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EXPERIMENTAL INVESTIGATIONS INTO ACOUSTIC EMISSION IN COAL SAMPLES UNDER UNIAXIAL LOADING

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The results are presented for the experimental investigations into acoustic emission during mechanical uniaxial testing of coal sample at the assigned rates of loading. Proceeding from a comparison between the parameters of acoustic-emission and stress-strain curves, the stages of deformation are identified and the physicomechanical properties of coal are determined.

Coal, acoustic emission, deformation stages, ultimate strength, experiment

INTRODUCTION

Acoustic emission (AE) is a phenomenon that accompanies any, even the most insignificant irreversible and partially reversible changes in structure of solids under the action of various external physical factors. In this connection, it is apparent that AE is a promising method of investigating deformation and failure of rocks. It is no coincidence that from the 1950s, recording and analysis of AE parameters has been used to predict hazardous dynamic phenomena in mines [1]. At the same period of time, the first laboratory investigations into AE regularities have begun on coal sample [2]. These studies established qualitative interrelations of AE parameters with strength and degree of inhomogeneity and showed that different stages of deformation are characterized by the particular features of emission.

It should also be noted that most acoustic emission investigations on coal were conducted in sound and low ultrasound frequency ranges, and the corresponding gaging equipment had low sensitivity and noise-immunity. As a consequence, taking into account high frequency-dependent attenuation of elastic waves in coal [3], AE allowed examination predominantly of macrofailure of geomaterials and did not provide an information on the “fine” structure dynamics. While this knowledge is required for revealing the mechanisms and quantitative regularities of deformation and failure of samples. Besides, there is up to now a limited number of the acoustic emission investigations that are carried out on coal samples. The investigations do not cover all practically important regimes, and AE features, which are characteristic of elastic and plastic rocks, cannot be studied on coal. This circumstance is explained by coal specificity owing to its very complex structure and properties (anisotropy, inhomogeneity, jointing, physicochemical activity, etc.). From the physicomechanical point of view, instaneous strain, elastic hysteresis, and irreversible plastic strain are intrinsic to coal as a viscoelastic material [4]. Coal is characterized by a variety of genetic types and petrographic composition, and by genesis peculiarities (biogenic high-polymeric sedimentary rock), which somewhat complicates interpretation of the received acoustic-emission information. There also exist technological problems since it is difficult to manufacture regular-shaped samples without additional disturbance and with reliable conditions of contact between transducers and the object under control.

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Acoustic emission investigations are extremely acute, as, first of all, microseismic activity of a whole coal-bearing rock mass is associated with coal failure. This fact is governed by lower strength and greater disturbance of coal as compared with enclosing rocks.

This paper is aimed at establishing AE regularities at different stages of coal deformation and estimating possibilities of determination its physicomechanical properties with due regard for the mentioned regularities.

METHODOLOGY OF THE EXPERIMENTS

The object of the present investigation was coal of the former "Zapadnaya" mine in the territory of Novoshakhtinsk town of the Rostov Region (Eastern Donetsk Basin). The measurements were conducted on cylindrical anthracite samples from the "Stepanovsky" stratum. The samples were drilled from solid blocks extracted from a depth of about 700 m and were 50 mm in diameter and 100 mm in height.

These anthracites are related to the genetic type III (low-recovery) with high anisotropy of vitrinite reverberation. They belong to mixed clarains, durain-clarains, and rare to clarains-durains; with respect to petrogrpahic compositions, they slightly differ from other medium-carbonic coals of the Donetsk Basin.

The characteristic averaged values of microcomponent composition and content of mineral admixtures of coal substance are presented in Table 1. The data indicate a peculiar geology of pet formation. Practically all microcomponents of coals vary greatly, and mineral admixtures are mainly represented by clayey substance. In the studied sample of coal, epigenetic minerals of formations of carbonates, quartz, and sulfide iron are present in interstitial cavities.

Enclosing rocks and rock interlayers are mostly clayey and sandy shales with an organic substance content of up to 40 – 45 % and are classified as coaly ones. Clays have predominantly hydromicaceous mineral composition.

