UDC 622.(23.02:02):622.232

Estimation of abrasiveness impact on the parameters of rock-cutting equipment

Aleksandr B. ZHABIN[1], **Andrey V. POLYAKOV**[1]✉, **Evgenii A. AVERIN**[2], **Yuri N. LINNIK**[3], **Vladimir Yu. LINNIK**[3]
[1] *Tula State University, Tula, Russia*
[2] *OOO «Skuratovsky Experimental Plant», Tula, Russia*
[3] *State University of Management, Moscow, Russia*

Development of equipment, which provides access to underground mineral deposits and their extraction, requires the use of all the accumulated experience and advanced scientific research in the area of mechanical rock cutting. The most important issues of using mechanical rock cutting tools are their wearability and consumption, which have an impact on technical and economic indicators of project efficiency. The paper describes Russian and foreign practices of estimating tool wear resistance, expressions to determine critical cutting speed, methods to evaluate tool consumption. It is demonstrated that wearability of mechanical tools and associated effects are to a large extent defined by rock abrasiveness. It is highlighted that in Russia the index is calculated using Baron-Kuznetsov method, which is briefly described in the paper. In many countries with a highly-developed mining industry, rock abrasiveness is estimated with a Cerchar Abrasiveness Index (*CAI*), recommended by the International Society for Rock Mechanics. Its description is also presented in the paper.

Key words: cutting pick; wear; abrasiveness; calculation method; experimental method

Acknowledgement. Research results are published with financial support of Tula State University under the Scientific project N 2018-18.

How to cite this article: Zhabin A.B., Polyakov A.V., Averin E.A., Linnik Yu.N., Linnik V.Yu. Estimation of abrasiveness impact on the parameters of rock-cutting equipment. Journal of Mining Institute. 2019. Vol. 240, p. 621-627. DOI: 10.31897/PMI.2019.6.621

Introduction. Coal industry is one of the most mechanized branches of Russian mining sector; however, expanding of coal production and reduction of its costs require technical and engineering re-equipment of coal mines [2]. Rational use of tools and machinery is crucial for its successful implementation. It should be noted that the efficiency of road header use is to a great extent dependent on wear accounting and estimation of tool consumption. These processes influence the costs of mining project both directly (through the cost of tools) and indirectly (through time expenditure on their replacement, shorter life of the cutting tool, transmission elements, driving motor and other units of the machine).

Nowadays road headers as working tools are equipped with skew (rotary, conical, circular) cutting picks [7]. In the process of exploitation rotary picks break down due to failure of hard-alloy inserts, collapse and deformation of holders, it is not uncommon that the cutting picks get lost (Fig.1). Such kinds of breakages are caused by imperfect construction, manufacturing technology and holding tools, as well by mishandling and violation of operational conditions. Examples of the latter are: use of cutting picks under rock strength conditions beyond their technical characteristics, increased load on the picks due to wear failure of adjacent ones, not timely detected by personnel. But in most cases under ordinary conditions cutting picks fail due to their wear. It is the only natural and inevitable reason of tool resource depletion.

Russian research in the area of wear estimation of skew cutting picks. Wear of skew picks is a complex process, the history and intensity of which depend on a number of factors. It is unjustified to explain the wear mechanism by only one single factor, it can be a critical, a defining one, but it is bound to be accompanied by others.

All the factors, affecting the intensity of cutting pick wear, can be divided into three groups:

