Experimental Study of Dynamic Fracture in Structurally Heterogeneous Materials on the Example of Rocks

Alexei N. Kochanov*

Melnikov Institute of Comprehensive Exploitation of Mineral Resources, Russian Academy of Sciences, Kryukovskiy tupik 4, Moscow, 111020, Russia

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Abstract

The development of micro- and macrocracks in rocks under dynamic influence is considered. The important role of structural features of rocks on this process is noted. Based on ultrasound studies, it is shown that rock samples, as a rule, are heterogeneous and differ in the distribution of longitudinal wave velocity values in certain local regions. The initial heterogeneity determines the spatial development of the microcrack development area under external influence. Using optical microscopy and computer X-ray microtomography, the parameters of microcracks were determined on the example of granite after exposure. Experimental studies using optical, electron and scanning confocal laser microscopy were performed to evaluate the parameters of microcracks in granite. Structural features of rocks affect the nature of the development, trajectory and speed of crack propagation.

Keywords: Fracture; Rocks; Structure; Experiment; Crack; Blast effect

1. INTRODUCTION

Within the framework of modern concepts of mechanics and strength physics, the destruction of materials under external energy influences is a spatio-temporal process caused by the formation and development of defects at various structural (scale) levels. Quite close attention is paid to this problem and a lot of experimental and analytical studies have been devoted, some of which reflect the works [1–5]. The patterns of this process are largely determined by the structure of materials, which is characterized by the shape and size of grains, porosity, the presence of microdefects, and along with the chemical composition determines the physical properties of materials, including strength. Typical representatives of polycrystalline materials are rocks—natural formations representing a set of minerals with various elastic and strength properties. A characteristic feature of rocks is their heterogeneity, which is understood as the spatial variability of their structure, condition and properties, due to the peculiarities of genesis, the history of development and dynamics of endo- and exogenous processes. The heterogeneity of rocks manifests itself at any scale of the study, has a multilevel character and is the main factor affecting the strength and the process of destruction as a whole, making it difficult to evaluate mechanical processes based on mathematical and computer models. The heterogeneity at the sample level is due to the polymineral composition of rocks, as well as local residual stresses and the presence of microdefects. The purpose of these experimental studies is to study the influence of heterogeneity and structural features of rocks on the process of destruction.

* Corresponding author: Alexei N. Kochanov, e-mail: kochanov@mail.ru

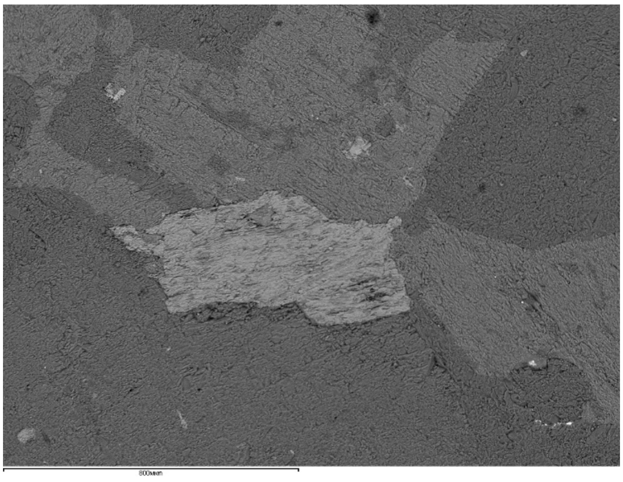
2. RESEARCH METHODOLOGY

The experiments were carried out on samples of quartz sandstone, granite and limestone, the maximum size of which was 25 cm or 50 cm, and the other two dimensions were usually 20–25 cm and 12–15 cm. Structural properties of quartz sandstone: grain size is 0.2–0.3 mm, quartz content is 99%, pore size is 0.06–0.13 mm, microporosity is 4–10%. The main rock-forming minerals of granite are sodium-potassium feldspar (37–42%), quartz (36–45%), plagioclase (18–22%). In quartz grains, intra- and intergranular cracks up to 0.05–0.1 mm in width are noted. They have cracks in up to 18–20% of quartz grains. The chemical composition of limestone corresponds to calcium carbonate and insignificant percent of impurities, i.e., it is homogeneous. As an example, Fig. 1 presents images of the surface fragments of granite, limestone and sandstone samples obtained by electron microscopy and characterizing their structural features.

