UDC 622.831.1:539.37 DOI: https://doi.org/10.15407/geotm2025.172.093

RESIDUAL DEFORMATIONS OF COAL DURING DESTRUCTION UNDER PRESSURE

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Abstract. Deformation and destruction of rocks and coal during underground workings are the primary processes that define the stability of these workings, the nature and intensity of potential gas-dynamic phenomena. Rocks, from the viewpoint of mechanics, are complex and contradictory objects: they are highly heterogeneous in small volumes, whereas they tend to be relatively homogeneous in larger volumes. They act as solid bodies in small volumes but as discrete bodies in larger ones. Importantly, the concept of destruction includes elastic, plastic, and brittle stages of deformation. The authors examine the properties of residual deformations in coal that occur during its destruction under external pressure. The physical and mechanical properties of coal were analyzed during loading to destruction and after the removal of the load. The established relationship between the level of residual deformations and the structural characteristics of coal enables an assessment of its deformation resistance.

The work aimed to develop theoretical and experimental approaches to studying the mechanical properties of coal at the microlevel and estimating the magnitude of the energy of elastic deformations.

For the first time, it is shown for coal at the microlevel that under force loading, the direction of brittle (crack) and plastic (surface corrugation) deformations most often coincide, which reflects a gradual transition from plastic to brittle deformations.

It is shown that in samples of crushed coal during compression, deformations are distributed unevenly due to critical fluctuations in local differently activated zones: the energy of elastic deformations is concentrated in harder particles, and the distribution of both the particles themselves and the deformations in them has a local (random) character.

The elastic strain energy accumulated in crushed coal (size class 0.10–0.16 mm) during compression was calculated for coal grade LF, ranging from 0.20 J/g to 0.50 J/g with a change in compressive force of 0.03 kN to 0.05 kN. The results obtained can be used to improve models of mining pressure and predict the stability of mining operations in coal deposits. Additionally, research in this area is extremely important both for industry (efficiency and safety of mining operations) and for fundamental science related to the strength and deformation of materials to better understand the behavior of complex deformation systems.

Keywords: coal, compression, residual deformation, fracture, physical and mechanical properties, structural changes.

1. Introduction

Deformation and destruction of rocks and coal during underground workings advancing are the primary processes that define the stability of these workings, the nature and intensity of potential gas-dynamic phenomena. Rocks, from the viewpoint of mechanics, are complex and contradictory objects: they are highly heterogeneous in small volumes, whereas they tend to be relatively homogeneous in larger volumes. They act as solid bodies in small volumes and as discrete bodies - in larger ones. Importantly, the concept of destruction includes elastic, plastic, and brittle stages of deformation. However, each rock possesses unique characteristics (structure, composition, physical, and mechanical properties) that affect the destruction process. Consequently, much of the focus of scientists in laboratory research was directed toward clarifying the physical and mechanical characteristics of rocks concerning the scale factor, and most researchers examined either a specific type of rock or a particular stage in the overall destruction process.

In essence, theoretical developments were founded on experimental data derived from the research of the mechanical behavior of coal samples subjected to various types of loads (for example, cyclic, uniaxial, or triaxial loading). The authors re-

Received: 08.01.2025 Accepted: 06.02.2025 Available online: 17.03.2025

searched variations in the mechanical properties of coal at different degrees of carbonization and the mechanisms of its destruction under various conditions [1].

Among others, the behavior of coal during the destruction process was the least researched. Its significant brittleness, complex microstructure, high fracturing, and other properties notably affected the unambiguity of the conclusions. In researching coal destruction processes, more emphasis was placed on coal brittleness, which is one of the most important indicators for assessing the operational value of unconventional oil and gas deposits [2–8].

Currently, there is a substantial amount of researches focused on damage theory and rock constitutive models. Krajcinovic and Silva [9] developed a damage evolution equation using the concept of damage change under pressure based on the assumption of a random distribution of the rock microelements' strength. Using statistical damage theory, Francisconis and Desai (1987) [10] devised a statistical constitutive damage model of the rock deformation process that accurately depicts the characteristics of rock deformation. Dai et al. (2004) [11] described coal damage and analyzed the change in damage based on the law of deformation development during the coal destruction process under uniaxial compression. Zhang et al. (2005, 2010) [12, 13] pointed out that the macroscopic nonlinear mechanical behavior of samples during fracture is attributed to microheterogeneity.