Coals of the studied samples belonged to the subgroup of the third vitrinite anthracite. With respect to the values of volatile substance yield, organic mass density, volume yield of volatile substances, and logarithm of specific electric resistance, the described stratum coals are related to metamorphism groups 13 – 14 A_2.

The averaged parameters qualitatively characterizing the coals investigated are cited in Table 2.

On the whole, physicomechanical properties of the coal samples investigated are typical to their grade and petrographic composition, also, the samples have high mechanical indices as strong and very strong coals.

TABLE 1

Pure coal composition, %						
Vitrinite	Semi-vitrinite	Inertinite group				
		semi-fusenite	fusenite	sclerotinite	micronite	liptinite
71.0	1.3	8.9	9.8	2.1	0.7	5.5
Weighing down components		Content in coal, %				
		iron sulfides	clayey substance		carbonates	other
19.0		3.6	8.8		2.6	1.1

TABLE 2

Coal grade	Moisture content, %		Ash content in dry mass, %		Total sulfur content in dry mass, %	Volume yield of volatile substances per combustible mass, cm^3/g (limits)	Heat of combustion per mass, MJ/kg	
	in analyzed sample	in working fuel mass	pure coal	for recovery thickness			combustible	working
A	1.92	5.04	12.3	27.1	2.4	63 – 100	33.5	27.0

Uniaxial loading of the samples was conducted at constant rates of stress or axial strain. The tests were carried out with the use of a triaxial compression machine designed in the Institute of Problems of Complex Development of Bowels. To measure and record the stresses σ_1, the longitudinal ε_1 and transverse ε_2 strains, as well as the acoustic emission rate $\dot{N}$, a computer-based measurement system including strain-gage and acoustic-emission sets was employed. For measurement of ε_1 the strain gage with clockwork indicators was used, and ε_2 were measured by the strain gages in the form of elastic rings with glued strain-resistive sensors. The AE signals were recorded by piezoelectric transducers within a band of frequencies from 30 to 500 kHz. Values of the volumetric strain $\varepsilon = \varepsilon_1 + 2\varepsilon_2$ and the total acoustic emission N were calculated.

EXPERIMENTAL RESULTS

Figures 1 and 2 present the most characteristic graphs of dependence between the stresses and strains, and the acoustic emission rate that were obtained during loading of coal samples. It is noted from an analysis of the graphs that manifestation of the emission as well as the change in the longitudinal and transverse strains are not gradual. The AE rates vary in the well-known manner: the rises, falls, minima, and maxima that are in the graphs correspond to the definite stages of deformation and typical sections of $\sigma_1 - \varepsilon_1$ curves strengths reached.

During the experiments it was revealed that in coal, values of $\dot{N}$ are, as a rule, higher than those in plastic rocks (rock salt) by 40% on average and in brittle rocks (limestone, dolomite) by an order of magnitude under the same testing conditions [6].

A complex analysis of the dependences $\sigma_1 - \varepsilon_1$, $\varepsilon - \sigma_1$, $\dot{N} - \sigma_1$, and $\dot{N} - \varepsilon_1$ by the known procedures, with respect to characteristic bends in the graphs of $\sigma_1 - \varepsilon_1$ or $\varepsilon - \sigma_1$ and certain anomalies in the graphs of $\dot{N} - \sigma_1$ and $\dot{N} - \varepsilon_1$, made it possible to distinguish four common stages of coal deformation: load (I), linearly elastic (II) and elastoplastic (III) stages, and limiting failure (IV). When coal was tested at the constant rate of ε_1, the stages of postlimiting failure (V) and postlimiting disintegration (VI) were noted. The stages of coal deformation are separated by dotted lines and are denoted by Roman figures (Figs. 1 and 2).

In spite of the fundamentally different experimental procedures, their results indicate that the character of coal deformation and AE manifestation in coal are almost similar. Stage I is accompanied by the peak in AE rate, in II $\dot{N}$ are minimal, stage III is described by an increase in $\dot{N}$, and in IV $\dot{N}$ are close to maximal.

