The mechanism of destruction under the influence of shock waves

SHCHERBAKOV I.[1a], MAKHMUDOV Kh. [1b]

[1]Ioffe Institute, Saint-Petersburg, Russia

[a]Sherbakov.Mhd@mail.ioffe.ru, [b]h.machmoudov@mail.ioffe.ru(corresponding author)

Abstract. The spectra of the plasma emitted from the studied samples consist of several dozens of narrow bands superimposed on each other. Tables of spectral lines were used to interpret the spectra. It turned out that the largest number of bands corresponds to the radiation of positively charged ions and atoms of elements that make up the crystal lattices of minerals that make up the studied rocks. Thus, the spectra of the plasma emitted from quartz corresponded to the radiation of atoms and positively charged silicon ions, the charge of which varied from 1 to 4, as well as atoms and positively charged oxygen ions, the charge of which varied from 1 to 3. Positively charged ions and atoms of Si, O, K, Ca, Al and Na, which are part of the crystal lattices of quartz and feldspar, flew out of granites. Positively charged ions and Ca, C and O atoms flew out of the calcite.

Keywords: shock waves, mechanism and dynamics of destruction, quartz, granites, calcite.

Introduction

An experimental technique that allows finding out the mechanism of destruction with such fast-flowing effects of shock waves was previously absent. It was judged mainly by the results of the study of the fracture surfaces after the action of shock waves. A few years ago, we built installations that allow studying the mechanism of destruction with a time resolution of 2 ns. This made it possible to experimentally study the mechanism and dynamics of rock destruction directly during the action of a shock wave. In the plasma spectra of granites, the spectra of positively charged impurity ions - Fe and Mn, as well as Cu ions that flew out of the walls of the copper chamber, and nitrogen ions formed when air nitrogen molecules were bombarded by plasma flows were observed. After the destruction, fragments of samples with sizes from several microns to several mm remained. Their weight was ~ 20% of the original sample weight. The plasma released from the minerals also mainly consists of positively charged ions. This allowed us to suggest that the shock wave, reflecting from the rock surface, distorts the crystal lattices of minerals so much that the interatomic bonds in them disintegrate. As a result, the rock surface evaporates by the departure of positively charged ions and electrons. The improvement and application of fundamental and field studies of shock wave parameters for the analytical assessment of geomechanical stability and operational safety of various large-scale underground structures, such as hazardous waste storage facilities, tunnels and liquefied gas tanks, remains relevant [1-5]. The main research method is the analysis of acoustic emission pulses (AE), which is widely used to study the process of pre-destruction (nucleation and accumulation of microscopic cracks) in heterogeneous materials, such as rocks [6-10]. Unlike homogeneous materials-glasses, single crystals destroyed according to a quasi-critical scenario due to the growth of a localized foci with the release of energy from a limited number of simultaneously growing cracks, the development of damage under mechanical loading of brittle heterogeneous bodies occurs through the gradual accumulation of microcracks, since there are many "weak points" in such materials, primarily in the intergranular layers.

The recent creation of increasingly large infrastructure facilities and the emergence of new technologies, in particular, the spread of the method of hydraulic fracturing in the oil and gas industry has led to an increase in attention to the problem of the stability of systems that are in a metastable state, since the destruction of such systems remains unpredictable and leads to irreparable economic and human losses. This determines the relevance of research on trigger states, which is confirmed by a sharp increase in the number of publications on the development of the concept of a trigger mechanism in geosystems in the last decade [11]. At the same time, the main areas of research in the world are full-scale observations and the construction of mathematical models of the phenomenon, as a rule, only for specific objects. There are very few reports in the

