Monotonous and stepwise character of deformation accumulation as a hierarchically organized process under high-temperature deformation of aluminum-magnesium alloy

S. V. Makarov, V. A. Plotnikov, and M. V. Lysikov

Citation: AIP Conference Proceedings **1909**, 020131 (2017);
View online: https://doi.org/10.1063/1.5013812
View Table of Contents: http://aip.scitation.org/toc/apc/1909/1
Published by the American Institute of Physics

Monotonous and Stepwise Character of Deformation Accumulation as a Hierarchically Organized Process under High-Temperature Deformation of Aluminum-Magnesium Alloy

S. V. Makarov[a)], V. A. Plotnikov, and M. V. Lysikov

Altai State University, Barnaul, 656049 Russia

[a)] Corresponding author: makarov@phys.asu.ru

Abstract. Stepwise kinetics of deformation accumulation and monotonous and pulsed acoustic emission bear witness to the active role of acoustic emission in deformation processes. A standing acoustic wave in the region of deformation localization determines the effect of self-organization of dislocations on macroscopic scales around the natural resonator of the system.

INTRODUCTION

Numerous experimental and theoretical studies indicate a hierarchy of processes of plastic deformation of metallic materials and effects of self-organization of dislocation ensembles on macroscopic scales [1]. We can speak about the individual behavior of dislocations as an elementary event of plastic deformation only in early stages of deformation. At large deformations, a dislocation ensemble is strongly interacting so plastic deformation is determined by their collective behavior. In so doing, the collective behavior is such that it makes sense to talk about coherent cooperative states of dislocation ensembles during plastic deformation of metal materials [2]. For example, the well-known effect of Portevin–Le Chatelier, that represents the instability of plastic flow in conditions of discontinuous macroscopic deformation of metals, is associated with coherent sliding of large groups of dislocations [3]. During the stepwise deformation of the formed deformation band this is the output of the dislocation ensemble at the boundary [4].

At the microstructural level, the Portevin–Le Chatelier effect is implemented in the form of the formation of deformation bands, which represent the region of localization of plastic deformation [5]. Discontinuous flow in the stress-strain curve presents stress jumps (saw teeth), and the deformation band responsible for the acts of discontinuous flow is a macroscopic object and develops from a critical band nucleus. In the analysis of the surface topography of AMg6 alloy specimens we discover two types of deformation bands: spatial unorganized and spatially organized. Every act of discontinuous flow has the appearance of one single strip deformation. Discontinuous flow is accompanied by pulses of acoustic emission correlating with the appearance of bands of deformation, i.e. each voltage jump corresponds to a pulse of acoustic emission [6]. The expression patterns of discontinuous flow and acoustic emission is a consequence of the wave nature of deformation in aluminum-magnesium alloys, deformation waves, spreading from the hub of stress, stimulates the formation of bands of deformation and acoustic emission [7]. Another manifestation of discontinuous flow is serrated creep (or the effect of Savart–Masson [8]) that shows up in alloys in creep curves as a sequence of strain jumps up to 1 μm [9]. Serrated creep at room temperature develops as a spontaneous loss of mechanical stability by initiation and propagation microlocalization deformation bands on the specimen surface accompanied by the formation of a deformation jump. Localization of deformation is a sequential nucleation and growth of deformation bands, and a deformation jump presents a spatial and time organization that characterizes plastic instability of the loaded material [9].

