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Acoustoplastic effect and activation mechanism of defect generation under conditions of quasi-static deformation of metals

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The processes of elastic and plastic deformation of materials are considered within the framework of the acoustoplastic effect. A model proposed is based on the processes of defect formation during the deformation of materials according to the activation mechanism. The dynamic equations for the formation of defects are considered in view of the change in their activation energy caused by the defect interaction. It is shown that by comparing experimental data with the obtained theoretical results, it is possible to obtain information about such characteristics of materials as the concentration of defects, their relaxation time, the nature of interaction, and internal friction stress. These parameters were obtained for aluminum and copper alloy M1.

Keywords: metal deformation, defects, mechanical stress, activation volume.

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Analysis of reconstruction of the material structure under impact of external loads is of significant interest, as it can determine mechanisms of transition from a mode of elastic deformation to a mode of plastic deformation. Experimentally, these dependences are obtained using loading devices, which are designed to specify a certain strain rate and record a value of applied stress corresponding thereto [1,2]. The results obtained in this way are usually analyzed within the framework of respective empirical dependences or by means of certain thermodynamic models. The first case includes, for example a John-Cook model, which relates the sample stress to deformation, its rate and the sample temperature, as well [3,4]. At a specified loading rate and an unchanged temperature, this model characterizes the material with five parameters, and in order to describe change-temperature experiments, it additionally uses the sixth parameter. The thermodynamic approach is aimed at establishing relation of bond energy of plastic deformation (or a rate of accumulation thereof) to work to be done by the loading device. Several mechanisms of plastic deformation of the material can be considered within its framework [5].

If it is necessary to take into account the change of the sample temperature during deformation, a Taylor-Quinney factor is additionally determined, which takes into account a portion of energy of plastic deformation of the sample as spent for its heating [6,7]. In all the said cases, the obtained parameters characterize macroscopic properties of the material. However, specification of the physical processes accounted for the change of mechanical properties of materials at various stages of deformation requires more detailed description of micromechanisms of development of the material's defect structure in a plastic flow. For analysis of evolution of the microstructure of the sample under loading, it is desirable to have a theoretical model designed to trace changes of the physical processes therein when the material passes from the area of elastic deformation to the plastic flow.

In this regard, the present study is mainly aimed at developing a simple physical model of transformation of the mechanical properties of the material when it passes from the area of elastic deformation to the area of plastic deformation. Presently, the elastic and plastic deformations of the materials in quasi-static deformation are usually studied within the framework of an acoustoplastic effect [8–11]. In this approach, the dynamics of behavior of the sample stress at its nonstationary deformation with the constant rate described based on Eq. [12]:

$$\frac{1}{E}\frac{\partial\sigma}{\partial t} = \dot{\varepsilon} - \dot{\varepsilon}_p, \tag{1}$$

where E is the Young's modulus of a material, $\dot{\varepsilon}$ is the total strain rate, which is specified by an external source, $\dot{\varepsilon}_p$ is the plastic strain rate of the material.

In order to determine the plastic strain rate $\dot{\varepsilon}_p$, it is usually believed that defects in the material are generated as per an activation law of Arrhenius, and it can be found from the relationship

$$\dot{\varepsilon}_p = \dot{\varepsilon}_p^{(0)} \exp\left(- \frac{U - \Omega(\sigma - \sigma_f - \sigma_p(\varepsilon))}{k_b T} \right), \tag{2}$$

where U is the activation energy of the metastable defects, σ_f is the stress due to internal friction for the defects, $\sigma_P(\varepsilon)$ is the sample stress related to generation of the defects therein, the pre-exponential factor $\dot{\varepsilon}_p^{(0)}$ describes the defect generation rate and it is usually assumed to be a constant one, Ω is the activation volume of the defect, k_b is the Boltzmann constant, T is the sample temperature.

The solution of Eq. (1) in relation to the stress at the plastic strain rate, which is determined by Eq. (2) and a start of operation of the deforming device at the point of time $t = 0$, can be presented as follows

$$\sigma(t) = E\dot{\varepsilon}_0 t - \frac{k_b T}{\Omega} \times \ln\left[1 + \frac{\Omega E}{k_b T}\,\dot{\varepsilon}_U \int_0^t dt' \exp\left(\frac{\Omega(E\dot{\varepsilon}_0 t' - \sigma_f - \sigma_p(\varepsilon))}{k_b T}\right)\right], \tag{3}$$

where $\dot{\varepsilon}_0 = \dot{\varepsilon}_p^{(0)} \exp(-U_0/k_bT)$.

In accordance with Eq. (3), in order to determine dependence of σ on time (or strain), it is necessary to know the dependence $\sigma_p(\varepsilon)$. When using the acoustoplastic effect, it is often specified empirically. In particular, it has been assumed in the study [12] that $\sigma_p(\varepsilon) \propto \sqrt{\varepsilon}$.

The present study suggests to determine the dependence $\sigma_p(\varepsilon)$ within the framework of the activation model instead of using the empirical relationships. For this, we shall use a relationship that relates the sample stress to concentration of the defects therein. In the simplest case of one-dimensional deformation this relationship takes the form [13,14]:

$$\sigma = E\varepsilon_e + \Omega E n, \tag{4}$$

where ε_e is elastic deformation of the sample, n is concentration of the defects in its material.