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 4 October 2021 doi:10.20944/preprints202110.0047.v1

scientific literature about laboratory studies of the trigger phenomenon, which are necessary to identify the criteria for the danger of certain natural phenomena and anthropogenic factors on the stability of engineering structures.The factors influencing the danger of metastable states for large-scale infrastructure facilities (spent nuclear fuel storage facilities, underground coal gasification, mining workings, etc.) are largely known, but the mechanism of occurrence of such states in geosystems is currently understood only in general terms. In this paper, the accumulation of structural defects under double loading will be observed by the methods of acoustic emission (AE), electromagnetic emission (EME) and fractoluminescence (FL). The combination of these methods makes it possible to register elementary processes of destruction – breaks of interatomic bonds (FL), the occurrence of microcracks (AE) and their relaxation (annihilation, EME) during the collapse of the crack banks, that is, during their spontaneous healing. Statistical processing of time series of emission activity of these types will consist in constructing distributions of the released energy in pulses and intervals between pulses, which, as can be expected, reflect the stability of the sample or the approach of the material to a critical state. Varying the values of loads of two types and directions in different combinations will allow one to assess the "dangerous" load combinations for granites from different deposits. As far as we know, neither emission methods nor experiments on the combination of shock and static load have ever been used to study the trigger destruction of rocks.

To date, numerous attempts have been made to study the mechanism of destruction and deformation of rocks under the influence of shock waves [12]. The main difficulty faced by the authors of these works is that the speed of shock waves coincides with the speed of the longitudinal acoustic wave, which is greater than the speed of the transverse sound wave. At the same time, cracks in the rockbody can grow at a speed of no more than ~ 0.3-0.5 of the speed of the transverse wave [13, 14]. Therefore, during the action of the shock wave, cracks do not have time to form and grow.

Most of the papers describing the results of studies of destruction due to the impact of a shock wave were published in the journals "Physics of the Solid State" and "Journal of Applied Physics". Here is a brief overview of the works performed by us, in which the mechanism and dynamics of the destruction of quartz, granites, gabbro-diabase and marble are studied.

Before moving on to its presentation, we note that studies of the mechanism of other solids (metals, crystals, polymers and composites) with a time resolution of 2 ns have not been carried out until now. Therefore, the question of to what extent the results described below can be valid for other solids remains open.

Materials and Methods

The samples were prepared from quartz crystals, granites (alaskite and plagiogranite), gabbro-diabase and calcite. Each of them was a parallelepiped with dimensions of ~ 4x2. 7x6 cm (Fig. 1), in which a slot was cut with a depth of ~ 1.3 cm and a width of ~ 2-3 mm.

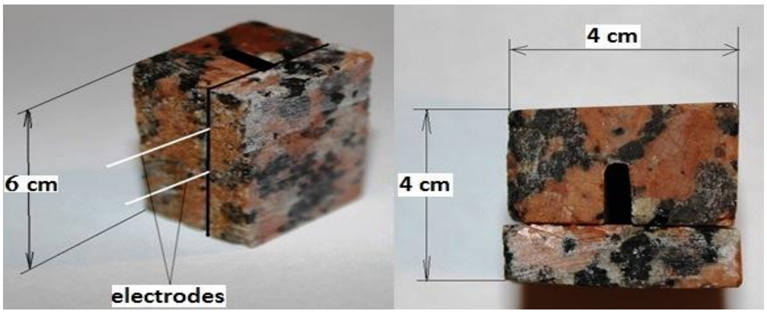


Figure 1. View of the granite sample

It contained copper electrodes, the distance between which is ~ 3 mm. The slot was closed by another parallelepiped having dimensions of 4x1,3x6 cm. The samples were placed inside a copper chamber, which was part of the installation.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 4 October 2021 doi:10.20944/preprints202110.0047.v1

Block schematic diagrams of the installation for studying the destruction under the influence of shock waves. A block schematic diagram of the installation for studying the destruction mechanism is shown in fig. 2.

