DNIPRO UNIVERSITY
of TECHNOLOGY
1899

Mining of Mineral Deposits
ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)
Journal homepage http://mining.in.ua
Volume 12 (2018), Issue 3, pp. 45-55

UDC 622.73: 55

https://doi.org/10.15407/mining12.03.045

THEORETICAL BACKGROUND OF ROCK FAILURE AT HYDRAULIC SEAM FRACTURE AND AFTEREFFECT ANALYSIS

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ABSTRACT

Purpose. Theoretical substantiation of the methodological foundations of possible effects and aftereffects identification of the hydraulic seam fracture (HSF) technology.

Methods. The research structure and procedure includes: studying the power engineering aspect of the rock failure, the acoustical wave effects; thermodynamic analysis of rock failure, analysis of surfaces mechanoactivation at rock failure and aftereffect of the primary pore space self-development at the HSF due to the Rebinder's effect.

Findings. It was established that among the fundamental consistent patterns that determine the formation and development of the HSF technology aftereffects during formations mining, are the methodological provisions and criteria for failure parameters prediction and grinding effects, namely: the average and local energy density of geoenvironment destruction, efficiency of grinding, the average particle and pore size, the specific surface area, the specific energy consumption per unit of the resulting surface. The connection between the parameters of the acoustic wave and the size of the fractures, which forms the basis of the acoustic emission (AE) method, is experimentally confirmed.

Originality. It is established that the database for evaluating the expected fracture effects in the working zone of the HSF is: AE activity, specific acoustic radiation, spectrum of signals, characteristic amplitudes under the condition of physical modeling on the model samples of the geoenvironment behavior. It is shown that the critical state of a substance corresponding to the beginning of failure at the microlevel should be considered from the standpoint of thermodynamics as a phase change (evaporation, sublimation) near the critical point, based on the temperature critical values and the specific energy of the phase change. The presence of surfaces mechanoactivation in the rock failure is experimentally proved. The hypothesis concerning the rock pore space development aftereffect during hydraulic seam fracture due to the Rebinder's effect is presented.

Practical implications. It is proposed to size up the degree of geoenvironment destruction in the process of the HSF by the K_d parameter, which is equal to the product of the maximum amplitude of acoustic signals on the total acoustic activity of the destruction zone. It is established that the conditions for rock failure at the HSF are determined by the relationship between the rock pressure P and the volume energy density W of the failure. It is shown that the level of surfaces mechanoactivation can be estimated by adsorption characteristics – the adsorption potential and the pH of the newly discovered surfaces.

Keywords: *hydraulic seam fracture, acoustical waves, thermodynamic analysis, mechanoactivation, the Rebinder's effect, acoustic emission, potentiometry, pH measurement*

1. INTRODUCTION

In recent decades, for the intensification of the fluids extraction (oil, natural gas), mainly from tight stratum, the hydraulic seam fracture (HSF) technology or shortly "frecking" is being actively implemented in the world. It involves the formation of induced fractures in the formation by gradual pumping into it a special liquid under high pressure – mainly water or hydrocarbon liquid with a certain content of sand or other proppant and thickeners. In this way, forced pore space in the formation substantially increases its current capacity and provides an intensification of the fluid entry into the seam after the end of the hydraulic fracture process. The frecking technology is at the basis of extraction, in particular, of shale oil and gas (Gandossi & Von Estorff, 2015; Gandossi & Von Estorff, 2016). As of 2012, 2.5 million people are involved in

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freking operations at oil and gas wells worldwide, including 1 million in the United States (King, 2012). According to the U.S. Department of Energy (DOE), the volume of "technically extractive" world shale gas reserves in 41 countries of the world is over 200 trillion m^3 (Shcherba, 2013). At the same time, the resources of the "traditional" natural combustible gas in the world are estimated to be 327 – 546 trillion m^3 (Biletskyi, 2004; Biletskyi, 2007; Biletskyi, 2013), which illustrates the significance of the fluid extraction problem using the HSF technology.

However, the application of the HSF technology, according to many studies and expert assessments, has environmental risks. So, the European Parliament's study on "The Impact of Shale Gas and Shale Oil Extraction on the Environment and Human Health" has shown that 58 of the 260 substances used in the process of fracking have one or more hazardous properties (Lechtenböhmer et al., 2011). Which includes, 6 the highest hazard substances, according to the European Commission classification, 38 are classified as hazardous toxins, 8 substances are classified as known carcinogens, 7 are classified as mutagenic, 5 – as having an effect on reproductive processes.

In the conclusions of another study "Chemicals used for hydraulic fracturing" by the US House of Representatives on energy and trade, carried out in 2011, it was noted, firstly, that this analysis was the most comprehensive national assessment of chemicals types and volumes, which were used in the process of hydraulic fracturing; secondly, in 2005 – 2009, the 14 leading companies in the field of the HSF in the United States used more than 2500 hydro-dispersive products (reagents) containing 750 compounds and more than 650 of them contained chemicals known to be potentially human carcinogens or introduced to the list of dangerous air pollutants (U.S. House of Representatives, 2011).

In addition to these estimates, there are many more local studies and observations that contain both arguments for and against the HSF technology, which basically correlate with the above arguments of the HSF technology significance and its risks.

Environmental risks of the HSF technology are mainly due to the probability of earthquakes, as well as the penetration of chemicals used in this technology in the aquifers and above – up to the surface of the earth. Detailed studies (Skoumal, Brudzinski, & Currie, 2015) have shown that earthquakes may in some cases be caused by fracturing, but this effect is not widespread, and the magnitude of earthquakes is small – about 2 – 3 on the Richter scale.

The reasons for the chemical substances migration in the rock massif are different, in particular, earthquakes with low magnitude caused by drilling wells and conducting HSF (according to Shcherba, 2013) thousands of micro-earthquakes are observed), natural and newly formed fracturing of rocks, capillary suction (Birdsell, Rajaram, Dempsey, & Viswanathan, 2015), etc. The decisive influence of the geological environment characteristics on the ascending migration phenomenon, its speed and time frame from the location of the HSF through the indigenous rocks to shallow aquifers are estimated. Myers (2012) suggested that such migration could occur in less than 10 years. In work (Flewelling & Sharma, 2013), the time frame for such migration is estimated at over 100 years. The presence of a hydraulic connection between black shales and shallow aquifers is also noted by Rozell & Reaven (2011) and Warner et al. (2012).