With small concentration of the defects and absence of the diffusion processes, we have shown that its change was quite well described by the equation [15–19]:

$$\frac{dN}{dt} = \frac{1 - N}{\tau}, \tag{5}$$

where $N = n/n_r$, n_r is a certain equilibrium value of concentration of the defects in the material, $\tau = \tau_0 \exp(U_0/k_bT)$, τ_0 is the time reciprocal to the Debye frequency ($\tau_0 \sim 0.1\,\text{ps}$).

For using the equation (5), it is assumed that the activation energy of the defects is unchanged. We have shown usefulness of its use for explaining peculiarities of oscillations of thin aluminum membranes [15], when analyzing a nature of behavior of the laser ultrasound signals in stressed ceramics and metals [16,17], effects of „fast“ and „slow“ dynamics when considering relaxation processes in the plastically deformed aluminum rods [18,19].

Generally, the activation energy depends on concentration of defects. In the first approximation for the concentration of defects this dependence can be presented by the equation [20,21]:

$$U = U_0 + U_1 \frac{n}{n_r}. \tag{6}$$

The studies [20,21] have shown that at the high concentrations of defects when their interaction with each other is substantial, an equation of the following kind shall be used instead of (5)

$$\frac{dN}{dt} = \frac{1 - N}{\tau} \exp(-\alpha N), \tag{7}$$

where $\alpha = U_1/k_bT$.

Equation (7) can not be solved analytically. But in accordance with [20,21] it is quite well approximated by a function

$$N = 1 - \exp\left\lfloor -(t/\tau)^{\beta} \right\rfloor. \tag{8}$$

Equation (8) describes a non-exponential law of defects. The exponent $\beta \geq 0$. The case $\beta = 1$ corresponds to low concentration of defects. Usually, the value β is within the range from 0 to 1, but in some conditions the values $\beta \geq 1$ are also possible [21]. Within the framework of our proposed model, it is considered to be a constant value, which is determined from comparison of the theoretical results and the experimental data.

In Eq. (4), the second summand is related to generation of plastic strain in the material. Taking into account Eqs. (4) and (8), we obtain the dependence of stress of the plastic flow on time as follows

$$\sigma_p(t) = \Omega E n = \Omega E n_r \left\lfloor 1 - \exp\left(-(t/\tau)^{\beta}\right) \right\rfloor. \tag{9}$$

After inserting the expression (9) into Eq. (3) and passing from time integration to strain integration, we obtain the dependence of the stress $\sigma(\varepsilon)$ as follows

$$\sigma(\varepsilon) = E\varepsilon - \frac{k_bT}{\Omega} \ln\left[1 + \frac{\Omega E}{k_bT}\frac{\dot{\varepsilon}_T}{\dot{\varepsilon}_0} \times \int_0^{\varepsilon} d\varepsilon' \exp\left(\frac{\Omega(E\varepsilon' - \sigma_f - \Omega E n_r \Phi(\varepsilon'))}{k_bT}\right)\right], \tag{10}$$

where the function $\Phi(\varepsilon)$ is

$$\Phi(\varepsilon) = 1 - \exp\left(-(\varepsilon/\dot{\varepsilon}_0\tau)^{\beta}\right). \tag{11}$$

Equation (10) can trace the dependence $\sigma(\varepsilon)$ both in the elastic and the plastic area. The similar expression, which is obtained in the study [12] and used for computer simulation of the dependence $\sigma(\varepsilon)$ corresponds to a particular case of Eq. (10) at $\varepsilon < \dot{\varepsilon}_0\tau$ and $\beta = 1/2$.

The experiments show [22] that at low strain rate σ weakly depends on $\dot{\varepsilon}_0$. In accordance with Eq. (10), this situation is realized under the condition $\dot{\varepsilon}_U \approx \dot{\varepsilon}_0$. The expression (10) has five unknown (or hardly accessible) parameters Ω, σ_f, n_r, β, τ. If $\dot{\varepsilon}_U$ is unknown, it is still five parameters as in this case the multiplier $\dot{\varepsilon}_U \exp(-\Omega\sigma_f/k_bT)$ is unknown. At high strain rates, the sample temperature can change during deformation. In these conditions its determination is a separate task. At the low rates of deformation, its change is usually insignificant. The framework of the present study limits review by this case and further on the sample temperature is considered to be specified. It should be noted that