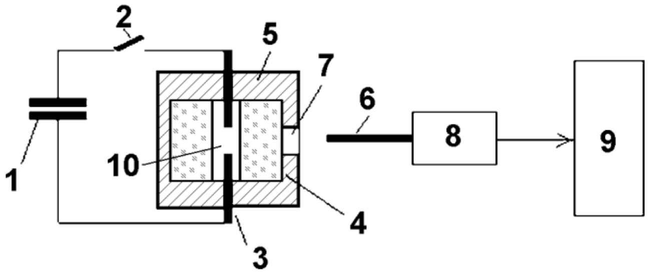


Figure 2. Block schematic diagram of the installation for studying the radiation spectra of rock samples that occur during destruction: 1-a capacitor, 2-an electronic start circuit, 3-electrodes between which an electric breakdown occurs, 4-a sample, 5-a copper chamber, 6-a quartz light guide, 7-a window in the chamber for the output of light radiation, 8-an AvaSpec-ULS3648 spectrometer, 9-a computer

The capacitor (1) with a capacity of 40 μF was charged to 2 kV, which corresponds to the stored energy of 80 J. Using the electronic start-up circuit (2), it was discharged through the air gap between the electrodes (3), which led to an air breakdown and an electric discharge between them. To obtain sufficiently intense luminescence spectra arising under the action of shock waves, the discharge power was 8 MW.

During the discharge, a shock wave appeared in the sample, which, having reached the sample surface, caused the plasma jet to fly out (Fig. 3).

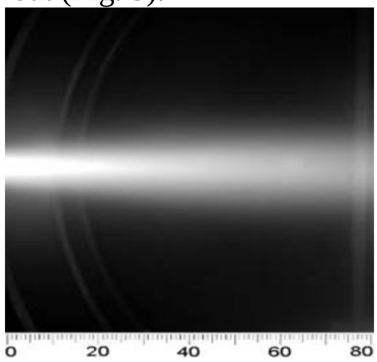
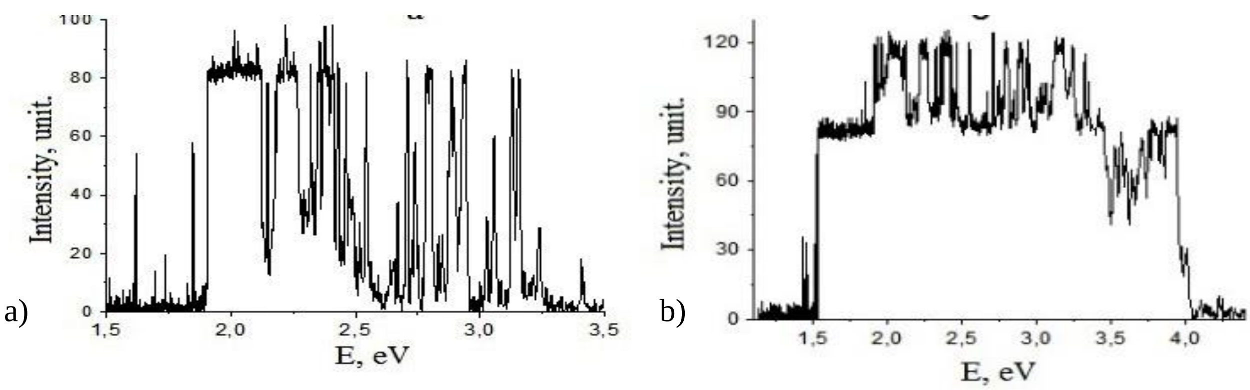


Figure 3. A photo of a plasma ejected from quartz under the influence of a shock wave

Results and Discussion

The length of the jet was several tens of centimeters. The plasma radiation fell on the input of a quartz light guide (6) located at a distance of ~ 1 m from the sample. The second end of the light guide was located in front of the entrance window of the AvaSpec-ULS3648 (8) spectrometer. The signal from the output of the spectrometer was fed to the input of a personal computer (9). The spectra of the plasma emitted from the studied samples are shown in fig. 4.



Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 4 October 2021 doi:10.20944/preprints202110.0047.v1

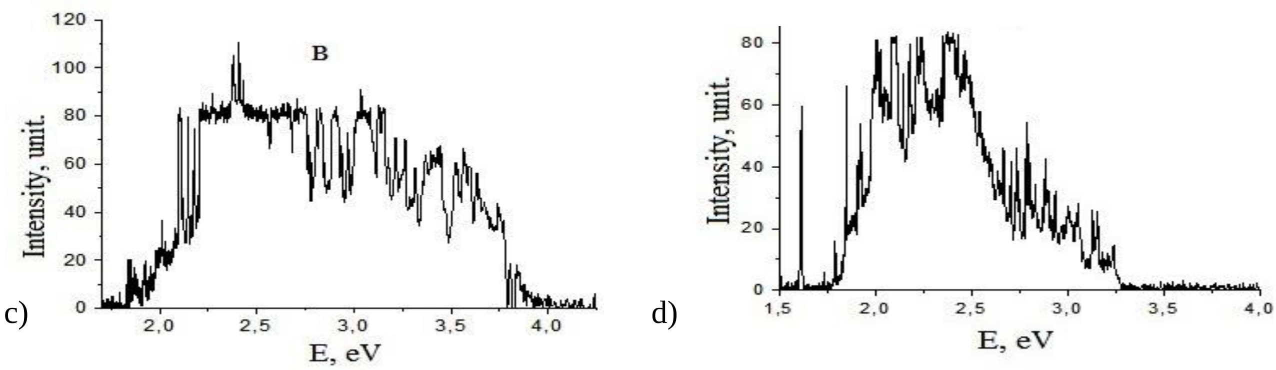


Figure 4. Radiation spectra of plasma emitted from a- quartz crystal, b - calcite, c - alaskanite, d - plagiogranite

The plasma spectra consist of several dozens of thin bands superimposed on each other. Tables of spectral lines were used to interpret the spectra. It turned out that the largest number of bands corresponds to the radiation of positively charged ions and atoms of elements that make up the crystal lattices of minerals that are part of the studied rocks [15,16]. Thus, the spectra of the plasma emitted from quartz corresponded to the radiation of atoms and positively charged silicon ions, the charge of which varied from 1 to 4, as well as atoms and positively charged oxygen ions. Their charge varied from 1 to 3.Positively charged ions and atoms of Si, O, K, Ca, Al and Na, which are part of the crystal lattices of quartz and feldspar, flew out of the granites [17]. Positively charged ions and Ca, C, and O atoms flew out of the calcite [18].

What is the reason for the different values of charges in ions? During the existence of the plasma, ions collide with electrons and with each other. This leads to a decrease in the charge of the ions down to zero, i.e. the appearance of atoms.

It is known that luminescence occurs during fracture, friction and impact with a striker on the rocks surface [19-21]. It turned out that the luminescence spectra arising from such effects differ from the spectra of the plasma caused by the shock wave. For example, figure 5 a, b shows the luminescence spectra of granite (alaskanite) and calcite under friction.

