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Experimental research of the influence of the strength of ore samples on the parameters of an electromagnetic signal during acoustic excitation in the process of uniaxial compression

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Abstract. Parameters of electromagnetic responses (EMRe) generated during uniaxial compression of rock samples under excitation by deterministic acoustic pulses are presented and discussed. Such physical modeling in the laboratory allows to reveal the main regularities of electromagnetic signals (EMS) generation in rock massive. The influence of the samples mechanical properties on the parameters of the EMRe excited by an acoustic signal in the process of uniaxial compression is considered. It has been established that sulfides and quartz in the rocks of the Tashtagol iron ore deposit (Western Siberia, Russia) contribute to the conversion of mechanical energy into the energy of the electromagnetic field, which is expressed in an increase in the EMS amplitude. The decrease in the EMS amplitude when the stress-strain state of the sample changes during the uniaxial compression is observed when the amount of conductive magnetite contained in the rock is increased. The obtained results are important for the physical substantiation of testing methods and monitoring of changes in the stress-strain state of the rock massive by the parameters of electromagnetic signals and the characteristics of electromagnetic emission.

1. Introduction

Extraction of minerals by mining method with increasing depth inevitably leads to the growth and redistribution of the stress-strain state (SSS) of the rock massif. With explosive methods of mining, the rate of SSS change increases. Probability of damage to the mine field, equipment and maintenance personnel increases. Electrometric, seismic and acoustic methods of monitoring are used to monitor the state of the massive. One of the most promising methods for continuous monitoring of the development of geodynamic events is the method based on mechanoelectric transformations in rocks with simultaneous generation of electromagnetic signals.

Laboratory investigations of changes in the electromagnetic signals parameters of various types of rocks subjected to uniaxial compression are important for understanding the preparation and development of destruction processes in mines when the massive SSS is changing. In this regard, electromagnetic radiation, arising from the change in the mechanical effect on rock, is the subject of study in many countries of the world in order to control and monitor geodynamic manifestations. Registered signals carry valuable information on the mechanisms and sources of mechanoelectric transformation in a variety of materials such as crystals [1], composite materials [2], plastics [3–5],



rocks [6–9], ice [10, 11] and metal [12]. The study of EMS parameters allows to know the dynamics of formation and propagation of cracks in real time. EMS is recorded in a frequency range from a few Hertz to a few megahertz.

Measurements, made on rock samples, show that EMS is a good precursor for determining the maximum strength of samples [13]. This can be used to monitor changes in the stressed state of the rock mass [13–17]. The basis of these studies is an increase in electromagnetic activity during the pre-destruction stage experimentally proven on rock samples [18]. However, the process of mechanoelectric transformations occurs at all stages of deformation, from the moment of the initiation of microcracks to failure. Depending on the stage of deformation, EMS characteristics have their own peculiarities [19, 20].

The main attention of researchers is drawn to EMS sources. It was found in [21, 22] that the origin of EMS corresponds to the creation of cracks in time. Simultaneous recording of EMS and acoustic signal (AS) was performed during the monotonous loading of the granite samples. It is established that EMS is associated with the creation or growth of microcracks. It was also observed that the EMS appears several microseconds before the generation of the AS. The same lag of the AS from the EMS was noticed in [5]. This delay, according to the authors, is due to the fact that the EMS propagates at the speed of electromagnetic waves. Also, this effect can be used to determine the locations of cracks.

Creation of cracks is accompanied by a redistribution of electric charge due to weakened chemical bonds, noted in [23, 24]. Electric charges create dipole moments. The vibrations of the beads of the cracks change the configuration of the dipoles, and, consequently, create electric and magnetic moments. This confirms the dipole mechanism of EMS generation in the process of mechanical action on rocks.

The study of model transparent samples made it possible to determine the sequence of crack initiation, their growth and interactions. Investigations of EMS in [25, 26] were carried out during compression of rock samples and model samples. It was established that, just as in [18], the EMS duration changes at certain stages of the load.

