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RELATIONSHIP OF ACOUSTIC EMISSION PARAMETERS WITH DEFORMATION STAGES AND MECHANICAL PROPERTIES OF COAL SAMPLES

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Regularities of acoustic emission (AE) manifestation in anthracite samples at various modes and at separate stages of deformation, and also on borders of transitions between the specified stages are experimentally established. Uniaxial tests were carried out with the given loading and displacement rate. Triaxial axisymmetric tests with constant longitudinal deformation rate at various values of a lateral stress were carried out. The relationship of informative AE parameters with mechanical properties and stress state of coal is revealed. Predicting AE attributes of approach dilatancy and destruction of coal are established.

INTRODUCTION

Mechanical loading of rock samples is accompanied by characteristic changes of informative acoustic emission (AE) parameters. AE is the effective means of researches in the field of strength, plasticity and destruction of geomaterials. The regularities of emission processes are determined substantially by type of tested rock, features of its structure, frame, and also conditions of realization of experiments. The peculiarities of AE dynamics are characterized by the certain stability in case of research of AE behaviour under loading on samples of one rock type in identical conditions of hardware and methodical maintenance of measurements.

During mechanical loading AE of geological media manifests presence of stages that is one from distinctive general regularities of AE. AE parameters at development of damage in geomaterial show dependence on characteristic stages of deformation of a sample. Natural change of AE stages can be used for identification of deformation stages. Thus anomalies of AE characteristics on borders between stages of deformation correspond to the certain parameters of mechanical properties of rock sample. AE stages of rock can be most precisely revealed by comparison of the results of AE parameters measurements to the deformation curves representing dependences of longitudinal ε_1, lateral ε_3 and volume ε_v deformation of a sample upon stress (or stress upon the specified deformations).

The limited number of works on study of AE in coal samples was carried out in a sound and bottom ultrasonic range of frequencies under uniaxial compression mainly. However already in the first experimental researches executed in middle of the last century natural evolution in behaviour of AE parameters at various deformation stages of coal samples, dependence of AE peculiarities upon strength properties of the given geomaterial, and also an opportunity of forecasting under AE characteristics critical macro-fracturing of coal samples were noted.

The aim of the present work was the establishment of behaviour features of informative AE parameters in coal samples at various deformation stages and borders of transition between the specified stages at a number of loading modes.

EXPERIMENTAL PROCEDURE

Researches were carried out on cylindrical samples of anthracite from the mine "Zapadnaya" (Novoshakhtinsk, Rostov region). Specimens were height 100 mm and diameter 50 mm. Samples of coal were tested in modes of uniaxial and triaxial axisymmetric loading. Uniaxial compression was carried out with the given loading and displacement rate. Triaxial axisymmetric tests ($\sigma_1 > \sigma_2 = \sigma_3$, σ_i – principal stresses, i = 1, 2, 3) were carried out with constant longitudinal deformation rate at various values of a lateral stress ($\sigma_2 = \sigma_3$).

Experiments were carried out in stabilometer by means of test machine EU-100 (Germany). Computerised measuring system allowed to carry out automated registration of mechanical parameters. AE was investigated with the help of AE measuring complex A-line 32D in the ultrasonic range of frequencies from 30 to 500 kHz. During experiments values of longitudinal ε_1, lateral ε_3 deformations, an axial stress σ_1 under uniaxial loading, differences of the principal stresses $\Delta\sigma_1 = \sigma_1 - \sigma_3$ and the lateral stress σ_3 under triaxial compression were registered. Values of volume deformation were calculated: $\varepsilon_v = \varepsilon_1 + 2\varepsilon_3$. As the basic informative parameters at the analysis AE behaviour of coal samples were used AE activity $\dot{N}$ and cumulative AE N_{Σ}.

Diagrams of dependences $\sigma_1 - \varepsilon_1$, $\Delta\sigma_1 - \varepsilon_1$, $\dot{N} - \varepsilon_1$, $N_{\Sigma} - \varepsilon_1$, $\varepsilon_v - \sigma_1$, $\varepsilon_v - \Delta\sigma_1$, $\dot{N} - \sigma_1$, $\dot{N} - \Delta\sigma_1$, $N_{\Sigma} - \sigma_1$, $N_{\Sigma} - \Delta\sigma_1$ were plotted by results of experiments. The revealing of anomalies in AE dynamics for various deformation stages and borders of transitions between the specified stages was made by comparison curves dependences of stress and AE parameters upon deformation, and also volume deformation and AE characteristics upon stress.