Experimental methods of ultrasonic, optical, laser scanning confocal and scanning electron microscopy, computer X-ray microtomography were used to study the structural elements of rocks and its evolution under dynamic impact.

When conducting ultrasonic measurements, the velocity of longitudinal waves was taken as an informative parameter. This method of non-destructive testing is especially convenient for studying the structural features of materials, the evolution of their structure under the action of external influence [6,7]. The specificity of elastic wave propagation in inhomogeneous media is that the change in the kinematic and dynamic characteristics of waves is associated not only with the geometry of the front and absorption, but also with the processes of wave scattering by inhomogeneities.

The condition of the rock samples was monitored according to the sounding technique, when the sensors were located on opposite sides of the samples. The method of determining this parameter is well-developed, simple and reliable. Mass-produced equipment and a set of small-sized sensors with their own resonant frequencies of 100 and 150 kHz were used. Ultrasonic measurements were carried out in two mutually perpendicular directions with a step of 3 cm. Several profiles P1, P2,…, P7 were split along one of the faces of the samples (Fig. 2), which made it possible to obtain a spatial picture of the velocity distribution at different points of the sample. The number of profiles was determined by the size of the samples. When conducting studies in a different direction, one profile was usually used with measurement points that were located in the middle of the sample. The results of such investigations are presented in Tables 1 and 4.



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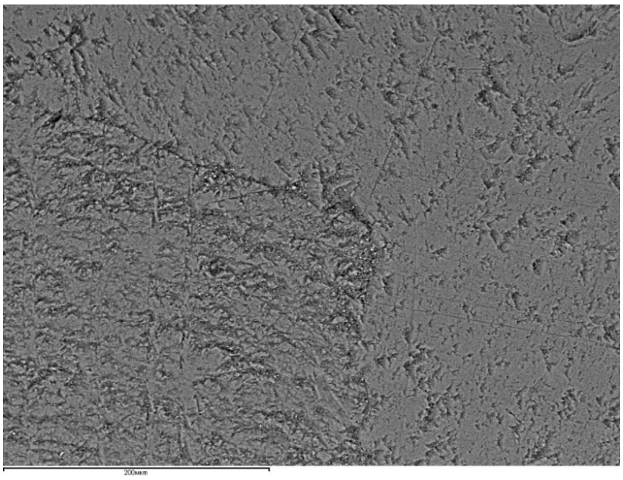

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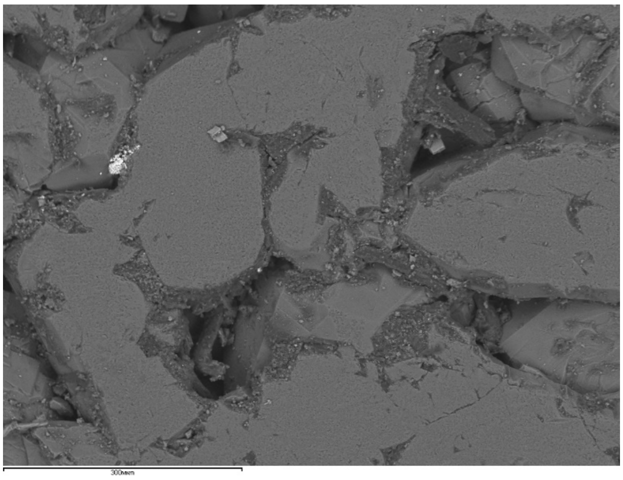


(c)

Fig. 1. Structural features of granite (a), limestone (b) and sandstone (c) according to electron microscopy data.