EMS measurements of hard coal, gray dolomite, sandstone and magnesite samples, subjected to uniaxial compression presented in works [27]. Measurements show that EMS is a good precursor for determining the maximum strength of materials and is suitable for determining the state of tension in a rock massif. This was demonstrated in laboratory tests on coal samples, where EMS and AS were observed immediately before the sample failure.

In work [15] it was shown that the generation of EMS in rocks is caused both by the effects associated with the formation of microcracks, and by the passage of acoustic waves through them, which cause vibrations of charged defects. In this case, as will be shown below, the influence of the material properties on excitation of EMS by acoustic waves is similar to the effect of material properties on the parameters of EMS, which is excited by mechanical action. In the presented work, excitation of EMS was created during the passage of AS at various stages of the samples stress-strain state under uniaxial compression.

In connection with this, the aim of this work is to determine the influence of the petrographic properties of rock samples on the parameters of the EMS excited by a deterministic acoustic pulse during uniaxial compression.

2. Objects of research

The test samples of rock, represented by magnetite ore, were selected at the Tashtagol iron ore deposit (Russia, Western Siberia). Samples were cut from the core material and had the shape of a cylinder 42 mm in diameter and 80 mm high. Before carrying out the research, the end faces of the sample were ground to a plane parallelism. This ensured the alignment of the sample and the press plates and the uniformity of the load distribution on the end surface of the sample. Table 1 shows the petrographic data of the investigated samples of iron ore.

Table 1. Petrographic data of the test samples.

Magnetite ore samples							
Sample number	Sample mass, g m_o	Sample density, g/cm ³ ρ_o	Sample volume, cm ³ V_o	Magnetite volume in the sample, cm ³ V_{mag}	Magnetite mass in the sample, g m_{mag}	Magnetite content in the sample, %	Ultimate compressive strength, kN P_{ult}
4	456	4.15	110	59	302	66	167
5	399	3.66	109	33	172	43	261
7	384	3.52	109	27	137	36	120
10	401	3.68	109	34	177	44	273
13	434	3.98	109	50	256	59	131
16	463	5.45	104	70	362	78	213

The mass of magnetite in the samples was calculated by the equation:

$$m_{mag} = \rho_{mag} \cdot V_o \cdot \left(1 - \frac{(\rho_o - \rho_{mag})}{(\rho_{encl} - \rho_{mag})} \right)$$

where m_{mag} – mass of magnetite; ρ_{mag} – density of magnetite; V_o – volume of the sample; ρ_o – the sample density; ρ_{encl} – density of the enclosing rock.

3. Research Methodology

Experimental studies were carried out on a stand, the block diagram of which is shown in Figure 1. Uniaxial compression was carried out on a press with a movable (1) and supporting (2) plates, developing a force of up to 50 tons and an integrated force measuring system (8). The analogue signal of the load-measuring system and the values of the longitudinal deformation arising during the compression of the sample were recorded in the computer (PC) memory (9) using a special program. A deterministic acoustic signal was introduced to the sample through an acoustic contact (mineral oil) using a piezoelectric transducer (PET) (3). The acoustic signal, passing through the sample, was recorded with a piezoelectric sensor (PES) (7). A differential capacitive electric field sensor with an integrated power amplifier (EFS) (6) received the electrical component of the EMS generated by the sample during the passage of the acoustic signal and then recorded the signal using a multifunction digital input / output board BNC-2120 (5) for further analysis of its parameters. A subsubsection. The paragraph text follows on from the subsubsection heading but should not be in italic.

3.1. Acoustic stimulation

In experiments, the source of the deterministic pulsed acoustic signal was PET made on the basis of piezoceramics ZTS-19 (lead zirconate-titanate). For such a piezoceramics, the coefficient of electromechanical coupling is 0.523 [28]. The transmitter was supplied with rectangular pulses, which were obtained using a high-voltage generator (HVPG). The duration of high-voltage pulses can vary within 10-6-10-4s. In this case, the value of the high-voltage pulses can vary from 100V to 800V. A wide-band PES, also based on the ZTC-19 [29], was used to record the acoustic signal transmitted through the sample. The signal, generated by the similar in construction and characteristics receiving piezoelectric sensor, was applied to the Tektronix TDS2024B oscilloscope. In the experiments described in this paper, the duration and voltage of the HVPG pulses were 5 μ s at the excitation voltage of the 800 V.

