The Regularities of the Acoustic Emission at High-temperature Deformation and Fracture

Mikhail D. Starostenkov [1, a], Vladimir A. Plotnikov [2,b], and Sergey V. Makarov [2]

[1]Altai State Technical University, Lenin St., 46, Barnaul, 656038, Russia

[2]Altai State University, Lenin St., 61, Barnaul, 656099, Russia

[a]genphys@mail.ru, [b]plotnikov@phys.asu.ru

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Abstract. Two types of deformation behaviour were observed at high-temperature loading of Al. The first type represented the monotonous accumulation of deformation at continuous heating of the loaded sample at pre-melting temperature. The second type of deformation behaviour was in quasiperiodic alternation of monotonous and jumplike accumulation of deformation.
As the first type so the second type of deformation accumulation was accompanied by:
1. monotonous accumulation is accompanied by monotonous increase of mean-square tension of acoustic emission;
2. jumplike accumulation of deformation of acoustic emission in single acoustic signals of anomalously big amplitude.
The amplitude of single acoustic signals correlated with the velocity of deformation accumulation at the spasmodic section. The square of amplitude of acoustic signals was linear dependent on the deformation velocity. The correlation coefficient was close to 1. It corresponded to elementary events responsible for the accumulation of deformation at the spasmodic section which were highly-correlated. The amplitude of acoustic signals can be considered as the criterion of correlation of elementary deformation events at the spasmodic section.

Introduction

The effects of jumplike deformation in metallic materials are well known [1, 2]. Thus the studies of jumplike Al deformation at low temperature show that they are stipulated by the dynamics of the interacted movement of dislocation clusters and thermostimulated formation of dislocation avalanches [1]. Jumplike plastic flow of diluted alloys at room temperatures and more high temperatures is connected with the effect of Portevin-Le Chatelier [2]. Thermomechanical instability of a plastic flow of alloys is considered to be stipulated by a momentary coherent slipping of large groups of dislocations and spatial correlation of deformation processes in mesoscopic scale [1, 2]. Here, the notion "coherent slipping" is used within the framework of presentation on coherent cooperative states of matter [3].

Macroscopic deformation jumps and anomalously high amplitude signals of acoustic emission obtained at high temperature deformation of Al [4, 5] can not be understandable only within the framework of explanations suggested in papers [1, 2]. That is why, the paper presents the experiments, the results of analyses of acoustic and deformation effects in Al at high temperatures and interpretation of the obtained data.

The Experimental Methods

Al of technical purity was chosen as the object of experiments. The experiments represented thermomechanical cycling of samples by a cyclic change of temperature at a constant stress or stress at a constant temperature.

Cyclic change of temperature was made in the interval from room temperature to melting temperature of Al. Cyclic change of stress was made up to the values including yield stress. The temperature, the value of accumulated deformation, root – mean stress of acoustic emission, stress were registered in the experiments. The experimental plant had been described earlier [4].

The Experimental Results

Fig. 1 shows the data of acoustic emission and deformation accumulation at a cyclic change of temperature (heating – cooling with moderate velocity at a constant loading) in the first cycle. It follows from the mentioned data that monotonous increase of root-mean stress of acoustic emission corresponds to the heating of monotonous character of deformation accumulation to 0.6 – 0.7 %. Monotonous character of deformation accumulation of the value of about 0.7 % is changed by a microscopic jumplike deformation act having the value of about 0.5% (Fig.1 shows 2 deformation jumps divided by small monotonous section) at the temperatures which are higher then 0.5% Tmelt and the loading in the cycle of about 18 MPa. Single acoustic signal of anomalous big amplitude corresponds to such deformation jump. Further conducting of cycles at the increased stress is accompanied by macroscopic deformation jumps and high amplitude acoustic emission which alternates with monotonous accumulation of deformation and monotonous increase of root-mean stress of acoustic emission.