The basics of the ultrasound research methodology are reflected in the works [8–10]. To study the micro- and macrocracks formed in granite, separate plates with a thickness of 3 cm were cut from the sample, fragments of which were studied using optical and electron microscopy, and slots were made from them.

The dynamic effect was modeled by the action of an explosive charge, which, as a rule, was located in the center of the sample in a special hole with a diameter of 4.2 mm and a length of 6–7 cm. Its mass was selected in such a way as to exclude the destruction of samples into individual fragments.

Optical and electron microscopes were used to obtain images at different scale levels of fragments of the sample surface and cracks formed after dynamic exposure.

In order to study the microdefects of the structure, experimental studies were carried out using the method of computer X-ray microtomography. X-ray microtomography is a non-destructive method of studying the internal structure of solids during X-ray transmission of a material containing components of different density and chemical composition. This method involves scanning the sample over the entire volume in different directions with a step of ~ 1 microns, which allows you to visualize the internal three-dimensional structure of the samples. The method is now widely used to study the structural elements of various materials, including rocks [11].

The method of scanning confocal laser microscopy (CLSM) was used to assess the depth of the crack in its selected area. CLSM is a method of optical three-dimensional (3D) surface profiling with high resolution.

It should be noted that some results using these experimental methods are published in Refs. [12–14]. In this publication, an attempt is made to generalize them with an emphasis on structural features and the role of heterogeneity in the process of crack development at different scale levels.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The studies carried out on ultrasonic monitoring of the condition of rock samples (granite, sandstone, limestone) show that their local volumes can be characterized by a significant spread in the velocity of longitudinal waves due to the presence of residual stresses and microcracks (Table 1). Similar results obtained for a sandstone sample under ultrasonic testing show that the range of changes in the velocity of longitudinal waves in the sample is from 3320 to 4670 m/s (Table 2). The distribution of the propagation velocity of longitudinal waves after dynamic impact for this sample is presented in Table 3. The data in this table indicate that the initial structural heterogeneity of the sandstone sample affects the nature of the development of microdefects. In graphical form, the results of ultrasonic studies are presented for granite before and after exposure in Fig. 3. As a result of the explosive impact, a decrease in velocity is observed in certain areas of the sample, and the configuration of the microcrack development region is determined by the initial heterogeneity.

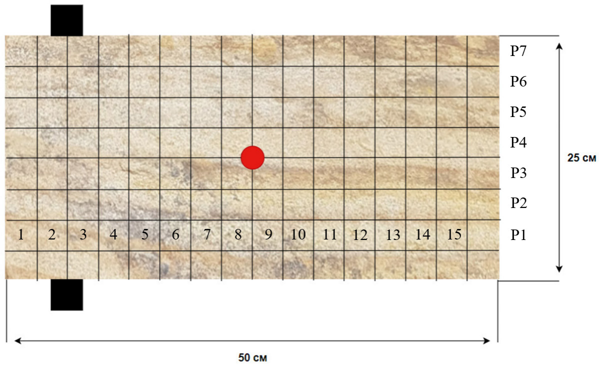


Fig. 2. Scheme of ultrasound examinations.

The influence of the initial heterogeneity on the results of the explosive effect is confirmed by an experiment also performed on a granite sample, the results of which are presented in the form of a relative change in velocity in Table 4. As part of the experiment, measurements of the velocity were carried out in a granite sample after two microexplosions with epicenters at points No. 4 and No. 9, located at a distance of 15 cm from each other. As a result of explosive impact No. 1, a maximum change in velocity at its epicenter is equal to 10.2%. A rather curious fact is that after the second microexplosion there is a relative decrease in speed down to 18% at a considerable distance from its epicenter. Thus, it can be argued that the initial microstructural damage (heterogeneity) of rocks, natural or, as in our case, man-made, has a significant impact on the results of the explosive impact.

Table 1. Distribution of longitudinal wave velocities in various rocks during ultrasonic examinations.

