Evaluation of the Quality of Conical Picks and the Possibility of Predicting the Costs of Their Use

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INTRODUCTION

The mining of minerals consists in separating their parts from the whole by well-known mining methods, using appropriate technology and machines or a set of machines. In general, these methods can be divided into mechanical (milling, planing, digging, tearing, drilling) and non-mechanical ones, the former being used in practice (Jonak, 2002; Krauze, 2002; Kotwica and Krauze, 2007). Milling, planing or drilling are commonly used for the extraction of minerals in underground plants, whereas digging and picking are opencast technologies. It is solely borehole technologies that rely on drilling as the only method.

Machines and devices implementing these processes are dedicated for each method and technology of exploitation (underground, opencast, borehole). In underground mining, these are longwall shearers, roadheaders and shaft shearers (Fig. 1) or plows, while in road construction and opencast mining, these are cutting machines (Fig. 2), excavators and rippers. The machines have cutting elements or units called cutting heads. The largest group of cutting heads are the milling heads (Fig. 3) equipped with cutting tools, i.e. radial, flat tangent picks and conical picks (Fig. 4). Especially the latter are widely applied in the mining of natural and artificial minerals. They are commonly used not only in underground or opencast mining, but also in construction (road cutters, cutting heads).

Conical picks, as already mentioned, are commonly used in cutting heads due to their greater durability compared to radial or tangential flat picks. They owe it to a specific structure, where the pick body is a solid of revolution, consisting of a working part and a handle (Fig. 5). The working part is reinforced with a WC insert, which is a pick tip.
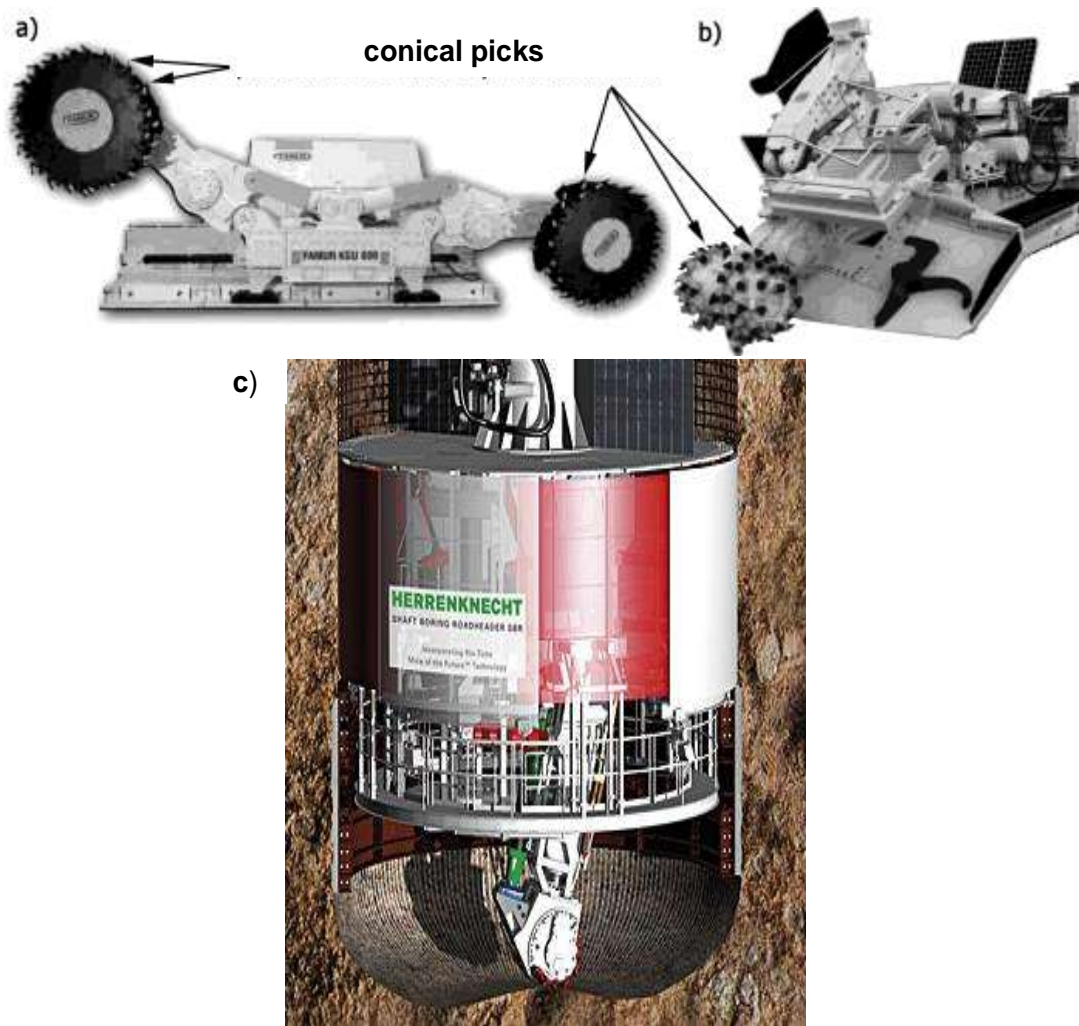
Fig. 1 Shearers:
a-longwall shearer, b-roadheader, c-shaft-sinking roadheader
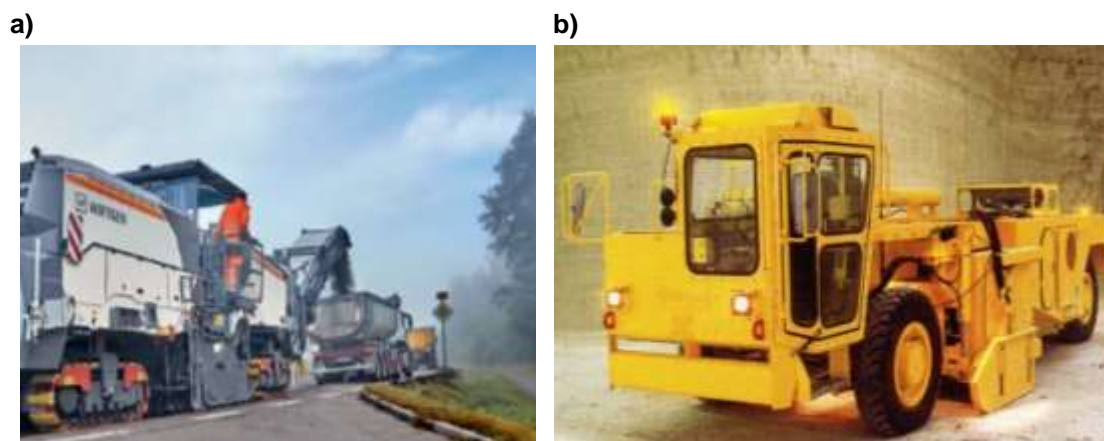Source: (Famur, 2017; Herrenknecht, 2019)

Fig. 2 Cutting machines:
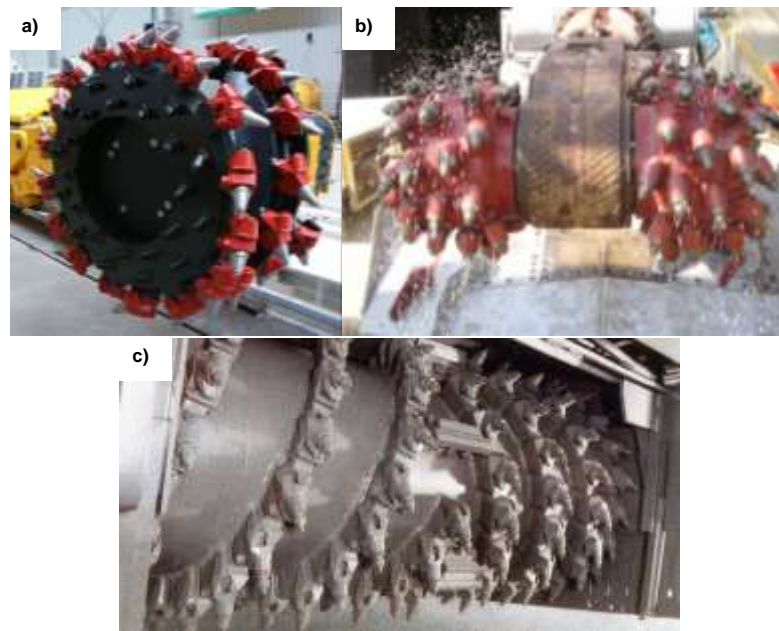**a-road cutter, b-mining cutting machine**
Source: (Wirtgen, 2020)

