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Decreasing Energy Consumption in Mining by Combined Plasma-Mechanical Rock Fracturing

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Abstract: This research focuses on a novel approach to increasing the productivity of rock fracturing by combining plasma and mechanical fracturing. The combination of plasma and mechanical stress increased the productivity of fracturing hematite with a SBSh-250 drilling unit by more than 50%. By applying a current of 10 A the advance rate increased from 14.32 m/day to 22.39 m/day. A new mathematical model for electro-thermal rock fracturing was designed integrating the effect of the plasma stream with given inductance and current into a drilling model.

Keywords:plasma-mechanical stress; crystalline structures; rock fracturing;productivity

1. Introduction

Issues of fracture mechanics to improving the technology of rock fracture, were investigated by such scientists as Babat G.I., Bartenev M. M., Boldyrev G. G., Vorobiev AA, Vorobyov G. A., Griffiths A., DenisyukT.D., DodysYa.M., Zinoviev N.T., Narisava I., Regel V., Somkin B.V., Usov A.F., Cherepanov G.P. and other. However, in their studies, the energy of molecular bonds is considered as the force of counteraction to external energy influence. The possibilities of release and directing this energy for the development and propagation of natural fracturing are not considered. Classical destruction (cutting, flying, rotating, exploding, etc.) in combination with physical destruction (thermal, impulse, hydraulic, etc.) of the crystalline structure of the arrays allows the use of internal and external sources of energy. Their combined effect on the rocks and on the productivity of its fracturing was not investigated. Therefore, it is relevant to establish the laws of decreasing of energy consumption of rock fracture by physical and mechanical loads of external and internal energy sources for the mining. The relevance of the chosen topic is in line with paragraph 7, article 4, chapter 2 of the Directive of the European Parliament and the Council "On Energy Efficiency" 2012 / 27EU of October 25, 2012.

2. Problem Statement

The most popular theories of rock fracture mechanics used are those of Griffiths [1] and Irwin [2]. In the 1940s, G. I. Babat and A. V. Varzin [4] described the behavior of dielectric materials in high frequency electromagnetic fields induced between flat electrodes using natural rock formations as test material. They found that electromagnetic fields developed between the electrodes which apparently caused thermal stress in the rock formations. As a result, cracks formed in the rock formations and spalling was observed. These studies did not take the anisotropy of rock structures into consideration. Accounting for anisotropy is important for selecting appropriate parameters of a high-frequency oscillator circuit.

Griffith [1] stated that a crack will begin to propagate if the elastic energy released by the growth of the crack is greater than the energy required to create the fractured surfaces. The theory of cracks [2] defines the criterion for local fracture at the tip of the crack periphery: deformations do not propagate towards the boundaries of the body, but they spread towards any defects the internal structure of the body has. Irwin found in 1957 that stress can be calculated assuming ideal elasticity of the body [2].

The Leonov – Panasiuk model was proposed in 1959 [3]. It assumes that near the crack tip there is an area of weakened bonds. When the random accumulation of defects increases to such an extent that the probability of further damage is the highest, the preconditions for fracturing are established and the phase of propagation of cracks starts due to thermofluctuational effects [4].

A description of crack propagation in random continuous environments was presented by Cherepanov, 1967 [5]. His theory of brittle cracks forms the basis of modern fracture mechanics. In real world conditions, the strength of solids depends on the following main factors: material, shape and size of the body, loading method,

number of loading cycles, temperature, aggressiveness of the environment, speed of deformation and deformation history.

In practice [6] a transition zone separates the region of ductile fracture from the region of brittle fracture. Experiments on real rock were conducted by Kravchenko, Zrazkovyi, and Semenov (1961 – 1963) [4]. The theories of high-frequency thermal rupture and electrical breakage link physical properties of materials undergoing fragmentation with field parameters. Further research in this area was done by Itskhakin, Zrazkovyi, and Ustinov (1962-1964) examining the structural complexity and anisotropy of rock, the variability of it´s properties and dependence on temperature, field strength and frequency [4].

According to [4], in the 50-s Babat and Varzin discovered that a high-frequency wave of 3 GHz impacting on sandstone causes spalling. The depth and distribution of the electromagnetic energy flow in a material depends on the electromagnetic wave length, the method of their reflection and the electrophysical properties of the material. This process was further tested on granite by Kravchenko, Zrazkovyi and others in 1965 [4].

In 1970 Blumenauer [7] and Yokobori [8] showed that fracture is always initiated by cracks. The critical size of a defect results from the growth of existing cracks leading to the destruction of rocks. Blumenauer first identified the need of stress variation for fracturing solids [7]. Yokobori [8] found that the distribution of stress and dislocations are the main factors that determine the tension in the tips of natural cracks in rocks. His theory describes the mechanism of the emergence and spreading of cracks under stress.

In the 1970 – 1980s, Kausch [9], Regel [10], and Narisava [11] found that the main reason of crack formation is the number of inclusions in a crystal. The potential energy in a crystal lattice can be calculated from the displacement of atoms from their equilibrium position, the forces of interaction between the atoms, and the energy of free electrons. This approach is an advance from the classical to the molecular-kinetic fracture theories. These theories represent interaction of crystal structures of massifs as a set of forces of plasticity and elasticity, assuming that the physical-mechanical parameters of rock are constant. The major factor in the formation of micropores assuming there is no slide of macromolecule chains [11] is breaking of the chains themselves. Breakdown of chains is achieved by the deformation of amorphous regions and deformation of flat passage monocrystalline chains (lamellas).

Volkenštejn [12] and Yastrebov [13] developed the zone theory. They used the following assumptions in their research [13]:

- the solid rock is considered as a periodic crystal;
- equilibrium positions of the crystalline structure's assemblies are fixed;
- the vibrations of atoms around the equilibrium positions can be described;
- the individual electron structures are considered as one electron structure;
- the influence on this electron is described by the model of a periodic field.