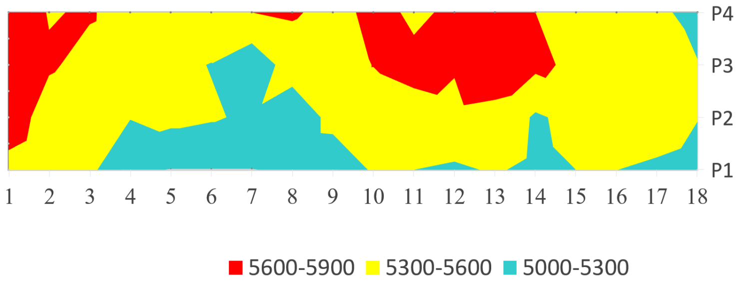
Test point No.	Rock Formation		
	Granite	Sandstone	Limestone
1	6590	2560	4670
2	6600	2210	4810
3	6550	2070	4160
4	6770	2250	4050
5	6770	2330	4160
6	6760	2560	4530
7	6730	2840	5130
8	6600	3050	–
9	6580	3280	–
10	6670	3460	–

Table 2. Distribution of longitudinal wave velocities (m/s) in a sandstone sample according to ultrasound data before exposure. Test point numbers and profile numbers (P1–P7) refer to the sample area under ultrasound examination (see Fig. 2).

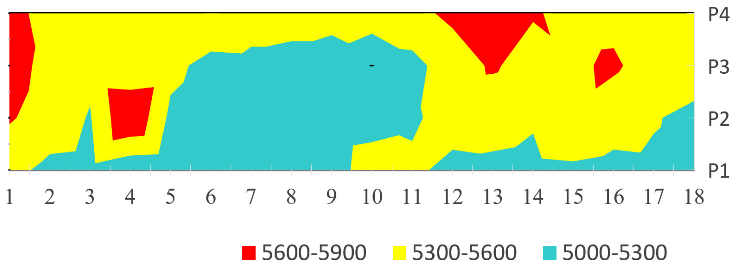
Test point No.	P1	P2	P3	P4	P5	P6	P7
1	4200	3940	4200	4200	4200	3940	4200
2	3710	3500	4200	4200	4200	3940	4200
3	3820	3500	4500	4500	4500	4200	4200
4	4200	3600	4500	4500	4500	4200	4500
5	3940	3320	4500	4500	4500	4200	4200
6	3600	3500	4500	4500	4500	4200	4350
7	3500	3940	4670	4500	4500	4200	4500
8	3940	4500	4500	4500	4500	4200	4350
9	4500	4850	4500	4500	4500	4200	4200
10	4670	4500	4500	4500	4200	4200	4200
11	4500	4500	4200	4200	4200	4200	4200
12	4200	4200	4200	4200	4200	4200	4200

Table 3. Distribution of longitudinal wave velocities (m/s) in a sandstone sample according to ultrasound data after exposure. Test point numbers and profile numbers (P1–P7) refer to the sample area under ultrasound examination (see Fig. 2).

Test point No.	P1	P2	P3	P4	P5	P6	P7
1	4200	3940	3940	3940	3940	3710	3940
2	3940	3500	3710	3940	3710	3500	3940
3	3940	3150	3940	3710	3500	3500	3940
4	4200	3000	3500	3150	3150	3320	3940
5	4200	2520	3150	2800	2520	3150	3500
6	3410	2250	2520	2250	2290	2740	3000
7	3230	3150	3150	2100	2100	2740	3320
8	3710	3940	4200	2520	2520	3000	3710
9	4500	4500	4200	3320	3150	3500	4200
10	4670	4500	4200	3710	3320	3940	4200
11	4500	4500	4200	3710	3500	4200	4200
12	4200	4200	4200	3820	3500	4200	4200



(a)



(b)

Fig. 3. Distribution of longitudinal wave speed values (m/s) in a granite sample before (a) and after (b) dynamic impact.

