UDC 533:622.01.18

Makeyev S.Yu., Ph.D. (Tech.), Senior Researcher,
Osenniy V.Ya., M.S (Tech),
Ryzhov G.A., M.S (Tech),
Osennyaya N.V., M.S (Tech)
(IGTM NAS of Ukraine)
Holyavik O.V., Ph.D. (Tech.), Associate Professor
(National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute")

THEORETICAL CONSIDERATION OF PLASMA ENERGY TRANSFER TO THE ROCK MASS

Макєєв С.Ю., канд. техн. наук, ст. наук. співр.,
Осінній В.Я., магістр,
Рижов Г.О., магістр,
Осіння Н.В., магістр
(ІГТМ НАН України),
Холявік О.В., канд. техн. наук, доцент
(Національний технічний університет України
«КПІ ім. І. Сікорського»)

ТЕОРЕТИЧНЕ ОБҐРУНТУВАННЯ ПЕРЕДАЧІ ЕНЕРГІЇ ПЛАЗМИ В ГІРСЬКИЙ МАСИВ

Макеев С.Ю., канд. техн. наук, ст. науч. сотр.
Осенний В.Я., магистр,
Рыжов Г.А., магистр,
Осенняя Н.В., магистр
(ИГТМ НАН Украины)
Холявик О.В., канд. техн. наук, доцент
(Национальный технический университет Украины
«КПИ им. И. Сикорского»)

ТЕОРЕТИЧЕСКОЕ ОБОСНОВАНИЕ ПЕРЕДАЧИ ЭНЕРГИИ ПЛАЗМЫ В ГОРНЫЙ МАССИВ

Abstract. The article is devoted to the problem of hard ores, in particular of ferruginous quartzites, thermodynamic destruction with the help of new environmentally friendly and saving-resource technologies of blasting operations in the Kryvyi Rih basin. Until now, no more effective methods have been developed for making underground chambers for explosive substances, than the plasma method, though control of plasma torch thermodynamics remains a live problem. This method allows making chambers of any configurations. The article presents results of theoretical studies of how plasma impacts on the iron ore mass. The dependencies of distribution of temperature loads and normal and tangential stresses in the rock on time and coordinate are specified. It is stated that tensile stresses of magnetic quartzites being treated by plasma is ten times greater than compressive stresses. Calculations, which take into account rock pressure, convective and radiant heat transfer from the plasma jet specify essentially more exactly geometry of stress distribution, time of stress diffusion, density of thermal field in the surface sector of the borehole. Scientific novelty of the presented results lies in justification of models of plasma-flow impact on the iron ore mass in the pre-fracture zone at the borehole expansion. The results can be used in technological processes of breaking hard ores into the camera, during sinking the raise workings and during construction of the cutting slots and other workings for domestic purposes.

Keywords: chamber cavity, plasma, temperature loads, tensions.

Introduction

At the turn of the twenty-first century low-temperature plasma has shown itself as an important element of the new industrial technologies. Plasma technology allowed us to implement processes, not occurring in the usual classical conditions. The simplest way to obtain plasma is in thermal ionization in electric discharge. The plasma temperature of monatomic gases does not exceed 13000 ^{0}K, diatomic – 8000^{0}K.

Due to the high temperature and electrical conductivity, plasma has an extremely powerful energetic impact on the treated material, in its role as a universal coolant and reactant. Using plasma can be performed practically any exothermic reaction [1].

Over the last 30-35 years in various industries around the world, the wide application of plasma technology have been found – hardening the surface layer of the products [2], welding and cutting of metals [3], the processing of superhard materials [4, 5], coating [6], the burning of low-grade coals [7].

After a period of formation and development, plasmotron engineering has become an independent branch. Scientific researches in the field of gas dynamics and electrophysics, study of the principles of the plasma torch operation, the interaction of the electric arc with the gas flow, as well as the search for new design schemes and technical solutions have no borders [8].