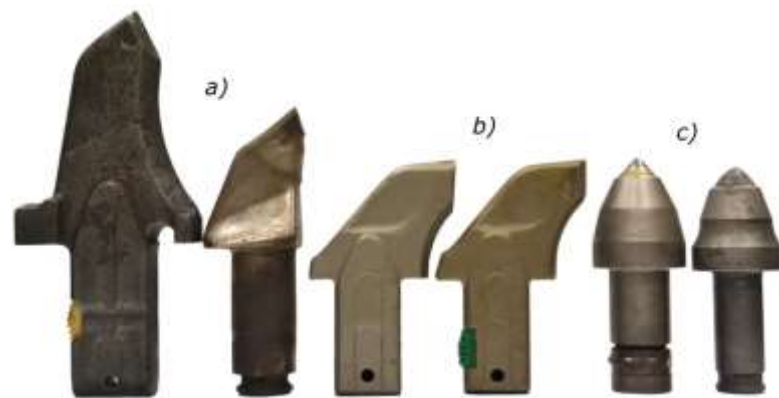**Fig. 3 Cutting heads of: a - longwall shearer, b - roadheader, c - road cutter**

Fig. 4 Cutting picks: a - flat tangent, b - radial, c - conical
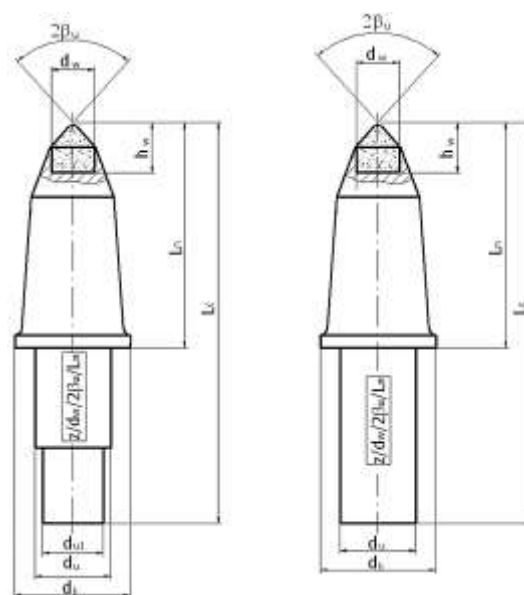

**Fig. 5 Diagram of a one-stage and two-stage conical pick with
its measured design parameters**

The pick is mounted in a pick holder, furnished on the lateral surface of the cutting head, and, together with other picks, forms a system of picks. The rotary mounting of the pick in the holder allows for its stochastic rotation and symmetrical wear (Fig. 6).