Proceedings of the International Conference on Advanced Materials with Hierarchical Structure for New Technologies and Reliable Structures 2017 (AMHS'17)
AIP Conf. Proc. 1909, 020131-1–020131-4; https://doi.org/10.1063/1.5013812
Published by AIP Publishing. 978-0-7354-1601-7/$30.00

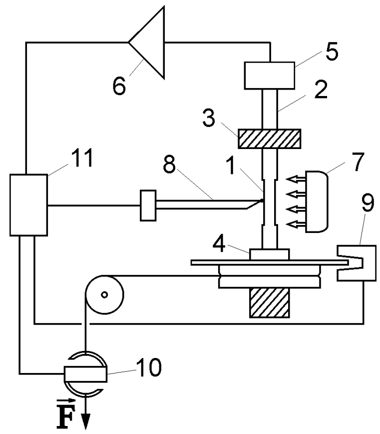

FIGURE 1. Block diagram of the experimental setup: *1*—specimen, *2*—waveguide, *3*—fixed holder, *4*—movable holder, *5*—piezoelectric transducer with the preamplifier, *6*—amplifier, *7*—heater, *8*—thermocouple, *9*—strain sensor, *10*—load sensor, *11*—analog-to-digital converter, computer

Relay transmission of deformation from one page to another is a major structural characteristic of discontinuous flow that propagates in the specimen region of localization of deformation [10]. The characteristic feature is an oscillating kind of power response of the machine-specimen system to an abrupt strain increment in the loaded specimen to 1–4%. The growth of one of the bands is accompanied by one power oscillation with the duration 1–3 ms; the oscillating power response is a mapping of the spatiotemporal structure of deformation bands whose spontaneous emergence creates an abrupt macroscopic increase in strain [9, 10].

Spectral and dynamic analysis of discontinuous flow detects reveals the presence of long-range long-term correlations in the deformed material [11]. The nature of spatial and temporal correlations according to Shibkov et al. [9] is connected with the cascade mechanism of propagation of deformation bands. However, the correlation factor is stress localized at the front of the deformation band boundary as well as long-range bending stresses. Based on the spectral and dynamic analysis it is stated that the flicker-noise structure and power response monofractality bears witness to the state of self-organized criticality of a deformed material. In this regard, the role of acoustic emission in the organization of long-range and long-term correlation of elementary deformation events in the deformed material is unclear.

The aim of this work is to analyze acoustic effects of self-organization in an aluminum-magnesium alloy under loading in a wide range of temperatures up to the melting point.

EXPERIMENTAL METHODS

Specimens in the form of rods made of sheets of aluminum-magnesium alloy AMg6 with the length 300 mm are waveguides where regions of deformation localization 4 mm in diameter and 30 mm in length are formed. Heating of the specimen is carried out exactly in the deformation localization region. The rest of the rod is not heated; it plays the role of a waveguide. Mechanical loading, measurement of strain, temperature, and root-mean-square stress of acoustic emission is carried out using a setup whose schematic is shown in Fig. 1. The specimen is loaded by shear stress to measure its shear strain. Constant loading in the thermomechanical cycle is performed during continuous heating of specimens at a rate of about 1 deg/s. In the experiments, we analyze the integrated energy parameter of acoustic emission $J = \sum U^2 \Delta t_i$, which is proportional to the energy of acoustic emission, where Δt is the step of partitioning of the time interval of the process.

EXPERIMENTAL RESULTS

The accumulation of deformation due to high-temperature heating with a constant velocity up to 580°C and the load (e.g. 100 MPa) is carried out in two ways (Fig. 2, dependence *4*): up to a critical temperature (T_{cr}) in a monotonous way (region *1*), and then in quasi-stepwise way (region *2*). The monotonous character of deformation accumulation is accompanied by a monotonous increase of the root-mean-square stress of acoustic emission.

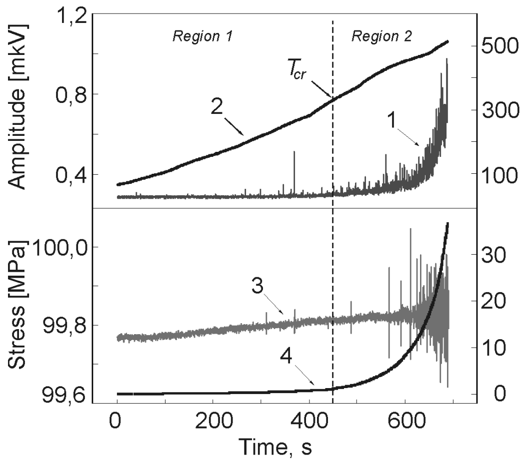

FIGURE 2. Acoustic emission (*1*), temperature (*2*), stress (*3*), and deformation accumulation (*4*) in heating of the aluminum-magnesium alloy at a constant load of 100 MPa