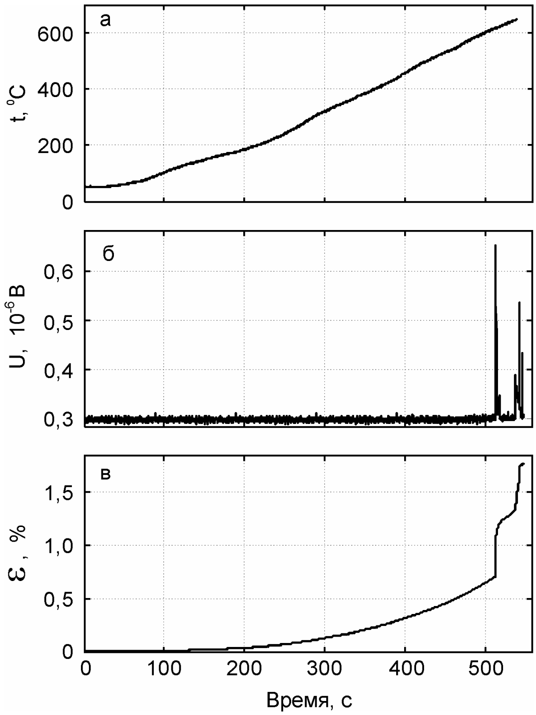

Fig. 1 Monotonous and jumplike nature of deformation accumulation and impulsive nature of acoustic emission in thermomechanical cycles at a mechanical stress of about 18 MPa: a) the dependence of temperature on the process duration; b) the dependence of root-mean stress of acoustic emission on the duration of heating; c) the dependence of deformation on the duration of heating.

Fig. 2 shows the data on deformation accumulation in isothermic cycles loading – unloading of the sample representing monotonously increasing dependence of deformation value on the process duration. In the first isothermic cycle at 600 ^{0}C, the considerable accumulation of deformation has been already observed at 10 MPa. On the dependence of it's linear increase to 33 MPa, the deformation value reaches the value of about 26%. Monotonous increase of root-mean stress of acoustic emission and the formation of single acoustic signals during the whole process of deformation correspond to such nature of deformation accumulation. The cycles loading to 30-35 MPa – unloading to zero stress are made for the temperatures: from room temperature and further after every 100 ^{0}C up to 600 ^{0}C. To analyze the determined peculiarities of deformation accumulation in thermomechanical cycles, presented in Fig.1 and 2, the analysis of activation parameters should be made.

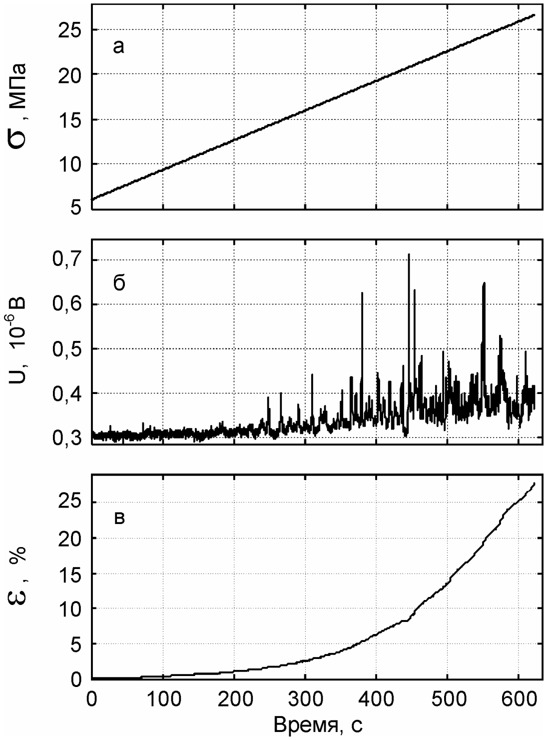

Fig. 2 Acoustic emission and deformation in the first isothermic (T=600^{0}C) thermomechanical cycle: a) linear increase of mechanical stress in the cycle; b) the dependence of root-mean stress of acoustic emission on the duration of loading in the cycle; c) the dependence of deformation on the duration of loading in the cycle.

The analysis includes the study of activation volume of elementary deformation act using the data of Fig. 2 and similar isothermal thermomechanical cycles made for the other temperature. The determination of activation volume is carried out by the analysis of the dependence of acoustic emission on stress and traditional method [6] analyzing the dependence of deformation velocity on stress. According the expression [6],

$$\frac{d\varepsilon}{dt} = \frac{d\varepsilon_0}{dt}\exp\left(-\frac{\Delta H_0 - \sigma b \Delta B}{RT}\right) \tag{1}$$

activation volume $b\Delta B$ (here b – Burger's vector) or activation area ΔB are calculated using experimental data on deformation accumulation in isothermal conditions given in coordinates $ln(d\varepsilon/dt)–\sigma$. Here, constant $(d\varepsilon_0/dt)$ – pre-exponential factor directly connected with the number of structural elements included in the elementary act of plastic deformation, $(\Delta H_0 - \sigma b\Delta B)$ activation enthalpy identical to "apparent activation energy", ΔH_0 - activation enthalpy in the absence of external loading, $\sigma b\Delta B$ – the work made by applied stress σ over the displacement of a dislocation segment.