Fig. 6 Properly worn (symmetrical) conical picks

This process can occur if certain conditions related to the cutting angles are fulfilled (Fig. 7).
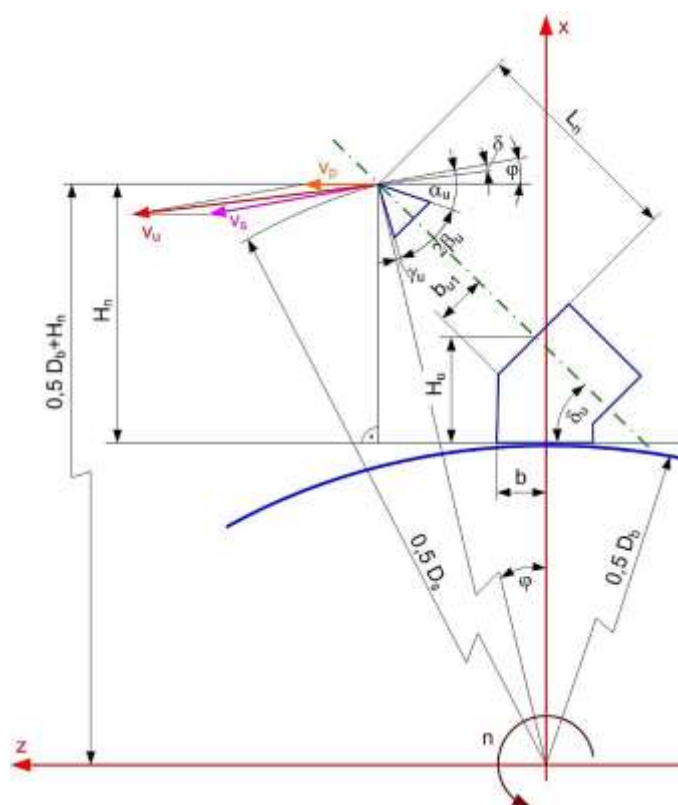

**Fig. 7 Diagram of a conical pick with a holder on the cutterhead
for analytical determination of cutting angles**
Source: (Krauze, 1999; Krauze et al., 2002; Krauze et al., 2015)

Otherwise, the pick is blocked in the holder and its wear is asymmetrical (Fig. 8).

Fig. 8 Improperly worn (asymmetrical) conical picks

That is why the process of selecting the design parameters of the picks and holders is so important, taking into account the constructional and kinematic parameters of the cutterheads and the cutting machine (Jankowski, 2005; Jonak, 2002; Krauze, 2002; Krauze et al., 2002). At the same time, mining and geological conditions must be taken into account, in particular the properties of the mineral being extracted (cutting resistance, abrasivity) (Biały, 2005; Jonak, 2002; Kotwica and Krauze, 2007; Krauze, 2002; Mucha, 2019/1; Mucha, 2019/2). Hence, the user should use conical picks of the quality required for the projected cutting efficiency and costs.

In this case, the required quality of conical picks is related to their proper construction parameters (cutting angles, dimensions, picks arrangement) and the design of the pick and pick tip in the form of a WC insert made from appropriate materials (technology, chemical composition of steel, grade of WC, the hardness of the pick body and WC insert). A better quality of the pick is obviously related to its higher price. This translates into investment costs involved in the purchase of picks, but also into the costs connected with their replacement (operating costs). The quality of picks should therefore be considered from the aspect of having the required design and material parameters, as well as the rate (intensity) of their wear. This becomes especially important when buying picks from different manufacturers and at different prices. Therefore, the user should first of all specify his requirements and expectations with regard to the design and material parameters of the picks, and, next, define the method of their control (Kotwica and Krauze, 2007; Report, 2010; Krauze et al. 2012). Then, the question is: which pick meets the user's requirements and expectations, and, at the same time, has a price adequate to its quality, value and operating costs as well as the assumed cutting efficiency. Hence, as already mentioned, the method of assessing the quality of conical picks, both at the stage of purchase and operation, as well as the procedure for their selection in terms of investment and operating costs should be determined (Report, 2010; Krauze et al. 2012).

BENCH TESTING OF CONICAL PICKS

The aforementioned problem related to the assessment of the quality of conical picks has been solved by developing a method and an appropriate procedure for conducting the experiment (Report, 2010). Bearing in mind the correct operation of the conical pick, the following elements have been taken into account:

−   measurement of geometric parameters of the whole pick and the tip in the form of a WC insert,
−   testing of pick body material parameters,
−   testing of pick tip material parameters,
−   measurement of the hardness of the working part and handle body,
−   measurement of tip hardness,
−   determination of pick wear rate in laboratory conditions.

Therefore, the research is carried out in three stages. The first stage involves measuring the geometric parameters, the second stage is material testing, and the third stage – measuring the wear rate of conical picks in a laboratory workstation.

The testing of geometric parameters is carried out first for the complete pick, and, next, for the WC insert obtained in the machining process.

