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ACOUSTIC EMISSION MEMORY EFFECT IN COAL SAMPLES UNDER UNIAXIAL CYCLIC LOADING

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This paper gives results from experimental studies of the acoustic emission and strain memory effects in anthracite samples under cyclic loading. Trends and regularities were found in the formation and manifestation of the acoustic emission memory effect of coal in nonmonotonic uniaxial tests.

Key words: *coal, acoustic emission, Kaiser effect, experiment, cyclic loading.*

Introduction. The acoustic emission memory effect (the Kaiser effect) is observed during cyclic loading of a solid with a stress amplitude increasing from cycle to cycle. The effect consists of the nonreproducibility of acoustic emission (AE) up to the maximum stress of the previous cycle, when the AE parameters are suddenly restored to the level corresponding to this maximum stress. Since the time of the discovery of this effect in metals, timber, and sandstone in the beginning of the 1950s [1], a considerable amount of experimental data have been accumulated on the manifestations of this effect in various structural materials and classical brittle and ductile rocks. Theoretical models explaining the nature and mechanisms of this effect have been proposed, and prerequisites for using it to estimate the type of stress state and the directions and values of the principal stresses in a rock mass have been justified [2].

The variety of structures and properties of geological materials predetermines the special features in the formation and development of the Kaiser effect depending on the conditions of the mechanical effects tested [3–6]. This circumstance motivates the need for studying the indicated effect in natural materials of various genetic groups and fields. This is true, in particular, for mineral coals, in which the Kaiser effect has been studied only in uniaxial tests at a constant longitudinal strain rate [7].

Coals exhibit elevated heterogeneity, anisotropy, viscoelastic properties, physicochemical activity, lithological diversity, and other characteristics that make it difficult to study their acoustic emission and mechanical properties. The difficulty and, sometimes, impossibility of manufacturing samples with the required parameters without introducing additional disturbances into them and the high parameters of the frequency-dependent damping of elastic waves in coal are further factors that complicate the investigation of AE in this material. An integrated targeted study of ultrasonic acoustic emission of coal samples for some mechanical test conditions has been performed recently [8–10].

The goal of the present work was to study the mechanism of formation and manifestation of the Kaiser effect in coal samples at specified rates of uniaxial cyclic loading.

Experimental Technique. To study the acoustic emission memory effect, we used cylindrical anthracite samples from the i_3^{n} Stepanovskii bed of the former Zapadnaya mine (Novoshakhtinsk, Rostov Region). Samples 50 mm in diameter and 100 mm high were prepared by drilling out from monolithic blocks collected from a depth of about 700 m.

Petrographically, the anthracite samples tested are mixed clarains, duroclarains or less often to clarodurains. The coal composition is characterized by significant concentration variations of almost all microcomponents, and the main mineral admixtures are clay materials. The samples also contain epigenic minerals of quartz, carbonate, and iron sulfide formations, which are found in fracture cavities.

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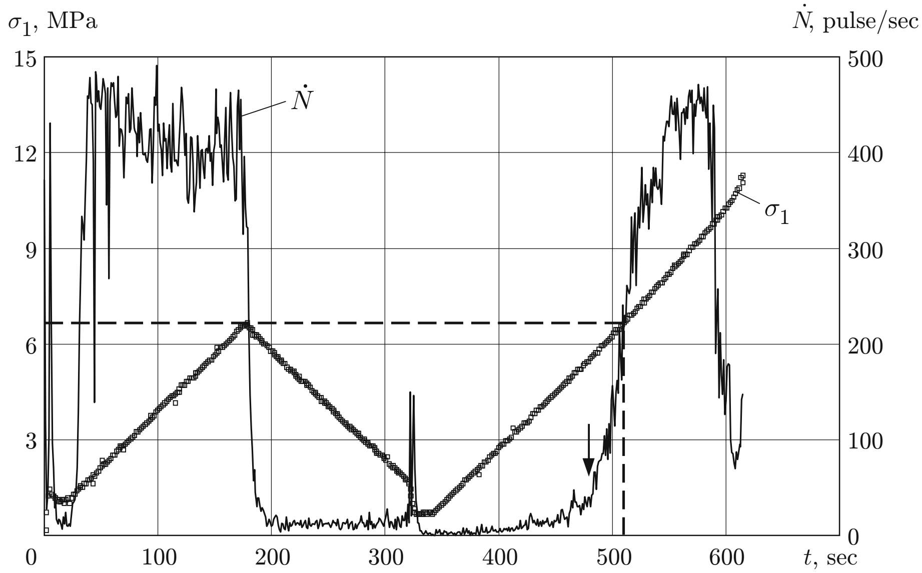

Fig. 1. Curves of $\sigma_1(t)$ and $\dot{N}(t)$ for two-cycle loading of coal.

