

Optoacoustic spectral control of structural materials damage rate during their deformation. Experiment

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An optoacoustic method for monitoring and developing the process of damage in structural materials in mesoscale during their (nonlinear) deformation is outlined. The occurrence and development of the damage process during uniaxial stretching of metal specimens (M1 copper, BT6 titanium) is shown. The possibility of a separate assessment of material damage occurred from external loading and shear deformations is highlighted.

Keywords: optoacoustics, heat dissipation, spectral analysis, longitudinal and transverse waves, Poisson's ratio.

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1. Introduction

To date, almost all theories of plasticity are based on dividing the rigidity of the material into two deformation mechanisms, one of which determines the change in volume, and the other determines the change in shape. In this case, it is the shape change mechanism that defines all types of nonlinear behavior of the material, and almost all theories of plasticity and creep are based on it [1–5].

In the process of nonlinear deformation, at each moment of time the tested material is in a new state, which is determined by rebuilding of its structure, caused, first of all, by the action of shear stresses, as well as by the processes of interaction and formation of meso-structures characteristic of different stages of deformation. For example, in metals, up to four stages are distinguished at the stage of plastic flow, differing in the nature and scale of structural transformations [6–8], which is primarily due to the action of shear stresses.

Changes in the mechanical properties of materials during their deformation can have a different nature, which can be interpreted as the accumulation of various structural defects — variations in the shape of fragments, cells, blocks, polygons, and so on are often determined by the degree of disorientation of structural elements.

The durability of materials impacted by external mechanical stresses is described within models of accumulation of this kind of scattered damage as part of mechanical behavior of a damaged medium.

Fundamental in assessing the degree of damage are the studies by L.M. Kachanov, Yu.N. Rabonov and V.V. Bolotin [2–4], where the parameter of the internal state is used as a measure of damage, the physical nature of which is determined by the choice of a specific model.

Diagnostics using non-destructive testing methods, in particular, acoustic methods with high sensitivity and versatility,

play a special role in assessing the degree of structural change and damage.

The rationale for the use of acoustic methods for quantifying and stages of development of structural materials damage is based on the studies describing propagation of elastic waves in damaged media under various types of impact.

Recently, variants of spectral acoustic measurements have been proposed, which have increased sensitivity to structural rearrangements in materials, and seem promising for solving problems of damage control of structural materials [11,12].

The expansion of the possibilities of such techniques is the study of changes in the coefficient of transverse deformation (Poisson's ratio) in the process of deformation of materials using acoustic techniques. This allows to get an insight on the nonlinear deformation processes, since the transverse deformation coefficient (ν), as well as the Gruneisen parameter (γ) in the mechanics of a deformable solid, determines the thermodynamic and mechanical characteristics of the state of the material:

$$\gamma = \frac{3}{2} \cdot \frac{1 + \nu}{2 - 3\nu}; \quad \nu_{td} = \frac{c_1^2 - 2c_t^2}{2(c_1^2 - c_t^2)}, \quad (1)$$

where c_1 and c_t — velocities of longitudinal and transverse waves.

The structural inhomogeneities that arise at the stage of the nonlinear deformation process are actually meso-resonators themselves characterized by their own frequency spectra. When interacting with these structures, the spectra of nanosecond acoustic diagnostic pulses change, which makes it possible to control the process of damage to materials.

Modern methods of laser optoacoustics significantly expand the pool of data on acoustic diagnostics due to the non-contact excitation of nanosecond acoustic pulses and the possibility of simultaneous excitation of pulses