The authors (Flewelling & Sharma, 2013) have investigated the factors that control the fluid flow at a depth. In particular, they considered the fluid ascending migration of the HSF and salt solutions in black shales of the United States, depending on the permeability of the higher-layers of rocks and main gradients, since these variables, in their beliefs, determine the direction and magnitude of the vertical migration flows of fluids in the fractures. It is marked by a much larger (in order of magnitude) horizontal migration compared with vertical migration. The multifactor of the liquid phase migration process, which is particularly affected by the size distribution of the flakes is shown (note that the density of the disperse materials composition can be estimated, for example, by the Fuller criterion), the voltage in the seam, the degree of its fluid saturation, the cementation processes. These factors often cause a decrease in the permeability of the collector layer by a huge ratio. Multiple fluids (e.g., oil, natural gas, and water) in pore space also significantly reduce permeability. The prevalence of fine-grained rocks (shale, siltstones and argillites) and the bedded structure of sedimentary basins limits the vertical permeability of underlying rocks above black slates.

Particular attention deserves empirical studies of vertical fracture growth during the stimulation of HSF. Studies for US slate conditions (Barnett, Eagle Ford, Marcell, Woodford and Niobrara) are performed by Fisher & Warpinski (2011) fix the maximum height of fracture growth (the upper boundary of rock failure) during each recorded HSF stimulation, usually about 100 m from the place of fracture pressure application. At the same time, the HSF was implemented at a depth of 1500 – 2500 m. In different basins, the height of fractures varies slightly, which obviously depends on the geological situation, and the maximum recorded fracture height is just over 500 m (Davies, Mathias, Moss, Hustoft, & New-port, 2012). Note that the "primary fracture" height was investigated – immediately after the HSF. Its development has not been monitored.

Another important aspect of pore space development at the HSF is fracture-propagation pressure. It is established that besides the fracture network (that is, only outside the fracture surface or in the extremes of fracture-propagation), the change in seam pressure depends on the properties of the rocks and fluids that control the pressure propagation. The natural positive pressure gradients (which are a necessary condition for the bottom-up fluid flow) occur due to topographical factors or excess relic pressure at the depth (Flewelling & Sharma, 2013).

The performed review and analysis of the problem of the HSF effects and aftereffects shows its relevance. In this case, the existence of empirical research and analytical works create an information base for forecasting (in particular, through modeling) the pore space extension (the fracture development), as well as the fluids ascending migration in the rock massif due to the HSF. At the same time, it should be noted the lack of research on the conditions for the HSF rock failure and the problems of the pore space development aftereffects in the hydraulic seam fracture. In the above-mentioned studies there is no theoretical analysis of the rock failure process in the HSF, the possibilities of monitoring its kinetics, evolution and forecast of the HSF technology practical application consequences. The dynamics of fracturing in the rock massif at the HSF is practically unexplored. One of the possible mechanisms for such "self-development" of rocks fracturing in the presence of fluids is, as is known, the manifestation of the Rebinder's effect (Andrade & Randall, 1949; Goryunov, Pertsov, & Summ, 1966; Malkin, 2012).

The purpose of the work is theoretical substantiation of the methodological foundations of possible HSF technology effects and aftereffects identification. To achieve this purpose, it is necessary to consider:

– the rock failure energy aspect, in particular, the conditions for the formation and development of fractures in the formation; the effect of acoustic radiation, the sources of which are the cells of rocks grinding;

– the rock failure thermodynamics, in particular, the process of dispersion as a phase transition (evaporation, sublimation) near the critical phase point;

– the effect of surfaces mechanoactivation in the rock failure HSF and its expected technological effects (aftereffects);

– the Rebinder's effect is the disjoining pressure of the molecules, occurred along the upper reaches of the fractures, in particular the surfactants molecules at the HSF and also the cooling of tiny fractures in the size of several lattice atom in the water environment and, thus, preventing their "healing" (aftereffects of pore space self-development as a result of HSF).

Thus, the authors set the task of applying the modern theoretical level of the rock failure science to establish the conditions for the rock failure HSF and the justification of the HSF technology aftereffects. At the same time, it is important to analyze the patterns of the mechanism and the effects of the geological environment destruction during the formations development.

2. METHODOLOGY

The structure and sequence of the research includes: studying the rock failure energy aspect, the effects of acoustic waves; thermodynamic analysis of rock failure, analysis of surfaces mechanoactivation in the rock failure and aftereffects of pore space self-development as a result of HSF due to the Rebinder's effect. Applied: acoustic emission method, potentiometry, pH measurement. The original wideband acoustic sensor of V.M. Bovenko design was used in the acoustic emission method (Bovenko, 1990). The loading of model samples during their destruction was carried out at the original installation of A.D. Alekseev design (Donets'k Physical-Technical Institute of the National Academy of Sciences of Ukraine) (Gorobets, Bovenko, & Dubrova, 1995). The range of samples pressure loads in the studies: 0 – 150 MPa. Acoustic emission was evaluated by the activity of acoustic signals fixed by the sensor in the range 0 – 105 s^{-1} and specific acoustic radiation in the range of 0 – 10^{10} signals per m^3. In research using the potentiometry method the original method was developed by (Gorobets, Yur'yevskaya, Korsakov, & Vdovina, 1986). The adsorption potential of the serro-ferri system was detected in the presence of the test material joint hinge (15 mg). Patch clamp range is 550 – 0 mV. Test duration is 6 – 12 min, taking into account the buffer features of the system. At the same time, the pH parameter was recorded in the range 2.6 – 3.1.

3. RESULTS AND DISCUSSION

Microstructural dissipations are developed in activated structural damages in the material operation modes with accelerated accumulation of energy (seismic, tectonic processes, HSF). In particular, there are irreversible changes in the hanging layer consistence, creepages, fracture propagation, phase polymorphic changes, chemical reactions, material heating, local penetration of occluded molecules of liquids through fractures (Rebinder's effect), abnormal changes in the physical properties of a substance, as shown in previous papers (Gorobets, 2002; Gorobets & Safonov, 2002; Gorobets, 2004).

