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ON THE MECHANISMS OF DISINTEGRATION OF ROCKS UNDER THE EXPLOSIVE AND PULSE-DISCHARGE IMPACTS

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Abstract

This paper presents new experimental results derived from studies that involved the explosive impact and nonthermal effect of high-power nanosecond electromagnetic pulses have on the formation of microdefects in rock samples in the "pre-fracture" stage. Using atomic force and scanning electron microscopy, nanoindentation and microhardness testing, we studied the change in surface morphology (microdefects) and mechanical properties of rock samples and natural minerals under these dynamic types of impacts. The minimum values of the microcrack opening width in rocks after explosive and electromagnetic pulse impacts were ~0.2–0.5 μm, and the most typical opening width was 2–3 μm.

***Keywords**: Rocks, disintegration, microcracks, explosive impact, high-power nanosecond pulses*

1. INTRODUCTION

Pre-fracture state of rocks, minerals and ores (pre-destruction of geomaterials [1]) is considered as the initial stage of the evolution of the internal microstructure of geomaterials, on which the deformation and reorientation of individual grains of rocks, disruption of bonds, development of microdefects, change in the properties and state of a certain volume of the mineral environment occur [1,2]. It is at the stage of pre-fracture of solids that the sequential generation and development of the defects at various scale, mainly nano- and microstructural levels develops [2]. The prospects for the practical application of the explosion energy to improve the efficiency of the complex processing of hard-beneficiation mineral raw materials [3], and at the same time the introduction into industry of electric pulse technologies for crushing (comminution) and selective disintegration of rocks and ores [4], predetermine the need to conduct the research into the mechanisms of dynamic (explosive, electric explosive) destruction of rocks using modern methods of microstructural analysis. Analysis of the mechanical, electrical and physicochemical properties of the surface of natural mineral substances provides important information about the distribution of structural-material associations in geomaterials and their local properties. The research to determine the mechanical properties of individual mineral grains, micromechanisms of deformation and destruction of minerals that make up the rock, taking into account the influence of interphase boundaries, is relevant. This paper presents experimental data on the influence of shock-wave loading from an explosion, as well as the influence of high-voltage pulse discharges of nanosecond duration on the morphology, structure of surface defects and mechanical properties of rock samples and natural minerals with different mechanical and electrical (dielectric) strength.

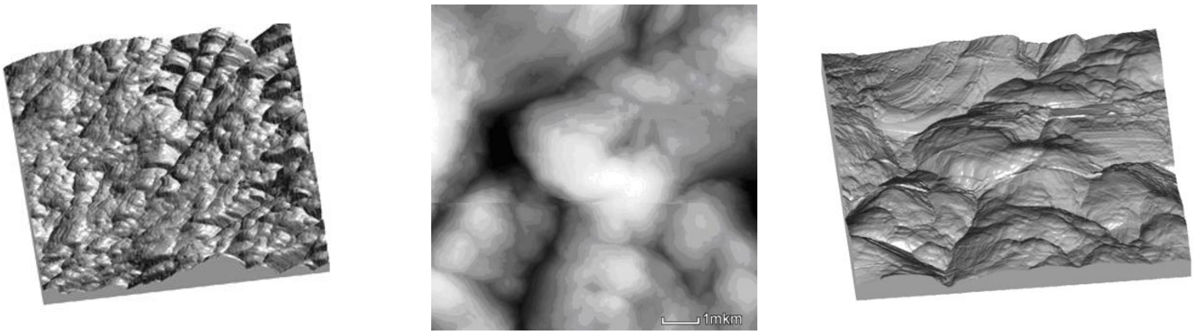
2. EXPERIMENTAL

Experimental studies were carried out on the samples of ferruginous quartzites, quartz, granite, dolomite and coal in the form of the specially prepared polished sections of minerals and rock plates, as well as fragments of irregularly shaped specimens 4–5 mm in size (wide). When conducting experiments on explosive impact, we used the samples (blocks) of granite with a characteristic size of one of the sides from 15 to 25 cm. A cylindrical hole was created in the center of the samples using a diamond drill, into which a charge of a small explosive substance of ~0.1 g was placed [5]. After the explosive impact, individual plates were cut from the samples for surface analysis by the methods of optical and electron microscopy. The conditions of exposing the mineral samples to the effect of high-power nanosecond electromagnetic pulses (HPEMP [6]) in air under standard conditions were described in detail in [7,8], along with the electro-physical parameters of the high-voltage pulse generators. The duration of sample treatment varied in the range t_{treat}= 10–100 s. Let us specify, that with the HPEMP effect, the duration of high-voltage nanosecond pulses was 4–10 ns, the leading edge of a pulse was 2–5 ns. Pulse amplitude was $U_A = 25$ kV, strength of the electric field in the 5 mm interelectrode gap, E~10^7 V×m^{-1}, and the rate of nanosecond pulse repetition was $f = 100$ Hz. The parameters of energy impacts established for conducting our experiments (both in the case of explosion and HPEMP) did not lead to fragmentation of samples into separate parts; however, the numerous traces of local violations of the continuity of the mineral substance in the form of macro- and microcracks, electrical breakdown channels and exposed microinclusions of secondary phases were formed on the surface of the samples.