It has been shown earlier [4] that the energy of acoustic emission $J = \sum U_i^2 \Delta t_i$ in thermomechanical cycles is proportionate to the increment of deformation, the capacity of acoustic emission dJ/dt (practically the square of the amplitude of acoustic emission) is proportionate to the velocity of deformation (in the formular Δt_i, - time of *i*-th interval, where U_i was measured). Thus, the expression (1) can be written as

$$\frac{dJ}{dt} \approx \frac{dJ_0}{dt}\exp\left(-\frac{\Delta H_0}{RT}\right)\exp\left(\frac{\sigma b\Delta B}{RT}\right) \tag{2}$$

The temperature is constant in our experiments, so the multiplier $(dJ_0/dt)\exp\left[-(\Delta H_0/RT)\right]$ in expression (2) is also constant. Thus, it can be determined activation volume $b\Delta B$ of the process temperature. Table 1 shows the data of the activation volume obtained from the analysis of the dependences of acoustic emission power (2) and deformation velocity (1) on stress according to the approach [7].

Table 1.

Activation volume of elementary deformation act in Al at thermomechanical cycling

Temperature of thermomechanical cycle, ^{0}C	Activation volume, $b\Delta B_1 \cdot nm^3$	Activation volume, $b\Delta B_2 \cdot nm^3$	Correlation coefficient r_1	Correlation coefficient r_2
25	0,34±0,01	0,41±0,02	0,985	0,993
100	0,53±0,02	0,57±0,06	0,987	0,996
200	0,57±0,05	0,65±0,08	0,986	0,995
300	0,94±0,11	0,84±0,1	0,988	0,997
400	0,93±0,1	1,5±0,014	0,986	0,994
500	1,36±0,12	1,72±0,16	0,987	0,998
600	2,70±0,23	2,59±0,25	0,994	0,997

Note. Activation volume $b\Delta B_1$ is determined by the analysis of acoustic emission, i.e. in correspondence with equation (2). Activation volume $b\Delta B_2$ is determined by the velocity of deformation accumulation, i.e. in correspondence with equation (1). The correlation coefficient r_1 defines the precision of the approximation of experimental data by equation (2), correlation coefficient r_2 by equation (1).

It follows from the comparison of activation volumes that they coincide within the limits of the experimental error. It testifies to the correctness of the analyses. Such coincidence can testify to the connection of the amplitude of acoustic signal with the value of activation volume of the elementary deformation act. This connection is determined by the size of dislocation segment moving towards the interface boundary. Such conclusion is in the agreement with classic presentation on the generation of acoustic signals by dislocations moving to the surface [8, 9]. It should be noted that deformation strip representing the rise of dislocation ensemble forms in thermomechanical cycle at high temperature [6].

It results from the obtained data that the activation volume increases with the increase of the experimental temperature. As it can be seen in Fig. 3, the dependence of the activation volume on temperature has the nonlinear nature. The dependence can be approximated by the exponential function with a high precision

$$y = y_0 + A\exp(T/T_k), \tag{3}$$

where $y_0 = 0.47 \pm 0.12$, $A = 0.0027 \pm 0.004$, $T_k = 130 \pm 29$ - the correlation coefficient which is equal to 0.986. The dimensions of the parameters A and y_0 coincide with the volume dimension in nm^3. The magnitude of the parameter y_0 exceeds the magnitude of the atomic volume by an order. The value of the atomic volume for solid states is close to 0.01 nm^3 according to [10]. Parameter T_k has a temperature dimension. It is evident that temperatures T and T_k determine thermal energy kT (k – Boltzman constant) of the atomic system. Parameter $A\exp(T/T_k)$ possesses the value 0.0073 nm^3 which is close in magnitude to Al atomic volume accounting the error when the temperatures $T=T_k$. Thus, temperature T_k determines some minimum energy kT_k, its fluctuation provides the increment of activation volume in minimum value which is equal to the atomic volume.