Table 4. Distribution of values of the relative change in the velocity of longitudinal waves (%) according to ultrasonic measurements in granite.

Test point No.	Impact No. 1	Impact No. 2
1	9.5	9.5
2	9.8	9.8
3	5.2	5.2
4	**10.2**	**18**
5	9.9	15
6	5.6	10
7	5.8	5.8
8	4.8	5
9	**2.5**	**5**
10	0	4.8
11	0	4.8
12	0	4.8
13	0	2
14	0	0

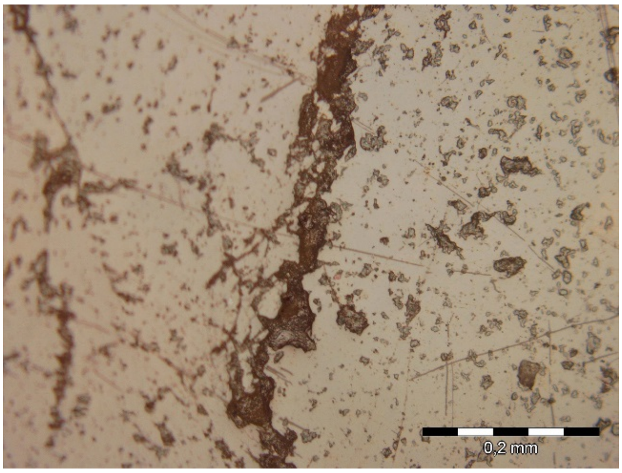


Fig. 4. View of a microcrack in a granite sample according to optical microscopy data.

To assess the parameters of microcracks formed after explosive impact, studies were carried out using optical microscopy and X-ray computed microtomography. Analysis of thin sections using optical microscopy indicates that after explosive action in granite samples, quartz grains have from 1–3 to 13 microcracks, and 70-80% of its grains have microcracks of technogenic origin. Microcracks are also observed in 40–50% of plagioclase grains and in 70–85% of potassium feldspar grains in the form of 2–3 microcracks at distances of 1.0–1.4 mm. The appearance of a microcrack when studying a polished granite surface is shown in Fig. 4.

According to X-ray computed tomography data, after explosive impact on granite, the opening of microcracks is several microns (Fig. 5.)

As a result of the dynamic impact, along with microdefects, radial cracks ~6–7 cm long were formed in the granite. To clarify the parameters and structure of the cracks,

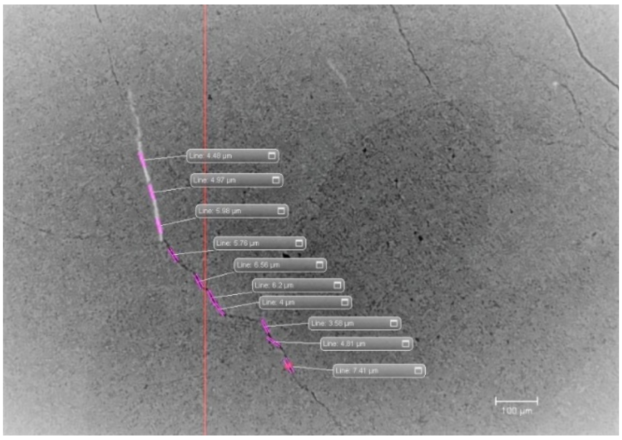


Fig. 5. Type of microcrack and assessment of the size of its opening based on X-ray computed microtomography data.

Fig. 6. View of a separate fragment of a crack in granite according to optical microscopy data.