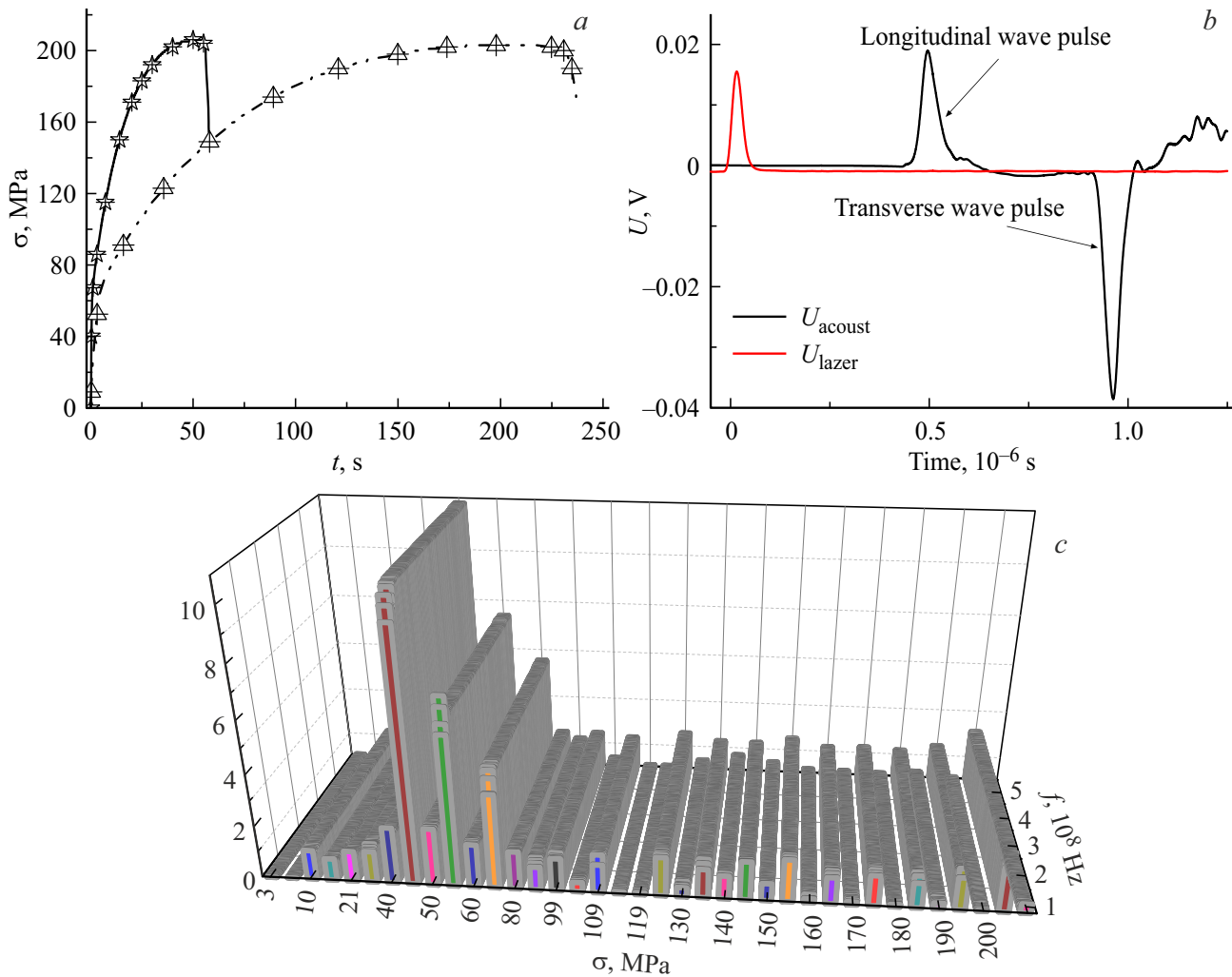


Figure 1. Dependencies σ - ε — *a*; oscillograms of laser pulse and piezoelectric transducer signal when testing the steel specimen — *b*, dependence of the power spectral density when testing M1 copper specimen at a speed of 5 mm/min — *c*.

of longitudinal and transverse waves [13,14], with their propagation velocity control containing information about changes in the volume and shear modules of materials.

A wide range of frequencies $\Delta f \sim 0.1 \div 50$ MHz, excited by laser radiation of acoustic pulses makes it possible to determine the occurrence of mesoscale inhomogeneities.

At the same time, when using such a method the medium diagnostics time is much shorter than the time of changing the parameters of quasi-static loading, and the energy of acoustic pulses excited by laser radiation is much less than the characteristic activation energies of the structural changes mechanisms.

Thus, monitoring the changes in the pulse spectra of longitudinal and transverse waves propagating through the test specimen makes it possible to assess structural changes, that is, the damage rate of the material.

Considering the material as an acoustic four-pole, the task of determining the characteristics of scattered damage can be defined as the task of getting required data from the transfer characteristics of the material.

Using this approach, the pulses of the linear system $F(t)$ response to an external influence $f(\tau)$ can be written as [15]:

$$F(t) = \int_{-\infty}^{\infty} H(t - \tau) f(\tau) d\tau, \quad (2)$$

where $H(t)$ is the system's response to the impact described by δ Dirac function, or the transfer function characterizing the studied medium.