In [14], the results of studying the mechanics of coal at great depths are presented. The authors revealed the influence of the force load, which is associated with an increase in the depth of development, on the energy conversion and the development of coal defects (brittle and plastic deformation) during cyclic triaxial loading and unloading. In particular, the amount of accumulated energy increased with increasing load, as was concluded after studying the evolution of energy in the substance. According to the authors [15], the evolution of energy and the development of coal deformation at different depths, i.e., at different pressures, will provide not only reference information but also make it possible to control the processes of structural reorganization of fossil organic matter.

Wang et al. [16] researched the evolution of cracks and energy characteristics of rock subjected to cyclic loading under unloading conditions. They found out that the accumulation of damage during cyclic loading affects the final fracture mode and energy conversion, and as the number of cycles increases, the stored elastic energy grows. The research showed that the mechanical properties of rocks (e.g., deformation, strength, damage) significantly depend on the loading conditions (or loading and unloading).

Much attention in many publications is paid to the relationship between the mechanical properties of coal and gas-dynamic phenomena (GDP) [17]. According to the authors, GDP is caused by a change in the energy state (including absorption, evolution, and release, and dissipation of deformation energy) in a three-dimensional stress field.

In work [14], an interesting feature in the behavior of rocks is noted, which manifests itself during cyclic loading of samples. With an increase in the degree of disturbance of rocks, their ultimate bearing capacity decreases, but elastic deformations remain of the same order of magnitude. This indicates that, under the same loads, disturbed rocks have a greater ability to accumulate elastic deformation energy. The authors believe that this feature is one of the main reasons for the occurrence of gas-dynamic phenomena. Indeed, if 90% of GDY are confined to disturbed zones, then why do GDY not occur in 90% of disturbed zones? The research of the deformation process in samples of destroyed coal may allow us to answer this question.

The M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine [14] proposes a phenomenological geomechanical behavioral model of rocks (sandstones, siltstones, argillites) under compression, which is based on the following provisions:

- During compression, there is a single sequential process of destruction in nature: volume reduction and accumulation of elastic potential energy → deformation without breaking continuity and changing volume → gradual rupture of internal bonds and increase in volume → division of the whole into parts;
- The process of destruction of a body located in rocks in a heterogeneous field of unequal component stresses occurs due to the formation of critical fluctuations in local differently activated areas.

Analysis of the above researches shows that the works only address individual aspects of the theory of deformation and destruction of rocks and coal under compression. There is no universal theory of destruction. The development of new deposits and the deepening of mines leads to increased stresses in the rock massif, which necessitates more accurate forecasts of working stability. Researching different stages of destruction helps in forming a comprehensive understanding of rock behavior in both natural and man-made conditions. Knowledge about rock behavior enables us to anticipate their reactions to technological loads, which is crucial for underground construction. The results obtained can be used to develop effective methods of drilling, supporting, and fastening workings.

The idea of the work is that during the sequential loading and unloading of a coal sample in vitrinite, both plastic and brittle deformations occur. These can be determined by the petrographic method, which allows us to estimate the tendency of coal matter to accumulate energy that can subsequently be used to activate a gas-dynamic phenomenon.

Purpose: to develop the theoretical and experimental approaches to the research of the mechanical properties of coal at the microlevel and to estimate the energy of elastic deformations.

The object of research: Hydrocarbon matrix and structural transformations of coal matter under equal-component loading.

2. Methods

The process of forming disturbed zones in the massif under pressure occurs at all levels from nano to macro, leading to the accumulation of energy in the form of elastic deformations, which contributes to gas-dynamic phenomena. The experimental research on coal deformation is characterized by significant difficulties associated with sample destruction. Therefore, a new methodological approach is proposed for researching the mechanical behavior of coal subjected to compression. Unlike previous works, the experiments were conducted on samples of crushed coal. Theoretically, the compression process can be represented as a process of changing the distances between individual particles of matter or even macromolecules, which leads to the accumulation of potential elastic energy in the form of the formation of conformational defects. When the stress state is removed, this energy is spent on changing the volume and shape of the sample and the formation of dislocations. Thus, the change in the geometry of the sample after removal from the mold, along with the number of microdislocations, can characterize the amount of elastic energy that the sample absorbed. In this approach, a key research method was the petrographic analysis of coal samples subjected to force loading. The petrographic method allows for researching the smallest level at which the results of coal deformation can be visually traced.