3.2. Recording of an electromagnetic signal

The acoustic signal from a piezoelectric transducer passing through a sample generates EMS, which is recorded using an electric field sensor, mounted 2 mm from the sample. The sensor has two copper plates that convert the electrical component of the electromagnetic field into a voltage supplied to the differential input. The high-impedance differential input of the sensor is made on precision amplifiers. The signal is differentiated to exclude the noise signal from the surrounding space, then the purified signal is amplified 100 times. Enhanced by the EFS, it is fed to the second input of the Tektronix TDS2024B oscilloscope. From the oscilloscope, the EMS is recorded in the PC.

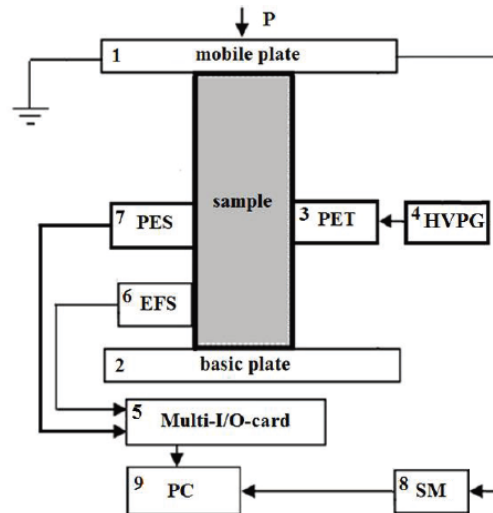


Figure 1. Block diagram of an experimental setup for recording electromagnetic signals under uniaxial compression of samples and deterministic acoustic action.

4. Experimental studies

Uniaxial compression of samples on the press was carried out stepwise. The loading rate was 0.3 kN/s. From the beginning of loading, after every 30–40 kN, the loading was stopped and the force was maintained at the reached level, thus it was possible to produce an acoustic impact. And so on until the sample failure. Depending on the samples strength, the number of steps were from 4 to 10, i.e. the stronger the sample, the more steps. At these levels, deterministic acoustic excitation was carried out. Figure 2 shows a typical loading curve showing stepped uniaxial compression of sample before failure.

Figure 3 shows the summary sequence of oscillograms of the change in the amplitude of the electromagnetic response (EMRe) under acoustic action at various stages of the sample loading. The numbering steps of compression are also shown in Figure 3.

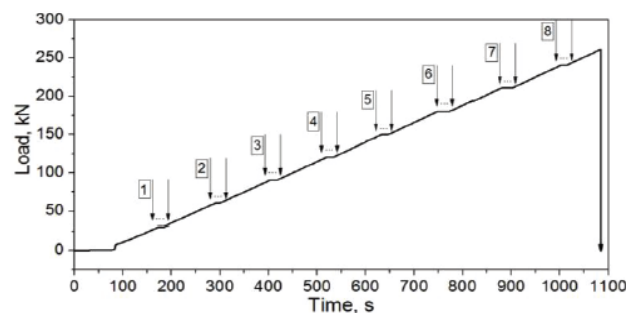


Figure 2. Typical loading curve for samples.

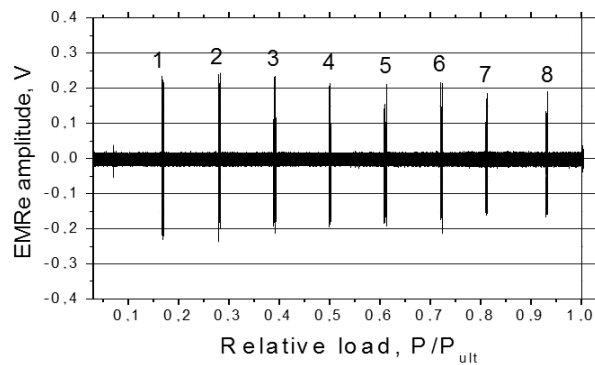


Figure 3. Dependence of the EMRe amplitude by the acoustic effect on the loading stages by uniaxial compression for sample No. 5. The stages are marked with numbers.