Problem and communication with scientific and practical tasks

The practice of underground mining of magnetite quartzite in Kryvyi Rih basin have shown the complexity of drilling and blasting complex of works at breaking strong ores. Preparation of cavities for placement of explosives in the rock mass is an important technological component during the roadway. The energy blast emitted by the rock mass of strong ores transforms using the chamber cavity in comparison with the explosion of the cylindrical charge. Nowadays it is possible to create the chamber cavity thermally method using plasma generators. Plasmatrons as a working part on mining machines have found their applications in technologies for mining and ore production, as the breaking of strong ores to the camera, sinking raising and horizontal workings, the creation of cutting slots, draw holes, and other workings for household purposes. Theoretical estimation the changing of the explosion energy, that was emitted in the rock mass during creation a chamber extensions in borehole previously drilled by mechanical means is given in paper [9].

After a period of formation and development of plasma technologies in mining enterprises of Kryvyi Rih basin, needed to produce analytical studies of stress fields in iron ore extended rock mass around the borehole.

A stress state of the rock mass, conditioned by pressure in rocks, affects essentially on process of rock destruction by means of thermal method in technology of the underground borehole reaming. The efficiency of this process is determined by the nature of thermoelastic stresses distribution, originating in surface layer of borehole. To estimate it and to select the operating conditions of the plasma generator was solved a problem by definition of temperature fields and thermoelastic stresses in borehole walls with allowance for thermal (radiant and convective) and mechanical (forces of a rock pressure) affecting.

Formulation and solution a problem

To determine a field temperature and elastic stresses and their time dependence outside of area, restricted walls of a cylindrical section cavity with radius r=R (fig. 1), inside which one constant temperature T_0 is maintained. The cylindrical surface is exposed to radiant and convective affecting. At the initial moment temperature on a wall equals to zero degrees. Temperature on infinity equals to zero degrees.

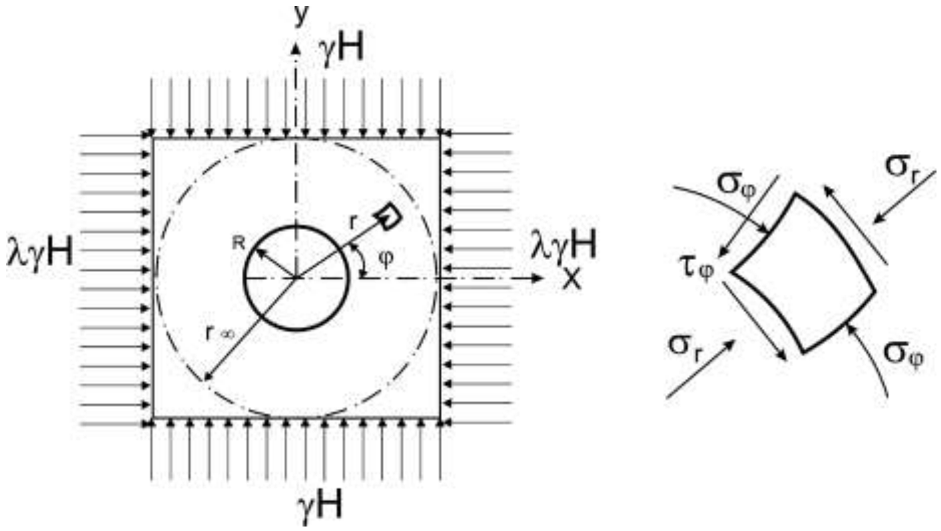


Figure1 – Transverse section of borehole and fragment of the rock mass with the distribution of tensions

It is necessary to solve two differential equations:

$$\frac{\partial^2 T(r,t)}{\partial r^2} + \frac{1}{r}\frac{\partial T(r,t)}{\partial r} = \frac{1}{a}\frac{\partial T(r,t)}{\partial t}$$

$$-\lambda \frac{\partial T(R,t)}{\partial r} = H\left(T_o - T(R,t)\right) + \sigma_o\left(T_o^4 - T^4(R,t)\right),$$

according to following initial and boundary conditions:

$$T(r,t=0)=0;\ T(r=\infty,t)=0.$$

In this equations a – thermal diffusivity coefficient, λ – thermal conductivity coefficient, H – heat transfer coefficient, σ_0 – Stefan-Boltzmann constant.

Solving a problem, the nonlinear boundary conditions are reduced to a linear disturbance method, then the solution is represented in the way of series with rising degrees and the problem is disintegrated on a sequence of boundary-value problems. After that the method of an integral Laplace transformation will be used and the field of solution is applied to a closed contour due to the functions of a complex variable. After integrating, having taken advantage asymptotic disintegrating of the Bessel functions, the final solution for thermal affecting is obtained.