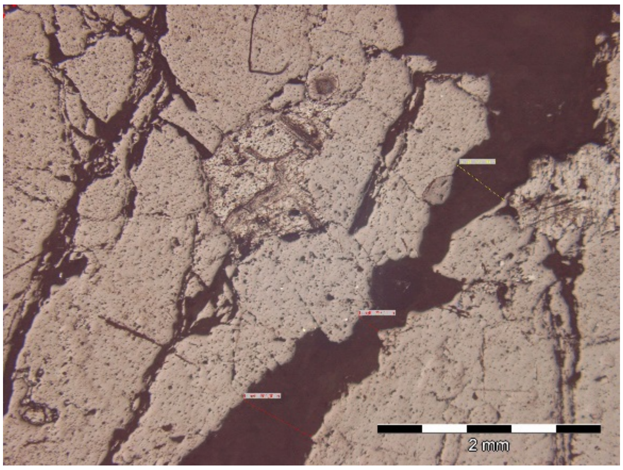
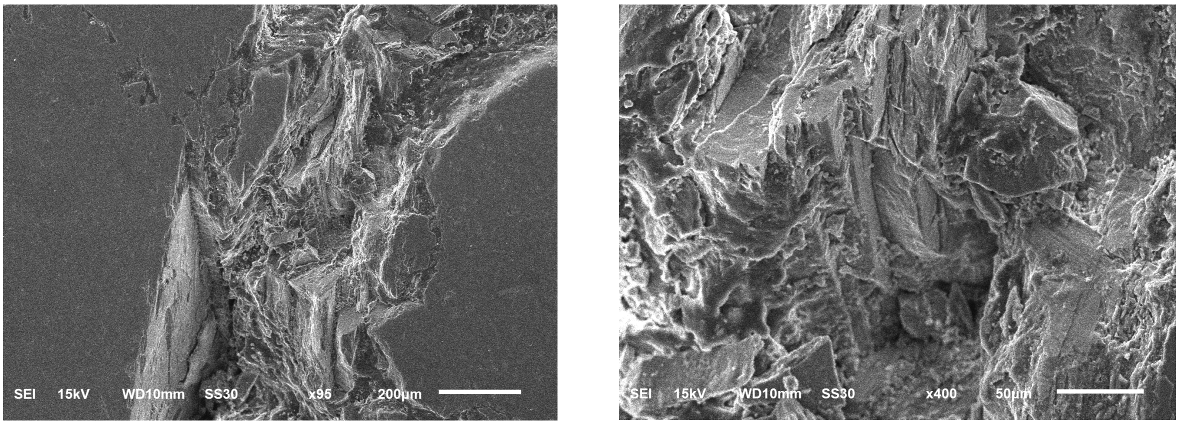


Fig. 7. View of a separate fragment of a crack in granite according to optical microscopy data.

studies were carried out using optical, electron and confocal laser microscopy. Images of a crack fragment obtained using optical and electron microscopy are presented in Figs. 6–8. An Olympus optical microscope with a DP-12



(a) (b)

Fig. 8. View of a crack fragment according to electron microscopy. Scale bars: 200 µm (a) and 50 µm (b).