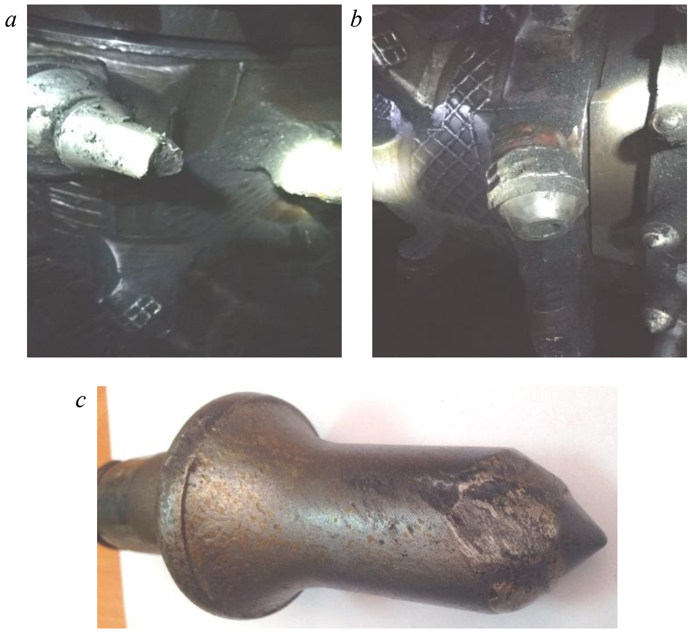

Fig.1. Several types of skew pick failure: *a* – failure of hard-alloy insert; *b* – pick loss; *c* – wear of holder head

- characteristics of the material, i.e. physical and engineering properties of the rocks, responsible for their wearing capacity;
- failure mode parameters and conditions of the external environment, where the process occurs;
- physical and engineering characteristics of the hard-alloy insert, holder head and their parameters.

Initial dependency for the calculation of specific pick consumption Z lies in the expression [5]:

$$Z = \frac{1000}{Lth}, \tag{1}$$

where L – length of cutting path before pick failure, km; t – spacing between the picks according to their location on the cutting tool, mm; h – chip thickness, mm.

Cutting pick failure can occur due to the wear of a holder head or a hard-alloy insert.

The length of cutting path before pick failure due to a holder head wear is estimated using the following formula [5]:

$$L_{\max h} = \frac{11.37\Delta_{\max}}{K_v K_0 K_{t/h} K_h K_d a^{0.69} \sigma_{\text{comp}}^{0.12}}, \tag{2}$$

where $\Delta_{\max}$ – maximum permissible exposure of hard-alloy insert, mm; K_v, K_0, $K_{t/h}$, K_h and K_d – coefficients taking into account, respectively: the impact of cutting speed, supply of water or water solutions into the zone of pick-rock interference, ratio between pick spacing t and chip thickness h, hardness of the holder head and diameter of the hard-alloy insert on the intensity of pick wear; a – abrasiveness index according to Baron-Kuznetsov, mg; σ_{comp} – tensile strength in uniaxial compression, MPa.

The length of cutting path before pick failure due to a hard-alloy insert failure is estimated using the equation:

$$L_{\max i} = L_{\max h} \frac{\psi_{\Delta i}}{\psi_{\Delta h}}, \tag{3}$$

where $\psi_{\Delta i}$ – wear intensity of hard-alloy insert, mm/km; $\psi_{\Delta h}$ – wear intensity of a holder head, mm/km;

The lower from two values $L_{\max h}$ and $L_{\max i}$ is used as L value in the estimation of specific pick consumption Z [see formula (1)].

The ratio $\psi_{\Delta i}/\psi_{\Delta h}$ is estimated as follows:

$$\frac{\psi_{\Delta i}}{\psi_{\Delta h}} = \frac{1}{0.346\,\text{arctg}(0.32a - 6.176) + 0.488}. \tag{4}$$

The maximum permissible exposure of hard-alloy insert can be derived from the dependency:

$$\Delta_{\max h} = \frac{(1.58d + 14.5)}{\sigma_{\text{comp}}^{0.346}}, \tag{5}$$

where d – diameter of a hard-alloy insert, mm.

Coefficient K_v is estimated using formula:

- for longitudinally rotating cutting heads

$$K_v = 0.24V + 0.754\,, \tag{6}$$

- for transversely rotating cutting heads

$$K_v = (0.24V + 0.754)\frac{t_p}{t_0}\,, \tag{7}$$

where V – cutting speed, m/s; t_p / t_0 – ratio of time when the cutting pick is in and out of contact with the rock per one head rotation.