RESULTS

In a case of uniaxial tests of the sample with the given deformation rate (Fig. 1*a*) it is possible to identify six deformation stages: 0*a* – initial, *ab* – linear elastic, *bc* – elastic-plastic, *cd* – ultimate destruction (four pre-failure stages), *de* – post-failure destruction and *eg* – post-failure desintegration (two post-failure stages). Thus the point *b* corresponds to achievement of elasticity limit of coal σ_e, the point *c* – long-term ultimate strength σ_∞, the point *d* – ultimate compressive strength σ_c. The point *e* corresponds to the long-term ultimate strength of coal in post-failure region σ_∞^*. The point *f* at a stage *eg* designates achievement of the residual strength σ_0.

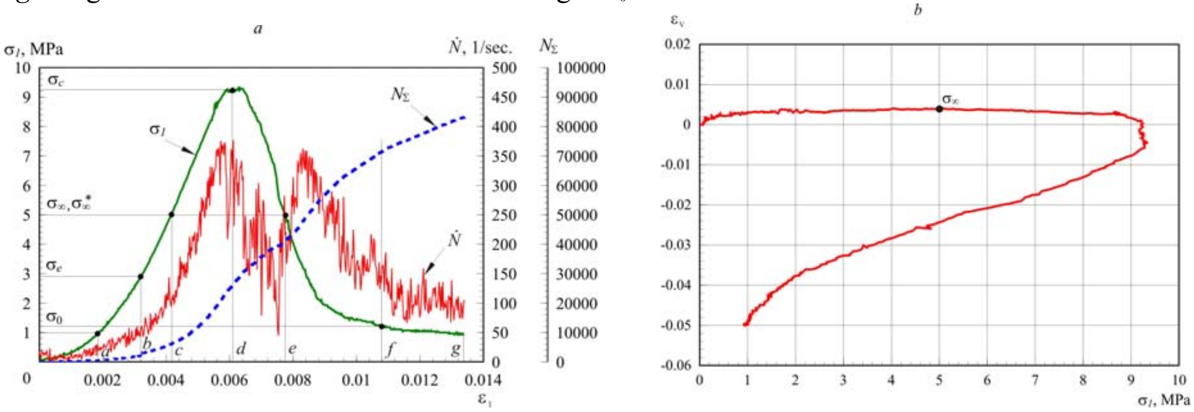

Fig. 1. Dependences of the stress and AE parameters upon longitudinal deformation (*a*) and volume deformation upon the stress (*b*) under uniaxial compression of the coal sample at the loading mode of constant deformation rate

In case of uniaxial tests of the coal sample with the given loading rate four deformation stages are identified: 0*a*, *ab*, *bc*, *cd*.

The burst of AE activity values at the stage 0*a* takes place, the values are minimal at the stage *ab*, the stage *bc* is characterized by the increase of $\dot{N}$ values, the stage *cd* is accompanied by the $\dot{N}$ values close to maximal. AE activity decreases and increases up to the values close to maximal at the stage *de* (on the limit σ_∞^* in the point *e*). Then gradual reduction of AE activity up to the values making 30–40 % from maximal (the limit σ_0 in the point *f*) at the stage *eg* takes place. On the borders between deformation stages appropriate to certain parameters of mechanical properties of coal the curve of dependence N_{Σ} upon time has excesses (inflexions) due to changes of the angle of diagram slope. Limits σ_e, σ_c and σ_0 are identified most precisely on cumulative AE behaviour.

To precise identification of the long-term ultimate strength of coal the additional analysis of diagrams of dependences of volume deformation and AE parameters upon σ_1 or $\Delta\sigma_1$ (for triaxial loading) is expedient to use. On Fig. 1*b* the estimation of the stress of long-term ultimate strength by the maximum of values ε_v (σ_∞ = 5 MPa) is shown.