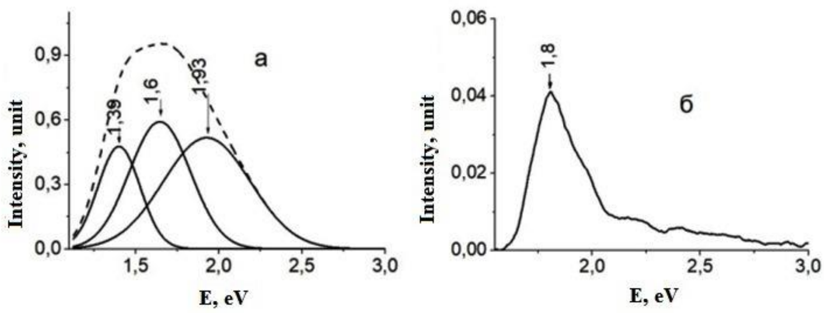


Figure 5. Radiation spectra of alaskite (a) and calcite (b) under friction

They consist of several superimposed bands that have a Gaussian shape. Thus, a maximum of 1.39 eV in the granite spectrum occurs when electrons pass from the conduction group into empty traps, which are formed when Si-O-Si and Si-O-Al bonds break in feldspar. The maximum of ~ 1.93 eV occurs during the relaxation of the electronic excitation of radicals $\equiv$Si-O^-formed during the breaks of Si-O-Si bonds in feldspar and quartz [21]. The maximum of 1.6 eV occurs when the electron excitation is relaxed in Fe^{3+} ions [21], which replace Si^{4+}ions in the crystal cells of feldspar. The maximum of 1.8 eV is attributed to the radiation of CO^{-2} radicals formed during the breaks of C-O bonds in calcite.

These data show that the mechanism of destruction under friction and impact differs from the mechanism of destruction under the influence of shock waves [22-23].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 4 October 2021 doi:10.20944/preprints202110.0047.v1

Discussion of the results and some features of the method in teaching materials science.

Measurements with nanosecond time of light, acoustic and electromagnetic radiation under pulsed impacts and the kinetics of the nucleation of microcracks in solid inhomogeneous materials (quartz, glass, concrete, granite, gneiss, marble) to determine their diagnostic parameters and the relationship between the characteristics of the structure and characteristics of mechanical properties (strength , durability) are important in their new "kinetic" understanding.

Modern trends in the development of diagnostic methods and the selection of these objects are due to the significant prevalence and importance of these types of solid natural inhomogeneous bodies. We have created a methodology and, with a resolution of 10 nanoseconds, conducted studies of the dynamics of natural vibrations and microcracks in rocks and polymer composites upon impact.

The question turned out to be debatable.Does the formation of cracks occur immediately afterwards - during the path of elastic waves [24-26]. This was due to the lack of direct methods for observing the formation and growth of microcracks. It is not known whether the waves of destruction previously found in glass exist in rocks.

The setup created made it possible to record the appearance of these emission phenomena and the growth of cracks with a nanosecond resolution. Figure 6 shows the spectrum of fractoluminescence of granite and broken chemical bonds in quartz [13].

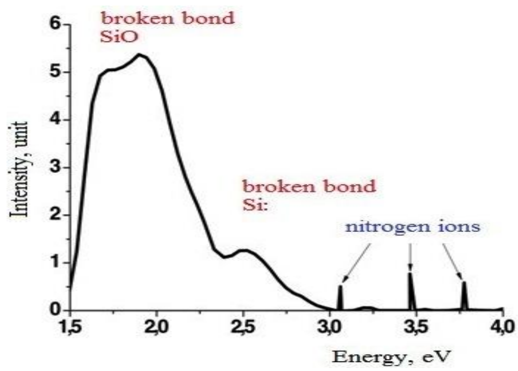


Figure 6. Spectrum of fractoluminescence of granite.

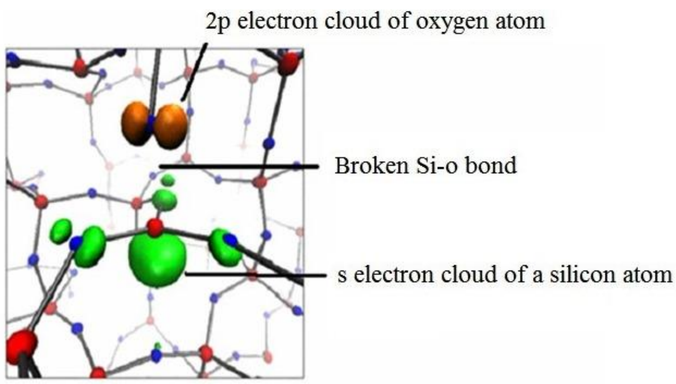


Figure 7. Disruption of the chemical bond in quartz

Presumably, conclusions are drawn on the composition of the plasma. First, the plasma spectrum consists of several tens of narrow (~ 0.5–1 nm wide) lines. They correspond to positively charged ions Si, O, K, Ca, Al, Na, Fe and Mn. Second, we can say that the surface of the granite evaporates into ions.