It can be seen that the amplitude of the electromagnetic response to the acoustic effect changes at all loading stages. To determine the amplitude-frequency characteristics of the EMS at each stage of loading, a calculation was made using a fast Fourier transform (FFT). In Figure 4 shows analogue EMRe and their amplitude-frequency characteristics for sample No. 16, obtained during the experiment. For this sample, excitation was carried out at seven stages with a load interval of 30 kN. The ultimate strength P_{ult} was 213 kN.

Similar results were obtained for the remaining samples. The Figure 4 shows the results obtained for the five stages (1, 3, 4, 5 and 7) of keeping under load. These stages corresponded to the relative load of $P / P_{ult} = 0.14, 0.28, 0.56, 0.7$ and 0.98 . The load is indicated in the upper right corner on the analog signal pictures. Analyzing the results presented in Figure 4, it can be said, that the amplitude and type of EMRe are changing with the increasing load. The spectral components of the EMRe are also changing their amplitude as the load increases.

5. Discussion

It is known, that rocks have pores filled with gas and mineralized liquid, and existing cracks increase in the process of loading and new ones appear with different orientations and sizes [30]. These violations of the samples homogeneity lead to the formation of double electrical layers (DEL). Compression and expansion of a rock, containing DEL, lead to a transformation of a part of the acoustic energy to electromagnetic energy. In addition, rocks consist of different minerals, which have different dielectric permeability and electrical conductivity. In addition, rocks consist of different minerals, which have different dielectric permeability and electrical conductivity.

Minerals are differently oriented in space in the process of their formation and growth. In [31], when studying the reaction of DEL to ultrasound, it was found that if ultrasound exposure to rocks with an intensity of 10^{-3} W/m^2 and above, than the DEL will generate EMS. In this case, the change in the DES parameters leads to an adequate change in the EMS spectral composition.

The test samples had differences in the texture structure, cracks of different orientation and sizes were observed, healed and unhealed with calcite. As a result, the heterogeneity of composition, inclusion, defectiveness lead to an increase in the number and extent of double electrical layers, and hence to an increase in the number of dipoles emitting electromagnetic pulses. When this sample is acoustically influenced, this circumstance facilitates the active transfer of mechanical energy into the energy of the electromagnetic field. The dependences of the peak-to-peak value on the relative strength calculated as P / P_{ult} were constructed to determine the regularities of the change in the amplitude of the EMRe. Here P is the current load value on which the acoustic effect was carried out, and P_{ult} – the load of the sample failure. Figure 5 shows the dependences obtained for sample No. 16 and Figure 6 for sample No. 5