The spectrum of the acoustic signal $\tilde{F}(\omega)$ transmitted through the deformed material is related to the spectrum of the input signal $\tilde{f}(\omega)$.

$$\tilde{F}(\omega) = \tilde{H}(\omega) \tilde{f}(\omega), \quad (3)$$

where $\tilde{F}(\omega)$ — Fourier transform $F(t)$.

The simplest damage parameter describing changes in a material during deformations can be described using the

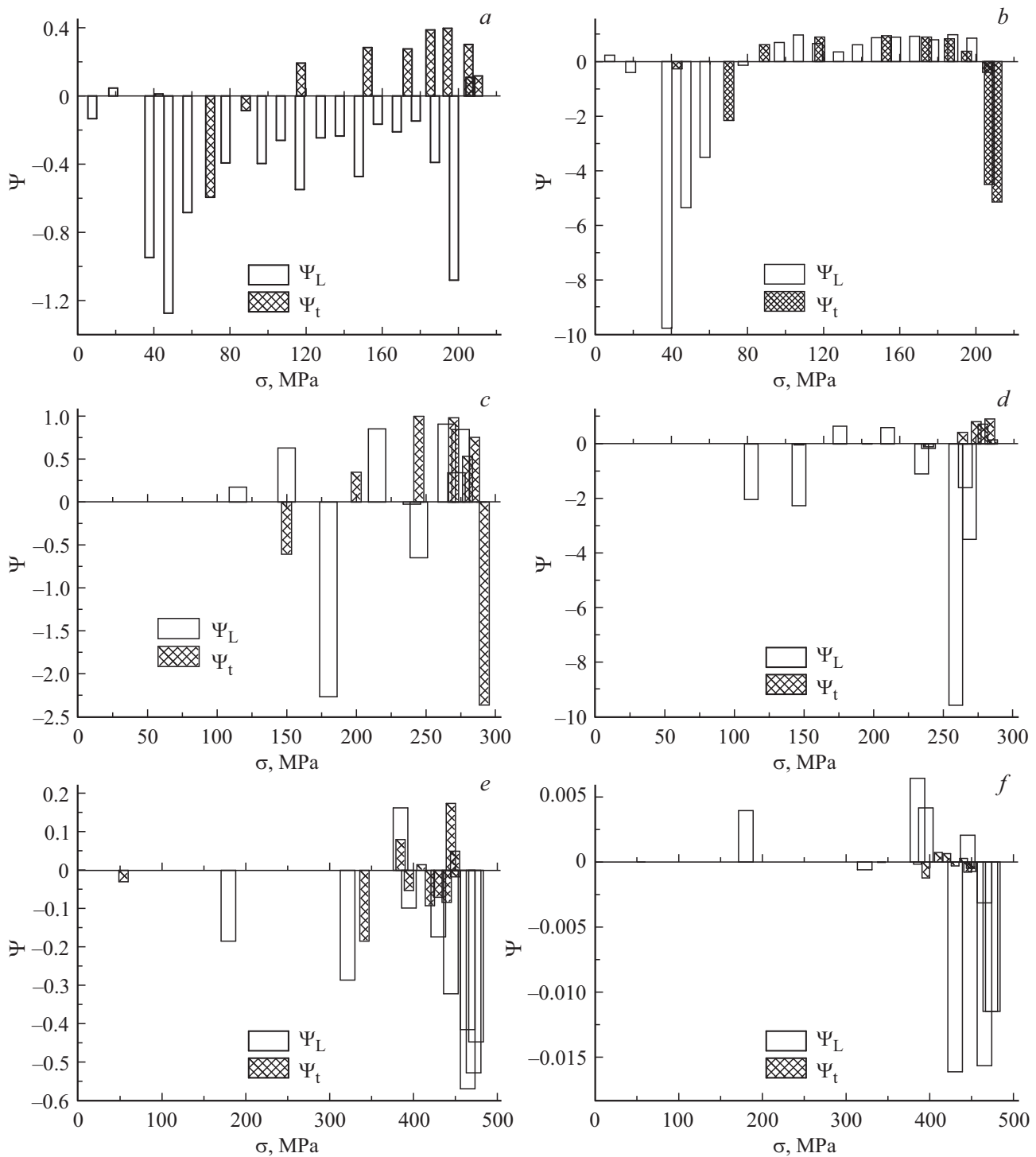


Figure 2. Damage processes of copper specimens M1 — (a, b), stainless steel 12X18H10T — (c, d), titanium alloy BT1 — (e, f) at tensile rates of 5 mm/min and 20 mm/min.

convolution theorem for the Fourier transform [16]:

$$\psi = 1 - \frac{|\tilde{F}(\omega)|_{\sigma}}{|\tilde{F}(\omega)|_0}, \quad (4)$$

where $|\tilde{F}(\omega)|_{\sigma}$ — system response with load σ , $|\tilde{F}(\omega)|_0$ — without load, ψ — damage rate parameter similar to that introduced in [17].