The acoustic emission and mechanical properties of the coal samples were studied under nonmonotonic uniaxial compression using a computer-controlled measuring system consisting of a SIIT-2 strain-gauge instrumentation and an A-Line 32D acoustic emission measuring complex. Emission was recorded by a piezoelectric transducer in a frequency range of 30 to 500 kHz. The testing machine was an EU-100 press (Germany). In the experiments, we measured the axial stress σ_1, the longitudinal strain ε_1 and transverse strain ε_2, and the AE activity $\dot{N}$. Longitudinal and transverse strains were recorded by resistance strain gages glued on indicating gages and elastic rings. Axial load was recorded by a strain force gauge. The volume strain $\varepsilon_v = \varepsilon_1 + 2\varepsilon_2$ and the total acoustic emission N_Σ were calculated.

The press was used in tests of coal samples at a specified rate of axial loading. The research program included experiments on cyclic loading of coal samples with increasing maximum stresses ($\sigma_1^{\rm I}$, $\sigma_1^{\rm II}$, etc.; I and II are the cycle numbers) without delays between successive cycles. In the experiments, the loading and unloading rates were varied in order to study their effects on the manifestation of the Kaiser effect. In addition, an analysis was made of the possibility of integrated estimation of the strain memory effect of coal, which is often manifested in rock together with the acoustic emission effect and serves as further evidence for the occurrence of the latter.

Results of Experiments and Discussion. Figure 1 shows typical curves of the parameters σ_1 and $\dot{N}$ versus time t for two-cycle loading of coal. It is evident from the figure that after rather rapid loading of the sample to 1–1.5 MPa, it was loaded monotonically at a rate $\dot{\sigma}_1 = 0.035$ MPa/sec to $\sigma_1^{\rm I} = 6.7$ MPa, after which it was unloaded at the same rate to 1 MPa. The sample was then loaded repeatedly up to complete failure at the same rate. In this case, $\sigma_1^{\rm II} = \sigma_c = 11.3$ MPa, where σ_c is the instantaneous strength limit under uniaxial compression (in this case in cycle II). The dashed lines in Fig. 1 and in the next figures indicate the maximum stress level of the previous cycle and the moment it is achieved in the subsequent loading cycle. The arrows in the figure show the anomalies corresponding to the manifestation of the acoustic emission memory effect.

From the curves of $\dot{N}(t)$ and $\sigma_1(t)$ (Fig. 1), it is evident that the values of $\dot{N}$ begin to increase at a stress smaller than its maximum level reached. However, at the moment the value of $\sigma_1^{\rm I}$ is achieved in cycle II, $\dot{N}$ increases sharply to values close to the corresponding level $\dot{N}$ of loading cycle I.

From the curve of $\sigma_1(\varepsilon_1)$ for coal, it was not possible to determine the stress in cycle II that corresponded to the maximum load of cycle I because the strain curve exhibited unstable behavior and had several characteristic points at which the slope angle decreased. This does not allow us to unambiguously assign these anomalies to the strain memory effect without knowledge of the loading prehistory of the samples. A similar picture was observed in the analysis of the curve of $\varepsilon_v(\sigma_1)$. From this curve, it is not possible to unambiguously distinguish the maximum load for cycle II that corresponded to the maximum stress in cycle I.