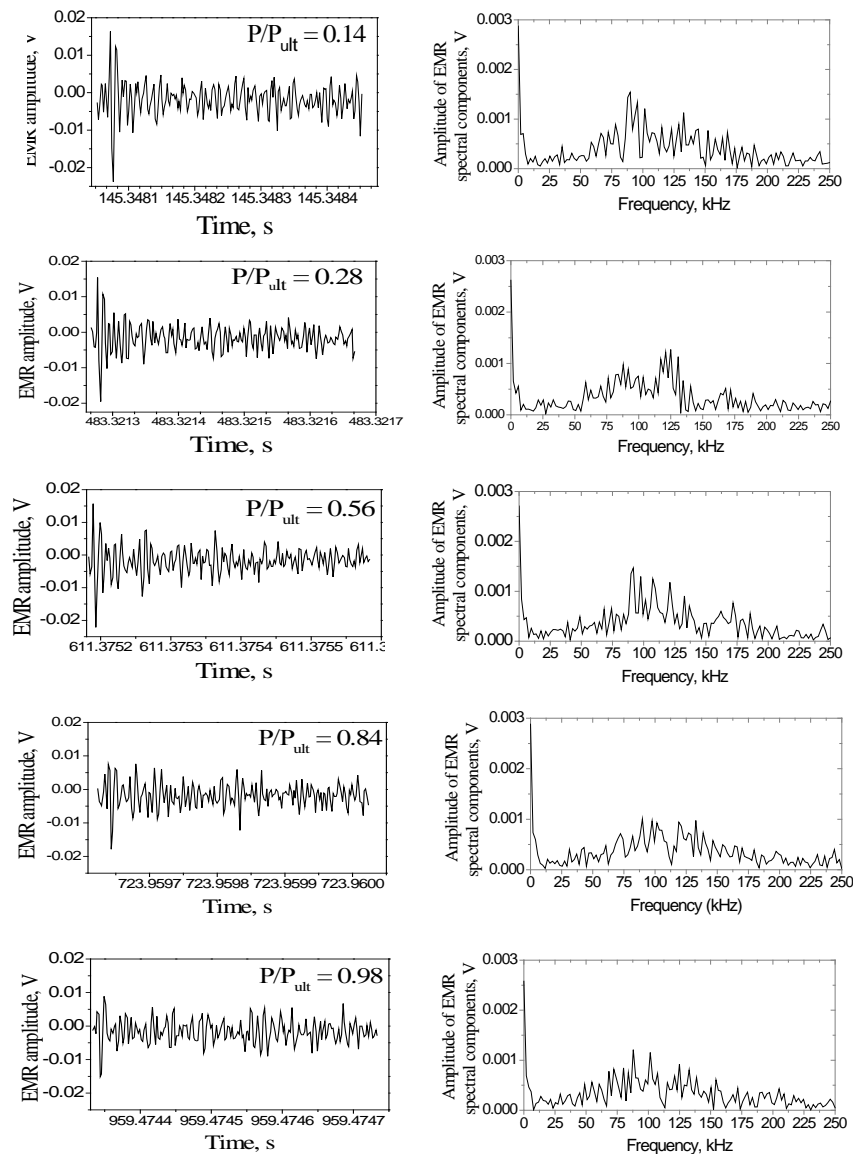


Figure 4. Analog electromagnetic responses and their amplitude-frequency spectra at the five excitation stages of sample No. 16.

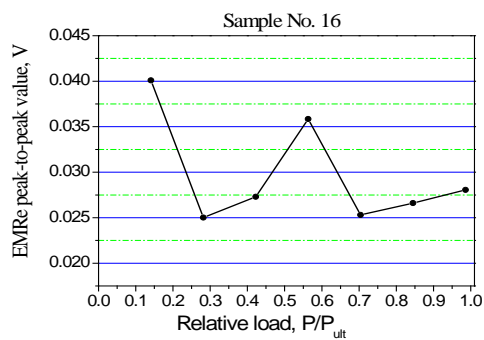


Figure 5. Dependence of the EMRe amplitude from uniaxial load for sample No. 16.

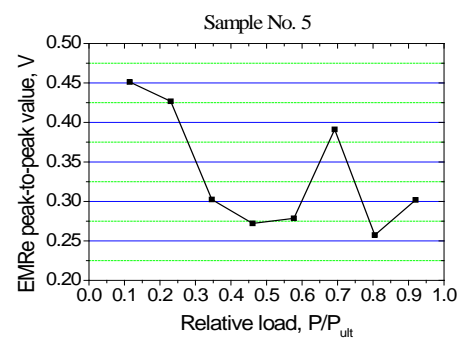


Figure 6. Dependence of the EMRe amplitude from uniaxial load for sample No. 5.

Analyzing the results, it should be noted that no matter how many times acoustic excitations are made, the trend of the EMO amplitude variation remains. The amplitude decreases from the beginning of the loading for the dependences shown in Figures 5 and 6. Since the strength of these samples was different, the decrease for sample No. 16 was noted at a relative strength of 0.28, and for sample No. 5 the reduction continued to a relative strength of 0.5-0.6. The increase in the amplitude of the EMO amplitude is observed for sample No. 16 at a relative load of 0.56, and for sample No. 5 at a relative load of 0.68. This relative load for the samples corresponds to the formation of a failure focus [32]. Then the amplitude decreases and, starting at a relative strength of 0.7–0.8, the amplitude of the EMO begins to grow until the samples reach ultimate strength and fracture.