The most important linear and angular dimensions of the conical pick are (Fig. 5):

−   working part length L_n,
−   total length L_c,
−   diameter or diameters of the holder part d_u,
−   diameter of thrust ring flange d_k,
−   angle of insert tip (aperture) $2\beta_u$,
−   height of tungsten carbide insert h_w,
−   diameter of cemented carbide insert d_w.

The linear dimensions are measured by means of an altimeter (maximum permissible error ±40 μm) and a calliper (maximum error ±30 μm), while the angles – with a protractor characterized by a maximum permissible error of ±2°). Figure 9 presents picks on a special measuring base, equipped with an altimeter, calliper and protractor, by means of which the aforesaid measurements are taken.

Determining the properties of materials that the conical pick is made of requires separation of the steel body from the tip made of sintered carbide. Consequently, two different materials have to be tested (Figures 10, 11):

−   the material of the pick body in order to determine the chemical composition of steel, its hardness and thermal treatment (metallographic testing),
−   material of the cemented carbide insert for determining the composite content, density and hardness.
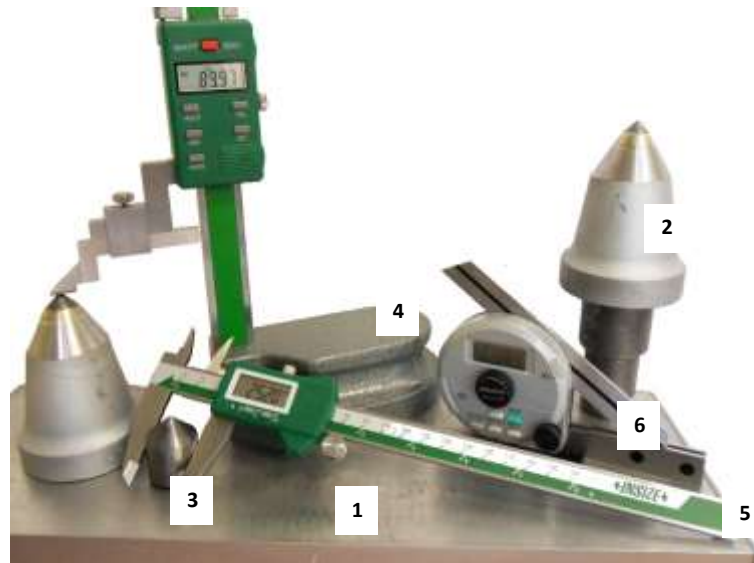
Fig. 9 Devices for measuring linear and angular dimensions: 1- surface plate, 2 - conical pick, 3 - WC insert, 4 - altimeter, 5 - calliper, 6 - protractor

Carbide insert:
- HV hardness measurement
- density analysis
- chemical composition analysis

Body working part:
- HV hardness measurement
- specimen surface
- chemical composition analysis

Handle part of the body:
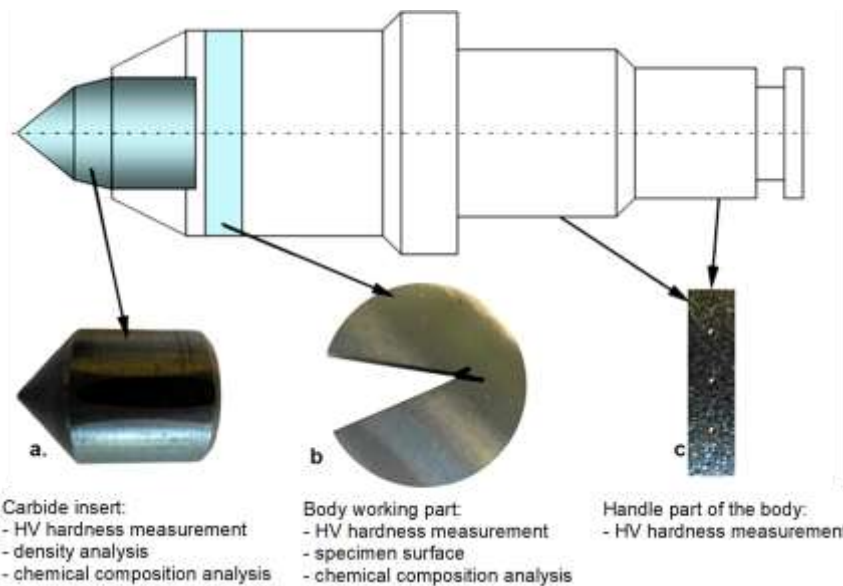- HV hardness measurement