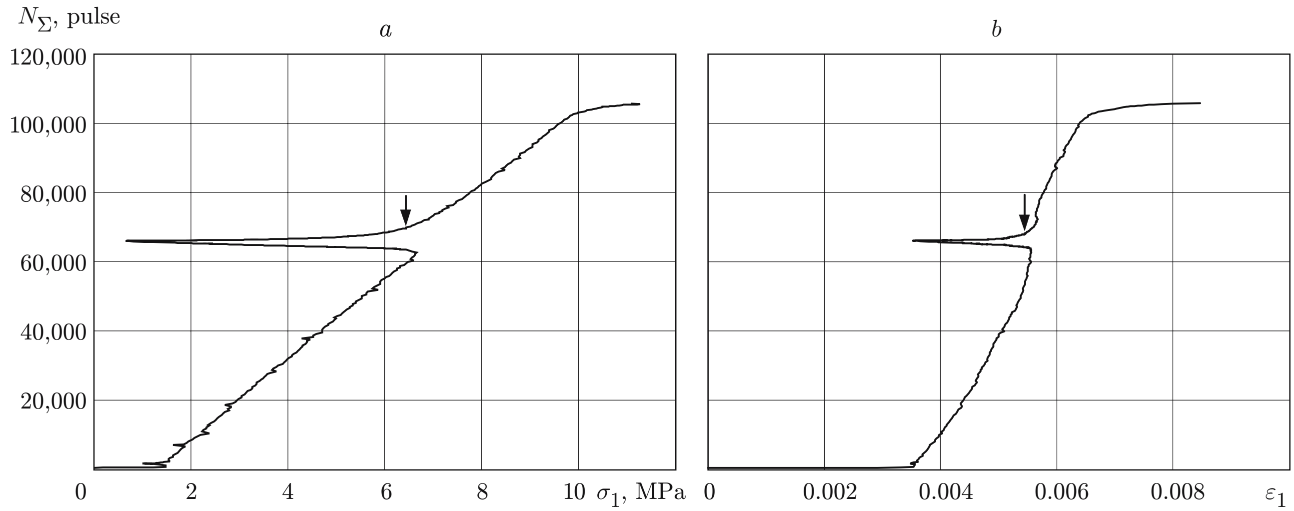

Fig. 2. Curve of $N_\Sigma(\sigma_1)$ (a) and $N_\Sigma(\varepsilon_1)$ (b) for coal under two-cyclic loading.

In rock-salts, the indicated manifestations of the strain memory effect were clearly observed in uniaxial tests at a constant longitudinal strain rate [11]. In coals under similar strain conditions, the memory effect in curves of $\sigma_1(\varepsilon_1)$ was observed in [12], where it was noted that the strain memory effect is most pronounced in ductile rocks. However, for strong sedimentary and eruptive rocks, this effect is comparable to the error of the recording equipment, which prevents a reliable estimation of the stress. Therefore, other methods, for example, studies of the Kaiser effect are required.

As shown by the experiments performed, the results of strain measurements in cyclic tests of coal at a specified uniaxial loading rate cannot be interpreted unambiguously. This is due to the fact that the structural nonuniformity of coal is responsible for the random nature of deformation under determined loading conditions.

The maximum stresses and longitudinal strains of the previous cycle under repeated loading can also be found using the curves given in Fig. 2, which have distinct bends that correspond to the memory of the previous maximum values of σ_1 and ε_1. The curve of $N_\Sigma(\sigma_1)$ gives more realistic values of $\sigma_1^{\rm I}$ than the joint analysis of the curves of $\dot{N}(t)$ and $\sigma_1(t)$ in Fig. 1. Thus, the felicity ratio (FR) determined by the curve of $N_\Sigma(\sigma_1)$ (Fig. 2a) was 0.96 (in the case of the ideal Kaiser effect, FR $= 1$). We note that the FR index is the ratio of the stress at which emission resumes to the previously reached maximum stress [2].

We also performed four-cycle loading of coal samples. Typical curves of $\dot{N}(t)$ and $\sigma_1(t)$ obtained for one of the samples under such loading are presented in Fig. 3. In this case, the maximum stresses in the cycles were as follows: $\sigma_1^{\rm I} = 2.9$ MPa, $\sigma_1^{\rm II} = 6.4$ MPa, $\sigma_1^{\rm III} = 13.4$ MPa, and $\sigma_1^{\rm IV} = \sigma_c = 24.8$ MPa (in cycle IV, the sample failed). The loading rates in the cycles were $\dot{\sigma}_1^{\rm I} = 0.012$ MPa/sec, $\dot{\sigma}_1^{\rm II} = \dot{\sigma}_1^{\rm III} = 0.014$ MPa/sec, and $\dot{\sigma}_1^{\rm IV} = 0.036$ MPa/sec. In this experiment (despite the different values of $\dot{\sigma}_1$), the Kaiser effect was clearly observed in all loading–unloading cycles, although the loading rate in the last cycle was approximately 2.5 times higher than that in cycles II and III and three times higher than that in cycle I. In cycle III, unloading was almost instantaneous. In approximately 120 sec, loading in cycle IV was implemented. The coal sample keeps in memory the maximum σ_1 of the loading cycle directly preceding this cycle, and the previous cycles are not manifested altogether. As in the case of two-cycle loading, in four-cycle loading, the memory effect is most pronounced in the variation of the parameters AE ($\dot{N}$ and N_Σ) rather than strains.