The main disadvantage of the resulting zone theory is the modelling of electron structures of solids as one aggregated electron structure. The application of quantum field theory was presented by Zi [14], Ipatova [15], and Glìm [16]. Quantum field theory describes the behavior of elementary particles with energies that substantially exceed their resting energy.

In the above described fracture theories, there are several common shortfalls:

- the physical-mechanical parameters of rock which is destroyed are taken as constant;
- energy in internal crystal structures is not considered or underestimated;
- empirical physical and mechanical parameters are used to describe crystal structures instead of describing the functionality changes in anisotropic rocks when they are under external fracturing influence;
- transition from molecular indicators to crystal structure's indicators of the rocks is not possible, which prevents the consideration of the activation of the internal energy;
- the impact of external energy sources on the physical and mechanical parameters of the crystal structures is underestimated.

It was experimentally demonstrated [3] that under the influence of an electromagnetic field, heat develops around the rocks. Using high frequency thermal breakdown can be induced. The use of sub-multiples of the resonant frequency plasma activates the internal energy of crystalline structures and directs energy to the fracture causing preliminary weakening of the rock. Therefore, electric discharge in combination with classical mechanical fracturing is an efficient way to reduce the energy consumption for rock fracturing. The application

of chemical band theory allows the estimation of the potential energy of the crystal structures of the rocks which can be used in this process.

The disadvantage of the known units for electro thermal fracturing [17] is the use of capacitors. To overcome this drawback, it was suggested to use electro thermal inductive plasma fracturing, with the following benefits:

- no use of capacitors;
- safety and environmental friendliness by minimizing hazardous materials;
- use of the internal energy of the crystalline structure itself as an energy source by using the sub-multiple of the resonant frequency;
- control of fracture mode by changing the characteristics of the plasma flow;
- no need for a special ignition system;
- the unique feature of electro thermal rock fracturing is the selectivity of the process [18].

The use of electro thermal fracturing allows:

- to create a pre-fracture zone in rocks with reduced strength characteristics;
- to eliminate friction losses, as in mechanical methods of rock fracture;
- to provide discrete adjustable fracturing that eliminates the energy costs for product shredding.

In [19] it was experimentally shown that the application of energy with frequencies from 0.3 GHz to 3.0 GHz reduces the strength of norite from 16 MPa to 6 MPa, the strength of granite from 11 MPa to 9 MPa, and the strength of basalt from 13 MPa to 8 MPa. The temperature impact of discharge decreased linearly with increasing length of this discharge. In [19] Ferri et al found that tensile strength and compressive strength decreased with increasing exposure time.

Vazhov et al. [20] determined the efficiency of electro thermal fracturing in combination with drilling. They found that the combination reduces the fracturing energy consumption by a factor of 5 - 11. Kweh et al. [21] determined the effect of different temperatures on the mechanical properties of rocks. The study found that at a temperature 1073 K, Young's modulus values of hydroxyapatite increases up to 0.05 MPa. A further increase in temperature up to 1173 K did not lead to an increase of the Young's modulus above 0.1 MPa. This is due to the thermal destruction of solids along already existed natural defects.

Fei et al. [22] described the change of the physical state of bicarbonate ions concentration during the influence of plasma. The aim of the research was to fracture bicarbonate ions. Plasma gliding arc was used in the experiments. Vazhov documented a reduction of specific energy of rock formations fracturing from 2000 J/cm^3 down to 170 J/cm^3 by using electric pulses [23].

In [24] Denisiuk et al derived a mathematical model for electro thermal fracturing. This model allows the representation of the relationship between the parameters of the electric discharge and the strength of the rock. This model does not consider the internal energy of molecular bonds, which can be activated to reduce the specific energy of destruction of rocks.

So, the following research question was formulated. It is assumed that the process of plasma-mechanical rock fracturing can be improved using inductive plasma. The application of inductive plasma should result in a more energy efficient and faster fracturing process. Therefore, this research studies the influence of the plasma on rock formations pre-fracturing and develops a model for the reduction of specific energy of rock formations fracturing using plasma-mechanical loads.

The aim of study is to the laws of decreasing of energy consumption of rock fracture by physical and mechanical loads of external and internal energy sources for the mining.

To achieve this aim, the following objectives are accomplished:

– to identify the mathematical model of the energy of an inductive plasma for the plasma fracturing unit;

– to adopt the mathematical model of plasma-mechanical rock fracturing, which needs to depict the influence of working parameters of the plasma fracturing unit on the specific energy consumption of plasma mechanical rock fracturing;

– to argue the rational working regimes for the plasma-mechanical rock fracturing;

– to identify dependences of decreasing the specific energy consumption of the plasma-mechanical fracturing on the working parameters of the plasma fracturing unit.

3. Specific Energy Consumption for Combined Drilling Machine with the Plasma Fracture Unit

3.1. Modeling Plasma-Mechanical Rock Formation Fracturing

The starting point for the modelling of the plasma-mechanical rock formation fracturing is the equation developed by Denisiuk et al [24]. The authors derived a model of the specific internal energy in the volume of the plasma flow. However, they did not take the possibility to use inductive plasma into account. So, in this research, their model was modified to include the effects of the inductive plasma rock fracturing unit, taking into account inductance and current strength of the plasma fracturing unit by Terentiev and Kleshchov in [33].

The proposed model of internal energy of the plasma flow differs from the known ones by establishing the dependency of the internal energy on the inductance and the current strength of the analysed element of the inductive plasma fracturing unit developed by two of the authors of this paper.

As a basis for the determination of the dependence of Young's modulus on the energy of crystalline structures, the model of Phortov [25] was used. It confirms the dependency of Young's modulus on the density of the rocks. However, it doesn't take into account the varying energy of crystalline rock structures. Therefore, an amended mathematical model was proposed by the authors of this research, which confirms the dependency of Young's modulus on the coordinate number of crystalline lattices and the energy of the bond of crystalline rock elements.