For definition of a stress tensor around of bore hole with round cross-section in a homogeneous isotropic elastic massif with allowance of thermal affecting and forces of a rock pressure we use a polar coordinate system with the beginning at center of hole. To determine three stress tensor components σ_r, σ_φ, $\tau_{r\varphi}$ and three strain tensor components ε_r, ε_φ, $\varepsilon_{r\varphi}$, is necessary to decide a set of equations, including two equilibrium equations:

$$\frac{\partial\sigma_r}{\partial r}+\frac{1}{r}\frac{\partial\tau_{r\varphi}}{\partial\varphi}+\frac{\sigma_r-\sigma_\varphi}{r}=0, \qquad \frac{\partial\tau_{r\varphi}}{\partial r}+\frac{1}{r}\frac{\partial\sigma_\varphi}{\partial\varphi}+\frac{2\tau_{r\varphi}}{r}=0,$$

the equation of strain compatibility:

$$\frac{\partial^2\left(r\varepsilon_\varphi\right)}{\partial r^2}-2\frac{\partial^2\left(r\varepsilon_{r\varphi}\right)}{\partial r\partial\varphi}-r\frac{\partial\varepsilon_r}{\partial r}=0$$

and three equations, depicting a Hooke law with allowance of thermal expansion:

$$\begin{aligned}\varepsilon_r &= \frac{1+\mu}{E}\left((1-\mu)\sigma_r-\mu\sigma_\varphi\right)+(1+\mu)\beta T\\ \varepsilon_\varphi &= \frac{1+\mu}{E}\left((1-\mu)\sigma_\varphi-\mu\sigma_r\right)+(1+\mu)\beta T\\ \varepsilon_{r\varphi} &= \frac{1+\mu}{E}\tau_{r\varphi}.\end{aligned}$$

In these equations μ – Poisson’s ratio, E – isothermal modulus of elasticity, β – linear thermal expansion coefficient, T – function, obtained as a result of a solution of the first part of the problem.

As boundary conditions we take into consideration: with removal from the hole stresses aim to those values, which one act in an undisturbed massif. It was comfort to transform them in Cartesian coordinate system:

$$\lim_{r\to\infty}\sigma_x=-\lambda\gamma H, \qquad \lim_{r\to\infty}\sigma_y=-\gamma H,$$

where γH – characterizes the quantity of a rock pressure, λ – side thrust coefficient.

On the contour of hole, where r=R, it is satisfied the condition $\sigma_r = \tau_{r\varphi} = 0$.

For a solution of this set of equations was used the method, which well-known in theory of elasticity, when three stress tensor components express through one required stress function F:

$$\sigma_r = \frac{1}{r}\frac{\partial F}{\partial r} + \frac{1}{r}\frac{\partial^2 F}{\partial \varphi^2}; \qquad \sigma_\varphi = \frac{\partial^2 F}{\partial r^2}; \qquad \tau_{r\varphi} = -\frac{\partial}{\partial r}\left(\frac{1}{r}\cdot\frac{\partial F}{\partial \varphi}\right)$$

Having substituted last three expressions in the equations, depicting a Hooke law, and obtained values ε_r and ε_φ in the equation of strain compatibility, finally we shall receive a partial equation for function F:

$$\nabla^2\nabla^2 F(r,\varphi,t) + \frac{\beta E}{1-\mu}\nabla^2 T(r,t) = 0, \quad \text{где } \nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \varphi^2}$$

The general solution is represented in the way of sum of general solutions of a biharmonic equation and particular solution of original equation.

Results

The example of calculation of a thermal field for initial temperature $T_0 = 1500$ °C is reduced in a fig. 2.

In fig. 3 are shown consequently dynamics of variation of values a stress tensor components σ_r and σ_φ for initial temperature $T_0 = 1500$ °C at a different valid time of this temperature.

In fig. 4 are shown the stress distribution in a near-surface layer of borehole during plasma exposure for different depth.