3.1. The rock failure energy aspect. The acoustic waves action

The most important achievements of science in handling a problem are multipurpose kinetic representations of destruction, which are experimentally confirmed for different types of materials (crystals, rocks, metals, glass, polymers) (Kuksenko, 1984; Petrov & Gorobets, 1987). Also important are the new provisions in the solids dispersion theory developed in the works (Gorobets, 2002; Gorobets, 2004).

In various concepts of destruction, the fundamental role is assigned to the critical state of materials. For example, in the dilaton theory (Vettegren', Kuksenko, & Tomilin, 2004) fracture formation is associated with the critical extension of interatomic bonds, in which the dilaton fracturing is achieved at phonon pumping. In the autovibrating theory (Bovenko, 1986; Bovenko, 1990) the critical state is considered as an analog of the resonance-wave (autoresonant) state. From the standpoint of this theory, precisely acoustic radiation leads to the interatomic bonds cleavages. Each of these cleavages initiates new fractures, acting as a trigger for releasing accumulated energy. Thus, the basis of the rock mass grinding effects are the elementary acts of destruction (irreversible interatomic bonds cleavages). These acts arise in the critical state of materials in local thermodynamically nonequilibrium zones by the autovibrating of atoms and their self-organization under the autoresonant mechanism.

The useful effect of new surface formation during destruction is due to the acoustic waves action that arise during interrupted condensed material automotive (Bovenko, 1987; Gorobets, Bovenko, & Dubrova, 1995; Gorobets, 2004). In the state of pre-destruction of the loaded solid, a mechanism is implemented in the form of an acoustic laser as an irreversible machine. The transformation of the lattice energy E into the acoustic E_a with the quantum efficiency η_q equal to the ratio of the phonons energy $(h \cdot \upsilon_m)$ to the energy of the interatomic bond $(m \cdot c^2)$ occurs:

$$\eta_q = \frac{h \cdot \upsilon_m}{m \cdot c^2} = \frac{V_b}{C} = 10^{-2}...10^{-3}, \quad (1)$$

where:

h – Planck's constant;

$\upsilon_m = c/a$ – maximum oscillation of atoms frequency in an acoustic wave;

c – the acoustic speed in a solid;

a – interatomic distance.

The natural vibration is of quantum mechanical nature, since they arise at a critical velocity of particles $V_b = h/m_a$, which value for most solids is $V_b/c = 10^{-2}\ldots10^{-3}$. In the presence of vibration, destructive processes begin to develop intensively at a rate of:

$$V_m = \sqrt{V_b \cdot c} = \left(10^{-2}\ldots10^{-3}\right)\cdot c, \qquad (2)$$

that characterizes the critical rate of autoresonance.

When the critical energy density (average in sample volume W_V and local $W_{\Delta V}$ – in the damage center) accumulated in the rock, energy is released by the new surface formation ΔS (with the HSF – the surface of the newly formed pores and fractures in the array of rocks). Critical density energy:

$$W_{\Delta V} = \frac{W_V}{\varepsilon_i} = \frac{\sigma_0 \cdot \varepsilon_0}{2 \cdot \varepsilon_i}; \qquad (3)$$

$$W_V = \frac{\sigma_0 \cdot \varepsilon_0}{2}, \qquad (4)$$

where:

σ_0, ε_0 – break-down point and deformation at the break-down point;

ε_i – relative deformation at the dispersion stage.

The W_V value characterizes the grinding mode (geological environment fracturing, the formation of large fragments and joints). The $W_{\Delta V}$ value determines the energy consumption for grinding (dispersing) and small pores and fractures formation, in particular, with HSF. The achievement of the critical energy density causes the rock failure at the HSF, and the degree of its excess – also the nature and parameters of destruction and the HSF aftereffects development.

The kinetic curves of tiny fractures accumulation under high pressure conditions are of particular interest for the volume natural objects fracturing process study. Information on the origin and development of fractures in the heterogeneous bodies volume of various nature is obtained by the method of acoustic emission (AE). AE method is used to study the size of fractures from tiny to kilometer. Figure 1 shows experimental data (Frolov, Kil'keev, Kuksenko, & Novikov, 1980), confirming the connection lg $(T/2) = f(\lg l)$ between the duration of the leading edge $T/2$ (sec) of the linear acoustic waves and the fracture size l m in the materials destruction in laboratory conditions on models and in the earth's crust (the turndown of fracture size is 0.1 mm – 1 km). It is believed that the equations of this connection correspond to the formula:

$$T = \frac{al}{v}, \qquad (5)$$

where:

v – fracture propagation rate;

α – the coefficient of proportionality.

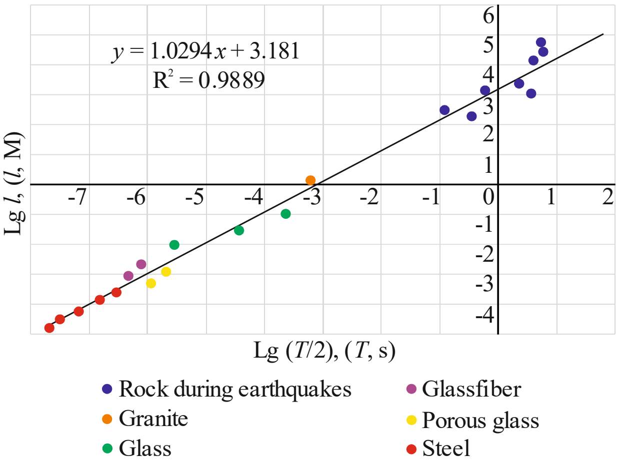

Figure 1. The relation lg (T/2) = f (lg l) between the duration of the acoustic wave leading edge T/2 and the fractures size l at the destruction in the laboratory and natural conditions (Frolov, Kil'keev, Kuksenko, & Novikov, 1980)

Kinetics of stresses and acoustic emission at iron-bearing rock sample destroying by simple compression (cube with 50 mm side) is shown in Figure 2a: σ – stress, MPa; N – AE activity, sec^{-1}; τ – load duration, sec; ε – current deformation, units ode. The change in the stress-deformed state and acoustic radiation of iron-bearing rocks sample is shown in Figure 2b (a cube with 50 mm side) in the simple compression process coupled with the radiation exposure of the sample by the UHF electric field (power – 70 W, frequency – 40 MHz).