The development of the base model for plasma-mechanical rock formation fracturing is shown by Terentiev and Kleshchov in [33]. The resulting equation is

$$\mathbf{U=(r_m^4\cdot \square_0\cdot N_{pl}\cdot V\cdot \square\cdot(r+l)\cdot U_a)/(2\cdot(\square-1)\cdot h\cdot \square_{pl}\cdot L\cdot I_m\cdot t)}, \quad (1)$$

where **U** is Specific internal energy in the volume of the plasma flow channel [kJ/m³], $\mathbf{r_m}$ is Maximum radius of plasma flows [m], $\square_0$ is Density of the unexcavated discharge medium [kg/m^3], $\mathbf{N_{pl}}$ is Concentration of flows of inductive plasma [m^{-3}], **V** is Volume of flows of inductive plasma [m^3], □ is Energy of the plasma flux [J], **r** is Radius of effective zone of compression wave [m], **l** is Length of inductive plasma flow [m], $\mathbf{U_a}$ is Voltage [V], □ is Index of adiabatic flux of plasma [--], **h** is Planck's constant [J · s]; $\square_{pl}$ is Circular frequency of the eigen fluctuations of the plasma flow [s^{-1}], **L** is Inductance [H], $\mathbf{I_m}$ is Current strength [A], **t** is Time of influence of inductive plasma flows on the crystalline structure [s].

The comparison of the results of the application of the proposed model and literature data is presented in Table I.

Table I:Calculated Young´s modulus and comparison with literature data

Crystalline structure	Calculated Young's modulus [GPa]	Young's modulus from the Cadastre [26] [GPa]	Difference between calculation and data from Melnikov et al [%]
Hematite	191.5	207.9	7.8
Quartz	107.0	101.0	5.9
Calcite	71.5	56.9 – 88.3	-
Magnesite	45.7	44.1	6.4

The proposed model allows the determination of the internal energy of crystalline structures which can be released and directed to the fracturing of the rock formations. The method for determining the energy of the bonds of structures corresponds to the approximation of the band theory, when the multi-electronic systems are reduced to single-electron ones. The quantum field theory and the chemical connection theory were combined. The basics of directed bonds (classical chemistry) and the presence of separated electrons (physics) responsible for interaction properties (bond energy, circular frequency of the eigenvalues of the structure) is taken into account in this approach.

The proposed model (equation 2) differs from the known ones by:

- determination of the energy potential of crystalline structures;
- taking into account the influence of Unit Cell Parameter on Young's modulus;
- determination of the quadratic dependence of the Young's modulus on the internal energy of crystalline structures;
- considering the coordinating number taking into account the type of crystalline structure.

The following mathematical model was proposed by the authors of the current research, which confirms the dependency of Young's modulus on the coordinate number of crystalline lattices and the energy of the bond of crystalline rock elements:

$$E_0=(Z\cdot h\cdot(\square\ \square_i)/h\cdot m\cdot c)^2\cdot\square, \qquad (2)$$

where E_0 is Young's modulus of rock formation [Pa], **Z** is Coordinate number of crystalline lattices [atoms], $\square_i$ is Energy of the bond of elements [J/atom], **h** is Planck's constant [J·s], **m** is Mass of elementary particles [kg], **c** is Speed of light [m/s], $\square$ is Density of rock [kg/m^3].

For the basic model of the Young's modulus after the plasma fracture, the Dodis model [27] of electrothermal influence on the rock was adopted:

$$E_K=(124\cdot t\cdot\square_p\cdot\square\cdot[((1-\square)\cdot V_{por}\cdot k_{pl})/R]^{0.5})/(\square\cdot(L\cdot I_m^2+C\cdot U_a^2)\cdot\ln R), \qquad (3)$$

where E_K is Young's modulus after the plasma fracture [Pa], **t** is Time of applied load [s], $\square_r$ is Rock strength on the gap [Pa], $\square$ is Coefficient of thermal conductivity [W/(m·K)], $\square$ is Poisson coefficient [-], V_{por} is Volume of rock sample [m^3], k_{pl} is Coefficient of plasticity [-], **R** is Radius of the heated sample [m], $\square$ is Coefficient of linear thermal expansion [K^{-1}], **L** is inductance [H], I_m is current [A], **C** is capacitance [F], U_a - voltage [V].

In order to accurately describe the physical phenomenon, it is necessary that all external and internal influence factors of the plasma fracture system are taken into account. It is not possible to achieve this condition analytically. So, according to the method of experimental modeling, correction functions for the model (3) were calculated. Young's modulus after plasma fracturing for a two-component (current strength and inductance) plasma fracture system is limited by operating parameters:

$$E_K=(496\cdot t\cdot\square_{por}\cdot p\cdot\square\cdot[((1-\square)\cdot V_{por}\cdot k_{pl})/R]^{0.5}\cdot(4144.4526\cdot 1.9584^{\ln L})\cdot$$
$$\cdot(9.0295\cdot\ln(Im)-17.8055))/(\square_{por}\cdot h\cdot a_{cr}\cdot\square_m^2\cdot\square\cdot(L\cdot I_m^2+(C_M\cdot U_a\cdot\square^2\cdot L)\cdot N_{pl}\cdot\ln R), \qquad (4)$$

where E_K is Young's modulus after the plasma fracture [Pa], $\square_{por} = Z\cdot\square\ \square_i$ is internal energy of the crystalline structure [J], **Z** is Coordinate number of the crystalline structure [atoms], $\square_i$ is Energy of the element's bond [J/atom], **p** is Atmospheric pressure [Pa], $\square$ is coefficient of thermal conductivity [W/(m·K)], $\square$ is Poisson coefficient [-], V_{por} is Volume of rock sample [m^3], k_{pl} is Coefficient of plasticity [-], **R** is Radius of the heated sample [m], $\square_{por}$ is Circular frequency of the crystalline structures own oscillations [s^{-1}], **h** is Planck's constant [J·s], a_{cr} is Unit Cell Parameter [m], $\square_m$ is Diameter of the unit cell of the crystalline structure [m], $\square$ is Coefficient of linear thermal expansion [K^{-1}], **L** is Inductance [H], I_m is Current [A], C_M is Capacitance between coil turns [F], U_a is Voltage [V], $\square$ is electric grid circular frequency [s^{-1}], N_{pl} is Inductive plasma flow's concentration, [m^{-3}].