2. Research technique

Quasi-static stretching of standard flat specimens with dimensions of the work part $50 \times 5 \times 2$ mm was carried out on a universal testing machine SHIMADZUAG-X50v at room temperature at deformation rates of 5 and 20 mm/min. The specimens temperature variation was monitored by

infrared radiation recorded by ThermaCAM SC 300 thermal imaging camera with a frequency of 50 Hz.

In the stretching process, the optical-acoustic method was used [14,18] based on sounding a specimen with short acoustic pulses of longitudinal and transverse waves excited by nanosecond laser pulses following a frequency of 1 Hz.

The laser radiation with duration $\tau_{0.5} = 10^{-8}$ s and energy $E \leq 10^{-3}$ J was transmitted using an optoacoustic fiber with a diameter of 0.6 mm. Under this action the pulse of both longitudinal and transverse waves is excited in the studied specimens.

In order to improve the measurement accuracy of spectra and velocities c_l and c_t the simultaneous recording of longitudinal and transverse wave pulses by one piezoceramic transducer was made. For this purpose, the piezoelectric plate 3 mm thick was cut from thick plane-parallel piezoceramics ZTC19 at an angle $\sim 45^\circ$ to the polarization direction.

Signals from the piezoelectric transducer were recorded using Lecroy oscilloscope with $\Delta f \approx 600$ MHz. The measurement diagram and typical oscillograms of the laser pulse, as well as the piezoelectric transducer signal when the steel specimen is stretched, are shown in Figure 1.

The newly automatic data processing algorithm based on MATLAB enabled to identify the longitudinal and transverse waves pulses from the oscillograms corresponding to the points on the curves σ - ε (Figure 1, *a*). Further, a separate spectral analysis of the normalized longitudinal and transverse pulses corresponding to different load values was carried out.

The methodology and research results shown in Figures 1 and 2 made it possible to diagnose the nature of the development of damage to the tested materials during stretching using a simple parameter Ψ from the ratio (4).

3. Discussion of findings

Figure 2 shows the results of assessing the damage rate (Ψ) of copper specimens M1 — (*a, b*), stainless steel specimens 12X18H10T — (*c, d*), titanium alloy specimens BT1 — (*e, f*) at the tensile rates of 5 mm/min and 20 mm/min.

The left column shows the results obtained by analyzing the pulse spectra of longitudinal waves, and the right column shows transverse waves. For the loading rates of 5 mm/min the damage rate diagrams — Ψ_l are colorless, and for the rate of 20 mm/min — Ψ_t they are shaded.

There is an uneven development of damage processes for all tested metals, as well as a significant difference in the nature of Ψ_l and Ψ_t changes obtained by spectral analysis of longitudinal and transverse wave pulses.

This is due to the significant difference in damage (mesoscale) under the action of external work of volume change and the action of volumetric (internal) forces determining transverse deformations. The observed change in the sign of the damage rate can be explained by

change in the shape and characteristic size of the resulting inhomogeneities, which alters the way of interaction of the spectrum components of the diagnostic pulse spectrum with defects. Scattering for some frequencies can be replaced by absorption for other components of the spectrum.

It should also be noted that there is a significant difference in the development of the damage process at different loading speeds, represented in the left (5 mm/min) and right (20 mm/min) columns of Figure 2.

Both the values of damage entered in (4) Ψ and the nature of the development of this process differ.

4. Conclusion

Thus, the outlined method can make it possible to control the structural changes in the processes of nonlinear deformation of solids and make a great contribution to the development of methods for diagnosing stress-strain conditions of materials and structural elements.

It should also be added that this method makes it possible to obtain not only data on changes in the spectra and accumulation of damage to materials, but also to control the energy balance variation during deformation [18] when controlling the heat release.

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Conflict of interest

The authors declare that there is no conflict of interest.

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