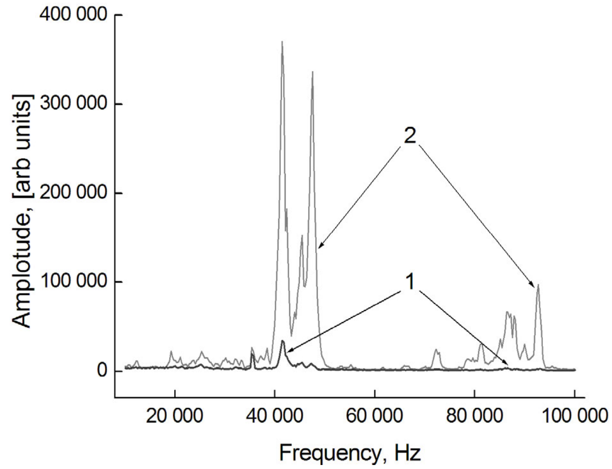

FIGURE 3. Spectral density of acoustic emission signals corresponding to monotonous (dependence *1*) and quasi-stepwise (dependence *2*) deformation accumulation. The rate of strain accumulation: 0.03 (*1*) and 0.2 s^{-1} (*2*)

Upon reaching the critical temperature (T_{cr}) (the transition temperature from region *1* to region *2* in Fig. 2), the root mean square stress of acoustic emission (dependence *1*) and the rate of accumulation of deformation significantly increases, which corresponds to the oscillation of mechanical stress (dependence *3*), and the amplitude of oscillations increases with increasing temperature.

Spectral analysis of acoustic emission signals carried out according to the method presented elsewhere [12] bears witness to redistribution of the spectral density to the frequency bands 40–50 and 85–95 kHz (Fig. 3). Moreover, the spectral flux density of acoustic emission signals in these frequency bands in the region of quasi-stepwise deformation accumulation significantly (an order of magnitude) higher than the spectral density of acoustic emission in the same range in the monotonous curve of deformation accumulation.

DISCUSSION OF EXPERIMENTAL RESULTS

The analysis of deformation accumulation in the aluminum-magnesium alloy under thermomechanical loading from the viewpoint of the evolution of structural levels of plastic deformation is presented below. In the low-temperature region, the deformation accumulation with a low velocity corresponds to monotonous low-amplitude acoustic emission, which indicates a low correlation of elementary deformation acts. In fact, the accumulation of deformation in this region is due to the initial dislocation structure recorded in the bulk of grains.

In the high-temperature area, the rapid accumulation of deformation corresponds to the fast monotonic growth of high-amplitude acoustic emission. Such character of deformation indicates a high correlation of elementary deformation acts. In region *2*, with increasing strain the grain boundary is saturated with dislocations, thus leading to grain boundary sliding and the generation of pure dislocations by the grain boundary, which are involved in the accumulation of deformation.

We can state that the transition from region *1* to region *2* represents the change of the process of deformation accumulation at low rate controlled by thermally activated creep of dislocations to the accumulation process controlled by the production process of dislocations by nonequilibrium grain boundaries during grain boundary sliding. The transition to high-temperature region *2* occurs when the temperature-force parameters and vibrational energy of acoustic emission in the deformed volume reach critical values. Oscillations of mechanical stress bear witness to significant changes in the micromechanisms of deformation accumulation at the critical point of T_{cr}, and the increase in the amplitude of acoustic pulses with increasing temperature characterizes an increase in vibrational energy of acoustic emission within the deformed material. The effect of discontinuous deformation and impulse acoustic emission bear evidence to both high correlations and macroscopic localization of elementary deformation acts (deformation bands) and coherence of basic primary acoustic emission signals.

