emission signals in the specimen-waveguide system is represented by a system of discrete lines distributed in the low frequency range and is significantly different from that of the piezoceramic noise and amplifier stage of the recording system, whose spectral density is a slightly increasing function with the maximum lying near 11 kHz. The spectral density of acoustic emission signals for monotonic strain accumulation is represented by three spectral lines located below 60 kHz, and some area of about 90 kHz. At the same time, the spectral density of acoustic emission signals for the stepwise region is characterized by a significant complication of the spectrum and the appearance of new spectral lines at 90 kHz. Table 1 shows measured and calculated parameters of the specimen-waveguide system of resonators for the entire set of spectral lines that characterize the process of strain accumulation in aluminum. Geometric parameters of cavities are calculated on the basis of the standing wave conditions $2L = k\lambda$ (λ is the wave length).

The discrete nature of the spectral density of the acoustic emission signal indicates that our specimen-waveguide system is a resonant system consisting of multiple resonators distributing vibrational energy as acoustic noise and primary elementary radiators of acoustic emission by our spectral range in the form of longitudinal and transverse standing waves. This means that the acoustic emission spectrum is provided by a secondary effect in relation to the primary acoustic signal. According to our publications, the primary source of acoustic emission is the exit of a dislocation ensemble of the slip system to the surface and formation of a single band of deformation [8].

TABLE 1. Parameters of acoustic resonators for $k = 1$ of the specimen-waveguide system for abrupt strain accumulation

No.	Frequency, Hz	L of the longitudinal wave, mm (V = 6420 m/s)	L of the shear wave, mm (V = 3040 m/s)	L of the shear wave, mm (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

During monotonic strain accumulation, the spectral density of acoustic emission signals is presented mainly in the form of three resonance peaks. During the stepwise strain accumulation, there is the maximum of the spectral density at a frequency of about 90 kHz characterized by the formation of standing waves in the field of deformation localization.

ACOUSTIC WAVE FACTOR OF SELF-ORGANIZATION OF ELEMENTARY DEFORMATION EVENTS

By introducing the concept of the weak-stable lattice state, we assume a crystalline state of the medium as active medium [5, 10]. Thus, when plastic flow of the crystal lattice is an oscillating system excited in the standing wave mode, the activation of an elementary deformation event results from both thermal fluctuations [9] and the influence of acoustic oscillations [11]. Since the standing wave has the macroscopic scale, the expansion and activation of elementary events is carried out on the macroscopic scale in a certain set of slip planes favorably oriented with respect to the vibrational displacement of the standing wave. In the context of the low-stability state of the crystal lattice, the vibrational displacement activates basic changes that will be correlated with a macroscopic ensemble of elementary deformation events, thus forming a macroscopic deformation jump. The standing acoustic wave determines the macroscopic scale correlation of elementary deformation shifts. At the same time, the standing wave and the region naturally determine the localization of deformation, which is presented elsewhere [12] as an area of concentration of acoustic emission sources. In turn, the correlated ensemble of elementary deformation events forming a single acoustic signal results from the interference of a plurality of elementary acoustic signals satisfying the coherence condition. In this regard, our system is tightly synchronized in relation to elementary deformation events and with respect to formed acoustic signals.

CONCLUSIONS

The low-stability state of the crystal lattice and activation of elementary plastic changes may be affected as a result of the combined action of static forces, thermal fluctuations, and dynamic forces of standing acoustic waves. The analysis of the low frequency range of acoustic emission at high temperature plastic deformation of aluminum suggests that it is due to the discrete form of redistribution of vibrational energy of the primary acoustic signal at resonant vibrations of standing wave resonators. The low-stability crystalline medium with standing wave oscillations activated elementary deformation changes in a certain volume related to the length of the standing wave, which determines the macroscopic scale correlation. At the same time, correlated deformation shifts generate acoustic signals that meet the condition of coherence as a result of interference, which is formed of the single acoustic signal of abnormally high amplitude.

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