Expressions (6) and (7) are applicable at cutting speeds in the interval from zero to the critical value, defined as the lower of two results, estimated using one of the following dependencies – compilations of the study [1]:

- by factor of holder head wear

$$V_{cr.h} = \frac{38.3\sigma_{\text{comp}}^{-0.3}a^{-0.73}}{2.46\frac{t_p}{t_0} + 0.4}\,, \tag{8}$$

- by factor of hard-alloy insert failure

$$V_{cr.i} = \frac{59.2\sigma_{\text{comp}}^{-0.26}a^{-0.92}}{2.46\frac{t_p}{t_0} + 0.4}\,. \tag{9}$$

It is recommended to specify the value of coefficient K_0, which takes into account dependency between water supply into the cutting zone and the intensity of cutting pick wear, depending on water pressure. At pressures 3.5-4.0 MPa, characteristic of Russian equipment, $K_0 = 0.75\text{-}0.85$, at pressures 4.0-20 MPa – $K_0 = 0.55\text{-}0.65$.

Coefficient $K_{t/h}$ can be calculated using the following dependency:

$$K_{t/h} = \frac{0.27t}{K_g \operatorname{tg}\varphi h^{0.5}}\,, \tag{10}$$

where t – pick spacing, mm; K_g – coefficient that takes into account pick geometry; tgφ – indicator of brittle-ductile properties; h – chip thickness, mm.

For characteristic mining and geological conditions of road header use in Russian coal industry $K_{t/h}$ roughly equals 1.

Coefficient K_h is estimated using formula

$$K_h = 0.55 - 0.0012T^2 + 0.066T, \tag{11}$$

where t – Rockwell hardness of the holder head (HRC).

Values of K_d are calculated as follows

$$K_d = 9/d. \tag{12}$$

Foreign research in the area of wear estimation of skew cutting picks. Numerous foreign studies are dedicated to examination of different aspects of skew rotary picks wear. However, the majority of those are aimed at diagnostics of the physical phenomenon and the mechanism of rotary picks wear. Among the quantitative models of tool wear estimation, a classical Archard formula [8] is quite well-known. According to it, wear rate $\dot{w}$ is proportionate to the contact pressure p_n and the speed of relative movement (sliding speed) v_t:

$$\dot{w} = k\frac{p_n v_t}{H}, \tag{13}$$

where k – non-dimensional wear parameter; H – tool hardness.

Initially Archard model relied on adhesive tool wear. However, the same formula has been obtained for abrasive wear as well [13].

Equation (13) is realized in different numeric algorithms with the construction of 2D and 3D models in order to assess the character of wear distribution on the tool surface. Wearing process is relatively slow, and it can only be observed after multiple work cycles. In numeric algorithms, the wear process is accelerated using scale factor.

Archard model is used to identify quantitative and qualitative indicators of cutting pick wear, but with a certain degree of accuracy it cannot be used for estimation of tool loading.

There is also another widely used wear model [14]. It is founded on an assumption that there is a positive correlation of tool wear with quartz content in the rocks, average size of its grains, as well as with the ultimate tensile strength of the rock. The authors have proposed to use a wearability factor F (kg per cm), which can be estimated as follows:

$$F = Qd_q\sigma_p, \tag{14}$$

where Q – equivalent quartz content by volume, %/100; d_q – average size of quartz grains, cm; σ_p – ultimate tensile strength, kg/cm^2.

Equivalent quartz content in the rock Q can be defined using the following recommendations [14]: 1 – for quartz grains; 0.35 – for feldspar; 0.03 – for calcite and 0.04 – for clay minerals. It is claimed that, in case $F < 1$, rock destruction must be quite effective. Approximate estimation of tool consumption, taking into account the above-mentioned factor, can be carried out using data from the table.

Estimation of pick consumption using wearability factor

Factor F	Abrasiveness classification	Pick consumption, m^3/pcs
< 0.05	Non-abrasive rock	90-110
0.05-0.07	Low-abrasive rock	50-90
0.07-1.0	Abrasive rock	30-50
1.0-1.05	Highly abrasive rock	10-30
> 1.05	Very highly abrasive rock	1-10

This factor of tool wearability can be used to estimate critical cutting speed (m/s) by the criterion of tool heating:

$$V_{\text{crit}} = \frac{k}{\exp(F)}, \tag{15}$$

where k – a constant, depending on cutting pick geometry and critical temperature of its hard alloy heating, usually $k = 8.4$ [14].

The most widely-spread approach to estimate skew pick consumption is the method based on diagrams, plotted on empirical data and associating tool consumption with Cerchar Abrasiveness Index (*CAI*) and their tensile compression strength [11]. Examples of such diagrams, developed by Sandvik, are published in the study [12] and presented in Fig.2.

