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PHYSICAL SCIENCE OF MATERIALS

Correlation Wave Effects for Elementary Deformation Events during High-Temperature Loading of Aluminum and Its Alloys

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Abstract—We report on the results of experiments on straining of aluminum and its alloys in conditions of mechanical loading and high temperatures. It is established that deformation accumulates in such conditions as a monotonic and abrupt process accompanied by monotonic and pulsed acoustic emission. It is found that the main contribution to strain accumulation comes from deformation jumps accompanied with not only acoustic emission, but also mechanical stress oscillation. The mechanical stress oscillation indicates rapid processes of strengthening and softening of metal materials. Spectral analysis of a series of acoustic emission signals indicates that in the course of strain accumulation, the volume being deformed is a natural resonator in which primary acoustic emission signals are transformed into a low-temperature spectrum of standing acoustic waves executing the correlation of elementary deformation events on a macroscopic scale, where the correlation scale is determined by the wavelength of a standing wave.

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INTRODUCTION

It is generally assumed that a plastic flow (especially large plastic deformations) cannot be described as an additive contribution from individual dislocations [1]. Therefore, the interest in the description of plastic deformation considering correlations in the dislocation ensemble system, which characterizes the straining behavior of the system in strongly nonequilibrium conditions, is not accidental.

Experiments on metal straining demonstrate [2] that during plastic deformation, deformation centers in which plastic flow is localized propagate in the direction of extension. It was concluded from these experiments that deformation embraces structural levels on different scales from microscopic to mesoscopic and macroscopic. Localization of instability of a crystalline structure under plastic deformation of crystals for the classical three-stage σ vs. ε dependence (σ is the mechanical stress and ε is the strain) is associated with self-organization of dislocations [3]. Accounting for the self-organization factor makes it possible to formulate the fundamental conclusion that the experimentally observed variety of deformation behavior and dislocation structures is the result of evolution of the dislocation ensemble via the evolution of collective and cooperative phenomena and their spatial ordering, which is manifested in the formation of slip lines and bands [3].

The necessary condition for an elementary plastic share event is the rupture of interatomic bonds along a dislocation line, which occurs as a result of action of thermal fluctuations and mechanical stresses [4]. This process is most effective under the action of mechanical stresses at high temperatures, which transform the crystalline medium into a weakly stable state. The state of a system referred to as weakly stable can be associated with the state of the atomic ensemble in the fields of mechanical stresses and thermal fluctuations; the joint action of these fields makes it possible to overcome the potential barrier of bond rupture [4, 5]. For an elementary bond rupture event (including that for plastic deformation), a positive fluctuation energy localized in a small ensemble of interacting atoms is required [4]. The simulation of such situations in an atomic system has made it possible to establish that a strong energy fluctuation of atoms can be treated as a stable dynamic state [6].

In the conditions when the state of a crystalline medium is weakly stable to external actions, the correlation in the system of structure defects determining self-organization of a dislocation ensemble plays a major role in the evolution of the structure of a strained material. One of the features of correlation of elementary straining events is the effect of abrupt accumulation of strains under thermomechanical loading of aluminum. However, in such an approach, the effect of acoustic emission and its role in plastic deformation are disregarded although the emission of acoustic signals is observed during thermomechanical loading of metals during the entire heating process [7]. It is observed that strains are accumulated in two ways

Table 1. Mechanical properties and structural state of AMg6 alloy and aluminum

Yield stress		Structural state
during torsion, MPa	during torsion, MPa	
AMg6 – 85	AMg6 – 170	Two-phase state: solid solution of Mg in Al and intermetallic phase Mg_5Al_8
Al – 15	Al – 30	Polycrystalline aggregate

(monotonically and abruptly) and acoustic emission is also manifested in two forms, monotonic and pulsed (discrete) [8–10]. It was shown that the acoustic signal amplitude can characterize correlation in an ensemble of elementary emitters (i.e., in an ensemble of elementary straining events) [8, 9].