During accumulation of deformation the vibrational energy of acoustic emission significantly increases, which accumulates within the deformed specimen (Fig. 3). The only process that can ensure the accumulation of vibrational energy is the formation of standing acoustic waves on natural resonators in the specimen- system waveguide [13]. A transition in the region of abrupt or quasi-stepwise deformation results from the joint action of thermal fluctuations, static displacements in the field of mechanical stresses, and dynamic oscillatory displacements of standing sound waves generated in natural cavities in the region of deformation localization in the specimen. This means that macroscopic deformation jumps can be associated with the formation of standing waves in weakly stable crystalline medium generated by the field of mechanical stresses, whose combined effect leads to synchronization of plastic changes on the scale determined by the wavelength.

Thus, the main factor of self-organization of dislocations in the region of strain localization is a standing wave formed by primary acoustic emission signals. A standing acoustic wave determines the macroscopic scale of correlation of elementary deformation shears on the scale determined by the wavelength.

CONCLUSION

The analysis of the monotonous and stepwise kinetics of deformation accumulation and monotonous and pulsed acoustic emission bears witness to the active role of acoustic emission in deformation processes.

A significant increase in the root-mean-square stress of acoustic emission in the high-temperature region, when the temperature-force parameters reach critical values (T_{cr}), indicates an increase in vibrational energy of acoustic emission in the deformed volume of the specimen. A discrete low-frequency spectrum of acoustic emission indicates the redistribution of vibrational energy of the primary acoustic signal over resonant oscillations of standing (longitudinal and transverse) waves of a natural cavity, which is the area of deformation localization. A standing acoustic wave in the region of deformation localization determines the macroscopic scale of correlation and synchronization of elementary deformation shears.

Thus, the effect of dislocation self-organization on macroscopic scales (deformation localization zone) is determined by the macroscopic scale of acoustic standing wave around the natural resonator of the specimen-waveguide system.

REFERENCES

1. V. A. Likhachev, V. E. Panin, E. E. Zasimchuk, et al., *Cooperative Deformation Processes and Localization of Deformation* (Naukova Dumka, Kiev, 1989).
2. L. A. Shelepin, in *Coherent Physics and Its Applications* (Nauka, Moscow, 1976), pp. 3–20.
3. A. Portevin and F. Le Chatelier, Acad Sci. Paris. **176**, 507 (1923).
4. M. A. Lebyodkin, JETP **113**(5), 1816–1829 (1998).
5. M. M. Krishtal, Phys. Met. Metallogr. **75**(5), 31–35 (1993).
6. M. M. Krishtal and D. L. Meyerson, Phys. Met. Metallogr. **81**(1), 156–162 (1996).
7. M. M. Krishtal and D. L. Meyerson, Phys. Met. Metallogr. **10**, 187–193 (1991).
8. A. A. Shibkov, R. Yu. Koltsov, M. A. Zheltov, A. V. Shuklinov, and M. A. Lebedkin, Bull. Russ. Acad. Sci. Phys. **70**(9), 1570–1575 (2006).
9. A. A. Shibkov, A. E. Zolotov, M. A. Zheltov, A. A. Denisov, and M. F. Gasanov, Tech. Phys. Russ. J. Appl. Phys. **59**(4), 508–514 (2014).
10. A. A. Shibkov, A. E. Zolotov, M. A. Zheltov, M. F. Gasanov, and A. A. Denisov, Phys. Solid State **56**(5), 881–888 (2014).
11. A. A. Shibkov, A. E. Zolotov, M. A. Zheltov, A. A. Denisov, and M. F. Gasanov, Phys. Solid State **56**(5), 889–893 (2014).
12. S. V. Makarov, V. A. Plotnikov, and A. I. Potekaev, Russ. Phys. J. **57**(4), 436–440 (2014).
13. S. V. Makarov, V. A. Plotnikov, and A. I. Potekaev, Russ. Phys. J. **57**(7), 950–955 (2014).