The morphological features of the mineral surface and the trajectories and characteristic sizes of cracks on the samples surface were studied by atomic force microscopy (AFM) and analytical scanning electron microscopy (SEM–EDX), and the elemental composition was determined by X-ray spectral microanalysis. Scanning probe microscope SMM-2000 (JSC "PROTON Plant", Zelenograd) and electron microscopes LEO-1420VP with an Oxford INCA Energy 350 EDX System, and JSM-6610LV microscope were used. AFM images of surface fragments (scans of 8x8 μm in size) were obtained in contact scanning mode using silicon cantilevers of the CSG01 series (the tip curvature radius was 10 nm, the force constant was 0.05 N/m, the resonance frequency was 12 kHz). The nanotriboindentometer TI-950 (Scientific Center of Tambov State University named by G.R. Derzhavin, Tambov, Russia) was used to measure the minerals hardness at the nanostructural level (nanoindentation testing). The microhardness of quarz samples was determined by the Vickers method (HV, kgf/mm^2) on a PMT-3M microhardness tester (LOMO, Russia), with an indenter load of 150-200 g and a loading time of 10–15 s.

3. RESULTS AND DISCUSSION

Analysis of AFM images of fragments of the surface of rock samples (Figure 1) in the initial state (after preparatory mechanical processing) showed that the spread of heights across the frame for quartzite, granite and dolomite was 1.2; 1.35; 2.33 μm, respectively; the average arithmetic roughness (S_a, nm; average roughness, ISO 4287/1) of the surface of the samples was 116, 141, 250 nm, respectively.



a *b* *c*

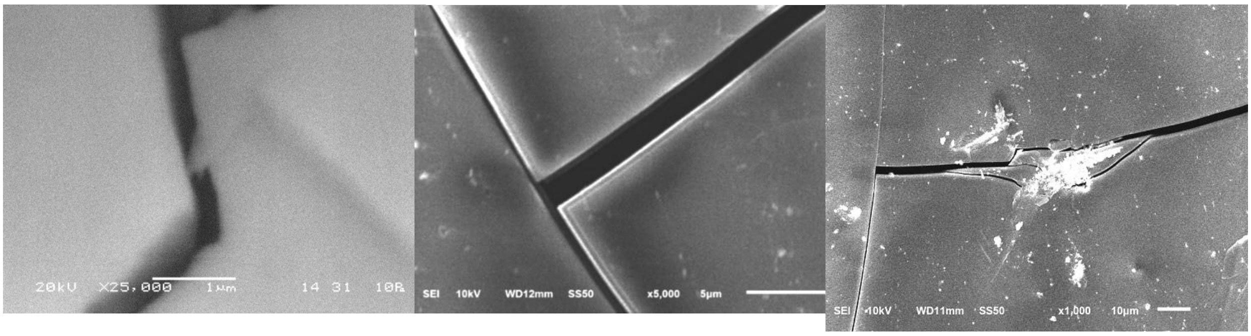
Figure 1. AFM images of 8×8 μm quartzite (a) and granite (b), (c) surfaces: 2D brightness image (b) and 3D relief visualization (a), (c) of rock surfaces

The average grain size of quartzite was $S_{gr} = 1.59$ μm, and the average subgrain size (or the nanograin from which the grains are composed) was $S = 277$ nm; for the granite sample – $S_{gr} = 2.73$

μm, $S = 234$ nm; for dolomite – $S_{gr} = 3.26$ μm, $S = 351$ nm. It's obviously that at the microlevel, the geometric characteristics of the morphological features of the samples surface are related to the parameters of the rocks grain structure. The microrelief of the granite surface (Figure 1*c*) was noticeably more pronounced compared to the quartzite sample (Figure 1*a*).