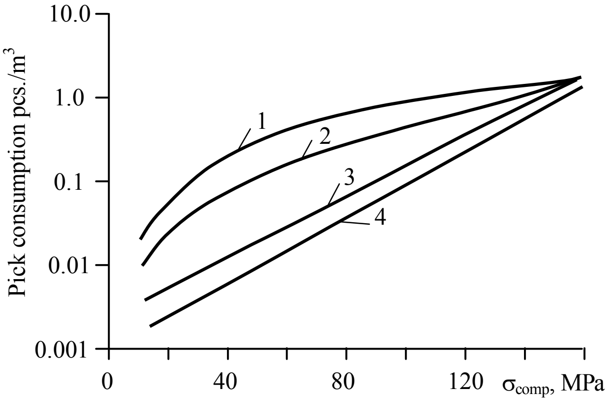

Fig.2. Specific pick consumption as a function of rock strength in uniaxial compression σ_{comp} and abrasiveness *CAI*

1 – *CAI* = 3; 2 – *CAI* = 2; 3 – *CAI* = 1; 4 – *CAI* = 0.6

Discussion of performed analysis between Russian and foreign studies. It is known that the most significant role in the wear of an operating tool in the process of rock destruction belongs to rock abrasiveness. In Russian coal industry the most frequently used way of estimating characteristics of abrasive rock properties is Baron-Kuznetsov method [6]. It is worth reminding that the summary of this method lies in the abrasion of a silver-steel cylindrical rod against the rock surface at rotation speed 400 rpm and axial loading 150 N over the period of 10 minutes. Abrasiveness indicator is estimated on the basis of rod mass reduction in milligrams in a specified time period. The attractiveness of this method lies primarily in its simplicity, considerable sensitivity to changes in abrasive rock properties and in a wide range of values obtained for various rock types (almost by two orders).

The very first experiments carried out at Skochinsky Institute of Mining and then at Novocherkassk Polytechnic Institute, have demonstrated the possibility to use Baron-Kuznetsov abrasiveness characteristics to estimate wear resistance of rock cutting instruments. According to practice, this method provides a considerably good (with a regard to calculation accuracy) estimation of abrasive capacity for strong and extra-strong rocks. The reverse is true for low-strength rock tests. Irrespective of quartz content, predicted value of pick wear resistance is constantly underestimated. This is explained by the fact that during the experiment a steel rod is indented into the rock surface. Depending on rock strength, the depth of indentation can reach up to 8-10 mm and more. As a result, the lateral side of the rod wears out. Moreover, due to indentation, quartz particles accumulate under the cutting face of the rod, and eventually the abrasiveness indicator gets overestimated, falling out of line with the intensity of pick wear in the actual process of rock cutting. However, research at Skochinsky Institute of Mining shows that these shortcomings can theoretically be eliminated by means of certain changes in the experiment procedure. Without changing total duration (10 minutes) at one test site, it has been proposed to perform each experiment at several test sites, accordingly reducing duration of a separate test. For example, 5 test sites two minutes each or 10 test sites one minute each. Such approach rules out significant indentation of the rod into the rock and consequently increases the accuracy of abrasiveness estimation. However, these studies have not been completed yet.

Outside Russia, the most widely spread method of coal and rock abrasiveness estimation was developed by the Coal Mining Research Center of France (CERCHAR – Centre d’E´tudes et Recherches des Charbonnages), which gave the name to the abbreviated form of *CAI* – CERCHAR Abrasivity Index. Nowadays this index is used as a standard in France and USA and recommended by the International Society for Rock Mechanics ISRM [9].

The main idea of *CAI* estimation is the following. A steel cutting pick (stylus), 6 mm in diameter and with a working face no less than 15 mm, is rubbed against a pre-treated surface of the rock sample. It has a conical working head with a wedge angle 90°. The stylus is made of alloy CrV instrument steel, e.g., DIN 115CrV3 (Germany), UNI 107CrV3KU (Italy), UNE 120CrV (Spain), hardness 55±1 HRC. A static force of 70 N is applied to the cutting pick, after which it is moved over the distance of 10 mm during 1±0.5 or 10±2 s depending on the construction of testing equipment. The procedure is repeated at least 5 times over the distance of at least 5 mm from each other and the edges of the sample. Throughout the entire experiment there must be a fixed contact between the stylus and the rock sample.