The active role of acoustic emission during plastic deformation and fracture has been considered for a long time [11, 12]. In such discussions, abrupt deformation and discrete acoustic emission were treated as manifestations of the spatiotemporal ordering in displacement of defects in a crystal [13]. For example, in the autoacoustic emission model, a crystal is a self-oscillating system (natural resonator in our terminology), which is characterized by excitation of oscillations, and microscopic plastic deformation processes occur cooperatively and self-consistently [11]. Abrupt deformation and large-amplitude acoustic pulses associated with it indicate not only spatiotemporal ordering in the displacement of defects, but also the acoustic wave mechanism of localization of deformation on the macroscopic scale, in which the localization scale is determined by the length of the standing acoustic wave formed via the transformation of primary acoustic emission signals in natural resonators of the volume being deformed [14–16].

In this article, we report on the results of analysis of abrupt accumulation of plastic strains from the standpoint of acoustic wave correlation and activation of elementary deformation events in aluminum and its alloys at high temperatures.

1. EXPERIMENTAL TECHNIQUE AND MATERIALS

The processes of strain accumulation in metals were investigated in soft loading conditions. In this soft loading scheme, the strain is treated as a function of parameters (mechanical stress and temperature). In our experiments, the sample was loaded by a shear stress, and shear strain was determined during sample heating to premelting temperatures.

As the object of investigations, we chose aluminum–magnesium alloy AMg6. Samples in the form of 300-mm-long rods, in which strain localization regions 4 mm in diameter and 30 mm in length were formed, were cut from the AMg6 alloy plate. Most of the rod served as a waveguide. Aluminum samples were prepared with the same configuration. The samples were preliminarily annealed for 1 h and cooled with an oven (AMg6 alloy at 500°C and aluminum at 600°C). Table 1 contains the mechanical properties and the structural state of the metal materials under investigation. Mechanical loading and measurements of strain, temperature, and mean-square acoustic emission stress were performed using the setup described schematically in [17].

2. EXPERIMENTAL RESULTS

During heating of a sample under loading by a constant shear stress on the order of the yield stress, monotonic and abrupt strain accumulation accompanied with monotonic and large-amplitude (pulsed) acoustic emission is observed. As shown in Fig. 1, each deformation jump correlates with a large-amplitude acoustic emission pulse. In fact, the total strain is the sum of abrupt events separated by monotonic segments that make a small contribution to the total strain. Typically, with increasing temperature, the time of monotonic strain accumulation decreases; i.e., strain accumulation is a certain quasi-periodic process in which deformation jumps change to monotonic events. Therefore, it can be expected that there exist thermomechanical action conditions, in which these time intervals are negligibly short.

Experiments show that the characteristic feature of high-temperature loading of aluminum and aluminum–magnesium alloys is an oscillating nature of mechanical stress. Figure 2 shows that under a stress of about 100 MPa and heating to 500°C, strain accumulation in AMg6 is a transition from the monotonic low-rate (region *1*) to high-rate process (region *2*). It should be noted that this transition is accompanied with a substantial increase in the mean-square value of acoustic emission.

3. DISCUSSION OF EXPERIMENTAL RESULTS

The oscillating nature of mechanical stress in region *2* (see Fig. 2) indicates that strain accumulation and acoustic emission are in fact discrete, but experimentally unresolved deformation and acoustic events. In other words, in region *2*, the multiple form of abrupt deformation events that make the main contribution to the total strain of the alloy is observed. In addition (which is more important), mechanical stress