Conclusion

An installation and a method of simultaneous measurements of light, acoustic and electromagnetic radiation (FL, AE and EME) under pulsed effects on samples of heterogeneous

 doi:10.20944/preprints202110.0047.v1

material with nanosecond time resolution have been developed, which allow tracking the shape of shock and elastic waves, allowed us to study the difference between the mechanism of destruction on impact and the mechanism of destruction under the influence of shock waves, as well as some characteristics of the material under study. The speed of the time of passage of the wave to the other end, on which the piezoceramic sensor CTS-19 was installed, was equal to ≈ 5 km/s. A more accurate value of the velocity of 4.8 km / s was obtained as a result of the analysis of the shock wave interference in a granite sample. It turned out that it is equal to the velocity of the longitudinal acoustic wave in granite-4.8 km / s, at the same time, the crack growth rate cannot be higher than ~ 0.3 - 0.5 acoustic wave velocity. For example, the velocity of a transverse acoustic wave in granite is ~ 3 km / s, i.e. the maximum rate of crack formation is ~ 1.0-1.5 km/s, which is ~ 3-5 times less than the velocity of the longitudinal wave. This difference in speeds (~ 1.5 and 4.8 km/s) is the main reason for the difference in the mechanisms of destruction. Conclusion: with strong distortions of the crystal lattice, the intersection of the main binding and excited non-binding molecular orbitals in crystals is possible. This can lead to the decay of interatomic bonds into positively charged ions. We note that the plasma released from minerals also mainly consists of positively charged ions. This allowed us to assume that the shock wave, reflecting from the surface of rocks, distorts the crystal lattices of minerals so much that the interatomic bonds in them "disintegrate". As a result, the rock surface "evaporates" due to the departure of positively charged ions and electrons.

References

[1] A.A. Kozyrev, O.G. Zhuravleva, Yu.V. Fedotova, Clustering of seismic events in blow-hazard mines in the Khibiny massif, Fundamental and Applied issues of Mining Sciences. 2 (2015) 108-113.

[2] Vladimir Litvinenko, Pavel Cvetko, K. Molodtsov, The social and market mechanism of sustainable development of public companies in the mineral resource sector, Eurasian Mining, 1 (2020) 36-41.

[3] S.V. Lukichev, O.V. Nagovitsyn, I.E. Semenova, O.V. Belogorodtsev, Digital technologies for sustainable engineering in mining – The first step towards a “smart mine”, Mining Journal, 8 (2015) 53-58.

[4] V.N. Oparin, V.I. Vostrikov, O.M. Usoltseva, P.A. Tsoi, V.N. Semenov, Measuring system and test bench for monitoring the evolution of acoustic-deformation and thermal fields induced in the processes of fluid destruction of solids, Physical and technical problems of mining development. 3 (2015) 180-191.

[5] A.N. Besedina, N.V. Kabychenko, G.G. Kocharyan, Low-Magnitude Seismicity Monitoring in Rocks, Journal of Mining Sciences. 5 (2013) 20-36.

[6] J. Davidsen, S. Stanchits, G. Dresen, Scaling and universality in rock fracture. Phys. Rev. Lett. 98 (2007) 125502.

[7] V.S. Kuksenko, H.F. Makhmudov, Fracture in heterogeneous materials: experimental and theoretical studies, Russian Geology and Geophysics. 58 6 (2017) 915-923.

[8] D.A. Lockner, S.A. Stanchits, Undrained poroelastic response of sandstones to deviatoric stress change, Journal of Geophysical Research B: Solid Earth, 107 (12) (2002) 1-14.