As it can be seen from the comparison of graphs $N(\tau)$ (Fig. 2a, b), the effect of the UHF field led to increased plasticity and the manifestation of sliding fracture mode of the sample (under the action of tangential stresses with the sliding planes formation) (Gorobets & Dubrova, 1991).

Thus, the use of acoustic data in the volume geoenvironment fracture allows us to obtain information for destruction mechanism monitoring and evaluation of the expected (in the V volume zone) grinding effects, in particular, with the HSF: the growth of the surface $\Delta S/V$ of the destroyed joints; medium particles density dx, γ grade yield:

$$\frac{\Delta S}{V} \cong \frac{N}{V} l \cdot \delta; \quad d_x \cong \frac{1}{K}\sqrt[3]{\frac{V}{N}}; \quad \gamma = \frac{\Delta V}{V} \cong \frac{N}{V} l^2 \cdot \delta, \qquad (6)$$

where:

N/V – the number of AE signals is shown;

l, δ – transverse and linear dimensions of structural flakes (blocks);

K – concentration criterion, $K = 2 – 5$ (Gorobets, 2004).

Listed in Figures 1 and 2 experimental data show the leading role of acoustic monitoring in forecasting the rock failure effects. Based on the carried out analysis and the obtained data, we believe that the degree of geoenvironment fracturing in the HSF process can be estimated by the K_p value, which is equal to the product of the $A_{\max}$ acoustic signals maximum amplitude to the total acoustic activity N_Σ of the destruction zone: $K_p = A_{\max} \cdot N_\Sigma$. In this case, the K_p criterion essentially characterizes the acoustic effect of the kinetic energy transformation in the drilling working zone into the acoustic energy of the geoenvironment fracturing.

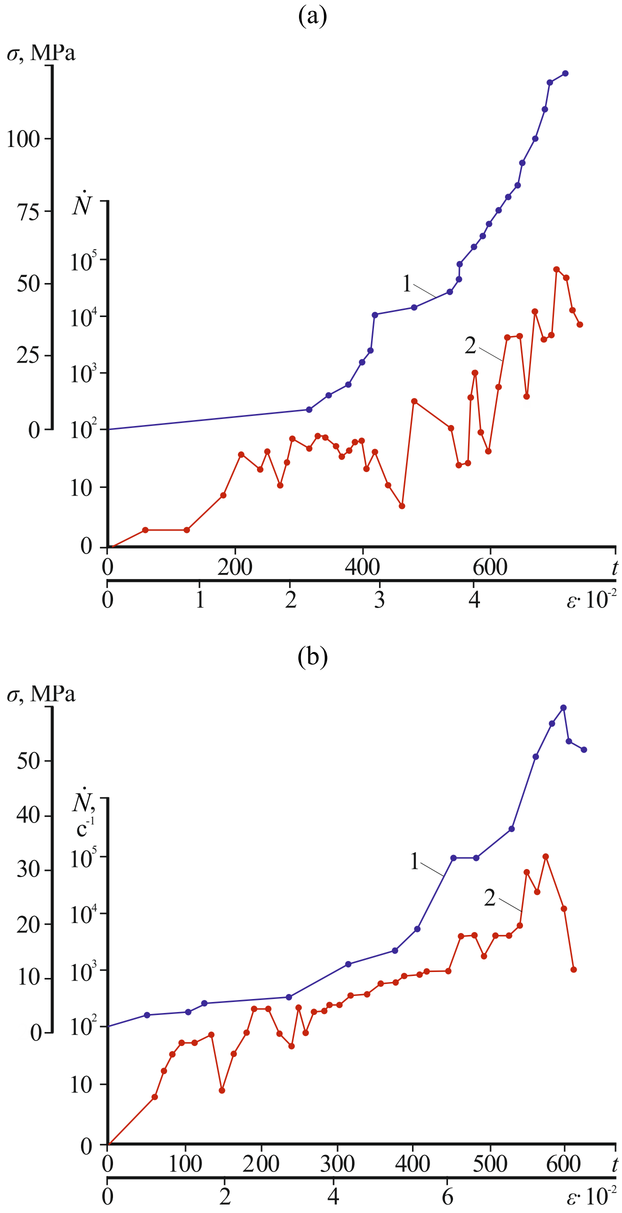

Figure 2. Stresses kinetics $\sigma(\tau)$ (1) and acoustic radiation $N(\tau)$ (2) at iron-bearing rocks loading with simple compression (a) and combined (compression with radiation) (b)

3.2. The rock failure thermodynamics

In the aspect of the methodology of the HSF technology aftereffects predicting, in our opinion, the thermodynamics of the rock failure process plays a special role. At the same time thermodynamic foundations consideration is important in all destruction manifestations: tectonic processes, rock bumps, coal and gas emissions, explosion, drilling, crushing and grinding. Experimental data have established the proximity of the fracturing activation energy values, indentation, thermal degradation, sublimation, and enthalpy per unit of atoms for a wide range of materials. In this connection, the critical (limit) state of a substance corresponding to the destruction beginning of the packed bed substance at the microlevel should be considered from the thermodynamics standpoint as a phase change (evaporation, sublimation) near the critical point, based on the critical values of the temperature T_{cr} and the specific energy ΔH_{cr}^{lab} of the phase change taking into account the ratio:

$$\Delta H_{cr}^{lab} \cong 3 \cdot R \cdot T_{cr}\,, \tag{7}$$

where:

R – universal gas constant, $R = 8.31$ J/mol·K (Gorobets & Lyutyy, 1997; Lyutyy, Gorobets, & Dubrova, 1997).