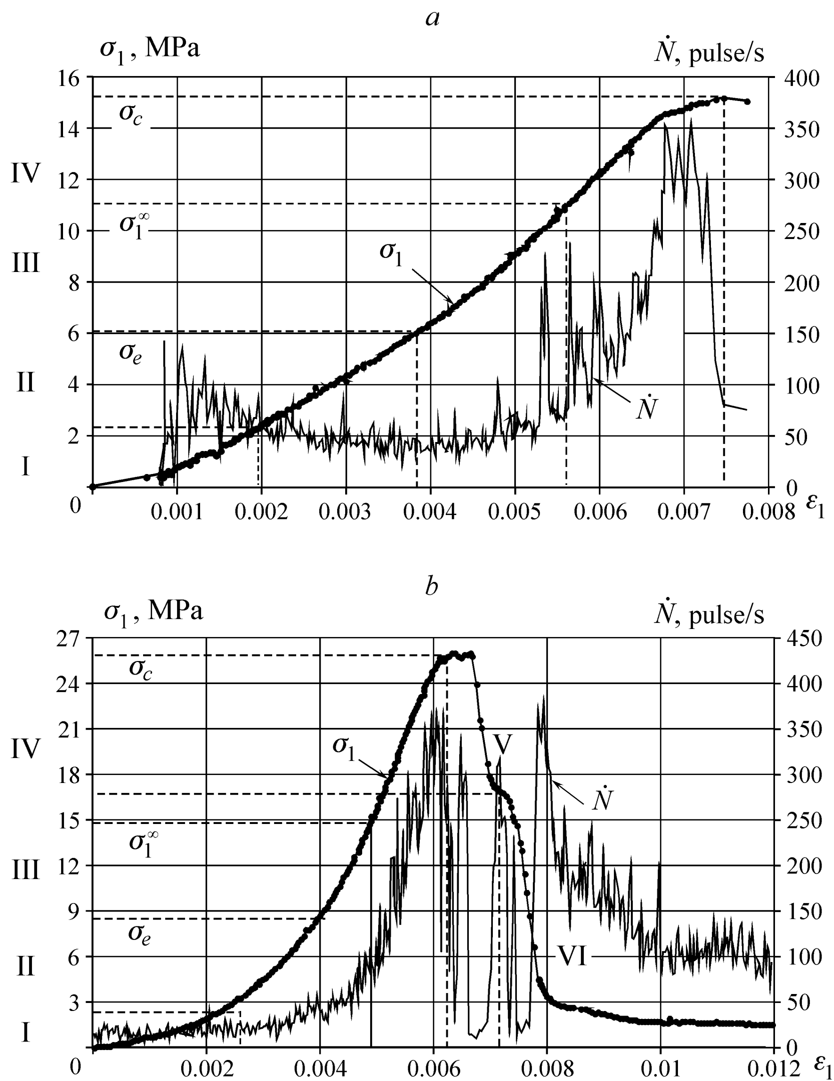

Fig. 1. Graphs of dependences (*a*) $\sigma_1 - \varepsilon_1$ and (*b*) $\dot{N} - \varepsilon_1$ during loading at $\dot{\varepsilon}_1 = \text{const}$

Transitions between the described stages of coal sample deformation correspond to certain parameters of physicomechanical properties of coal. For example, transition from II to III shows that the elastic limit σ_e of anthracite is reached. Transition from III to IV implies the ultimate long-term strength σ_1^∞. In Fig. 2*a*, *b* σ_1^∞ corresponds to ε maximum characterizing transition from strengthening to loosening of coal. Stage IV ends when the instantaneous compression strength σ_c which is consistent with the maximal values of $\dot{N}$ similarly to other rocks.

When coal is deformed at $\dot{\varepsilon}_1 = \text{const}$, in postlimiting zone, where $\sigma_1 = \sigma_c$ (stage V), AE rate falls. Then, $\dot{N}$ grows up again to the values close to the maximal $\dot{N}_{\max}$ that corresponds to the ultimate long-term strength σ_1^∞ in this zone. Further, $\dot{N}$ gradually decreases to $(0.3 - 0.4)\,\dot{N}_{\max}$ in the course of final disintegration of the samples in the stage VI.