Conclusions and recommendations

The solution algorithm of the problem about distribution of temperature and dynamic stresses in mining rocks is developed by means of boreholes expansion by thermal method with allowance for rock pressure and radiant heat change. It is established, that the value of tensile stresses for magnetite quartz in plasma processing is 10 times more than magnitude of compression stresses that confirms the results of the paper [9]. Moreover, the compression stresses are mainly massed in surface heating zone, and tensile stresses are affected further deep into the rock mass. The magnitude of the stresses is influenced by the pressure of rocks. Its contribution may reach 12-17 % in comparison with the values of the stresses in the unstressed rock mass.

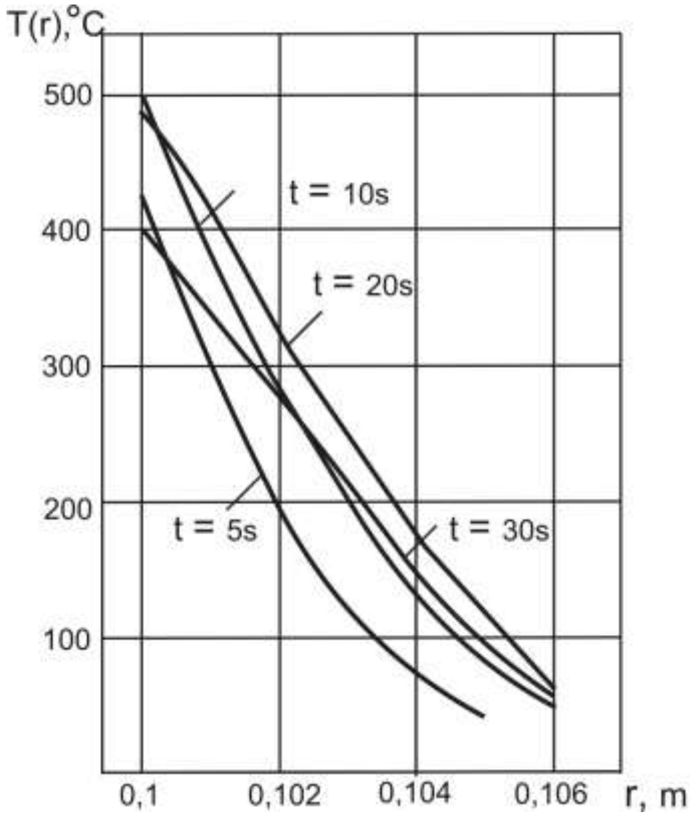


Figure 2 – Distribution of thermal field in a near-surface layer of borehole during plasma exposure