From this, it follows that when the energy of any type (mechanical, thermal, combined) is brought to the material at the pre-destruction stage in the local zones (near the space lattice defects) there are “hot spots” – areas of micro-destruction with the temperature T_{cr} of a critical value. We believe that the parameter ΔH_{cr} plays the role of a potential (energy) barrier that prevents the spontaneous substance phase change to the same extent as its self-destruction/dispersion. This means that the value $W_{\Delta V}$ of the local critical energy density at destruction (dispersion) is equivalent to the content and equal to the specific energy intensity of the substance phase change in a critical state.

In other words, in the microdispersion zones, the fair ratio is:

$$W_{\Delta V} \cong \Delta H_{cr}^{lab} \cong 3 \cdot R \cdot T_{cr}\,. \tag{8}$$

Experimental data on the activation energy of fracturing with microindentation or stretching are consistent with the turndown $\Delta H^{lab}{}_{cr}$, calculated for substances with known values of critical parameters, for example, 22 – 150 kJ/mole (coal), 319 (silicium), 298 – 344 (quartzite), 366 – 378 (silicate glass), 569 (magnesium oxide). The turndown of the local energy density $W_{\Delta V}$ in the natural materials dispersion process (iron ore, sandstone, talc, and coal) is also established in the conditions of volume compression: $W_{\Delta V} = 102 - 103$ MJ/m^3 at $\Delta S/V = 103 - 104$ m^2/m^3 (Gorobets, 2004). According to experimental data, the energy density during ferruginous rocks drilling is $W_{\Delta V} = 170 - 180$ MJ/m^3 (the particles size is about $10^{-1}…10^{-2}$ m), when the fracture is $W_{\Delta V} = 2.9 - 4.2$ MJ/m^3 (the particles size is $-10^0…-10^{-1}$ m).

After reaching the critical energy density in local zones where there is a strong deviation from the thermodynamic equilibrium, the body becomes a thermodynamic system of open type, that is, it can exchange energy and materials with the environment. The act of rock failure in nature and technology (seismic processes, rock bump, hydraulic seam fracturing) is accompanied by dispersion, rocks heating, changing the materials phase state, its properties and quality, the removal of small and fine particles into free space.

Rocks fracturing takes place under triaxial compression conditions at about ten kilometers depth at high stress levels – hundreds and thousands of MPa. Despite the great stress and accumulated energy in local areas, the rocks of the geological environment can not resist the array environment. However, the situation changes if there is baring, or the well being drilled. There is a possibility of stress discharge and energy release in the form of heat and self-destructive work. Similarly, in mining operations (especially explosive), coal and gas emissions, drilling wells, man-made seismic bumps serve as a trigger for the rock failure process implementation with all its consequences and the effects of temperature, pressure, energy and substance properties changes.

In the works (Gorobets & Lyutyy, 1997; Gorobets, 2004) thermodynamic parameters connection of the geological environment study is carried out on the basis of the relationship between the pressure P and the volume energy density W of the deformation: $P = 1/3W$. The value W is estimated from the formula:

$$W \cong \rho \cdot c \cdot \Delta T \,, \tag{9}$$

where:

c – the specific rocks heat;

ΔT – the growth of the rocks temperature at a depth of Δh in comparison with the temperature on the earth's surface.

The temperature plays the role of the parameter through which the elastic energy is expressed through its thermal equivalent. The increase in pressure ΔP with increasing depth Δh is described by the ratio:

$$\Delta P = \rho \cdot g \cdot \Delta h \,. \tag{10}$$

The value $\Delta T/\Delta h$, established by the results of temperature measurements in deep mines and wells, varies within 1 – 5°C at 100 m depth. Consequently, the conditions for rock failure at HSF are determined with the relationship between the rock pressure P and the volume energy density W of the deformation.

3.3. Surfaces mechanoactivation in the rock failure

Dynamic substance reorganization at the geoenvironment destruction is accompanied by the generation of space lattice defects, electromagnetic and acoustic radiation, the emission of electrons, atoms, particles, and luminescence. In nature and various technologies of processing geomaterials in areas of small scale (micro and nanoscale), at certain moments, energy may be concentrated, comparable to the activation energies of chemical reactions. This leads to changes in the energy state of the substance, the physico-chemical and technological properties of the fine fractions of the crushed material, which are called mechanical activation. The energy state of a substance determines the properties of the solids surface, in particular, its chemical structure, a set of functional groups associated with the number of structural defects in the form of fractures, pores and other deformations of the natural atoms location. The solid surface is characterized as a special materials state in physics of strength.

Among the factors that determine the effects of mechanoactivation, are the averaged W_V (in the sample volume) and the local $W_{\Delta V}$ (at the heart of destruction) energy density at destruction (Gorobets, 2004). The increase in the level of these energy parameters is due to the approach of mill feed material loading speed to the critical speed of the auto-resonance, in which the limiting speed of the substance space lattice at micro and nano levels is realized. From the standpoint of the destruction physics, the phenomenon of mechanoactivation can be imagined as one of the forms of substance activity natural vibration at the stage of spontaneous destruction (auto-rezonance) of a loaded solids (Bovenko & Gorobets, 1988; Gorobets, 2001).

The degree of mechanical activation can be estimated by the dispersion effect, that is, the specific newly-formed surface $\Delta S/V$ in the process of geomaterial destruction. It is stated (Gorobets, 2004) that the value $\Delta S/V$ is determined by the energy properties of the geomaterial, in particular, the surface energy γ, the efficiency of the dispersion η, the W_V parameters and energy density $W_{\Delta V}$ at fracturing in accordance with the ratio:

$$\frac{\Delta S}{V} \approx \frac{W_V \cdot \eta}{\gamma}\,; \quad \frac{\Delta S}{V} \approx \frac{W_{\Delta V} \cdot \varepsilon_i \cdot \eta}{\gamma}\,. \tag{11}$$

The value of the parameter $\Delta S/V$ is proportional to the ratio $W_{\Delta V}/\gamma$, which means the essence of the limits imposed by the energy properties nature (γ, η, $W_{\Delta V}$) of the geoenvironment on the limiting degree of its mechanoactivation. Let's consider in practical examples the estimability of the maximum realized degree of destroyed product particles mechanical activation.