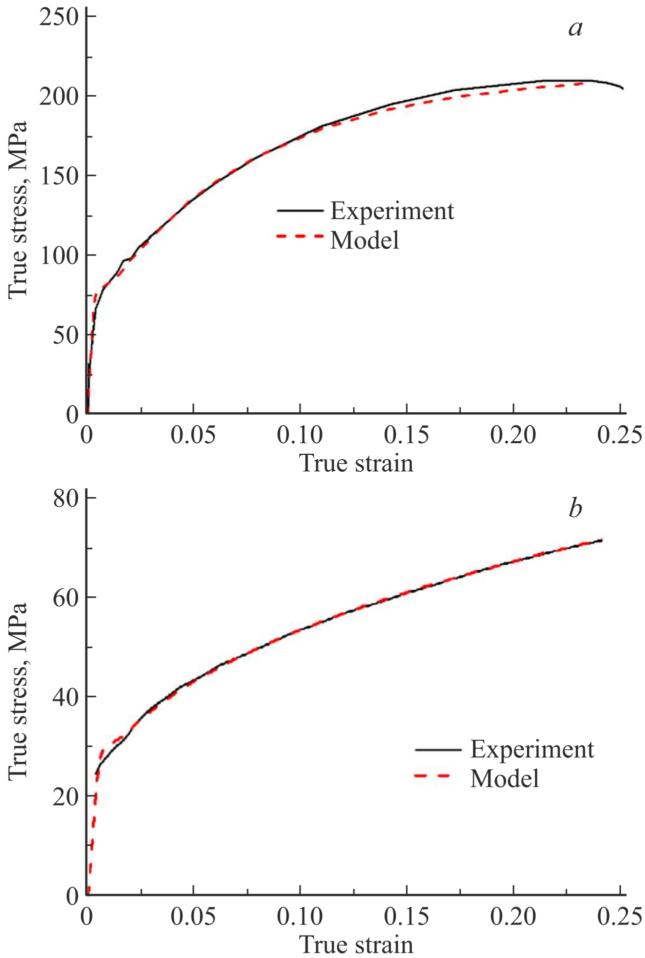
Parameters of approximation of the experimental stress-strain curves

Material	$\Omega \cdot 10^{28}$ (m^3)	$n_r \cdot 10^{-25}$ (m^{-3})	β	τ (s)	σ_f (MPa)	δ (MPa)
Copper M1	0.55 ± 0.14	2 ± 1	1.0 ± 0.15	0.08 ± 0.005	167 ± 8	2.5
Aluminum	1.65 ± 0.25	2.1 ± 0.6	0.46 ± 0.02	4200 ± 2500	82 ± 1	3.7

within the framework of the thermodynamic approach the description of the dependence of σ on εalso has five unknown parameters [3,4]. But in case of an approach within the framework of the acoustoplastic effect these parameters have a more transparent physical meaning.

Using the computer simulation, the study [12] has shown that the model of acoustoplastic effect studied therein could qualitatively describe the dependence of σ on ε when passing from the area of elastic deformation to the area of plastic deformation. At the same time, it has not analyzed an issue of its applicability for explaining experimental results for particular materials. In this regard, using the computer simulation, the present study has compared the theoretical results obtained by means of a generalized model of acoustoplastic effect and the available experimental data for some materials. The said experimental data were selected due to a relatively low rate of samples loading, at which the change of their temperature did not play a substantial role. To exemplify description of the experimental dependences of true stress on true deformation using Eq. (10), we consider the available experimental data of the standard tensile tests for two metals: aluminum and copper, which are published in the studies [23,24], respectively. The figure shows the experimental data and the respective theoretical curves obtained by means of Eq. (10). The values of the parameters that ensure the best compliance are shown in the table. It also has a mean-root-square deviation δ that is obtained in approximation of the dependence of σ on ε. As can be seen from the figure, Eq. (10) quite well describes the elastic and the plastic sections of the curves at the same time.

In accordance with the table, the activation volumes of the defects for both the metals have the positive values. The positivity of the activation volumes of defects means that during tension the metals under study have mainly exhibited generation of defects of a „vacancy" type. The values of the activation volume of the defects as obtained for all the cases are about 10^{-28} m^3, while the equilibrium value of concentration of the defects is about $10^{25}-10^{26}$ m^{-3}. Let us note that these concentrations and the volumes approximately correspond to the values that we have obtained in the studies [15–19]. As for the relaxation time for aluminum, it is well correlated to the relaxation time of the plastically deformed rods made of the aluminum alloy D16, which was observed without external effects [25]. At the same time, the value for aluminum $\beta \sim 0.46$ shows that interaction of the defects during deformation and change of the activation energy becomes substantial. We note that this value of β is close to that one used in the study [12].



Stress-strain dependence for *a* — the copper alloy M1 (the experimental data [24]) and *b* — pure aluminum (the experimental data [23]). The strain rate is 10^{-3} s^{-1}.

For copper M1 the relaxation times have substantially lower significance and, unfortunately, the literature has no data for it. For copper M1 the value $\beta \sim 1$ and interaction of the defects during deformation has not played the substantial role and the value of activation energy was unchanged during defect formation. The friction stress value σ_f obtained both for aluminum and copper is approximately $10^{-3}E$. These values of σ_f approximately correspond to evaluations used in the study [12], too.

Thus, the obtained results show that the modified model of acoustoplastic effect can be used to interpret the results of material deformation at the constant temperature. At the same time, it is possible to obtain information about such characteristics of the defects as their concentration and activation volume, the relaxation time, the internal friction stress, the degree of interaction of the defects with each other.

Conflict of interest

The authors declare that they have no conflict of interest.

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