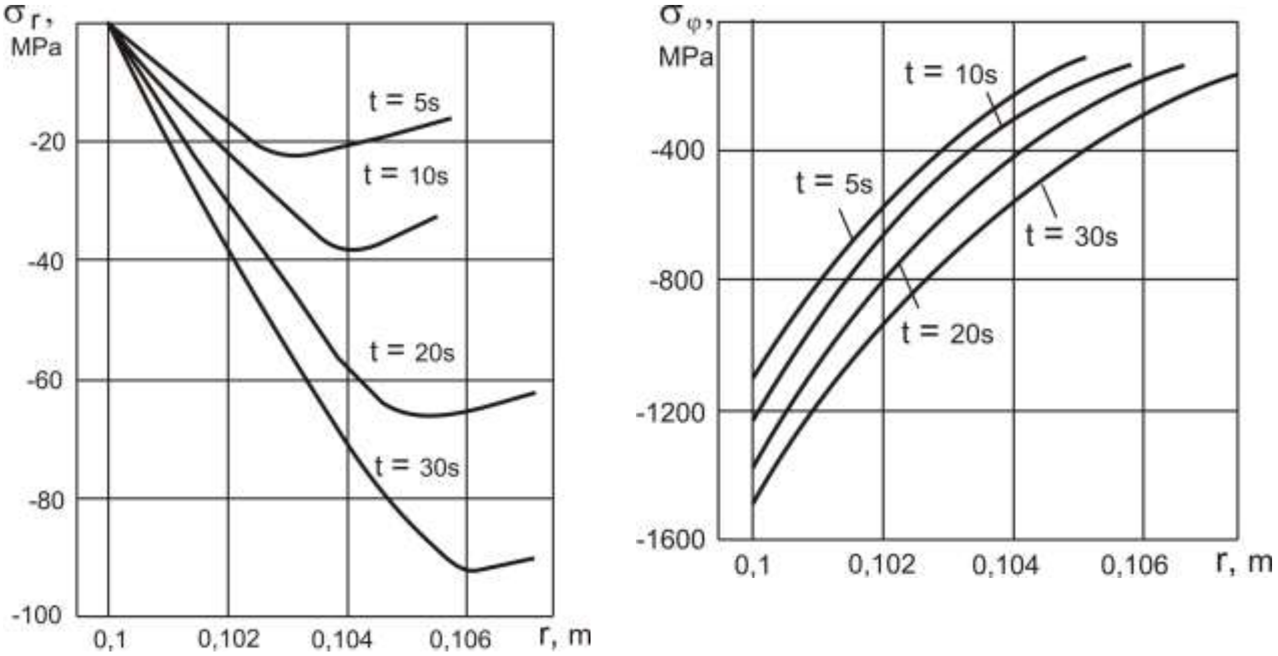
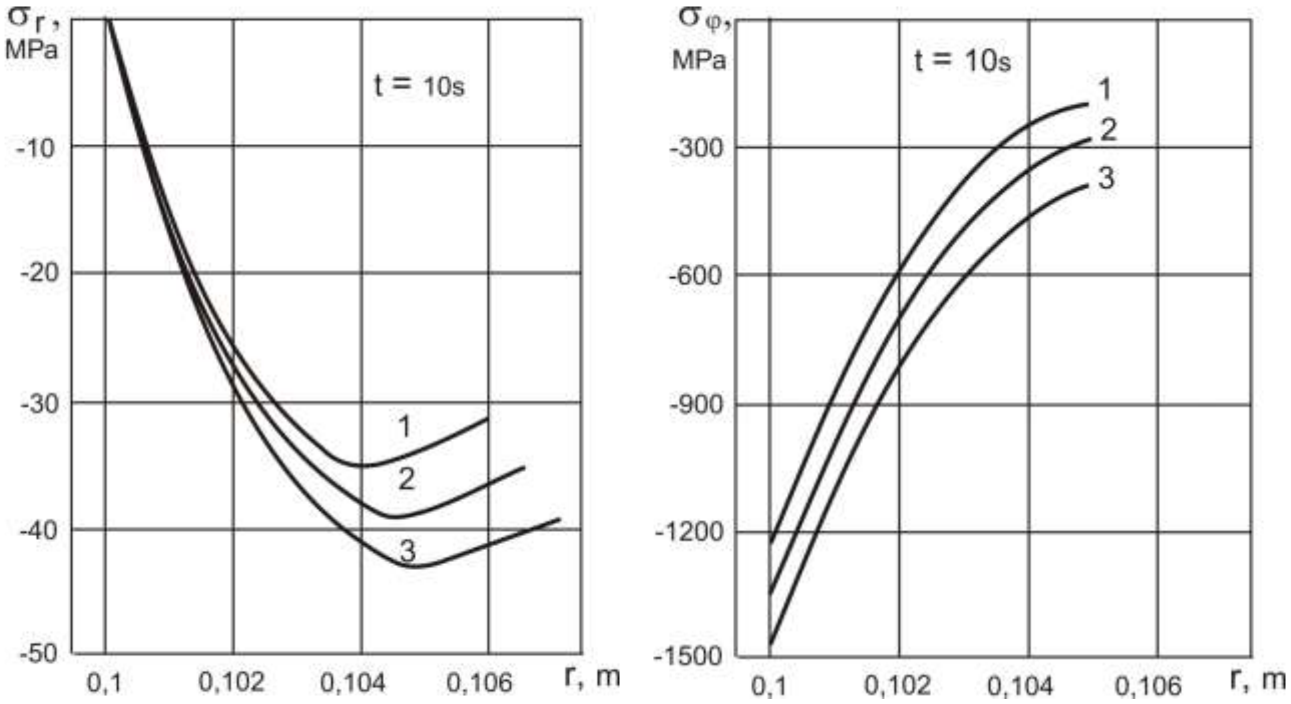


Figure 3 – Stress distribution in a near-surface layer of borehole during plasma exposure



1– γH = 100 MPa; 2– γH = 200 MPa; 3 – γH = 300 MPa
Figure 4 - Stress distribution in a near-surface layer of borehole during plasma exposure for different depth

The account in calculations of a rock pressure and radiant heat change from the plasma jet has allowed essentially updating geometry of the stress distribution, time of their propagation, density of temperature field in a surface band of borehole. Using the proposed algorithm of solution for each specific geological conditions it is possible to select thermal and structural parameters of the plasma torch ensuring the creation in the rock, the maximum thermal stress and higher productivity of the process of destruction. The obtained results were used in researches of boreholes plasma expansion. The installations have been tested in conditions a series Kryvyi Rih region mines.