Studies have shown that the effects of mechanoactivation vary depending on the way and mode parameters of the loading during machining, in particular, depending on the dynamic deformation velocity and the duration of pumping the body with energy. The way and mode of loading may change the following parameters: juvenile surface, number of functional groups, supramolecular structure, chemical composition, heat of materials wetting and dilution. The parameter for fine particle fraction activity comparison can be free energy of adsorption under other equal conditions.

In practice, the characteristic of adsorption activity, which is determined with the use of the potentiometric method, is tested and recommended for evaluation of the particle mechanoactivation (Gorobets, Yur'yevskaya, Korsakov, & Vdovina, 1986). The technique involves measuring potential of the crystal system oxidation-reduction ferro-ferri system (Fe^{3+}/Fe^{2+}) in the presence of a metal-oxide dispersion composite joint hinge to determine the equilibrium between the concentration of iron in the solution and metal-oxide substance surface. In essence, the value of the conventional adsorption potential $\Delta\varphi$ of the metal-oxide dispersion composite of a given physico-chemical system characterizes the amount of free energy stored by the solids during its destruction (compression, bumo, friction, drilling, explosion, etc.).

Let's consider the results of the mechanoactivation study on an example of a rock that was subjected to seismotectonic deformations and stresses at earthquake focus (analog to the HSF in active layer fracture zone). The main minerals of the investigated rock are epidote, chlorite, calcite. The essence of the applied method is as follows. A thin layer (up to 1 mm) is removed from the surface of the crude rock samples and glide plane (vitrified surface), pound with a pestle into a particle size of less than 100 microns, and the obtained material is subjected to a particle analysis. The isolated fractions –40 μm and 40 – 100 μm were investigated by a potentiometric method with control of potential change to a stable value. The initial value of the potential from which the study began, should be 500 – 530 mV. The equal value of the potential was considered to be the magnitude at which the potential changed for 3 min do not exceed 1 mV.

The test duration was 6 – 12 minutes. The weight of the test sample was 15 mg. In the process of ferric ion adsorption on the surface of fine particle fractions, the fall of the suspension potential was recorded. At the same time, the pH is recorded (the initial value was 2.6 – 2.7), as for some rocks the pH value can also be a characteristic of mechanical activation.

The adsorption characteristics change (φ and pH), which is an estimate of mechanically activated slicks on glide plane (or tectonic powder) of rocks, destroyed in the seismic process, is shown in Figure 3 and 4. As it can be seen, the effect of mechanical activation is mostly strong (in 3.5 – 4.0 times) in the glide plane substance compared with the inactive rock substance. In this case, the potential change for a thin fraction (less than 40 microns) is 1.5 – 9.0 times higher than for a fraction larger than 40 microns. As it is established, the level of mechanoactivation in natural conditions (seismic processes) is tens of times higher than in a laboratory experiment when the geographic environment is loaded with compression with sliding and separation.

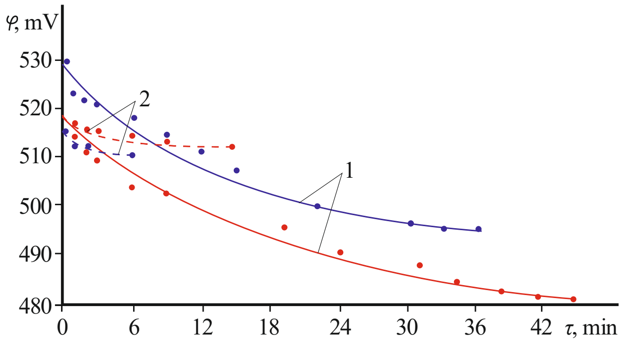

Figure 3. Kinetics of the rock parameter φ (–40 μm) activated in the seismic process: 1 – glide plane substance; 2 – the main rock substance

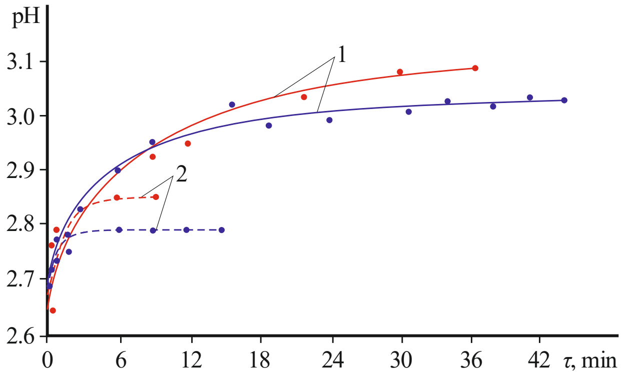

Figure 4. Dynamics of the rock indicator pH (–40 μm): 1 – glide plane substance; 2 – the main rock substance

The change in potential $\Delta\varphi$ (from the initial to the equal value) is characterized by the following ratio for different rock failure methods : creep : explosion (analogue of fractional pressure) : seismogenic fractures (glide plane) = 1:5:57 (30). Significant differences in the magnitude of the kinetic adsorption of the glide plane substance, which is an order of magnitude greater than that of an explosion, and almost 2 orders of magnitude greater than with a quasi-static load (creep regime), indicate the stability of the surface energy state of vitrified slicks formed in thick seismogenic strike slips of the distant geological past in the fault zone.

Experiments have shown that the pH value in the adsorption process of activated powders varies in a rather narrow range: ΔpH = 0.01 – 0.65. At the same time, the pH increase for thin fractions (less than 40 microns) is 1.6 – 3.0 times more significant compared to large particles (up to 100 microns). The results shown in Figure 3 and 4, give grounds to recommend the application of the described method for assessing mechanoactivation of destroyed geomaterials by the value φ or $\Delta\varphi$ (pH or ΔpH).

3.4. Aftereffect of initial pore space self-development at HSF due to the Rebinder's effect

The Rebinder's effect is the change in the solids mechanical properties as a result of physical and chemical processes that reduce the surface (interphase) energy of the body (Andrade & Randall, 1949; Malkin, 2012). It should be expected that in conditions of rock failure at HSF, the Rebinder's effect appears in the post-phase, firstly, in the disjoining pressure of the molecules, occurred along the upper reaches of the fractures, in particular the surfactants molecules and, secondly, the cooling of tiny fractures in the size of several lattice atom in the water environment and, thus, preventing their "healing". The following mechanical influences (e.g., microearthquakes, accompanying HSF, repeated HSF) intensify the expansion of these microfractures, which results in further rock failure, self-development of its fracture.