Some difference in the EMRe amplitude of samples with different contents of magnetite can be explained by the fact that the ultimate strength of these samples is different. It was 213 kN for sample No. 16, and 261 kN for sample No. 5. These samples differ by 50 kN for ultimate strength. It is known that the strength of real rock samples is greatly influenced by factors such as structural and texture structure, the presence of inclusions with different strength, pores, healed and untreated cracks. And the more inhomogeneities, the lower the ultimate strength, and hence the more sources of mechanoelectric transformations. However, it is seen from the experimental results shown in Figure 5 and 6 that sample No. 16, with a lower ultimate strength of 213 kN, has the less EMRe amplitude by an order than the sample No. 5, with the ultimate strength of 261 kN. This became the basis for analyzing the effect of the sample composition on the EMRe characteristics. It is known that the presence of piezoelectric quartz [33,34] and electrically conductive minerals such as pyrite, chalcopyrite, galena and graphite exerts a significant influence on the EMS amplitude of dielectric samples, including samples of magnetite ore. Quartz clusters in magnetite ore samples under the influence of mechanical forces (acoustic wave and loading) are capable of inducing an electric charge, which causes a large amplitude of EMRe. The higher the content of quartz in the sample, the higher the EMRe amplitude. The polarization effect is important for electrically conductive minerals of pyrite and chalcopyrite.

At the initial stage of loading, the sample becomes compacted due to presented cracks and pores. This causes the displacement of the gravity centers of unlike charges and as a result, electric dipoles arise. Their formation and relaxation are associated with the motion of charged particles, i.e. with the current. At the stage of consolidation of failure focus and formation of a main rupture ($P / P_{ult} \geq 0.7$), the current decreases, since the process of crack growth prevails at this stage. The interval 0.5–0.7 of P/P_{ult} is distinguished by the fact that the charged defects directed toward the newly formed microcracks, the contacts of grains and the fragments of inclusions of different minerals, directed by the applied static stresses. New DELs form or existing ones recharge. As a result of oscillation of these layers by any method, the intensity of EME and the amplitude of EMS will increase, which we observe in the experiment. The enlargement of failure focus and the formation of cracks in the separation lead to a change in the distance between their shores and to the partial destruction of the double electrical layers, which leads to a decrease in the amplitude of the EMS [32]. This is what we observe in our experiments at a load of 0.7–0.8 for both samples.

The dependences in Figure 7 were plotted for three samples of magnetite ore to determine the dependence of the peak-to-peak value on the relative strength for samples of different petrographic composition. The percentage of quartz (SiO₂), pyrite (FeS₂) and magnetite (Fe₃O₄) for each sample was indicated. The percentages of these minerals in the samples were obtained using an X-ray powder diffractometer ARLX'TRA [35]. The results of measuring the EMRe parameters of sample No. 13, whose ultimate strength was 113 kN, were added for comparison to the results of samples No. 5 and No. 16 (Figures 5 and 6).

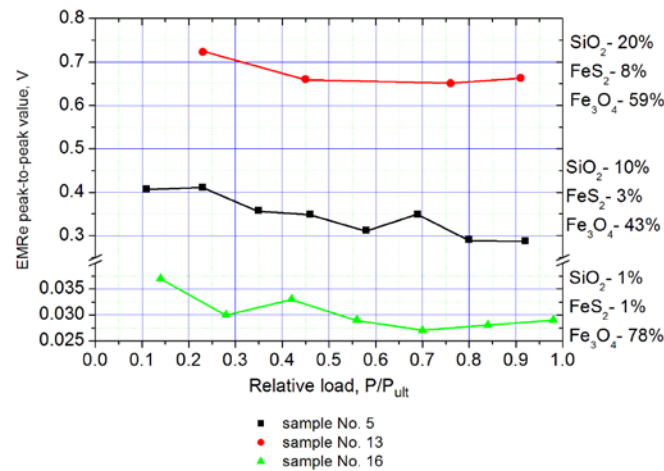


Figure 7. Dependence of the EMRe peak-to-peak value on the relative load for samples with different content of quartz and conducting minerals.