The tests are performed on discs or arbitrary shaped samples with the surface not yet subject to weathering. Rock samples remaining after experiments on ultimate tensile strength estimation are frequently used for this purpose [10]. There are no constraints on the size of mineral grains, but for materials with a grain size above 2 mm it is advisable to perform more than five tests. The size of the sample must allow to perform at least five tests with a regard to the following conditions: the distance from the edge of the sample to the scratch left by the pick must be no less than 5 mm, the distance between two adjacent scratches must be no less than 5 mm. For anisotropic samples it is recommended to select directions of relative stylus movement perpendicular to anisotropy boundary. Furthermore, it is important that the experiment reflects the texture and prevailing mineral content of the sample. Rock abrasiveness is defined as a dimensionless value, dependent on changes in stylus diameter in the zone of contact with the sample.

After the tests are completed, a report is put together, comprised of the following information: source of rock sample; date of sample reception and production; method of sample preservation in transit; experiment date; storage conditions of the sample; rock type (if available); maximum size of mineral grains; planes of faults or anisotropy (degree of inclination, banding etc.); direction of cutting pick relative movement against the planes of faults or anisotropy; sample surface state; cutting pick hardness; type of testing equipment; measuring method (lateral (top view)); optical (digital); average *CAI* value; abrasiveness classification.

As can be seen from the above brief description of the methods of determining the abrasiveness of rocks in mining industry, Russian and foreign abrasiveness indicators differ significantly, despite of the common approach – to measure the deformation of a standard metal sample in the process of its interaction with a rock sample under given loading. In the first case, the critical parameter is the mass reduction of a standard sample, in the second one – changes in its cutting head geometry.

In Russia and former USSR countries, Baron-Kuznetsov abrasiveness index lies at the foundation of numerous estimation methods, associated with cutting pick wearability and consumption, loading of working tool drive transmission of cutter-loading and heading machines with a regard to tool wearability, etc. However, outside the specified countries this indicator is completely unheard of [3]. In foreign countries the most widely used indicator of abrasiveness is *CAI*. Nowadays *CAI* is mostly used to estimate tool consumption (of any currently used type). Up to this day, there are no globally acclaimed methods to estimate critical cutting speed or loading on the worn-out tools that use *CAI,* but the amount of research, associated with the extension of its application area, increases rapidly.

Conclusion. Analysis of the performed study allows to state that rock abrasiveness is a critical parameter, which exerts an influence on technical and economic efficiency of mechanical rock destruction. It impacts the performance of production works by setting the upper limit of cutting speed [see formulas (8), (9) and (15)], and the coefficient of machine time use due to worn-out tool replacement. Moreover, abrasiveness influences conditions, necessary for rock destruction, i.e. power and energy characteristics of mining equipment. Hence, alongside rock strength and jointing [4], abrasiveness is one of the main parameters that define the efficiency of mechanization in mining construction and resource recovery.

Such incompatibility between rock abrasiveness indicators and methods of their estimation in Russia and abroad is currently a limiting factor in the development of Russian mining science and industry. Because of this contradiction, Russian scientists cannot take advantage of the advanced by world standards research results in the area of rock destruction with mechanical tools and their wearability. When mining plants import foreign equipment, they are taking some risk due to lack of awareness of its application field, whereas Russian manufacturers of similar equipment have difficulties finding common ground with foreign clients (especially working with strong and abrasive rocks). Companies working in mining construction need to seek expensive advice on the issues of tool wearability and associated conditions (e.g., planning with regard to equipment down time) from foreign specialists and companies. At the same time, the authors are certain that by having found an opportunity to describe accumulated Russian experience in this area in terms, accepted and understood worldwide, it is possible to achieve a breakthrough of Russian mining science in the area of mining mechanization research.

REFERENCES

1. Glatman L.B., Levankovskij I.A., Multanov S.I. Estimation of critical cutting speed for rock destruction by picks. Nauchnye soobshcheniya. IGD im. A.A.Skochinskogo. Moscow, 1994. Iss. 300, p. 149-155 (in Russian).