[9] Kh. F. Makhmudov, V.V. Nosov, Method of non-contact measurement of small potentials for quantitative study of polarization during deformation of rocks, In the book (proceedings) of the VII International Scientific and Practical Conference "Innovations and prospects for the development of mining engineering and electromechanics" IPDME-2020. (2020) 700-706.

[10] V.V. Nosov, G.S. Yelchaninov, Influence of the inhomogeneity of the strength state on the acoustic emission of structural materials, Defectoscopy. 12 (2011) 55-66.

[11] G.I. Kocharyan, A. Lyakhov, S. Kishkina, Triggering tectonic earthquakes by Mining, Springer Nature Switzer land AG. (2019) 319-328.

[12] V.V. Adushkin, A.A Spivak. Geomechanics of large-scale blasts, Moscow, 1993.

[13] V.I. Vettegren, V.S. Kuksenko, I.P. Shcherbakov, Kinetics of emission of light, sound and radio waves from a single crystal of quartz after impact on its surface, Journal of Technical Physics. 81 4(2011) 148-151.
[14] E.N. Sher, N. I. Alexandrova, M.V. Aizenberg-Stepanenko, A.G. Chernikov, Influence of the hierarchical structure of block rocks on the features of seismic wave propagation, J. Min. Sci. 43 (6) (2007) 20-28.
[15] A.A. Eremenko, V.A. Eremenko, V.V. Petin, O.V. Shipeev, V.A. Stirts, Deformation processes in a rock mass at impact-prone deposits under the influence of dynamic loads, Mining information and analytical bulletin, 8 (2000) 136-139.
[16] I.P. Shcherbakov, V.I. Vettegren, R.I. Mamalimov, Dynamics of the nanosecond destruction of stressed granite during shock loading. Tech. Phys. 62 (2017) 1194–1196.
[17] A.M. Molodets, V.V. Avdonin, A.N. Zhukov, Yu.M. Shulga, Destruction of fullerite as a result of exposure to strong shock waves, Deformation and destruction of materials. 9 (2008) 2-6.
[18] I.P. Shcherbakov, V.I. Vettegren, R.I. Mamalimov, The influence of stress on electron emission initiated by a shock wave from a heterogeneous material (granite). Phys. Solid State. 59 (2017) 575–577.
[19] H.I.P Galvez, Analysis of the state of the art of blast-induced fragment conditioning, Minerals Eng. 24(2011) 1638 –1640.
[20] S. Gunasekaran, G. Anbalagan, S. Pandi, Raman and infrared spectra of carbonates of calcite structure, J ournalof Raman Spectrosc, 37 (2006) 892–899.
[21] J. Gotze, Application of cathodoluminescence microscopy and spectroscopy in geosciences, Microsc. Microanal. 18 (2012) 1270 - 1284.
[22] P.P. Ananyev, S.A. Goncharov, O.M. Gridin, A.S. Samerkhanova, Influence of physical, mechanical and dielectric properties of rocks on the effect of their softening during magnetic pulse processing, Mining information and Analytical bulletin (scientific and technical journal). 10 (2010) 41-46.
[23] V.L. Shkuratnik, G.V. Danilov, Investigation of the influence of stresses on the velocity of elastic waves in the vicinity of an elliptical mining, Physical and technical problems of mining. 3 (2005) 3-10.
[24] G.I. Kanel, V.E. Fortov, S.V. Razorenov, Shock waves in condensed-state physics, Phys. Usp. 177:8 (2007) 809–830.
[25] T.V. Popova, A.E. Mayer, K.V. Khishchenko, Numerical investigations of shock wave propagation in polymethylmethacrylate, Journal of Physics: Conference Series. 653(2015) 012045.
[26] K.V. Khishchenko, A.E. Mayer, High- and low-entropy layers in solids behind shock and ramp compression waves, International Journal of Mechanical Sciences. 189 (2021) 105971.