Therefore, the experimental work includes: establishing the features of the maceral composition of coal, determining and calculating the manifestations of brittle and plastic deformations on coal of different grades (results of the action of mechanical loads on the coal microstructure) and measuring the stress energy at the molecular level [18].

Coal is a multicomponent system, each in the components of which has its own physical and chemical properties [19]: liptinites – the carbon atom content is 53.0–62.0%, they are the richest in aliphatic structural elements, have the longest aliphatic chains; they are characterized by the lowest density (1.18 g/cm^3) and microhardness, the largest amount is inherent in coal with a low degree of carbonization; fusinites (inertinites) – they have high hardness and density (1.5 g/cm^3), the most enriched in condensed aromatics, contain microscopic pores that can affect its ability to retain gases or liquids; vitrinites are a resinous substance with low strength properties, characterized by a high content of hygroscopic moisture (10–12%), density is 1.27 g/cm^3. This maceral is the most representative in terms of transformations in the process of coal carbonization. The vitrinite content in Donbas coal is ≈ 80%.

Coal of all stages of carbonization, including anthracite, is mined in the Donets basin. The conditions of accumulation and transformation of sediments, their diversity in area and depth, determine a wide range of changes in physico-mechanical indicators for each grade. This article highlights the deformation processes that were recorded in coal of grade LF; samples were taken at the “Trudivska” mine, bed l_4.

When preparing the specimens, the samples were crushed to a size of < 1 mm and dispersed using the Fritsch Analysette-3 unit. The specimens for petrographic research were in the form of tablets, which were formed in a manual press with a force of 10 tons from coal particles of size classes 0.10–0.16 mm and < 0.05 mm. Three tablets were made from particles of each size class to obtain statistically reliable results. In addition to controlling the progress of plastic deformation in the samples, three samples were additionally made from coal particles of size class 0.10–0.16 mm under single, double, and triple external force separately. The total number of additional petrographic samples was 9 pcs.

Petrographic analysis of all samples was carried out using a video-optical complex: MBI–11, HB 200 (Scope photo software [20]), 10 microphotographs were obtained for each sample. The size of the images was 283×213 microns (objective 20×;

transition lens 1.6; hardware magnification HB 200). The shooting was carried out using fixed software parameters: Exposure – 48\3488; White balance – avto; Color – white\black; Gamma – 0.28; Satur – 42; Contrast – 97.

All samples presented in the research are comparable in weight, the deviation is up to two percent.

During the experiment, we used a manual fifteen-ton press from Specac with a manometer, adapted for the manufacture of samples in the form of cylindrical tablets (the hole diameter of the mold opening is 13.0 mm). The compression force can be considered the same along all axes ($\sigma_x = \sigma_y = \sigma_z$).

The video recording of the experiment was carried out by three cameras with time fixation and subsequent data acquisition every 20 s. The time of one stage in the experiment was 500 s (until the indicators were stabilized). All experiments were conducted on one day at constant temperature and humidity.

At the previous stage – to eliminate gaps between coal particles – a force of 1000 kN was applied to the coal powder in the mold until the force stabilized (≈ 60 sec.). Such a state of the sample was taken as “zero”. The gauges were attached during stabilization, the experiment was video recorded, and the force on the press was increased to 10,000 kN (which marked the start of the first stage – A).

The data on the gauges and the manometer were recorded on cameras for further analysis from the moment the force value of 10,000 kN was reached. After 500 sec. (process stabilization), the force was reset to zero, but the system did not disassemble, the sample was not removed. Almost immediately after reducing the force and restarting the system, the force (10,000 kN) was applied again (it was the start of the second stage – B).

The second stage (measuring the height of the tablets and the force) also lasted 500 s. After stabilizing the process, the force was reset to zero, but the system did not disassemble, and the sample was not removed. Almost immediately after reducing the force and restarting the system, the force (10,000 kN) was applied again (it was the start of the third stage – C). The third stage, the purpose of which was to check for residual plastic deformations, also lasted up to 500 seconds.