The adapted model (equation 4) differs from the existing ones in that it takes into account:

- external plasma influence on the Young's modulus;
- dependence of the Young's modulus on working parameters of the plasma fracture unit;
- on the plasma flow's parameters; on the crystalline structure's parameters;
- correction functions for a two-component (current strength and inductance) plasma fracture system;
- external and internal energy sources while rock formation fracturing with the help of inductive plasma flows.

The relation of the Young's modulus of rock formation to the Young's modulus after plasma fracture, allows us to calculate the index of strength. The basic model of specific energy consumption for a drilling machine is taken from [28]. The proposed model defines the influence of current strength and inductance of the plasma fracture unit on the specific energy consumption of plasma mechanical rock formation fracturing with unimodal distribution.

In view of this, the specific energy consumption for combined drilling machine with the plasma fracture unit, which includes parameters of mechanical fracturing (first sum) and plasma fracturing (second sum), is

$$A_V=((P_C\cdot t\cdot m\cdot c)/(Z\cdot\square(\square_i)\cdot V_{por}\cdot(\square/E_a)^{0.5}))+((P\cdot t)/(V_{por}\cdot E_0/E_K)), \qquad (5)$$

where A_V is Specific energy consumption of plasma mechanical rock fracture [J/m^3], $\square_C$ is Power of drilling machine [W], **t** is Time of rock formation fracturing [s], **m** is Mass of elementary particles [kg], **c** is Light speed [m/s], **Z** is Coordinate number of the crystalline structure [atoms], $\square_i$ Energy of the element's bond [J/atom], V_{por} is Volume of rock sample [m^3], $\square$ is Density of rock formation [kg/m^3], E_a is Young's modulus at the moment of fracturing [GPa], **P** is Power of the plasma fracture unit [W], E_0, E_K are Young's modulus before and after plasma fracture, respectively [GPa].

3.2. Methods and Materials for the Experiments of the Plasma Fracturing Unit

An experimental unit of plasma rock fracture has been designed and built in the laboratory of high-voltage technology in the Kyiv Electromechanical College, Figure 1.

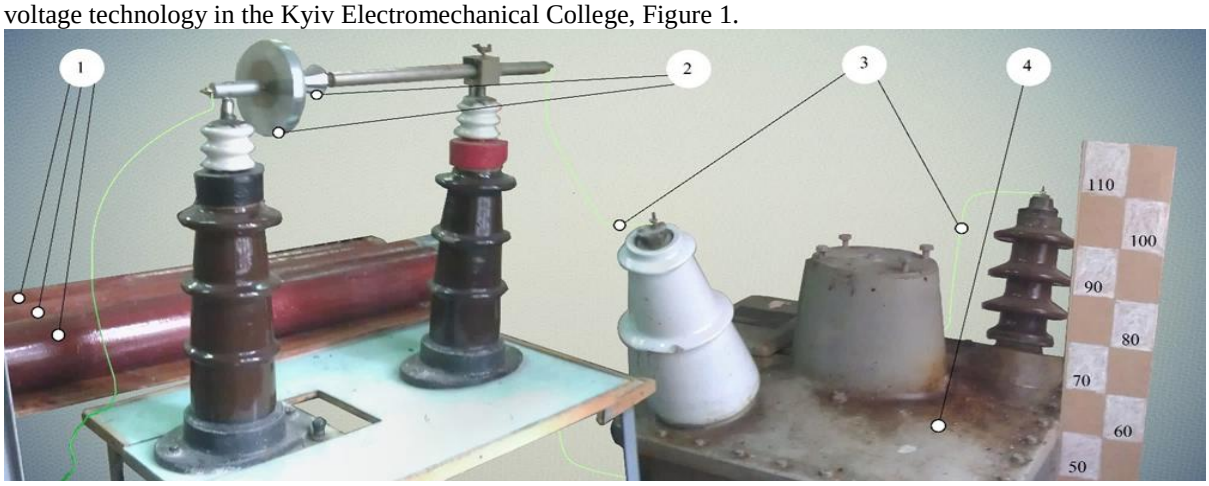


Figure 1: The experimental stand of plasma rock fracture, where 1 – inductance, 2 – dischargers, 3 – connecting wires, 4 – high-voltage transformer

The high-voltage transformer increases the input voltage from 127 V with a transformation coefficient of 295. The output voltage can be regulated. The inductance (1) is connected to the transformer (4) by the connecting wires (3). The dischargers (2) have a special design. It is possible to regulate the distance between the dischargers between 0 and 300 mm. During an experiment, the sample is fastened to the flat discharger. When the power source is on, an inductive plasma charge forms between the dischargers (2). This process destroys the sample.

Samples from hematite, quartz, calcite, and magnesite were used in the study. The samples were ground by using the Buehler PetroThin grinding system. The dependence of the depth of the imprint on the indentation force of the indenter was measured using a micro-meter (Larey MH-II). The external influence of inductive plasma flows on the investigated structures was analyzed using a raster electron microscope (REM-106I).

4. Results and Discussion of the Plasma-Mechanical Fracturing

The results of plasma fracturing of hematite are shown in Figure 2 (scale 1 to 1000).