If coal is testes at $\dot{\varepsilon}_1 = \text{const}$, some stages of this process and some ultimate strengths are somewhat worse identified as compared with the regime of loading at $\dot{\sigma}_1 = \text{const}$.

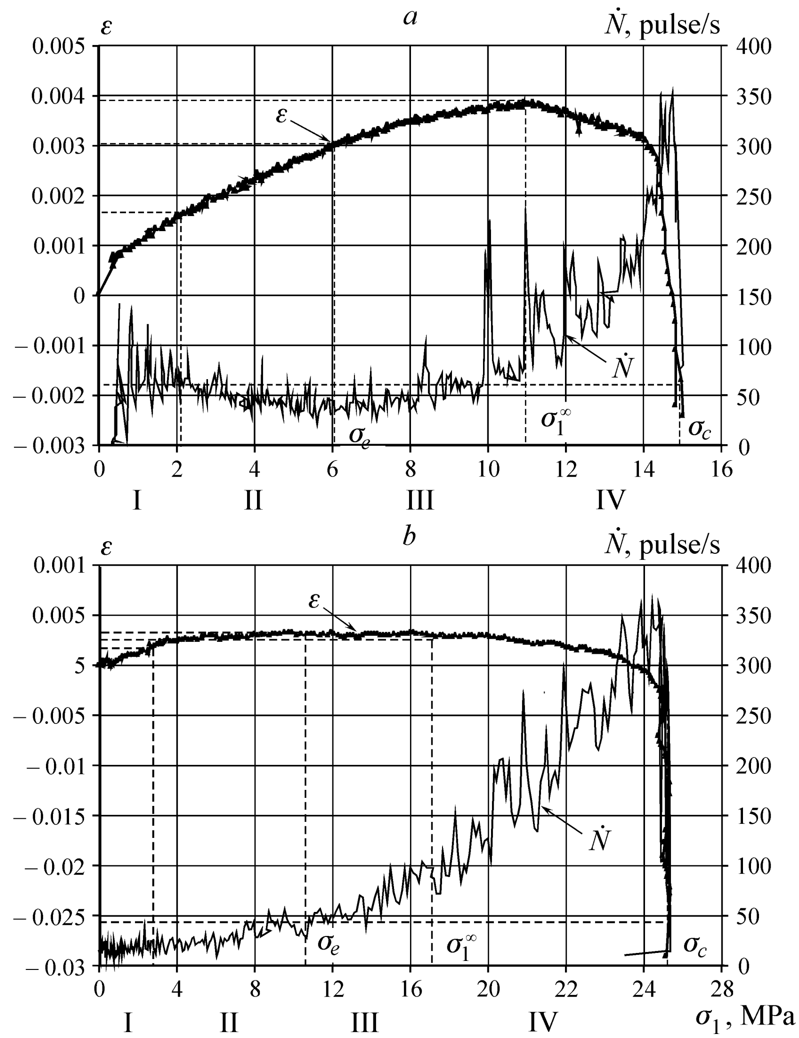

Fig. 2. Dependences (*a*) $\varepsilon-\sigma_1$ and (*b*) $\dot{N}-\sigma_1$ during loading at $\dot{\sigma}_1 = \text{const}$

As an informative acoustoemission parameter, *N* is very important. By a comparison of the dependences $N-\varepsilon_1$ and $\sigma_1-\varepsilon_1$, it is possible to identify some stages of deformation and ultimate strengths of coal. At loading of coal with $\dot{\sigma}_1 = \text{const}$ (Fig. 3*a*), in the characteristic cumulative graph of AE there are two almost linear sections where the values of $\dot{N}$ are different. These sections are separated by the bend point corresponding to the elastic limit σ_1 of coal. During coal testing in the regime of $\dot{\varepsilon}_1 = \text{const}$ (Fig. 3*b*), in the typical graphs of dependences of *N* and σ_1 on ε_1, there are four zones that can be approximated by linear sections. The sections are separated by the bend point and have different rates of AE accumulation. The first and the most marked bend point corresponds to σ_e. The second stage accompanied by elastoplastic strains is characterized by the highest rate of increase in *N* (similarly to the coal loading case, $\dot{\varepsilon}_1 = \text{const}$). Then, there is a bend point that marks the ultimate instantaneous strength (yield point). The third zone of total AE growth is in the postlimiting region and proceeds with the most stable increase in AE pulse accumulation. These features of *N* graphs in the zone under consideration are consistent with those for the dependences $\sigma_1-\varepsilon_1$ and, probably, describe transition to a spontaneous self-sustained failure in the postlimiting deformation stage.