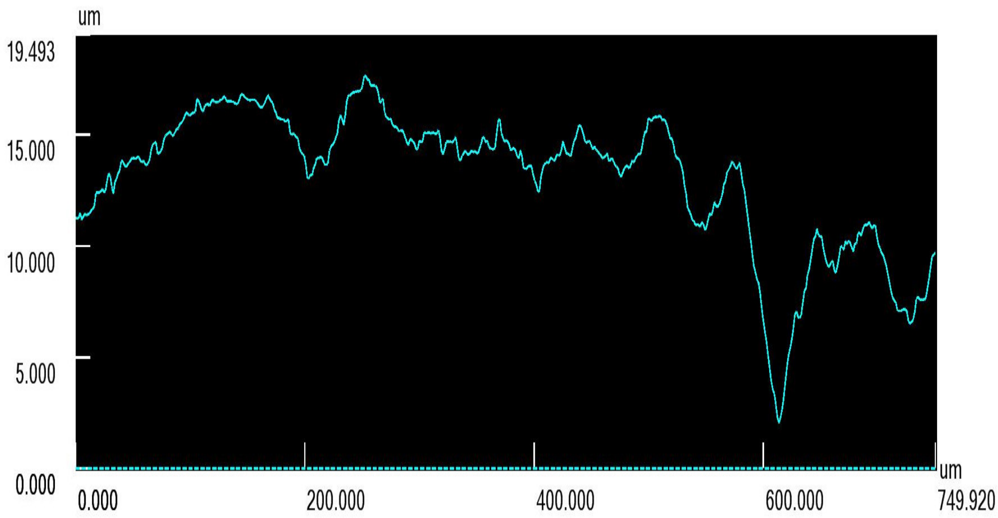


Fig. 9. Distribution of depth values for a crack fragment 750 µm wide according to laser confocal microscopy data.

digital camera and JSM-5910LV and JSM-6610LV electron microscopes were used in the research.

To assess the depth of the crack in a selected area, the SCLM method was used. Fig. 9 shows the distribution of crack depth values for a fragment with a width of ~750 µm, which were obtained using a Keyence VK-9710K microscope.

According to the experimental results, it is noted that uneven, abrupt development of macrocracks is observed in granite. This circumstance is obviously due to the polymineral composition of granite and the presence of mineral grains with different strength and elastic properties. The delay in the development of the main crack causes a fairly low speed of its propagation, which makes it possible for additional cracks to form and leads to multiple crack formation. In limestone, as a homogeneous rock practically consisting of carbonates, during experiments on dynamic impact, multiple cracking was not observed, but the formation and development of individual "radial" straight cracks of greater length took place, which were visually observed on the surface of the samples and reached their boundaries, which indicates higher speed of their spread. According to work [15], the speed of crack development in granite during explosive destruction is 230 m/s, and in limestone – 340 m/s. Thus, it can be argued that the structural features of rocks determine the nature and trajectory of crack development, the possibility of its branching, which affects the speed of their propagation.

4. CONCLUSIONS

On the basis of the experimental studies carried out, the role of structural features and heterogeneity of rocks on the process of formation of the microdefects and the development of macrocracks under explosive action is shown. Ultrasonic testing allows us to detect the heterogeneity of local areas of rocks by the velocity of longitudinal waves, the values of which may differ significantly for an individual sample. The initial inhomogeneity significantly affects the formation of microcracks. Structural features of rocks, which as natural formations represent a set of minerals with various elastic and strength properties, determine the nature of the development of macrocracks and the mechanism of their destruction. The images obtained using modern microscopy methods allow us to consider macrofractures formed during dynamic exposure as 3D objects. The change in the shape and relief of the crack as it spreads in certain areas may indicate changes in its propagation velocity associated with the formation of the fracture localization zone and subsequent abrupt advance. The experimental results are important for understanding the mechanisms of crack formation in rocks, for developing criteria corresponding to different stages of the fracture process, and can be used for engineering applications.

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Экспериментальное изучение процесса динамического разрушения структурно-неоднородных материалов на примере горных пород

А.Н. Кочанов

Институт проблем комплексного освоения недр им. Н. В. Мельникова РАН, Крюковский тупик 4, Москва, 111020, Россия

Аннотация. Рассматривается развитие микро- и макротрещин в горных породах при динамическом воздействии. Отмечается важная роль структурных особенностей горных пород на этот процесс. На основании ультразвуковых исследований показано, что образцы горных пород, как правило, являются неоднородными и отличаются распределением значений скорости продольных волн в отдельных локальных областях. Исходная неоднородность определяет пространственное развитие области микротрещин при внешнем воздействии. С помощью оптической микроскопии и компьютерной рентгеновской микротомографии определены параметры микротрещин на примере гранита после воздействия. Для оценки параметров макротрещин в граните выполнены экспериментальные исследования с использованием оптической, электронной и сканирующей конфокальной лазерной микроскопии. Структурные особенности горных пород влияют на характер развития, траекторию и скорость распространения трещин.

Ключевые слова: разрушение; горные породы; структура; эксперимент; трещина; взрывное воздействие