Analyzing Figure 7, it should be noted that a high content of magnetite (Fe_3O_4) 78% and 1% quartz (SiO_2) were detected for sample No. 16, whose ultimate strength was 213 kN, and the EMRe amplitude is an order of magnitude lower than for sample No. 5, which has almost half the amount of magnetite – 43%, but a higher content of quartz (SiO_2) – 10%, and sample No. 13, which has 20% quartz and 59% magnetite in its composition. For a low-strength sample No. 13, the amplitude of the EMRe is the highest. And this is due to the fact that he has a large content of quartz.

Thus, it can be concluded that the EMRe amplitude for samples with different contents of magnetite ore will be determined by the content of mineral inclusions of quartz and pyrite. When the quartz is close in quantitative content in the samples of magnetite ore, the amplitude of the EMRe will be determined by the amount of magnetite. One possible explanation for the observed effect is the loss of EMS energy in a conducting medium. Magnetite, as is well known, has an appreciable electrical

conductivity and its EMS absorption coefficient of can be written as $\beta \approx \sqrt{\frac{\pi\mu}{\rho}} f$, where μ – is the magnetic permeability; ρ – is the resistivity; f – is the frequency. For magnetite at a frequency of 1 kHz, $\rho = 10^3 \Omega \cdot \text{m}$ and $\mu = 10^5$. Then the absorption coefficient for a frequency of 1 kHz is $\beta = 500 \text{ m}^{-1}$. At a frequency $f = 10 \text{ kHz}$, $\beta = 1700 \text{ m}^{-1}$. The change in the amplitude of the harmonic at a frequency of 1 kHz is: $\frac{E}{E_0} = \sqrt{e^{\beta x}} \approx 0.1$, where E – is the electric field strength.

For a frequency of 10 kHz, this ratio is equal to $\frac{E}{E_0} = \sqrt{e^{\beta x}} \approx 2 \cdot 10^{-4}$, i.e. the amplitude of the

harmonic more than 10 kHz will decrease by 1000 times than the 1 kHz harmonic.

There is another possible explanation for the correlation of the EMS amplitude and their conductivity in the case of acoustic excitation of rocks. When an acoustic pulse is applied and the acoustic wave propagates the total effective charge of the sample changes as a result of mechanoelectric and acoustoelectric transformations. The magnitude of this charge will depend on the conductivity of the rock and will basically determine the drain time or charge compensation. As a result, the effective charge will decrease, and the electric field strength also decreases. Oscillations in the resulting acoustic field lead to a change in the electric field, and, as a consequence, to the occurrence of displacement currents. As a result of these oscillations, EMS is recorded with an amplitude that reflects the conductivity of the rock samples. The assumption is confirmed by the results of studies with acoustic effects on samples with different contents of magnetite. The amplitude of the EMRe from sample No. 16 is about of 30-35 mV, and for sample No. 5 – 3-4 mV.

6. Conclusions

As a result of the conducted studies, it was established that the sensitivity of electromagnetic signals to defectiveness with multiple passage of an acoustic excitation wave through a monitoring object makes it possible to track the evolution of accumulation of defects in conditions of a stress-strain state.

With an increase in the amount of a high-conductivity mineral contained in rocks, such as magnetite, the amplitude of the analog electromagnetic signal and the amplitude of the spectral components of the electromagnetic response are reduced in the uniaxial compression process, and, consequently, when the stress-strain state of the rock samples changes. The amplitude-frequency spectrum of electromagnetic responses of samples with a large magnetite content is characterized by ruggedness and wide limits.

The presence of quartz in samples of magnetite ore leads to an increase in the amplitude of the EMRe under acoustic excitation during uniaxial compression.

Thus, the physical modeling of the influence of the ore samples strength and petrophysical composition on the parameters of the electromagnetic responses, generated during acoustic excitation in the uniaxial compression process, promotes nondestructive testing and monitoring methods of the change in the stress-strain state of rock samples before their failure by parameters of the electromagnetic signals.

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