Curves of $N_\Sigma(\sigma_1)$ and $N_\Sigma(\varepsilon_1)$ for four-cycle loading of coal are shown in Fig. 4. The values of FR in cycles II, III, and IV determined from the curve of $N_\Sigma(\sigma_1)$ in Fig. 4a are 0.97, 0.98, and 0.93, respectively. The largest decrease in the value of FR is observed in cycle IV. This is due to the fact that the long-term strength limit of coal was achieved in this cycle, because of which the correlation between the stress level and the development of defects was violated and the background AE activity increased. In all cases, however, the parameter FR has high values (not less than 0.9). With increase in the cycle ordinal number during multicycle loading of the coal samples, the curves of $N_\Sigma(\sigma_1)$ and $N_\Sigma(\varepsilon_1)$ become steeper due to an increase in the values of $\dot{N}$ in successive cycles at the moment of manifestation of the acoustic emission memory effect. However, finding the stresses and longitudinal

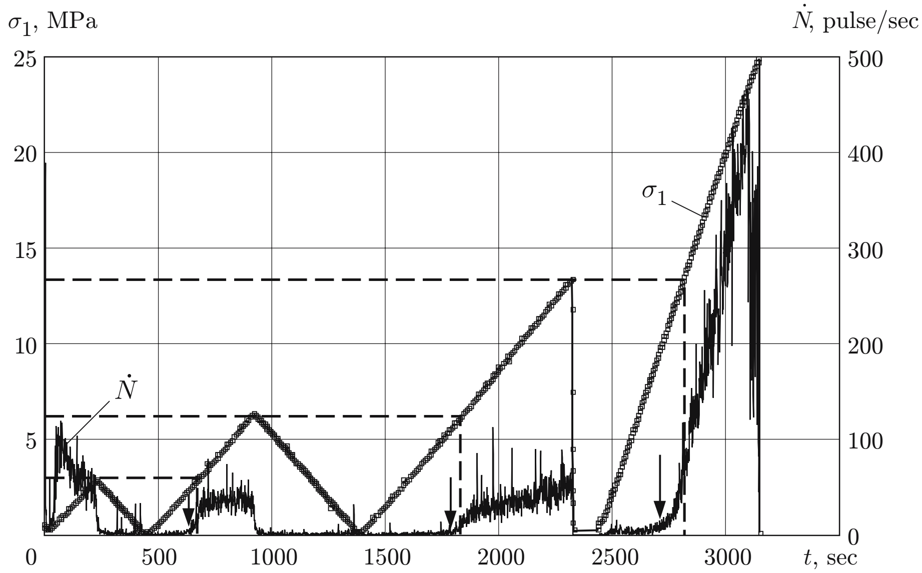

Fig. 3. Curve $\sigma_1(t)$ and $\dot{N}(t)$ for four-cycle loading of coal.