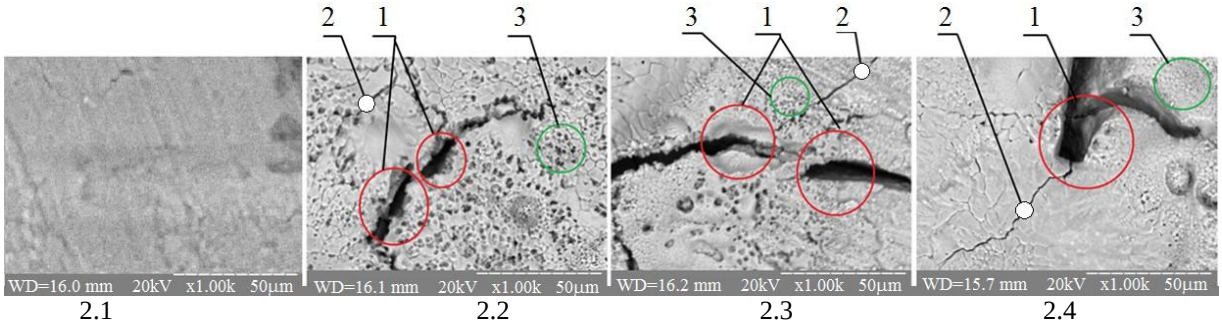


Figure2: The surface of hematite before and after plasma destruction, at 1000 times magnification, fragments from left to right: 2.1 - fragments before plasma fracture; 2.2 and 2.3 –Application of a current of 10 A, and an inductance of 11.92 µH; 2.4 Application of a current of 8 A, and an inductance of 35.72 µH; where 1 is the cavity of the lines of influence of the sub-multiple of the resonant frequency component of plasma, 2 are the cracks, and 3 are craters, as a result of the influence of the temperature of the plasma

An uneven change in the geometry of the hematite surface after plasma fracture was observed. The REM-106I recorded the appearance of oval and circular craters (3), with diameters ranging from 50 µm to 250 µm. This is due to the effect of the temperature of the inductive plasma. The cavities (1) with a thickness from

25 µm to 150 µm resulted from the influence of the sub-multiple of the resonant frequency component of the inductive plasma flow. Due to the destruction of cohesive bonds, part of the structures evaporated. From the peaks of the cavities on the surface, cracks occur (2). They discharge internal energy concentrated in the tips. Thus, artificial defects are added to the existing natural ones. On the sides of the cracks there are circular craters (3), with a diameter up to 5 µm. They are formed on the upper layer of hematite by the influence of temperature of the flow of inductive plasma.

There are two different effects observed on the hematite sample:

- impact of temperature - the kinetic energy of the inductive plasma flow is transmitted and propagates in the crystalline structures of hematite increasing the temperature;
- impact by the sub-multiple of the resonant frequency - the internal energy of crystalline structures is released upon the sub-multiple of the resonant frequency fluctuations of the inductive plasma flow.

Similarly, in Figures 3 - 5 the surfaces of quartz, calcite and magnesite samples after plasma fracture are shown.

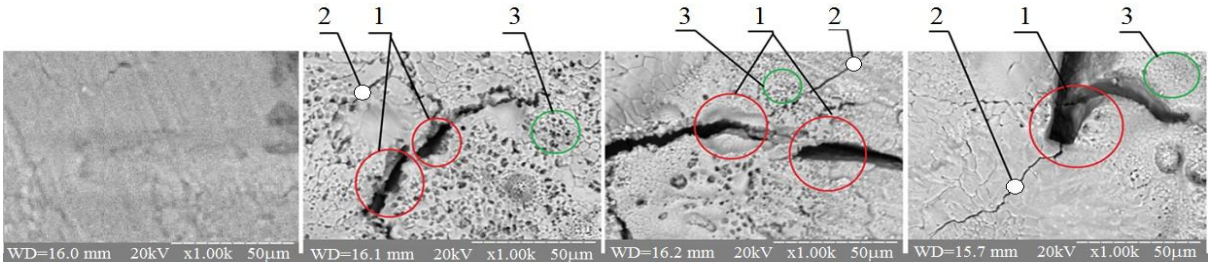


Figure3: The surface of quartz before and after plasma fracture, 500 times enlarged, from left to right: 1 - before plasma fracture; 2– Application of a current of 10 A and an inductance 11.92 µH; 3 – Application of a current of 8 A and an inductance 35,72 µH; 4 – picture from literature [29]; where 1 – exit of micro-impurities to the surface under the influence of the temperature component of plasma, 2 –the caverns from the influence of the sub-multiple of the resonant frequency component of plasma

Figure 3 confirms that under the temperature impact of plasma the micro-impurities move from the depth of the sample to the surface (Figure 3.2, 3.3, and 3.4). Figure 3.4 shows results with quartz from other authors [29]. In Figures 3.2 and 3.3, similar structures are observed generated by the relaxation of structures by inductive plasma. This confirms the introduction of artificial defects during this process. In Figure 3.4 there is no crack effect from the influence of the sub-multiple of the resonant frequency component. In Figures 3.2 and 3.3, caverns (2) appear. Their thickness is less than 2 microns, which is up to 100 times less than that of hematite specimens. This is due to the 2 orders of magnitude smaller rate of natural defects in quartz compared to hematite.