2. Zhabin A.B., Polyakov A.V., Averin E.A. A brief analysis of problems and solutions when upgrading the mining enterprise with modern equipment. *Ugol'*. 2018. N 1 (1102), p. 13-16. DOI: 10.18796/0041-5790-2018-1-13-16 (in Russian).

3. Zhabin A.B., Polyakov A.V., Averin E.A. On the need of introduction a state standard for estimation of rock abrasiveness. *Ugol'*. 2018. N 11, p. 86-91. DOI: 10.18796/0041-5790-2018-11-86-91 (in Russian).

4. Zhabin A.B., Averin E.A., Polyakov A.V. Integrated assessment of the complexity of mine construction projects. *Ugol'*. 2017. N 11, p. 60-63. DOI:10.18796/0041-5790-2017-11-60-63 (in Russian).

5. Levankovskij I.A. Calculation of the wear resistance of rotary picks during the operation of roadheaders. *Sb. nauch. trudov*. Akademiya gornykh nauk. Academy of Mining Sciences. Moscow, 1998. Iss. 1, p. 110-128 (in Russian).

6. Malevich N.A. Roadheaders and equipment for excavation. Moscow: Nedra, 1971, p. 384 (in Russian).

7. Zhabin A.B., Polyakov A.V., Averin E.A., Sarychev V.I. State of scientific researches in the field of rock destruction by picks at the turn of the century. *Izvestiya TulGU. Nauki o Zemle*. 2018. N 1, p. 230-247 (in Russian).

8. Archard J.F. Contact and rubbing of flat surfaces. *Journal of Applied Physics*. 1953. Vol. 24. N 8, p. 981-988. DOI: 10.1063/1.1721448

9. Alber M., Yarali O., Dahl F., Bruland A., Käsling H., Michalakopoulos T.N., Cardu M., Hagan P., Aydin H., Özarslan O. ISRM Suggested Method for Determining the Abrasivity of Rock by the CERCHAR Abrasivity Test. *Rock Mechanics and Rock Engineering*. 2014. Vol. 1. N 47, p. 261-266. DOI: 10.1007/s00603-013-0518-0

10. Käsling H., Thuro K. Determining rock abrasivity in the laboratory. *Rock Mechanics in Civil and Environmental Engineering – Proc EUROCK* 2010. London: Taylor & Francis, 2010, p. 425-428.

11. Mishnaevsky L.L. Mathematical modelling of wear of cemented carbide tools in cutting brittle materials. *International Journal of Machine Tools and Manufacture*. 1995. Vol. 35. N 5, p. 717-724. DOI: 10.1016/0890-6955(95)93040-D

12. Plinninger R.J., Restner U. Abrasiveness testing, quo vadis? – a commented overview of abrasiveness testing methods. *Geomechanics and Tunnelling*. 2008. Vol. 1. N 1, p. 61-70. DOI: 10.1002/geot.200800007

13. Rabinowicz E. Friction and wear of materials. New York: John Wiley & Sons. 1995, p. 336.

14. Schimazek J., Knatz H. The influence of rock structure on the cutting speed and pick wear of heading machines. *Gluckauf*. 1970. Vol. 106, p. 274-278. (in German).

***Authors*: Aleksandr B. Zhabin,** *Doctor of Engineering Sciences*, *Professor*, *zhabin.tula@mail.ru* (*Tula State University*, *Tula*, *Russia*), **Andrey V. Polyakov,** *Doctor of Engineering Sciences*, *Professor*, *polyakoff-an@mail.ru* (*Tula State University*, *Tula*, *Russia*), **Evgenii A. Averin,** *Candidate of Engineering Sciences*, *Construction Engineer*, *evgeniy.averin.90@mail.ru* (*OOO Skuratovsky Experimental Plant*, *Tula*, *Russia*), **Yuri N. Linnik,** *Doctor of Engineering Sciences*, *Professor*, *yn_linnik@guu.ru* (*State University of Management*, *Moscow*, *Russia*), **Vladimir Yu. Linnik,** *Doctor of Economics*, *Professor*, *d0c3n7@gmail.com* (*State University of Management*, *Moscow*, *Russia*).

The paper was received on 25 April, 2019.
The paper was accepted for publication on 26 June, 2019.