The elementary (single) Rebinder's effect is based on the destructive effect of the difference in the liquid surface pressure forces inside a solid body fracture. As a result of the disjoining pressure of aqueous slicks, the fracture at its peak gets self-development and "moves" along a rock massif. The effect depends on the initial structure of the solid (the presence of dislocations, fractures – at HSF they are created by the initial array initiation with high liquid pressure), the properties of the liquid (viscosity) and its quantity. As a result of surface tension forces there is a multiple drop in strength, increase of solid fragility, its hardening.

In accordance with the Griffiths equation, fractures are developing under conditions (Anderson, 2004):

$$\frac{\partial G}{\partial l} \geq \frac{\partial S}{\partial l} + \frac{\partial W}{\partial l}, \tag{12}$$

where:

G – all types of energy that contribute to the fractures development;

l – fractures length;

S - surface energy of "man-made" fractures;

W – the kinetic energy of the fractures elements.

Thanks to the surface-active reagent, the value of $\partial S/\partial l$ decreases, which in turn reduces the value of $\partial G/\partial l$, that is, the power input in fractures propagation.

Since the problem of rock pore space development aftereffects during hydraulic seam fracturing in the context of the Rebinder' effect rises for the first time, the actual tasks of the study are:

– defining the Rebinder's effect occurrence in the rock failure at the HSF technology;

– methodical basis formation for studying the processes of rock fracturing self-development in the HSF application in different geological conditions.

4. CONCLUSIONS

1. The basis of the rock grinding effects are the basic destructions (irreversible fractures in interatomic bonds). These fractures arise in the materials critical state in local thermodynamically unequal zones by the atoms autovibrating and their self-organization under the auto-resonance mechanism. The useful work of the new surface formation during destruction is due to the action of acoustic waves that arise during interrupted condensed material automotive. In the pre-destruction state of the loaded solid, a lattice energy transformation E into the acoustic E_a with the quantum efficiency η_q, equal to the ratio of phonons energy ($h \cdot \upsilon_m$) to the energy of the interatomic bond ($m \cdot c^2$), takes place.

The basis of the HSF aftereffects, as the theoretical analysis of the destruction process shown from the standpoint of kinetic and autovibrating theory, thermodynamics laws of the critical state and dispersion theory, are the effects of the dynamic rearrangement of the geoenvironment substance, including the formation of joints and thin fractions with enhanced energy (mechanoactivations) properties of their surfaces.

Among the fundamental patterns determining the formation and development of aftereffects of the HSF technology during the formation development, are the methodological provisions and criteria for destruction parameters prediction and the grinding effects: the average and local energy density at geographic environment destruction, the efficiency of grinding, the average size of particles and pores, specific surface area, specific energy consumption per unit of the resulting surface.

2. Connection between acoustic wave parameters and fractures size, which forms the basis of the AE method was confirmed experimentally. Based on the analysis carried out and the obtained data, we believe that the degree of geoenvironment destruction in the HSF process can be estimated by the K_p value, which is equal to the acoustic signals maximum amplitude product $A_{\max}$ to the total acoustic activity $N_{\sum}$ of the destruction zone: $K_p = A_{\max} \cdot N_{\sum}$. Experimental data show the leading role of acoustic monitoring in rocks destruction effects forecasting, in particular, in the HSF.

The basis for expected destructive effects (dispersion) evaluating in the working area is: AE activity, specific acoustic radiation, spectrum of signals, characteristic amplitudes under the condition of physical modeling on model samples of the geoenvironment behavior.

3. In the methodology aspect of the HSF technology aftereffects predicting, the thermodynamics of the microlevel process plays a special role; it should be considered from the standpoint of thermodynamics as a phase change (evaporation, sublimation) near the critical point, based on the temperature critical values and the specific energy of the phase change.

Conditions of rock failure at the HSF are determined by the relationship between the rock pressure P and the volume energy density W of the deformation.

Information on the critical limit state of the loaded geographic environment samples includes the theoretical preconditions for assessing the following energy indices of the geomaterial destruction:

– average volume energy density transferred to the geoenvironment;

– local density of elastic energy in the destruction;

– transformation coefficient of accumulated energy into the destruction.

4. On the basis of experimental data, the presence of surfaces mechanoactivation in the rock failure is proved. It is shown that the level of surfaces mechanoactivation can be estimated by adsorption characteristics – the adsorption potential and the pH of the newly discovered surfaces.

5. The hypothesis for the aftereffect of rock pore space development during the hydraulic seam fracturing in the context of the Rebinder's effect was proposed for the first time. The actual problems of the Rebinder's effect occurrence investigating at under the hydraulic seam fracturing are formulated. The degree of the Rebinder's effect occurrence and its role in the introduced fluid flow depends on the geomaterial nature.

5. FURTHER RESEARCH

A theoretical analysis of the HSF technology of shale oil and gas extraction aftereffects has been carried out, which showed the presence of potentially threatening factors that require further research:

– stress zones development with increasing fragments formation, joints, fine particles activated on the well drilling path and fracturing;

– systematic seismic activity of the developed layers as a result of the interaction of increased energies hearths (taking into account the principle of concentration fractures coarsening, relaxation of stresses, increase of acoustic activity, auto-resonance, self-destruction, dispersion, emission of gases and dust);

– filling fracturing zones of activated geomaterial with chemicals with organic layers of the earth and aquifers poisoning; temporal assessment of the pore space development (in the formation and perpendicular to its extension) due to the Rebinder's effect.

ACKNOWLEDGEMENTS

The authors express their gratitude to Doctor of Physical and Mathematical Sciences Vilian Mykolayovych Bovenko for valuable advices when conducting research. In addition, thanks to Doctor of Engineering Sciences Anatolii Dmytrovych Aleksieiev for the opportunity to use a unique research unit of non-uniform triaxial load and research method revision. The authors thank to Candidate of Engineering Sciences Iryna Mykhailivna Yuriivska for consultations on the use of her original method of mechanoactivation study.