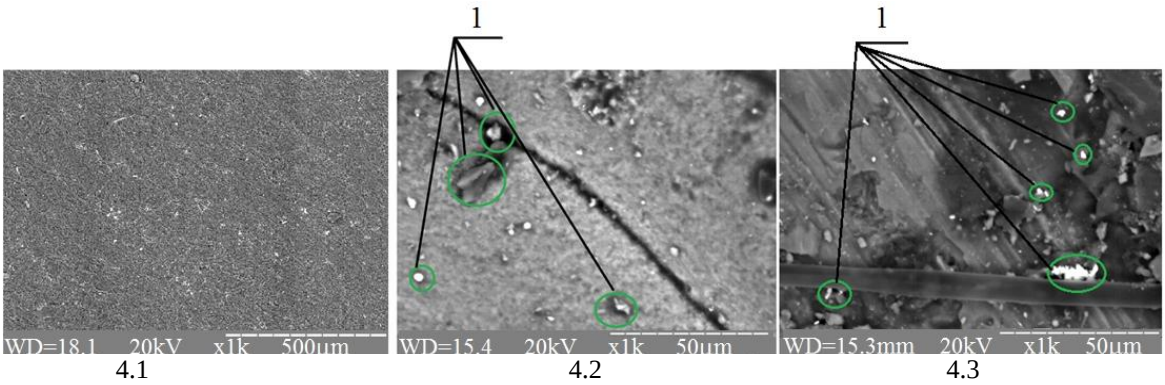
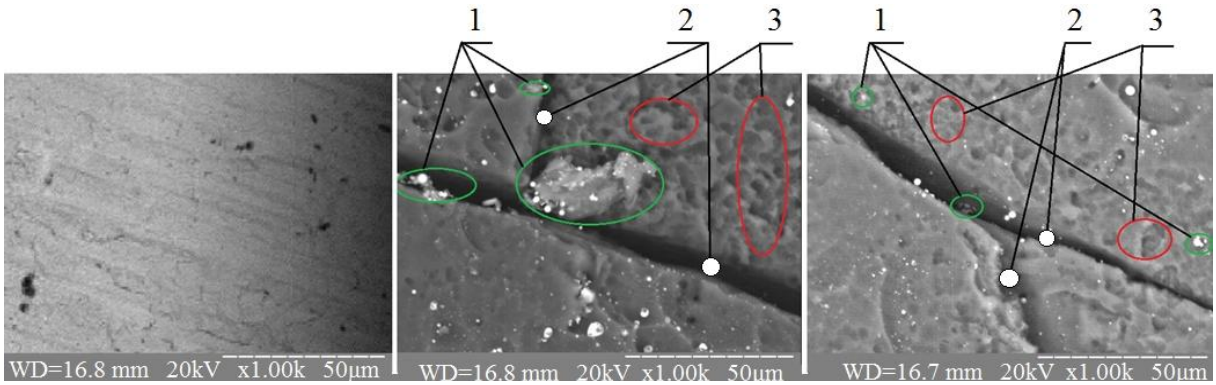


Figure4: The surface of calcite before and after plasma fracture, at 1000 times enlarged, from left to right: 4.1 - before plasma fracture; 4.2 – Application of a current of 10 A and an inductance of 11.92 µH; 4.3 –

Application of a current of 8 A and an inductance 35.72 μH; 1 - exit of micro-impurities to the surface under the influence of the temperature of the plasma

Under the influence of the temperature of the plasma, the micro-impurities (1) move to the surface. This is due to the fracture of weak adhesion bonds. With an increase in current strength up to 8 A, the hinge-shaped crystalline structures expand. This changes the anharmonicity of interatomic vibrations of weak fractions [31]. The Unit Cell Parameter increases by 0.5% [32] due to the expansion of crystalline structures, with the extension of their bonds. The crystalline structure is strengthened by reducing the concentration of defective structures and increasing the concentration of strong fractions.



5.1 5.2 5.3

Figure5: The surface of magnesite before and after plasma fracture, at 1000 times enlarged, Figure 5.1 - before plasma fracture; Figure 5.2 – applied current of 10 A, inductance 11.92 μH; Figure 5.3– applied current of 8 A, inductance 35.72 μH; where (1) – exit of micro-impurities to the surface under the influence of the temperature of plasma, (2) –are the main cracks from the influence of the sub-multiple of the resonant frequency, (3) are the craters from the influence of temperature

It was observed that under the influence of the temperature of the plasma, micro-impurities (1) move to the surface (Figure 5.2 and Figure 5.3). This is due to the fracture of weak fractions after the crystallization of magnesite. In Figure 5.2 and in Figure 5.3 there are cracks (2). Their thickness does not exceed 10 microns. They were formed as a result of the influence of the sub-multiple of the resonant frequency component of the inductive plasma flow on the crystalline structures of magnesite. The occurrence of oval shaped craters (3) with a diameter up to 10 μm is due to the effect of the temperature of plasma.

The reduction of the Young's modulus of samples in the region of indentation was experimentally determined before and after indentation according to ISO 14577-1: 2002:

$$\mathbf{E_r=(\square)^{0.5}/(2\cdot(dl/dF)\cdot A_p^{0.5})}, \qquad (6)$$

where $\mathbf{E_r}$ is Young's modulus of samples in the region of indentation [GPa], **dl** is Elongation of the sample [m], **dF** is Force applied to the sample [H], $\mathbf{A_p}$ is Cross-section of the contact surface between the indenter and the sample [m^2].

The area of the indenter is determined by the indirect method. A sample of hematite, which was not influenced by inductive plasma flows, was used to calibrate the indenter. In accordance with the introduced Young's modulus, a Young's modulus of samples has been determined, in accordance with the requirements of ISO 14577-1: 2002:

$$\mathbf{E=(1-\square_s^2)/((1/E_r)-((1-\square_i^2)/E_i))}, \qquad (7)$$

where **E** is the Young's modulus of sample [GPa], $\square_s$ is Poisson coefficient of sample [-], $\mathbf{E_r}$ is Young's modulus of samples in the region of indentation [GPa], $\square_i$ is Poisson coefficient of diamond indenter [-], $\square_{\square}$ isYoung's modulus of diamond the indenter [GPa].

Young's modulus depends on the current strength and inductance. The experimental values of the measured Young's modulus are compared with their theoretical values in the Figure 6.