At triaxial axisymmetric loading of coal samples (Fig. 2) the identification of the following deformation stages is possible: 0*A* – initial, *AB* – linear elastic, *BD* – elastic-plastic, *DE* – ultimate destruction, *EF* – post-failure destruction and *FG* – post-failure desintegration. The point *C* (long-term ultimate strength) is at the stage *BD* in this case. In behaviour of AE parameters the determined anomalies take place but it are distinct from the case of uniaxial loading. The anomalies appropriate to the characteristics of mechanical properties of coal designated on Fig. 2.

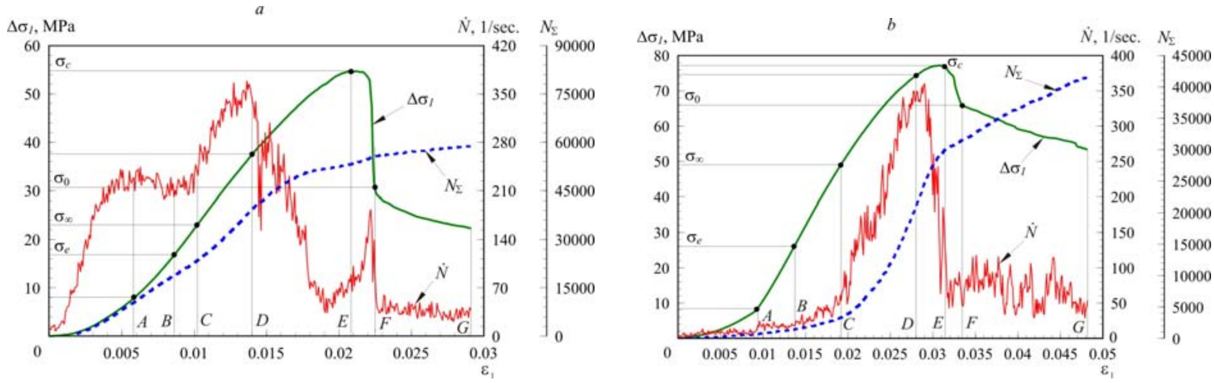

Fig. 2. Dependences of the difference of principal stresses and AE parameters upon longitudinal deformation under triaxial axisymmetric loading of the coal sample in conditions of the lateral stress equal 5 MPa (*a*) and 15 MPa (*b*)

Complex (triaxial) stress state is shown by the decreasing of $\dot{N}$ values considerably earlier, than the ultimate strength of the sample is reached, as against uniaxial compression. Also available "tooth-shape" burst of AE activity at achievement of the limit of residual strength that is most expressed at moderate lateral stresses (5, 10 MPa). Besides at triaxial axisymmetric tests two types of AE behaviour (Fig. 2) are possible. At moderate lateral stresses (5, 10 MPa) the basic share of defects in coal is realized in the pre-failure region of deformation (Fig. 2*a*). At the high lateral stresses (15 MPa and more) the majority of defects is initiated in ultimate and post-failure regions (Fig. 2*b*), and AE behaviour is similar in many respects to a case of the uniaxial compression with the given deformation rate.

By AE behaviour type of coal it is possible to define the mode of test: with the given loading or displacement rate, uniaxial or triaxial.

The relationship of informative AE parameters with deformation stages and type of stress state of coal samples is revealed with use of the analysis of «stress – strain» diagrams, that is one of the most widespread and authentic ways of the estimation of mechanical properties and state of geomaterial samples. However reception of the specified the experimental information demands measurement of forces and deformations. Thus deformation measurements are characterized by significant labourious. Due to the structure peculiarities and mechanical properties of coal the deformation measurements can not give unequivocal results (instability and heterogeneity of strain behaviour of coal sample). Also the deformation measurements can be impracticable in general for coal (for example, the sticking of strain gauges on a defective surface of coal sample).

In 1981 the way of stress state estimation of rocks was offered under uniaxial loading on the basis of reception of so-called "AE signatures" [3]. The AE signatures plot as dependences «cumulative AE – stress». On anomalies of AE behaviour during tests of rock samples it is possible to identify the certain deformation stages. On the basis of the received AE signatures the rocks were classified on four types. However, the specified researches concerned only to the mode of uniaxial loading and it did not include the data on AE behaviour of coal. But the results received for classical fragile and plastic rocks can not be distributed for coal.