With each compression, the tablet's height decreased, and the compression force also dropped, which is related to the buildup of structural stresses in the form of elastic deformations. The data on force and displacement changes allow us to estimate the work done by the system, resulting from the energy stored in the molecular structure of the substance as stresses. After three stages, the coal sample was removed from the mold. Under the applied force, the coal powder formed a relatively strong tablet, enabling us to measure the shape change after removing it from the mold and to determine the extent of mechanical deformations (plastic and brittle) in vitrinite particles using the petrographic method.

3. Results and discussion

3.1 Results obtained by the petrographic method

In this article, based on the stress-strain dependence, the development of coal disturbances under cyclic loading is considered. According to the theory of energy dissipation, the full stress-strain curve is an external characteristic of its internal energy transition [21–23]. Since we are interested precisely in the energy accumulation that can occur in disturbed coal, we will consider the deformations that formed in the samples under the action of compression. However, the particle sizes in crushed coal are different, which affects the amount of energy that they will accumulate during compression. The behavior of specimens of coal particles of size classes 0.10–0.16 mm and < 0.05 mm after three compressions was investigated (Table 1).

Table 1 – Geometric parameters of tablets obtained from coal grade LF, “Trudivska” mine, bed l_4

Coal particle size class, mm	Sample number	Tablet weight, g	Tablet height, mm	Tablet diameter, mm	Increase in the area of the tablet, %	Average value of the increase in area, %
0.10–0.16	1	0.2021	1.26	13.05	0.76	0.82
	2	0.2022	1.26	13.06	0.93	
	3	0.2004	1.25	13.05	0.76	
< 0.05	1	0.1984	1.22	13.01	0.15	0.10
	2	0.2005	1.27	13.01	0.15	
	3	0.2030	1.25	13.01	0.00	

It was found that the surface area of the tablets increases after three stages of the experiment. Since the process of rock destruction is essentially a balanced process of energy absorption and release, it can be assumed that after the load is removed, the absorbed energy is partly used to create plastic and brittle deformations, and partly, according to the theory of dislocation formation [14], it accumulates. After the load removal, the system spends energy on changing the shape of the tablets. The increase in the tablet geometry for the coal particle size class of 0.10 – 0.16 mm is because in a system of elements of different rigidity, the stresses during compression are concentrated in harder (vitrinite) particles, the distribution of which in the volume is local.

The increase in surface area for the size class < 0.05 mm is significantly smaller. This can be explained by the fact that the greater is the number of heterogeneous particles in the sample (size class <0.05 mm) and the smaller they are in size, the greater is the possibility that the stress centers can be mutually compensated. Therefore, there will be a significant decrease in energy accumulation in coal that has been significantly disturbed.

After removing the sample, its stress state changes, leading to the formation of deformations. The type and number of these deformations in each sample were determined by the petrographic method. A significantly larger increase in the area of the tablets for the coal particle size class of 0.10 - 0.16 mm indicates greater elastic energy that was accumulated and released in the sample, making this size class more interesting for further research.

Analysis of micrographs of specimens for coal samples of grade LF after consecutive three-fold compression showed that for grade LF the preparation is a set of coal particles, in the middle part of which the external force effect is realized as “corrugation" of the particle surface (plastic deformation; cracks form in the middle of the coal particles – manifestations of brittle deformation). Fig. 1, 2 show manifestations of plastic and brittle deformations in coal, grade LF.