Fig. 10 Conical peak with measurement points marked:
a) measurement of WC insert, b) measurement of specimen surface,
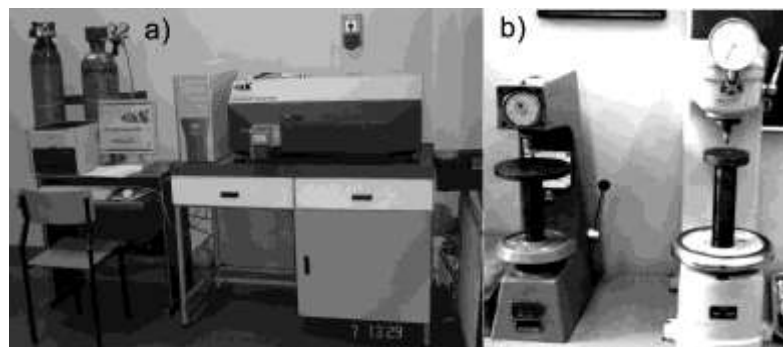**c) measurement of handle surface**

Fig. 11 Instruments for metallographic measurements: a) Foundry Master device,
b) hardness testers produced by Vickers and Rockwell

The chemical composition of the pick body material is analysed by the spark method using a Foundry Master device, whereas hardness measurements are carried out on a sample taken near the insert, in accordance with the Polish standard PN-EN ISO 6507-1:1999.

WC inserts used for conical pick tips have a specific chemical composition and mechanical properties that are important for the cutting process. It should be noted, however, that measuring all the parameters of the WC insert, although the most advantageous, entails a significant increase in research costs, while being relatively insignificant for the assessment of the insert suitability for mining a specific rock. Therefore, taking into account the costs of research and their subsequent application, it is proposed that a quantitative analysis of density and hardness be performed for a given WC insert.

The quantitative analysis of the chemical composition of carbide is performed by the X-ray method, using a Mini Pal4 EDXRF Analyser (Energy Dispersive X-ray Fluorescence), the specific density of carbide is determined by the hydrostatic weighing method, and hardness – by the Vicers method, using an HPO-250 hardness tester.

Measurement of the rate (intensity) of wear of conical picks is aimed at determining their durability. This measurement must always be carried out under the same conditions so that the results are reliable, reproducible and comparable. This allows for assessing the durability of the pick, but it also enables comparing different picks in this regard.

In order to evaluate the durability of conical picks, their wear rate index was adopted for tests, determined by $C2$, which is defined as the total loss of mass of the pick or picks in relation to the volume of the mined rock obtained (1).

$$C2 = \frac{\Delta m}{m} \cdot \frac{V_w}{V_{un}} \ [\text{-}] \tag{1}$$

where:

$C2$ – pick wear rate index based on mass,

Δm – loss of pick mass during tests (body with the tip) [g],

m – pick mass before tests [g],

V_w – sample standard volume [m^3],

V_{un} – volume of sample mined during tests [m^3].

The adopted definition of the parameter determining the durability of picks and the requirements for testing the rate of their wear necessitate the use of the following test methodology:

- cutting a cement-sand sample with almost isotropic properties,
- mining by cutting in laboratory conditions,
- measurement of the pick mass before and after the cutting process,
- measurement of the volume of mined rock obtained during the work of the examined picks.

Laboratory tests need to be conducted in a special workstation that meets the requirements of the adopted test methodology. Therefore, the research in question is carried out in a unique laboratory workstation for testing the cutting

process with single cutting tools or heads, belonging to the AGH University of Science and Technology (Fig. 12).

This workstation consists of two components: a head drive and a block feed system intended for mining. The working element is a special disc with holders of single-stage and two-stage conical picks.