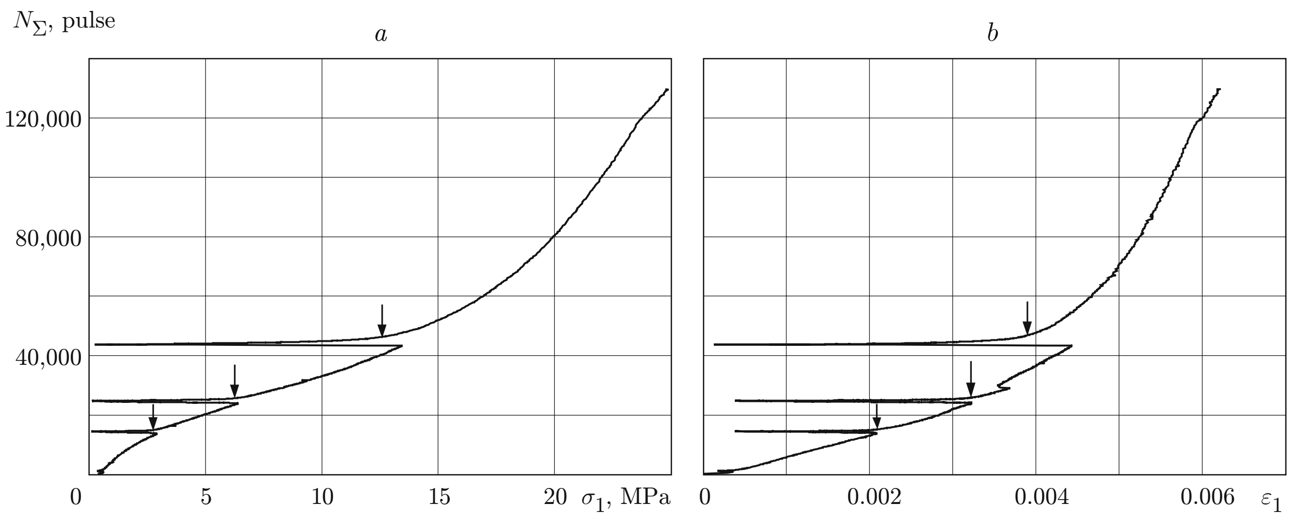

Fig. 4. Curves of $N_\Sigma(\sigma_1)$ (a) and $N_\Sigma(\varepsilon_1)$ (b) for four-cycle loading of coal.

strains for the subsequent loading–unloading cycles that were stored in memory was difficult because of increased background AE activity, resulting in the smearing of the characteristic bends in the curves.

In addition, it should be noted that in four-cycle tests, the maximum stress was $0.12\sigma_c$ in cycle I, $0.26\sigma_c$ in cycle II, and $0.54\sigma_c$ in cycle III. In this case, the Kaiser effect was pronounced in all cases of loading. The results obtained indicate that memory in coal is formed even for small values of uniaxial adjusting stress, whereas in some other types of rock, the acoustic emission memory effect is absent at low stresses in the region of zero to $(0.2–0.25)\sigma_c$ [2]. Furthermore, the first two loading–unloading cycles were performed in the elastic strain region of the coal samples, whereas the maximum load in cycle III was in the elastoplastic region, which, nevertheless, does not distort the manifestation of the Kaiser effect. The level of values of $\dot{N}$ for unloading in cycle II is lower than that in cycle I (see Fig. 3). In cycle IV, the value of $\dot{N}$ increased continuously up to the maximum after the attainment of the value $\sigma_1^{\rm III}$, and the AE activity before the manifestation of the Kaiser effect was higher in cycle IV than in cycles II and III. This is due to the fact that loading cycle IV was implemented in the region of intense dilatation of coal preceding failure. In addition, in this cycle, loading was implemented at an elevated rate.

Conclusions. The experimental studies of the acoustic emission and strain properties of coal under uniaxial cyclic loading showed the following.

1. The Kaiser effect is pronounced in coal under uniaxial loading. In this case, as in other types of rock, the resumption of AE occurs somewhat earlier than the attainment of the maximum level of σ_1 of the previous cycle, while the recovery of $\dot{N}$ to the values of the previous cycle at the indicated stress level in test cycles occurs with a delay.

2. The effect of loading and unloading rates in the ranges studied on the manifestation of the Kaiser effect in coal was not observed.

3. In the four-cycle tests of coal samples with an increasing load amplitude in the $(i+1)$th cycle, the maximum value of σ_1 of cycle i is stored. The maximum loads of the cycles preceding the ith cycle are not manifested by any anomalies in AE and strains.

4. The acoustic emission memory of the maximum stress and strain of coal is formed in both the elastic and elastoplastic regions, in particular, for extremely small values of the uniaxial stress not exceeding $0.2\sigma_c$.

5. In the tests of anthracite at the specified uniaxial loading rate, the acoustic emission memory effect is manifested most clearly. The strain memory effect is less pronounced or is absent altogether. The characteristic anomalies of the AE parameters allow the maximum previous values of stresses and strains to be determined most reliably.

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