The structure of rocks is heterogeneous, the rocks consist of individual mineral grains and they have structural features, including defects of different scale levels (cracking properties or fracturing). For the most rocks, the fracture toughness does not exceed 0.5 – 2.0 MPa×m$^{1/2}$ (for example, the fracture toughness of the marble, sandstone and serpentine is 0.75, 1.1, 1.4 MPa×m$^{1/2}$, respectively), while the crack resistance (K_{1c}) of brittle ceramics reaches ~5 MPa×m$^{1/2}$. For the ferruginous quartzite samples a comparatively low fracture toughness of the non-metallic phase (quartz) was established using the nanoindentation method. The fracture toughness of quartz was 0.5 MPa×m$^{1/2}$; the K_C of quartz was ~1.5 – 2.0 times lower than the fracture toughness of the iron ore mineral grains (hematite and magnetite). At the boundaries of the intergrowth of quartz-magnetite and quartz-hematite grains, the value of K_C was 0.68 and 0.38 MPa×m$^{1/2}$, respectively; this value is ~2–3 times smaller than at the boundary of the intergrowth of magnetite–hematite ore mineral grains.

SEM data show that most of the microcracks which developed in rocks due to the action of the blast wave (zone of the wave prefracturing of rocks under blasting [2]) are of the plane-mode type (mode I of the cracking). No shear-type (mode II) formation of defects was observed. Under explosive action, the newly formed cracks propagated inside the grain boundaries in the rocks; i.e., the character of disintegration was primarily transcrystalline. However, some number of microcracks were also observed along grain interfaces that were connected or coincided fully. The characteristic features of the crack propagation trajectories (discontinuity, discreteness, unevenness of crack edges (Figure 2*a*)) testify about dynamic, jump-like growth of cracks, which stop at the obstacles and overcome the areas of localization of microdamage at the crack tips.



a *b* *c*

Figure 2. Morphology of microcracks on the surface of rock samples after the various energy impacts: explosion (quartzite) (a), and HPEMP (coal) (b), (c). SEM, scale bars: 1 (a), 5 (b) and 10 (c) μm

As a result of HPEMP with $t_{treat} = 300$ s, the systems of microcracks formed on the surfaces of the coal samples and usually propagated along strictly linear trajectories (Figure 2*b*). The minimum values of the microcrack opening width in rocks were ~0.2–0.5 μm, and the most typical opening width was 2–3 μm. The formation and propagation of microcracks was affected by microinclusions in the coal (Figure 2*c*). Newly formed cracks exposed particles of secondary phases (sulfides), they spread along the boundaries of sulfide particles (selective disintegration of mineral complexes). Structural modifications after electropulse treatment were more typical of samples taken from seams of outburstprone coal that are brittle.

As a result of ultrasonic measurements of the propagation parameters of longitudinal and transverse waves in the rock samples, we found that the development of microcracks leads to a decrease in the velocity of longitudinal waves (possibly due to the development of fracture porosity), and, consequently, to the degradation of the strength properties of geomaterials. In this report we discuss the results of a study of the influence of explosion and high voltage nanosecond pulses on the mechanical properties of rock samples. For example, under non-thermal action of HPEMP for $t_{treat} = 150$ s, the softening of milky-white quartz surface (Mohs hardness 7) occurred, and a decrease in microhardness (HV) from 1430 to 1010 kgf/mm2 (ΔHV ~30%) was observed. Apparently, the mechanism of the quartz softening consisted of microwave decrepitation of gas-liquid inclusions in the host mineral. This effect can be used in the technologies of deep beneficiation of natural quartz at the stages of mechanical crushing (grinding) and electrical fragmentation to clean the mineral from microimpurities.

The formation of crystallographically oriented discharge channels in silicon dioxide suggests the realization of an specific (certain) electrical breakdown mechanism. The authors of paper [9] considered the formation of breakdown channels in silicon dioxide in terms of the model of impact ionization of the valence band by fast nonequilibrium electrons, and also, in terms of the model of primary electron generation by cascade Auger transitions in the valence band of the dielectric. The disintegration of mineral media, due to the formation of microchannels of electric breakdown, lie in planes of silicon ions, as a result of charge carriers (primary electrons) being generated by cascade Auger transitions in the valence zone of the dielectric mineral with regard to the crystallochemical stricture of quartz [9] is a possible mechanism of the quartz surface softening under the influence of high-voltage nanosecond pulses.

4. CONCLUSION

Under explosive type action, the newly formed cracks propagated inside the grain boundaries in the studied rocks; i.e., the character of disintegration was primarily transcrystalline. In contrast, under the impact of high-voltage nanosecond pulses, the formation and propagation of microcracks in the rock samples was recorded primarily along grain boundaries (intercrystalline fracture, which determines the selective disintegration of ores exposed to HPEMP). The effectiveness of the nonthermal effect high-power electromagnetic pulses has on the formation of microcracks in the considered rocks was most apparent in our coal samples. The minimum values of the microcrack opening width in rocks after explosive and electromagnetic pulse impacts were ~0.2–0.5 μm, and the most typical opening width was 2–3 μm.

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