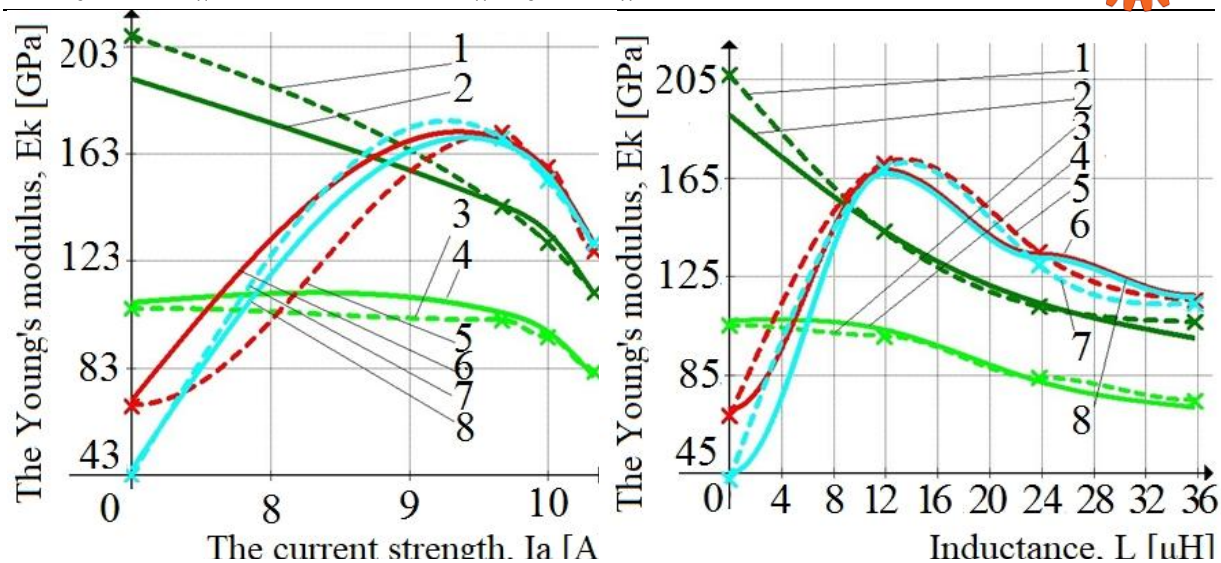


Figure 6: The dependence of the Young's modulus on the current strength (left) and the inductance (right), where 1, 2 are the curves of hematite values, 3, 4 - quartz, 5, 6 - calcite, 7, 8 – magnesite, theoretical and experimental, respectively

For the hardest of the samples, hematite, a reduction of the Young's modulus by half from 207.5 GPa to 107.3 GPa was achieved by an increase in inductance up to 35.76 µH. A reduction of Young´s modulus from 207.5 GPa to 111.7 GPa was the result of an increase in the current up to 10 A. The error between the experimental values of the Young's modulus and the theoretical values of the Young's modulus (calculated by applying equation (4)) does not exceed 7.7%. This means that experimental data converge with analytical ones. The experimentally determined values of the Young's modulus before and after the plasma fracturing can be used to calculate the specific work of the processes of weakening of minerals from equation (5).

The peaks for Young´s modulus for calcite and magnesite in Figure 6 can be explained by a larger energy of their crystalline structures, comparable to the energy of the crystalline structures of hematite and quartz (Table II).

Table II: Energy of crystalline structures of samples

Internal energy of crystalline structures of samples [34], $\sum\varepsilon_i \cdot 10^{-19}$ [J]			
Si_2O	Fe_2O_3	Ca_2CO_3	$MgCO_3$
8.5	7.4	11.0	10.0

As we can see from Table II, the energy of crystalline structures of hematite and quartz is less than $10 \cdot 10^{-19}$ J. So, the authors of this article are assuming that in the fracturing of rocks with a crystalline energy of less than $10 \cdot 10^{-19}$ J, it makes sense to use combined plasma-mechanical destruction applying a current of 10 A and an inductance of 35.76 µH. When the energy of crystalline structures is $10 \cdot 10^{-19}$ J and above, plasma-mechanical fracturing is not recommended.

The drilling speed depends on the Young's modulus. It determines the daily productivity of the drilling [30]. The drilling speed depends on the current strength and inductance:

$$\mathbf{Q_{T.DOB}=(2.5 \cdot F_0 \cdot n_B) \cdot t_{zminy}/(0.05 \cdot (K_T \cdot 3 \cdot E \cdot \square + \square \cdot g) \cdot d_K^2 \cdot P_{PYT})}, \quad (8)$$

where $\mathbf{Q_{T.DOB}}$ is the daily productivity of the drilling [m/8 hours], $\mathbf{F_0}$ is Axial force on the bit [N], $\mathbf{n_B}$ is Linear bit rate [m/h], $\mathbf{t_{zminy}}$ is Time of working change [h], $\mathbf{K_T}$ is Fracture coefficient of rock's formations [-], **E** is Young's modulus [Pa], □ is Relative elongation [-], □ is Density of rock's formation [kg/m^3], **g** is Acceleration of free fall [m/s^2], $\mathbf{d_K}$ is Diameter of the well [m], $\mathbf{P_{PYT}}$ is Pressure on the surface of the rock's formation [Pa].

The model described by equation 8 differs from existing ones by taking into account Young's modulus of the rock formation after plasma fracturing. In Table III the results of calculations of the daily productivity of the drilling according to equation 8 are presented.

Table III:Results of calculations of the daily productivity of the drilling

Parameter	The daily productivity of the drilling with SBSh-250 drilling unit [m/8 hours]		Working parameter of the inductive plasma fracture unit
Plasma mechanical fracturing			
Structure	Calculated with theoretical values of the Young's modulus	Calculated with experimental values of the Young's modulus	Inductance, μH
Hematite	15.20	14.32	0
	18.53	18.57	11.92
	21.45	21.64	23.84
	23.25	22.39	35.76
Quartz	2.63	2.68	0
	2.72	2.79	11.92
	3.39	3.32	23.84
	3.85	3.74	35.76
Calcite	43.40	44.26	0
	23.76	23.76	11.92
	28.28	28.28	23.84
	31.15	31.15	35.76
Magnesite	15.55	20.36	0
	5.94	5,86	11.92
	7.37	7.53	23.84
	8.36	8,50	35.76
Plasma mechanical fracturing			
Structure	Calculated with theoretical values of the Young's modulus	Calculated with experimental values of the Young's modulus	Amperage [A]
Hematite	15.20	14.32	0
	18.53	18.57	8
	19.42	19.84	9
	21.93	21.86	10
Quartz	2.63	2.68	0
	2.72	2.79	8
	2.91	2.98	9
	3.51	3.43	10
Calcite	43.40	44.26	0
	23.76	23.48	8
	25.11	25.02	9
	29.03	29.50	10
Magnesite	19.55	20.36	0
	5.94	5.86	8
	6.35	6.45	9
	7.55	7.53	10