The revealed relationship of AE parameters with mechanical properties and state of coal samples creates preconditions for development of the method of identification and quantitative estimation of this properties and state with use of AE measurements. This method provides the opportunity of exception of deformation measurements and registration of stresses only. That allows to reduce the expenditures of labour and the time of preparatory operations at experimentation. So, one of possible variants of the specified method realization can consist in the following.

By results of experiments with one coordinate plane the diagrams of dependences of axial stress σ_1 (or difference of principal stresses $\Delta\sigma_1 = \sigma_1 - \sigma_3$ in the case of triaxial axisymmetric loading), AE activity $\dot{N}$ and cumulative AE N_Σ upon time t are plotted (Fig. 3). Thus the axis of time (the axis of abscissas) is common. It is expedient the axes of functions upon time (the axes of ordinates) to plot three for convenience of results interpretation due to different value scales of parameters: σ_1 (or

$\Delta\sigma_1$), $\dot{N}$ and N_Σ. The moment of time of AE anomaly manifestation appropriate to the certain parameter of mechanical properties is estimated. In the point of the given time moment the perpendicular is plotted to the axis of abscissas to crossing with the diagram of dependency of σ_1 (or $\Delta\sigma_1$) upon time. From the specified point of crossing the perpendicular is plotted to an axis of values σ_1 (or $\Delta\sigma_1$). So numerical value of the stress appropriate to the parameter of mechanical properties of coal is estimated.

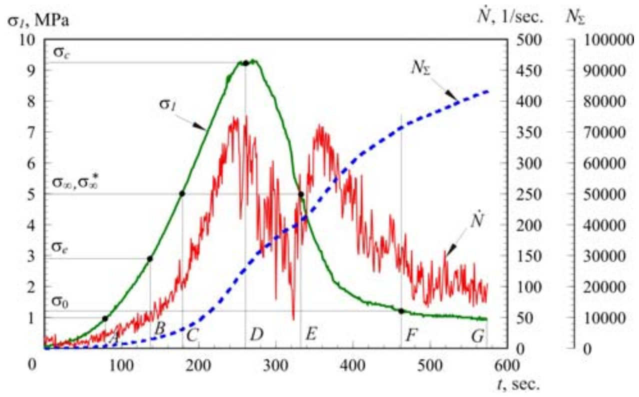

Fig. 3. Dependences of the stress and AE parameters upon time under uniaxial compression of coal sample in the loading mode with constant deformation rate

Comparison of Fig. 1*a* and Fig. 3 shows also the fact, that at constant longitudinal deformation rate the form of diagrams dependences of the stress upon longitudinal deformation and upon time are similar. That in addition facilitates of experimental data interpretation. The similarity takes place also at triaxial axisymmetric compression with the given longitudinal deformation rate for diagrams dependences $\Delta\sigma_1 - \varepsilon_1$ and $\Delta\sigma_1 - t$. It is explained by the fact that the time of loading is proportional to longitudinal deformation of samples in the test mode with constant displacement rate of the testing machine traverse.

Diagrams dependences of AE parameters upon the stress have character similar to dependences of AE parameters upon time and allow to estimate the parameter of mechanical properties of coal at once that appropriates to the certain anomaly of AE behaviour. However in the case of reception of full deformation diagrams (in the mode of the given deformation rate) the value of the stress is reduced in the post-failure region. That complicates the using of diagrams dependences of AE parameters upon the stress because of inconvenience of its interpretation. The values of time grow during all experiment continuously. Besides in the case of use of two independent systems of mechanical and AE parameters measurement the joint consideration of results as functions upon time is optimum for what the synchronization of the time readout beginnings of measurements for the specified systems is carried out.

CONCLUSIONS

1. The relationship of informative AE parameters in coal samples with various modes and separate deformation stages, and also with borders of transitions between the specified stages is established.

2. The revealed peculiarities of AE manifestations in coal samples under various loading modes can form the basis to development of the ways estimation of mechanical properties and state of coal with using of AE technique. The received results create preconditions for identification by anomalies of informative AE parameters of the modes, the stages and the borders of transitions between the stages, and the also the estimation of mechanical properties of coal specimens under deformation and destruction.

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