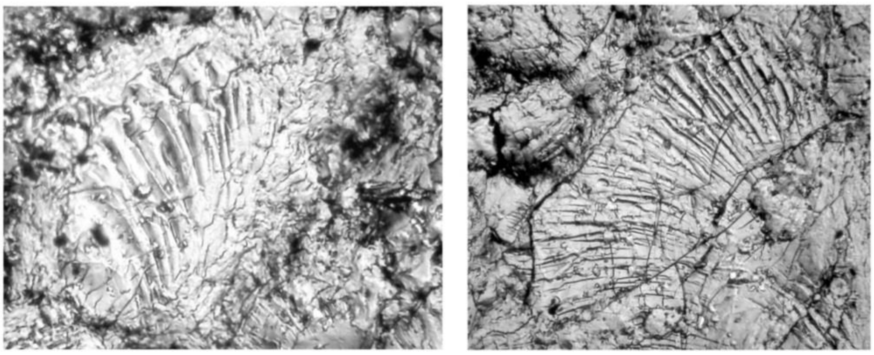


Figure 1 – Predominantly plastic deformations in LF-grade coal particles

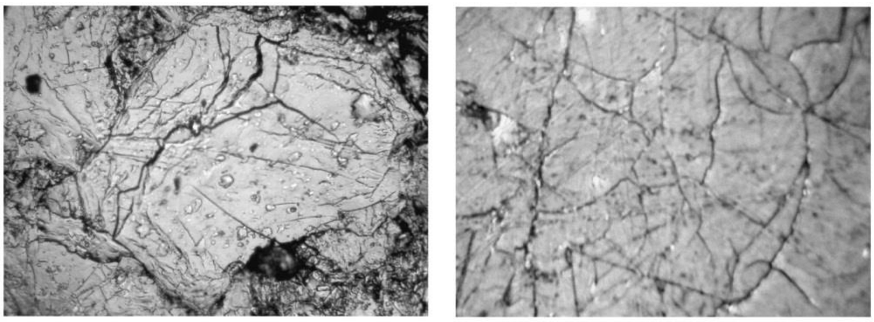
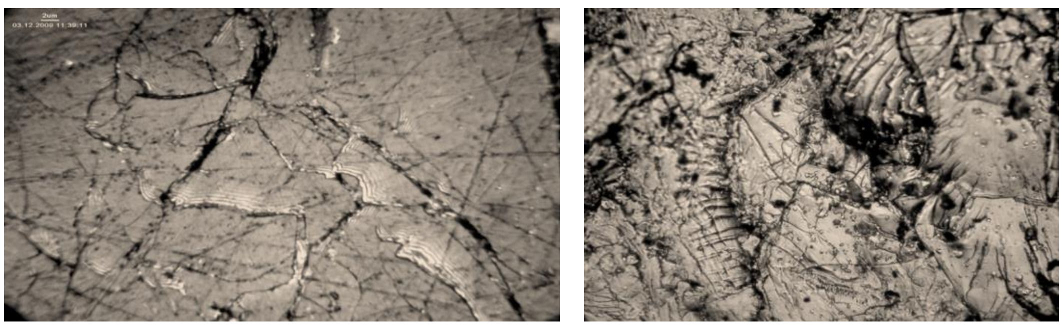


Figure 2 – Predominantly brittle deformations in LF-grade coal particles

The corrugation of the surface of coal particles and wave-like change in physical, in particular optical, properties of gelled coal matter expressed by parallel stripes is also observed along the edges of cracks in monolithic coal preparations. Similar changes in the optical properties of coal matter are probably of the same nature and are the result of a combination of plastic and brittle deformations (Fig. 3).



a b

Figure 3 – Deformations in monolithic (lump-polished section) coal specimens (a) and specimens from coal particles (b)

Analysis of specimens from coal particles of the fraction 0.1 - 0.16 mm, which were subjected to multiple fixed loads, firstly, shows that the maximum stresses arose in the harder particles (vitreous) and the distribution of both the particles themselves and the deformations in them has a local character, that is, it occurs due to the formation of critical fluctuations in local differently activated areas. Secondly, it allowed us to note an interesting trend in the behavior of coal particles under force loading: the direction of brittle (crack) and plastic (surface corrugation) deformations most often coincide, which reflects a gradual transition from plastic to brittle deformations (Fig. 4).

Figure 4 – Brittle and plastic deformation in a single coal particle

3.2. Results in the evaluation of the specific strain energy.

The obtained data on the changes in the force and height of the tablet after compression allowed us to quantitatively evaluate the work performed by the system due to the energy accumulated in the molecular structure of the substance in the form of stresses (Table 2).

Table 2 – Parameters of coal samples (grade LF) for the evaluation of the strain energy and structural stresses, particle size class is 0.10 – 0.16 mm.