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ТЕОРЕТИЧНІ ПЕРЕДУМОВИ РУЙНУВАННЯ ГІРСЬКИХ ПОРІД ПРИ ГІДРАВЛІЧНОМУ РОЗРИВІ ПЛАСТА ТА АНАЛІЗ ПОСТ-ЕФЕКТІВ

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Мета. Теоретичне обґрунтування методологічних основ встановлення умов прояву можливих ефектів і пост-ефектів технології гідравлічного розриву пласта (ГРП).

Методика. Структура та послідовність проведення дослідження включає вивчення енергетичного аспекту руйнування гірського масиву, дії акустичних хвиль, термодинамічний аналіз руйнування гірського масиву, аналіз механоактивації поверхонь при руйнуванні гірського масиву та пост-ефекту саморозвитку первинного пористого простору ГРП внаслідок дії ефекту Ребіндера. Застосовано метод акустичної емісії, потенціометрії та pH-метрії.

Результати. Встановлено, що до числа фундаментальних закономірностей, які визначають формування і розвиток пост-ефектів технології ГРП при відпрацюванні продуктивних пластів, відносяться методичні положення й критерії для прогнозу показників руйнування та ефектів подрібнення, а саме: середньої та локальної густини енергії при руйнуванні геосередовища, ККД подрібнення, середній розмір часток і пор, питома поверхня, питомі витрати енергії на одиницю одержаної поверхні. Експериментально підтверджений зв’язок між параметрами акустичної хвилі та розміром тріщин, що складає основу методу акустичної емісії (АЕ).

Наукова новизна. Встановлено, що базу інформації для оцінки очікуваних у робочій зоні ГРП ефектів руйнувань складають активність АЕ, питоме акустичне випромінювання, спектр сигналів, характерні амплітуди за умови фізичного моделювання поведінки геосередовища на модельних зразках. Визначено, що граничний стан речовини, що відповідає початку руйнування на мікрорівні, слід розглядати з позицій термодинаміки як фазовий перехід (випаровування, сублімація) поблизу критичної точки, виходячи із критичних значень температури і питомої енергії фазового переходу. Експериментально доведено наявність механоактивації поверхонь при руйнуванні гірського масиву. Висунута гіпотеза щодо пост-ефекту розвитку пористого простору гірського масиву при ГРП у контексті дії ефекту Ребіндера.

Практична значимість. Запропоновано оцінювати ступінь руйнування геосередовища у процесі ГРП показником K_p, що дорівнює добутку максимальної амплітуди акустичних сигналів на сумарну акустичну активність зони руйнування. Встановлено, що умови руйнування гірського масиву при ГРП детермінуються співвідношенням між гірським тиском P і об’ємною густиною енергії W деформації. Показано, що ступінь механоактивації поверхонь може бути оцінена за характеристиками адсорбції – потенціалом адсорбції та показником pH нововідкритих поверхонь.

Ключові слова: *гідравлічний розрив пласта, акустичні хвилі, термодинамічний аналіз, механоактивація, ефект Ребіндера, акустична емісія, потенціометрія, pH-метрія*

ТЕОРЕТИЧЕСКИЕ ПРЕДПОСЫЛКИ РАЗРУШЕНИЯ ГОРНЫХ ПОРОД ПРИ ГИДРАВЛИЧЕСКОМ РАЗРЫВЕ ПЛАСТА И АНАЛИЗ ПОСТ-ЭФФЕКТОВ

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Цель. Теоретическое обоснование методологических основ установления условий проявления возможных эффектов и пост-эффектов технологии гидравлического разрыва пласта (ГРП).

Методика. Структура и последовательность проведения исследования включает изучение энергетического аспекта разрушения горного массива, действия акустических волн, термодинамический анализ разрушения горного массива, анализ механоактивации поверхностей при разрушении горного массива и пост-эффекта саморазвития первичного пористого пространгства ГРП в результате действия эффекта Ребиндера. Применен метод акустической эмиссии, потенциометрии и pH-метрии.

Результаты. Установлено, что к числу фундаментальных закономерностей, определяющих формирование и развитие пост-эффектов технологии ГРП при отработке продуктивных пластов, относятся методические положения и критерии для прогноза показателей разрушения и эффектов измельчения, а именно: средней и локальной плотности энергии при разрушении геосреды, КПД измельчения, средний размер частиц и пор, удельная поверхность, удельные затраты энергии на единицу полученной поверхности. Экспериментально подтверждена связь между параметрами акустической волны и размером трещин, что составляет основу метода акустической эмиссии (АЭ).

Научная новизна. Установлено, что базу информации для оценки ожидаемых в рабочей зоне ГРП эффектов разрушений составляют актитивность АЭ, удельное акустическое излучение, спектр сигналов, характерные амплитуды при условии физического моделирования поведения геосреды на модельных образцах. Определено, что предельное состояние вещества, отвечающее началу разрушения на микроуровне, следует рассматривать с позиций термодинамики как фазовый переход (испарение, сублимация) вблизи критической точки, исходя из критических значений температуры и удельной энергии фазового перехода. Экспериментально доказано наличие механоактивации поверхностей при разрушении горного массива. Выдвинута гипотеза относительно пост-эффекта развития пористого пространства горного массива при ГРП в контексте действия эффекта Ребиндера.

Практическая значимость. Предложено оценивать степень разрушения геосреды в процессе ГРП показателем K_p, который равен произведению максимальной амплитуды акустических сигналов на суммарную акустическую активность зоны разрушения. Установлено, что условия разрушения горного массива при ГРП детерминируются соотношением между горным давлением P и объемной плотностью энергии W деформации. Показано, что степень механоактивации поверхностей может быть оценен по характеристикам адсорбции – потенциалом адсорбции и показателем pH новооткрытых поверхностей.

Ключевые слова: *гидравлический разрыв пласта, акустические волны, термодинамический анализ, механоактивация, эффект Ребиндера, акустическая эмиссия, потенциометрия, pH-метрия*

ARTICLE INFO

Received: 20 February 2018
Accepted: 6 August 2018
Available online: 16 August 2018

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