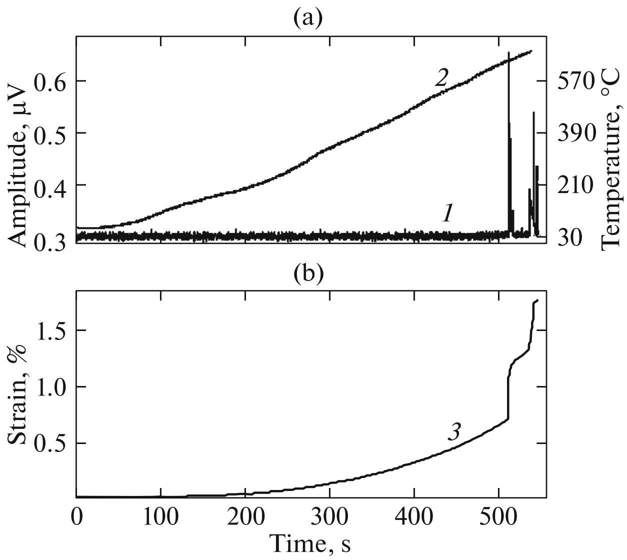

Fig. 1. Acoustic emission during the monotonic and abrupt strain accumulation in aluminum for a mechanical stress close to the yield stress in a nonisothermal thermomechanical cycle: (*1*) time dependence of mean-square acoustic emission stress; (*2*) temperature curve; (*3*) time dependence of accumulated strain.

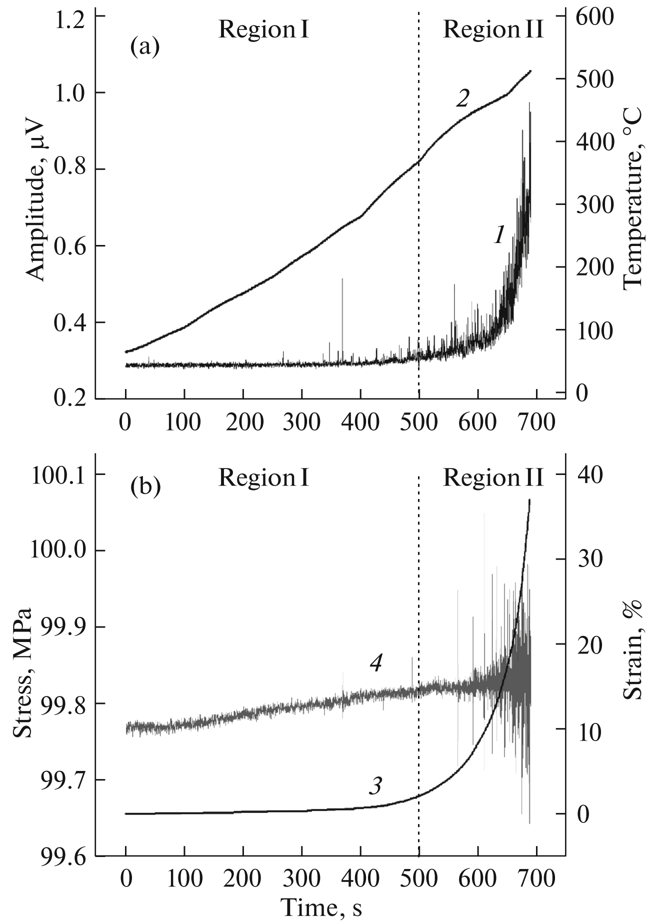

Fig. 2. Acoustic emission (*1*), temperature (*2*), strain accumulation (*3*), and mechanical stress (*4*) during heating of AMg6 sample under the action of a constant stress of 100 MPa. Dashed line divides the entire process of strain accumulation into two regions: accumulation rate in region I is low; accumulation rate in region II is substantially higher.

oscillations indicate the quasi-periodic nature of strengthening and softening processes occurring in the bulk of the material being deformed. Indeed, the dynamic recrystallization effect involving the softening of metals subjected to deformation at high temperature is well known; in the course of this effect, two competing processes (strengthening and softening) coexist [18, 19]. It was noted that the periodicity of strengthening and softening processes is manifested most clearly in the course of creep of metal materials.

Analysis of abrupt deformation and effects of correlation of elementary deformation events will be performed by considering the spectrum of the train of acoustic emission signals. Figure 3 shows the acoustic emission spectra typical of monotonic and abrupt strain accumulation.