Sample No., a stage of the experiment		Change in compressive force ΔP, kN	Change in tablet height after compression h, μm	Work, J	Specific strain energy, J/g	Specific elastic energy, J/g
1	A	0.040	3.4	0.069	0.341	–
	B	0.040	2.9	0.057	–	0.282
	C	0.035	2.3	0.041	–	0.203
2	A	0.040	3.4	0.068	0.336	–
	B	0.040	3.3	0.066	–	0.326
	C	0.040	3.0	0.060	–	0.296
3	A	0.051	3.9	0.099	0.494	–
	B	0.035	2.4	0.042	–	0.209
	C	0.030	2.4	0.036	–	0.180

The research on the deformation behavior of coal matter under load showed that compression leads to the accumulation of elastic deformation energy. The presence of such accumulated energy was recorded by the petrographic method in the form of "flaking-off" of rectangular plates from the surface of coal particles. The existence of such plates is due to cleavage cracks, which on medium grades of coal are located at a distance of 0.020 mm to 0.600 mm from each other (Fig. 5).

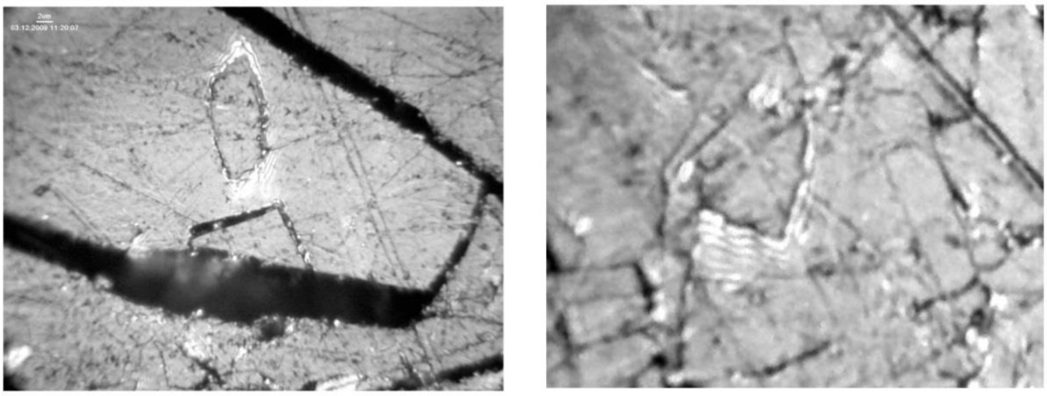


Figure 5 – Flaking-off of rectangular coal plates from the coal surface

So, the Figures show that during compression, deformations are distributed non-uniformly, that is, it can be assumed that they are formed due to critical fluctuations in local differently activated zones, which corresponds to the basic provisions of the model [14] of rock deformation.

3.3. Theoretical basis of the conducted research.

Let us assume that in a coal matter, carbon atoms, due to the Heisenberg indeterminacy principle, perform oscillatory motions in the total mass. In numerous particles of a coal matter consisting of carbon atoms that are in two quantum states and separated by a distance ΔL ($\Delta L \sim 1$Å), areas with two basic states *E2* and *E1* arise under the impact of external forces. A general property of systems with two allowed quantum states is that one of the states is energetically more favorable, and the other state has an energy greater by the value ΔE:

$$E2 = E1 + \Delta E.$$

The difference in energies between the two allowed states means that energy is “pumped” into the system.

The obtained data indicate that during the process of all-around compression, the height of the tablet, after the preliminary stage, when the sample was already partially pressed, continues to decrease. The decrease in the distances between particles can be explained by the fact that coal is a system in which a change in the conformational macromolecules, of which it consists, is observed. In this context, molecular conformation refers to different spatial forms of the molecule that can transform into each other by rotating atoms without breaking interatomic bonds as a result of external influence on the rock massif [25]. Under force loading, elastic energy accumulates in the form of conformational deformation defects, which, after unloading, leads to an increase in the size of the tablets.

It is fundamentally important that this accumulated energy in the process of its relaxation can be spontaneously spent by the matter on physicochemical transformations and structural transformations, which, in turn, can lead to changes similar to carbonization, including the generation of gases, in particular, methane.