REFERENCES

1. Bulat, A.F. and Osenniy, V.Ya. (2007), «The deforming and destruction of solid bodies in the plasma technology», *Materialy XVII Mezhdunarodnoy nauchnoy shkoly 17 sentyabrya 2007 g.* [Materials of XVII International Scientific School], *Deformirovaniye i razrusheniye materialov s defektami i dinamicheskiye yavleniya v gornykh porodakh i vyrabotkakh* [The deforming and destruction of materials with troubles and dynamic phenomena in rocks and excavations], . – Simferopol, UA, 17.09.2007, pp. 61–65.

2. Zreris, R., Nowotny, S., Bergel, k.-V., Hambold, L. and Beyer, E. (2003), «Characterization of coatings by laser-assisted atmospheric plasma spraying», *Proc. of Thermal Spray Conf,* Orlando, USA, pp. 567-572.

3. Anshakov, A. (1999), «Plasma welding of thin-wall tubes», *Progress in Plasma Processing of Materials. Eds. P. Fauchais and J. Amoroux. N.Y,* Begell House, Inc., pp. 501-505.

4. Bulat, A.F., P. V. Bulany, and V.Ya. Osenniy (2003), «Control of the heat flux distribution at the anode of a transferred arc argon stabilized and flowing in air», *Progress in Plasma Processing of Materials. Eds. P. Fauchais,* Begell House. N.Y. Wallingford, pp. 211-218.

5. Osenniy V.Ya., Osinnja, N.V. and Holyavik, O.V/ (2016), «Thermodynamic loads and plastic deformation in the cutting zone during processing of the cones crushers», *Materialy Mizhnarodnoyi naukovo-tekhnichnoyi internet-konferentsiyi, 14 grudnya 2016 r.* [Proceedings of the International Scientific

and Technical Internet-conference], *Innovatsiyniy rozvytok girnychodobuvnoy galuzi* [Innovative Development of the Mining Industry], Kryvyi Rih, UA, 14.12.2016, pp. 263.

6. Sasaki S., Shimura, H., H., Kawakami, Y. and Shahzad, A. (1995), «Laser assisted plasma spray coating method for surface modification of tribo-materials», *Proc. of ITSC'95*, Kobe, Japan, May, 1995, Vol. 1, pp. 267-271.

7. Bulat, A., Shumrikov, V. and Osenniy, V. (2005), «Sublimation and combustion of coal particles in the erosion laser torch», *High Temperature Material Processes: An International Quarterly of High Technology Plasma Processes*, Vol.9, pp.443-452.

8. Osenniy, V.Ya. (2015), «Electric-arc plasmatron is a device for mining machines of a new generation», *UUEE*, no. 2, pp.16-21.

9. Bulat, A.F., Nikiforova, V.A. and Osenniy, V.Ya. (2006), «Improving the efficiency of drilling and blasting operations in the hard ores», *Visnik KSPI*, Vol. 2/2006(37), pp. 93-94.

СПИСОК ЛИТЕРАТУРЫ

1. Булат, А.Ф. Деформирование и разрушение твердых тел в плазменных технологиях / А.Ф. Булат, В.Я. Осенний // Деформирование и разрушение материалов с дефектами и динамические явления в горных породах и выработках: Матер. XVII Межд. науч. школы 17-23 сентября 2007 г. – Симферополь: Таврич. нац. ун-т, 2007. – С. 61-65.

2. Zreris, R. Characterization of coatings by laser-assisted atmospheric plasma spraying / R. Zreris, // Proc. of Thermal Spray Conf. – 2003. – Orlando: USA, 2003. – pp. 567-572.