Fig. 12 Laboratory workstation for testing by cutting or rotary drilling with single cutting tools or heads: a) operator's cab, b) concrete sample with an assembly for its mounting and feed as well as a test cutting head; c) head drive

The rotations of the head and the rectilinear, reciprocating motion of the rock sample in the horizontal plane enable the mining process to be carried out by cutting while working within a specific web. The hydraulic feed mechanism allows the table to be moved together with the block. The engine revolutions are regulated by the control system installed in the control cabinet, while the value of feed rate during mining and sumping is regulated by a hydraulic power unit.

A sample of a natural or artificial mineral can be placed on the feed mechanism table. In the case of testing the wear rate of conical picks, it is advisable to mine artificial rock (cement-sand sample), which has strong abrasive properties (Mucha, 2019a; Mucha, 2019b). The workstation is equipped with a measuring system, which is its integral part (torque meter, pressure transducers, distance transducers, measuring computer). This allows for measuring the load of the

cutting element as well as the speed and pressure in the feed system, and, in consequence, enables determining the resistance or energy consumption of the cutting process.

Picks are weighed both before and after tests with an attested laboratory scale (verification scale interval 1g). The obtained weight loss and the volume of the excavated rock sample are used to determine the $C2$ index. It should be noted that the smaller the value of the $C2$ parameter, the smaller is the pick wear. In this case, laboratory tests are particularly recommended, but they need to be carried out in a special workstation that meets the requirements of the adopted test methodology.

PRICE OF THE CONICAL PICK AND ITS WEAR RATE VERSUS CUTTING EFFICIENCY

The previously described method and the manner of its implementation allow for checking the geometric parameters of the conical pick, the properties of the materials of the body and the tip, as well as the rate (intensity) of wear described by the $C2$ index.

The geometric and material parameters of conical picks may be within the range of the required values specified by the user, but it does not mean that they will have the same $C2$ indices, determined by the method described above. Some picks – n_{wz} with the $C2_1$ index will be slow-wearing, while others – n_{sz} with the $C2_2$ index – fast-wearing. Then $C2_1$ is lower than $C2_2$, and their ratio is less than one.

$$C2_1 < C2_2, \quad \frac{C2_1}{C2_2} < 1 \tag{2}$$

Assuming that the unit cost of C_{wz} picks with the $C2_1$ index is C_{n1}, and that of n_{sz} picks with the $C2_2$ index is C_{n2}, it is necessary to determine which of them should be chosen when:

$$C_{n1}(C2_1) > C_{n2}(C2_2); \qquad C2_1 < C2_2 \tag{3}$$
$$C_{n1}(C2_1) = C_{n2}(C2_2); \qquad C2_1 < C2_2 \tag{4}$$
$$C_{n1}(C2_1) < C_{n2}(C2_2); \qquad C2_1 < C2_2 \tag{5}$$
$$C_{n1}(C2_1) < C_{n2}(C2_2); \qquad C2_1 = C2_2 \tag{6}$$

As one can easily see, for cases (inequalities) (4), (5) and (6), one should select and use n_{wz} slower-wearing picks, that is, the better-quality ones. The decisive factors here are mainly the value of the $C2$ index, which is obviously lower for n_{wz} picks (4), (5) and the price (6).

It should be emphasized that the cases (4), (5) and (6) may theoretically occur, but as it was previously noted, picks that wear more slowly, i.e. are better in terms of quality, should have a higher unit price. Then, it is advisable to consider only the first case (3).