The exponential increase of the activation volume at the increase of temperature testifies to an essential increase of the number of cooperative atomic displacements controlling the single deformation act. The comparison of the exponential increase of the activation volume presented in Fig. 5 and jumplike nature of deformation accumulation shown in Fig. 2 testifies to the increase of the correlation of elementary deformation acts in a mesoscopic scale. The formation of deformation strips representing the rise of a big number of dislocations on the surface is considered as elementary deformation act at high temperature [6, 11]. Every jump according to [2] can be connected with the formation of localized strip of the width of about 1 mm. The dislocation ensemble forming a deformation strip can be presented as a dynamic system, its collective behavior is connected with a coherent slipping of big dislocation groups.

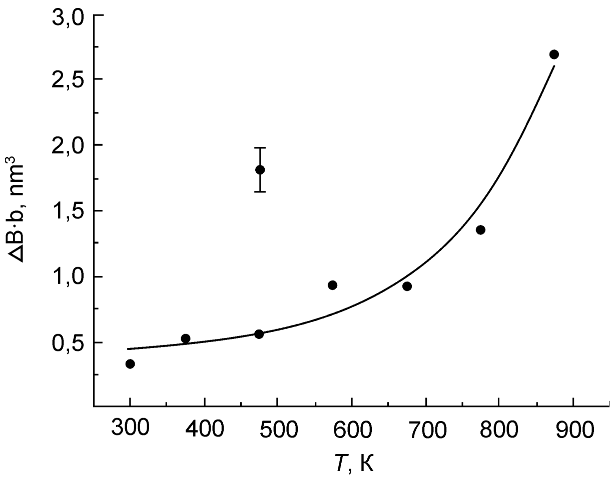

Fig. 3 The dependence of activation volume of elementary deformation act in Al on the temperature of thermomechanical cycle.

Thus, the formation of deformation strip is realized by the rise of the coherent dislocation ensemble representing the system of elementary radiators on the surface. They form an acoustic signal of anomalously high amplitude.

The enlargement of deformation strips takes place at the increase of deformation temperature [11] that correlates with the increase of activation volume under study (Fig. 3). But the macroscopic magnitude of deformation jump in our experiments testifies to the participation of more than one deformation strip in the act. In other words, the effect of correlation in the process of macroscopic jump should cover the system of deformation strips, the amplitude of acoustic signal can be the correlation measure.

As it can be seen in Fig. 4, the square of the amplitude of acoustic signal is proportional to the velocity of deformation at jumplike section. The dependence of the square of the acoustic signal amplitude on the velocity of deformation can be approximated by the linear function with a good precision (correlation coefficient is close to 0.9).

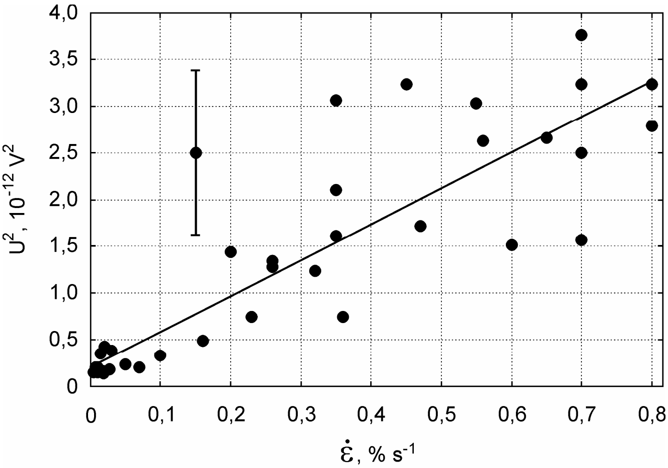

Fig. 4. The dependence of the square of acoustic signal amplitude on the velocity of deformation at jumplike section. The linear approximation of the dependence is made at the correlation coefficient 0.9.

Conclusion

Thus, experimental results testify to non-monotonous accumulation of deformation at high temperatures. These non-uniformly scaled deformation jumps (up to macroscopic ones) are accompanied by acoustic signals having the amplitude which correlates with the increment of deformation velocity. It is worth to note that the size of activation volume grows at the increase of temperature testifying to the increase of correlated atomic displacements in elementary deformation act. It follows from the experimental data that the effect of correlation can cover more than one deformation strip of dislocation ensemble.

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