3. Anshakov, A. Plasma welding of thin-wall tubes / A. Anchakov // Progress in Plasma Processing of Materials. Eds. P. Fauchais and J. Amoroux. - N.Y.: Begell House, Inc., 1999. – pp. 501-505.

4. Bulat, A. Control of the heat flux distribution at the anode of a transferred arc argon stabilized and flowing in air / A. Bulat, P. Bulany, V. Osenniy // Progress in Plasma Processing of Materials. Eds. P. Fauchais. Begell House. - N.Y.: Wallingford, 2003. – pp. 211-218.

5. Осінний, В.Я. Термодинамічні навантаження та пластичні деформації в зоні різання при обробці конусів дробарок / В.Я. Осінний, Н.В. Осіння, О.В. Холявік // Інноваційний розвиток гірничодобувної галузі: Матеріали Міжнародної науково-технічної інтернет - конференції, 14 грудня 2016 р. - Кривий Ріг: ДВНЗ Криворізький національний університет, 2016. – С. 263.

6. Sasaki, S. Laser assisted plasma spray coating method for surface modification of tribo-materials / S. Sasaki, H. Shimura, Y. Kawakami, A. Shahzad // Proc. of ITSC'95 - Kobe, May, 1995 - Vol. 1. – pp. 267-271.

7. Bulat, A. Sublimation and combustion of coal particles in the erosion laser torch / A. Bulat, V. Shumrikov, V. Osenniy // High Temperature Material Processes: An International Quarterly of High Technology Plasma Processes. – 2005. – Vol. 9. – pp.443-452.

8. Осенний, В.Я. Электродуговой плазмотрон – рабочий орган горных машин нового поколения / В.Я. Осенний // УСИВ. – 2015. – № 2. – С.16-21.

9. Булат, А.Ф. Повышение эффективности буровзрывных работ в крепких рудах / А.Ф. Булат, В.А. Никифорова, В.Я. Осенний // Вісник КДПУ. – 2006. – Вип. 2/2006(37). – С.93-94.

About the authors

Makeyev Sergey Jurievich, Candidate of Technical Sciences (Ph.D), Senior Researcher, Senior Researcher in Department of Mineral Mining at Great Depths, M.S. Polyakov Institute of Geotechnical Mechanics under the National Academy of Sciences of Ukraine (IGTM, NASU), Dnipropetrovsk, Ukraine, symakeyev@nas.gov.ua

Osinniy Valentin Yakovlevich, Master of Science (M.S), Researcher in Department of Mineral Mining at Great Depths, M.S. Polyakov Institute of Geotechnical Mechanics under the National Academy of Sciences of Ukraine (IGTM, NASU), Dnipropetrovsk, Ukraine, vyosinniy@nas.gov.ua

Ryzhov Gennadiy Aleksandrovich, Master of Science (M.S), Junior Researcher in Department of Mineral Mining at Great Depths, M.S. Polyakov Institute of Geotechnical Mechanics under the National Academy of Sciences of Ukraine (IGTM, NASU), Dnipropetrovsk, Ukraine, goryzhov@nas.gov.ua

Osinnyaya Nataliya Volodymyrivna, Master of Science (M.S), Junior Researcher in Department of Elastomeric Component Mechanics in Mining Machines, M.S. Polyakov Institute of Geotechnical Mechanics under the National Academy of Sciences of Ukraine (IGTM, NASU), Dnipropetrovsk, Ukraine, osennjaja1@yandex.ru

Holyavik Olga Vitaliyvna, Candidate of Technical Sciences (Ph.D), Associate Professor, Associate Professor of Department of Mechanics Plasticity of Materials and Resource-Saving Processes, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnical Institute", Institute of Mechanical Engineering (I. Sikorsky KPI), Kyiv, Ukraine, k_omd@ukr.net

Об авторах

Макеев Сергей Юрьевич, кандидат технических наук, старший научный сотрудник, старший научный сотрудник в отделе проблем разработки месторождений на больших глубинах, Институт геотехнической механики им. Н.С. Полякова Национальной академии наук Украины (ИГТМ НАН Украины), Днепропетровск, Украина, symakeyev@nas.gov.ua