According to the results depicted in Fig. 3, the spectral density of acoustic emission signals in the sample–waveguide system is represented by a system of discrete lines distributed in the low-frequency range of 30–120 kHz. The discrete nature of the spectral density of acoustic emission signals indicates that the sample–waveguide is a resonant system consisting of several resonators. The vibrational energy of acoustic noise as well as of primary elementary acoustic emitters of standing longitudinal and transverse waves is distributed over the resonators. It should be noted that during abrupt strain accumulation, the spectral density of acoustic signal power has a much more complex structure as compared to the spectral density for the monotonic segment due to a substantial increase in the flux density of acoustic emission signals in region *2*. The spectral density peak at frequencies 48–54 kHz and 67–90 kHz, which characterize the formation of quite stable standing waves in the strain localization region (i.e., in the stress concentration region with a length of 30 mm), are well resolved. According to Table 2, for a resonator with a length of about 30 mm, resonances at transverse waves are possible at frequencies of 48–54 kHz, while resonances at frequencies of 67–90 kHz are possible for longitudinal and transverse waves.

Table 2 contains geometrical sizes of ten resonators for the recording of ten spectral lines. The geometrical parameters of the resonators were calculated proceeding from the condition $2L = k\lambda$ of standing wave formation (λ is the wavelength and k is the spectral order assuming values of 1, 2, ...).

Since a standing wave has the macroscopic scale, the activation of elementary deformation events occurs on the macroscopic scale in a certain set of slip planes oriented favorably relative to oscillatory dis-

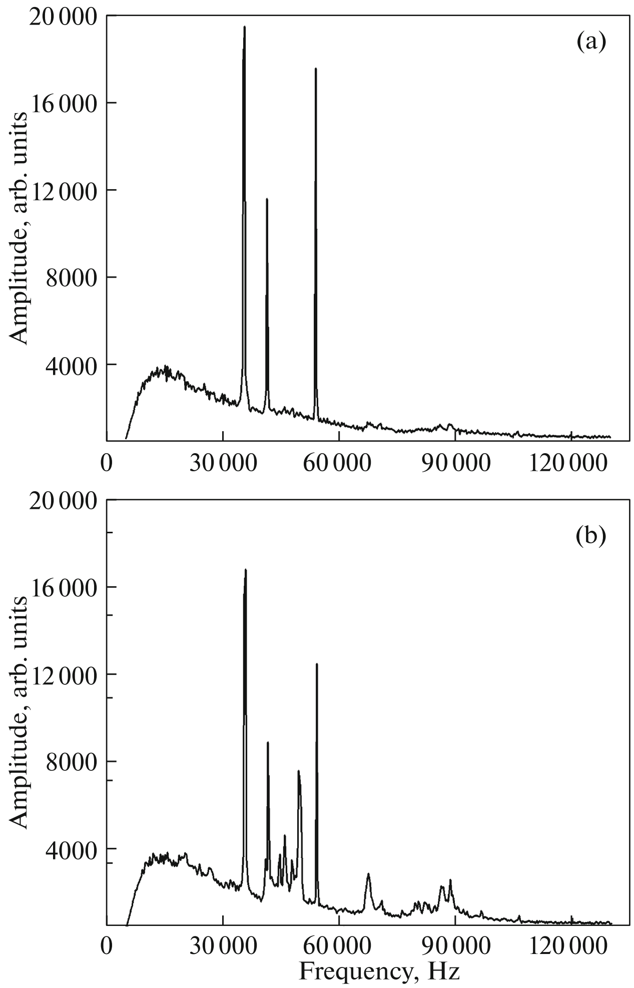

Fig. 3. Spectral composition of a train of acoustic emission signals during strain accumulation: (a) in region I; (b) in region II.

placements of the standing wave. In the conditions of a weakly stable state of the crystal lattice, oscillatory displacements activate elementary shears that represent a correlated macroscopic ensemble of elementary deformation events forming a macroscopic strain jump. In turn, correlated shear strains generate acoustic signals compensating vibrational energy loss in standing waves in a resonator associated with the strain localization region.

Thus, a standing acoustic wave determines the macroscopic correlation scale for elementary deformation shears. At the same time, the standing wave also naturally determines the strain localization region, which is also the region of concentration of acoustic emission centers.