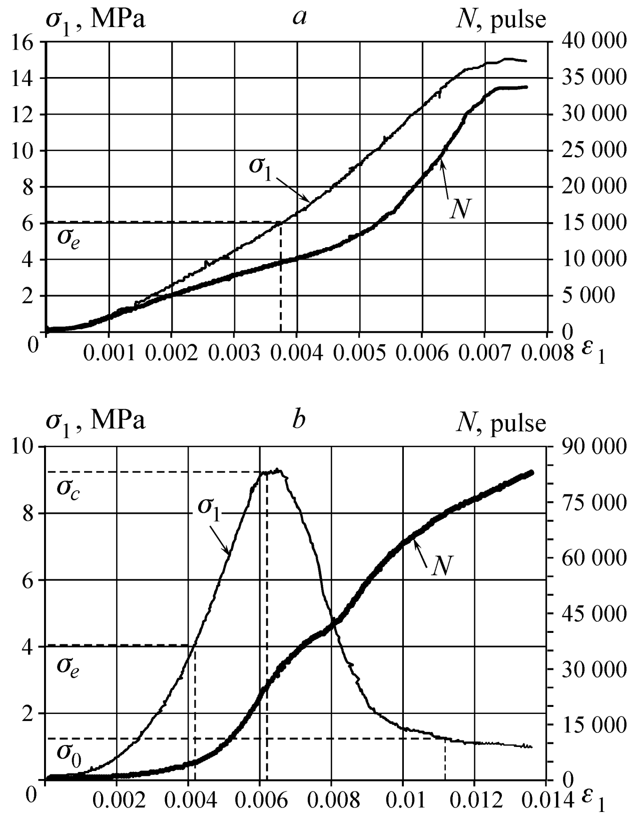

Fig. 3. Dependences $\sigma_1 - \varepsilon_1$ and $N - \varepsilon_1$ for coal under loading at (*a*) $\dot{\sigma}_1 = \text{const}$ and (*b*) $\dot{\varepsilon}_1 = \text{const}$

The bend point preceding the last stage of a slower increase in total number of acoustic pulses as compared with the previous stage indicates the ultimate residual strength of coal.

It should be noted that in [7], three sections of increase in N and two points of transition between them were distinguished under stiff uniaxial loading of coal. This fact might be connected with the absence of a clear zone of residual strength due to the drawbacks of testing equipment that was used by researchers.

CONCLUSIONS

1. As compared with other sedimentary rocks, including enclosing coal strata, coal may be considered as a peculiar, especially sensitive indicator of geomechanical state of a coal rock mass due to anomalously high level of the acoustic emission.

2. Totally 10 samples have been tested in each deformation regime. Repeatable character of time-change in the acoustic emission behavior is observed in all cases. The difference was in the absolute values of AE rate in each deformation stage due to the strength and structural features of the tested samples of coal. Besides, these differences of the samples governed a shift of distinguished transitions between the deformation stages within 50 % of the average values for each testing regime. When stronger samples were tested, the shift was towards higher stress values, in opposite case, it was towards lower values.

3. Despite the fact that coal is mostly a brittle body with respect to its properties, the distinguished deformation stages and characteristic transitions between them are analogous to those in plastic rocks of a rock salt type. This confirms the validity of relating coal to a separate class of geomaterials for acoustic emission investigations.

4. By informative parameters of the acoustic emission, the distinguished stages of deformation and the obtained characteristics of physicomechanical properties of coal indicate a promising use of acoustic emission as a method of controlling and predicting stress-strain state of coal.

In natural conditions coal is as a rule not in the state of uniaxial deformation. Therefore, the further studies are to be aimed at revealing the regularities of the acoustic emission in coal under complex stress state as well as under creepage, relaxation of stresses, and nonmonotone loading.

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