The obtained scientific results can have further practical applications in many areas. These are mining engineering and coal mining, materials science and mechanics of materials, energy and ecology, in particular:

– Optimization of coal mining technologies, in particular methods of its crushing and beneficiating;

– Improving the safety of coal mines by understanding the mechanisms of coal beds destruction;

– Reducing energy costs for coal grinding, using knowledge about the accumulation and release of energy in fine particles;

– Research into the mechanisms of gas and dust emissions, since deformations of coal masses can cause sudden emissions of methane;

– Estimating the possibilities of controlling the degassing processes of coal beds before their development;

– Using knowledge about the accumulation of energy in crushed coal to develop new approaches to energy storage or utilization;

– The effect of mechanical activation of coal on its combustible properties and combustion efficiency;

– Modeling the behavio undergo similar deformations, in particular in construction or the production of composite materials;

– Using knowledge about stress localization to increase the strength of materials or optimize their structure.

Therefore, research in this area is extremely important both for industry (efficiency and safety of mining operations) and for fundamental science regarding the strength and deformation of materials to understand the behavior of complex deformation systems.

4. Conclusions

1. For the first time, it is shown at the micro level for coal that under force loading, the directions of brittle (crack) and plastic (surface corrugation) deformations most often coincide, reflecting a gradual transition from plastic to brittle deformations.

2. It is shown that in samples of crushed coal during compression, deformations are unevenly distributed due to critical fluctuations in local activated zones: the energy of elastic deformations concentrates in harder particles, and both the distribution of the particles themselves and the deformations within them have a local (random) character.

3. The energy of elastic deformations that accumulates in destructed coal (the grain-size class is 0.10–0.16 mm) during compression was calculated; its value for LF-grade coal is within 0.20–0.50 J/g with a change in compressive force of 0.03–0.05 kN.

Conflict of interest

Authors state no conflict of interest.

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ЗАЛИШКОВІ ДЕФОРМАЦІЇ ВУГІЛЛЯ ПРИ РУЙНУВАННІ ПІД ТИСКОМ

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Анотація. Деформація та руйнування порід і вугілля при проходженні підземних виробок – це основний процес, що характеризує стійкість виробок, характер і інтенсивність можливих проявів газодинамічних явищ. Гірські породи, з точки зору механіки, – складний і суперечливий об'єкт: в невеликому об'ємі вони дуже неоднорідні, в великому – досить однорідні; в малому об'ємі вони поводять себе як суцільні тіла, в великому – як дискретні. При цьому треба відзначити, що поняття руйнування включає пружну, пластичну і крихку стадії деформації. У статті досліджено особливості залишкових деформацій вугілля під час його руйнування в умовах дії зовнішнього тиску. Проведено аналіз змін фізико-механічних властивостей вугілля в процесі навантаження до руйнування, а також після зняття навантаження. Встановлено залежність між рівнем залишкових деформацій і структурними характеристиками вугілля, що дозволяє оцінити ступінь його деформаційної стійкості.

Метою роботи була розробка теоретичних і експериментальних підходів дослідження механічних властивостей вугілля на мікрорівні і оцінки величини енергії пружних деформацій.

Вперше для вугілля на мікрорівні показано, що під силовим навантаженням: напрямок крихкої (тріщини) та пластичної (гофрування поверхні) деформацій найчастіше збігається, що відображує поступовий перехід від пластичних до крихких деформацій.

Показано, що в зразках подрібненого вугілля при стисненні деформації розподіляються нерівномірно за рахунок критичних флуктуацій в локальних різноактивованих зонах: енергія пружних деформацій концентрується у більш жорстких частках і розподіл як самих часток, так і деформацій в них має локальний (випадковий) характер.

Розрахована енергія пружних деформацій, що накопичується у зруйнованому вугіллі (клас крупності 0,10-0,16 мм) при стисненні, її величина для вугілля марки Д знаходиться в межах 0,20-0,50 Дж/г при зміні стискаючого зусилля 0,03 – 0,05 кН. Отримані результати можуть бути використані для вдосконалення моделей гірничого тиску та прогнозування стійкості гірничих виробок у вугільних родовищах. Крім того, дослідження у цьому напрямку є надзвичайно важливими як для промисловості (ефективність та безпека ведення гірничих робіт), так і для фундаментальної науки стосовно міцності та деформації матеріалів для розуміння поведінки складних деформаційних систем.

Ключові слова: вугілля, стискання, залишкові деформації, руйнування, фізико-механічні властивості, структурні зміни.