CONCLUSIONS

The oscillatory nature of mechanical stresses indicates the occurrence of rapid quasi-periodic processes of strengthening and softening of the crystalline medium during high-temperature strain accumulation.

The above analysis of the low-frequency acoustic emission spectrum for high-temperature plastic deformation of aluminum indicates that its discrete form is due to redistribution of the vibrational energy of the primary acoustic signal over resonant oscillations of standing waves of resonators. In a weakly stable crystal lattice, elementary deformation shears are activated as a result of joint action of static forces, thermal fluctuations, and dynamic forces of standing acoustic waves in a certain volume associated with the wavelength of the standing wave determining the macroscopic correlation scale. Correlated deformation shears generate acoustic signals of anomalously high amplitude,

Table 2. Parameters of acoustic resonators in the sample–waveguide system

Resonance number	Frequencies, Hz	L, mm	L, mm	L, mm
		Wave		
		longitudinal, $k = 1$, $V = 6420$ m/s	shear, $k = 1$, $V = 3040$ m/s	shear, $k = 1$, $V = 2530$ 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

The results correspond to two values of shear wave velocity: 3040 m/s (at room temperature) and 2530 m/s (at a temperature of about 600°C).

which compensate the vibrational energy loss in the system of standing waves in a natural resonator formed by the strain localization region, which supports the correlation of elementary deformation events.

CONFLICT OF INTEREST

The authors claim that there is no conflict of interests.

REFERENCES

1. V. V. Rybin, *Severe Plastic Deformation and Metal Fracture* (Metallurgiya, Moscow, 1986).
2. L. B. Zuev, V. I. Danilov, and V. V. Gorbatenko, Zh. Tekh. Fiz. **65** (5), 91 (1995).
3. G. A. Malygin, Phys.-Usp. **42**, 887 (1999).
4. V. R. Regel', A. I. Slutsker, and E. E. Tomashevskii, *Kinetic Nature of Strength of Solid Bodies* (Nauka, Moscow, 1974).
5. S. V. Makarov, V. A. Plotnikov, and A. I. Potekaev, Russ. Phys. J. **54**, 314 (2011).
6. A. I. Slutsker, A. I. Mikhailin, and I. A. Slutsker, Phys.-Usp. **37**, 335 (1994).
7. V. A. Plotnikov and S. V. Makarov, Tech. Phys. Lett. **34**, 255 (2008).
8. S. V. Makarov, V. A. Plotnikov, and A. I. Potekaev, Russ. Phys. J. **54**, 314 (2011).
9. S. V. Makarov, V. A. Plotnikov, and A. I. Potekaev, Russ. Phys. J. **56**, 630 (2013).
10. V. A. Plotnikov and S. V. Makarov, Phys. Met. Metallogr. **105**, 395 (2008).
11. V. N. Bovenko, Izv. Akad. Nauk SSSR. Met., No. 1, 129 (1984).
12. V. N. Bovenko, Izv. Akad. Nauk SSSR. Ser. Fiz. **50**, 509 (1986).
13. A. A. Shibkov, A. E. Zolotov, M. A. Zheltov, A. A. Denisov, and M. F. Gasanov, Phys. Solid State **56**, 881 (2014).
14. S. V. Makarov, V. A. Plotnikov, and A. I. Potekaev, Russ. Phys. J. **57**, 436 (2014).
15. S. V. Makarov, V. A. Plotnikov, and A. I. Potekaev, Russ. Phys. J. **57**, 950 (2014).
16. S. V. Makarov, V. A. Plotnikov, A. I. Potekaev, and L. S. Grinkevich, Russ. Phys. J. **57**, 1676 (2014).
17. S. V. Makarov and V. A. Plotnikov, Deform. Razrushenie Mater., No. 10, 21 (2015).
18. S. S. Gorelik, *Recrystallization of Metals and Alloys* (Metallurgiya, Moscow, 1978).
19. S. V. Lubenets, Phys. Solid State **44**, 75 (2002).

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