The values of the daily productivity of plasma-mechanical rock fracturing were calculated using the theoretical values of the Young's modulus (from equation (4)) and compared with the values of the daily productivity of plasma-mechanical rock formation fracturing calculated using experimental values of the Young's modulus (according to Table III). Equation (8) takes into account the influence of plasma on the rock surface, which causes a change of the Young's modulus. The mechanical fracturing is taken into account by applying equation (8) to the working parameters of drilling unit, such as: axial force on the bit, linear bit rate, pressure on the surface of the rock's formation. An increase in the current of up to 10 A raises the daily drilling depth of the SBSh-250, which is a drilling unit commonly used in the Ukraine, in the fracturing of hematite by 52% from 14.32 m/day to 21.86 m/day. This is due to the decrease of the Young's modulus due to the lowering

of the rock's hardness by the plasma. When the inductance is increased to 35.76 μH, the daily drilling depth of the SBSh-250 unit in hematite increases by 56% from 14.32 m/day to 22.39 m/day. In quartz, the daily drilling depth of the SBSh-250 unit increases from 2.68 m/day to 3.43 m/day increasing current up to 10 A, and from 2.68 m/day to 3.74 m/day increasing inductance up to 35.76 μH. With an increase of current up to 10 A and of inductance up to 35.76 μH, the daily productivity of the destruction of calcite and magnesite decreases by more than 30%.

The error between the experimental and theoretical values does not exceed 8%. Therefore, the results of mathematical modeling can be considered to represent the real value.

In the study, an analysis of relevant literature sources was carried out starting from the 1940´s. The classic researches of Griffiths, Irvine and others are the foundation for the analysis of energy of crystalline structures of rock formations. Based on these and on contemporary literature, the authors assessed the potential to use energy of crystalline rock structures to increase the productivity of plasma-mechanical fracture of rock formations.

For rocks with an internal energy of the crystalline structures of less than $10 \cdot 10^{-19}$ J, it makes sense to use combined plasma - mechanical fracturing applying a current of 10 A or an inductance of 35.76 μH. When the energy of crystalline structures is $10 \cdot 10^{-19}$ J and above, it is not recommended to use plasma-mechanical fracturing, because the specific energy consumption will be higher than the specific energy consumption of purely mechanical drilling.

A model of the specific energy consumption of combined plasma-mechanical destruction was derived. It takes into account:

- the circular frequency of own oscillations;
- the internal energy of the rock;
- the Unit Cell Parameter;
- the diameter of the unit cell of the crystalline structure.

This allowed to determine the effect of a rock´s physical parameters on the energy consumption of fracturing. Corrective functions were introduced in equation 4. The influence of internal and external sources of energy on the specific energy consumption for the destruction of crystalline structures was described.

When the current strength is more than 10 A and the inductance is higher than 35.76 μH, a significant fraction of crystalline structures was destroyed by the plasma. Therefore, the specific energy consumption of the plasma-mechanical fracturing decreased by 25% compared to mechanical fracturing. For hematite, compared to purely mechanical drilling, the specific energy consumption of plasma-mechanical fracturing

- decreased from 0.575 GJ/m^3 to 0.414 GJ/m^3 when the current strength is 10 A;
- decreased from 0.575 GJ/m^3 to 0.350 GJ/m^3 when an inductance is 35.76 μH.

For example, for a quarry with an annual production of 100,000 m^3/a hematite, energy savings can be up to 16,100 GJ/a or 4.47 GWh/a.

5. Conclusions

In this research, the following results were achieved:

1. A mathematical model of the energy of an inductive plasma flow was modified. The resulting model differs from the existing ones by describing the dependency of the inductance and the current strength of the analysed inductive plasma fracturing unit.
2. A mathematical model of plasma-mechanical rock fracturing was adopted for the plasma rock fracturing unit. It depicts the influence of current and inductance of the plasma fracturing unit on the specific energy consumption of plasma mechanical rock fracturing with a unimodal distribution.
3. It was found, that in the destruction of structures with an internal energy of crystalline structures less than $10 \cdot 10^{-19}$ J, it makes sense to use a plasma - mechanical fracturing applying a current of 10 A or an inductance of 35.76 μH. When the energy of crystalline structures is $10 \cdot 10^{-19}$ J and above, it is not recommended to use plasma-mechanical fracturing, because then the specific energy consumption of plasma-mechanical fracture will be higher than the specific energy consumption of mechanical drilling.
4. The specific energy consumption of plasma-mechanical fracturing for hematite was reduced by 28% from 0.575 GJ/m^3 to 0.414 GJ/m^3 using a current strength of 10 A compared to the conventional process. With an increase in the current strength of the plasma fracture unit up to 10 A, the daily drilling depth of the SBSh-250 drilling unit in the fracturing of hematite increased by 52% from 14.32 m/day to 21.86 m/day. The plasma induced decrease of Young's modulus lowers the hardness of the rock. Increasing the inductance to 35.76 μH, improves the daily drilling depth of the SBSh-250 in hematite by 56% from

14.32 m/day to 22.39 m/day. In quartz, the daily advance of the SBSh-250 increases from 2.68 m/day to 3.43 m/day increasing the current to 10 A, and from 2.68 m/day to 3.74 m/day elevating the inductance up to 35.76 μH.

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