Осенний Валентин Яковлевич, научный сотрудник в отделе проблем разработки месторождений на больших глубинах, Институт геотехнической механики им. Н.С. Полякова Национальной академии наук Украины (ИГТМ НАН Украины), Днепропетровск, Украина, vyosinniy@nas.gov.ua

Рыжов Геннадий Александрович, младший научный сотрудник в отделе проблем разработки месторождений на больших глубинах, Институт геотехнической механики им. Н.С. Полякова Национальной академии наук Украины (ИГТМ НАН Украины), Днепропетровск, Украина, goryzhov@nas.gov.ua

Осенняя Наталья Владимировна, младший научный сотрудник в отделе механики эластомерных конструкций горных машин, Институт геотехнической механики им. Н.С. Полякова Национальной академии наук Украины (ИГТМ НАН Украины), Днепропетровск, Украина, osennjaja1@yandex.ru

Холявик Ольга Витальевна, кандидат технических наук, доцент, доцент кафедры механики пластичности материалов и ресурсосберегающих процессов, Национальный технический университет Украины Киевский политехнический институт им. И. Сикорского, Механико-машиностроительный институт («КПИ им. И. Сикорского»), Киев, Украина, k_omd@ukr.net

---

Анотація. Стаття присвячена проблемі термодинамічного руйнування міцних руд, зокрема залізистих кварцитів із застосуванням нових екологічних ресурсозберігаючих технологій ведення підривних робіт у Криворізькому басейні. Для підземних умов до теперішнього часу не розроблено більш ефективних методів утворення котлових порожнин для розміщення в них вибухових речовин, ніж плазмовий. Актуальною є проблема управління термодинамікою плазмового факела. Завдяки цьому можна створювати котлові порожнини різних конфігурацій для розміщення вибухових речовин. У статті наведено результати теоретичних досліджень плазмового впливу на залізорудний масив. Отримані залежності розподілу температурного навантаження, нормальних і тангенціальних напружень у гірській породі від часу і по координаті. Встановлено, що величина розтягувальних напружень для магнетитових кварцитів при плазмовій обробці в десять разів більше величини стискуючих напружень. Облік в розрахунках гірського тиску, конвективного і променистого теплообміну від плазмового струменя дозволив істотно уточнити геометрію розподілу напружень, час їх поширення, щільність теплового поля в поверхневій зоні свердловини. Наукова новизна наведених результатів полягає в обґрунтуванні моделей впливу плазмових потоків на залізорудний масив в зоні передруйнування при розширенні свердловини. Наведені результати можуть бути використані в технологічних процесах відбивання міцних руд на камеру, при проходці підняттєвих виробок, при спорудженні відрізних щілин та інших виробок господарського призначення.

Ключові слова: котлова порожнина, плазма, температурне навантаження, напруження

Аннотация. Статья посвящена проблеме термодинамического разрушения крепких руд, в частности железистых кварцитов с применением новых экологических ресурсосберегающих технологий ведения взрывных работ в Криворожском бассейне. Для подземных условий до настоящего времени не разработано более эффективных методов образования котловых полостей для размещения в нем взрывчатых веществ, чем плазменный. Актуальной является проблема управления термодинамикой плазменного факела. Благодаря этому можно создавать котловые полости различных конфигураций для размещения взрывчатых веществ. В статье приведены результаты теоретических исследований плазменного воздействия на железорудный массив. Получены зависимости распределения температурной нагрузки, нормальных и тангенциальных напряжений в горной породе от времени и по координате. Установлено, что величина растягивающих напряжений для магнетитовых кварцитов при плазменной обработке в десять раз больше величины сжимающих напряжений. Учет в расчетах горного давления, конвективного и лучистого теплообмена от плазменной струи позволил существенно уточнить геометрию распределения напряжений, время их распространения, плотность теплового поля в поверхностной зоне скважины. Научная новизна приведенных результатов заключается в обосновании моделей воздействия плазменных потоков на железорудный массив в зоне предразрушения при расширении скважины. Приведенные результаты могут быть использованы в технологических процессах отбойки крепких руд на камеру, при проходке восстающих выработок, при сооружении отрезных щелей и других выработок хозяйственного назначения.

Ключевые слова: котловая полость, плазма, температурная нагрузка, напряжения.

Статья поступила в редакцию 25.06. 2016
Рекомендовано к печати д-ром техн. наук А.П. Круковским