If we assume that the number of worn n_{wz} picks replaced for new ones is n_1, and for n_{sz} picks – n_2, the costs of their replacement are as follows, respectively:

$$\text{for } n_{wz} = n_1 \qquad K_{n1} = n_1 \cdot C_{n1}(C2_1) \tag{7}$$
$$\text{for } n_{sz} = n_2 \qquad K_{n2} = n_2 \cdot C_{n2}(C2_2) \tag{8}$$

Assuming that an increase in the wear of picks is related to an increase in their wear rate, it can be written for $C2_2 > C2_1$, and their ratio higher than one ($C2_2 \cdot C2_1^{-1} > 1$) that:

$$n_2 = n_1 \cdot \frac{C2_2}{C2_1} \tag{9}$$

then:

$$K_{n2} = n_1 \cdot C_{n2}(C2_2) \cdot \frac{C2_2}{C2_1} \tag{10}$$

And a difference in pick replacement costs ΔK_n

$$\Delta Kn = Kn_1 - Kn_2 = n_1 \cdot [C_{n1}(C2_1) - C_{n2}(C2_2) \cdot \frac{C2_2}{C2_1}] \tag{11}$$

ΔK_n can have a positive, negative or zero value. For a positive value, n_{sz} picks should be applied, for the zero value – n_{sz} or n_{wz} picks, and for a negative value – n_{wz} picks, if their unit price is lower than the price of n_{sz} picks multiplied by the $C2_2/C2_1$ ratio, i.e.:

$$C_{n1}(C2_1) < C_{n2}(C2_2) \cdot \frac{C2_2}{C2_1} \tag{12}$$

Assuming that the price of a lower quality pick C_{n2} is equal to PLN 80 per piece and the $C2_2/C2_1$ ratio equal to 1.5, the price for a better-quality pick $C_{n1}(C2_1)$ cannot exceed PLN 120.

Dependence (11) is very important for the selection of picks, provided that the $C2$ wear indicators for at least two picks are determined in accordance with the previously described method. Then, the costs of purchasing the picks can be minimized, taking into account their price and the rate (intensity) of their wear. On the other hand, an increase in the number of replaced picks results in a decreased cutting efficiency.

Assuming that the volume of mined rock in the whole excavated face obtained from one cutting cycle is V_{uj}, and its time is t_c, then, during the time of mining machine availability T_d it is possible to perform n_c cycles and obtain the mined rock volume V_u.

$$n_c = \frac{T_d}{t_c} \tag{13}$$

$$V_u = V_{uj} \cdot n_c = V_{uj} \cdot \frac{T_d}{t_c} \tag{14}$$

The time of carrying out one cutting cycle t_c is a sum of the time of mining t_{c1} (time of performing one cut having a length L with a speed v_p) and operational time t_{op}, related among others to an inspection of the mining machine, mainly the picks.

$$t_c = t_{c1} + t_{op} = \frac{L}{v_p} + t_{op} \tag{15}$$

$$V_u = \frac{V_{uj} \cdot T_d \cdot v_p}{L + v_p \cdot t_{op}} \tag{16}$$

By multiplying the right-hand side of the equation (16) by the specific mass of the excavated rock γ_w, a dependence for mined rock mass M_u is obtained:

$$M_u = \gamma_w \cdot \frac{V_{uj} \cdot T_d \cdot v_p}{L + v_p \cdot t_{op}} \tag{17}$$

As mentioned before, time t_{op}, is in this case related to the time of pick replacement, that is:

$$t_{op} = n \cdot t_{wn} \tag{18}$$

where:

n – number of picks to be replaced after one cutting cycle, [pcs]

t_{wn} – time of replacing one pick, [s].

However, it should be remembered that this time may be increased due to the adopted mining technology (longwall, drift, road).

Using the symbols as before, for n_{wz} picks the time is $t_{op} = t_{op1}$, and for n_{sz} picks the time is $t_{op} = t_{op2}$. Therefore:

$$t_{op2} = n_2 \cdot t_{wn} = n_1 \cdot t_{wn} \cdot \frac{C2_2}{C2_1} \tag{19}$$

The volume of mined rock obtained with n_{wz} picks is V_{u1}, and for n_{sz} picks – V_{u2}, hence:

$$\Delta V_u = V_{u1} - V_{u2} > 0 \tag{20}$$

$$\Delta V_u = \frac{V_{uj} \cdot T_d \cdot v_p}{L + v_p \cdot n_1 \cdot t_{wn}} - \frac{V_{uj} \cdot T_d \cdot v_p}{L + v_p \cdot n_1 \cdot t_{wn} \cdot \frac{C2_2}{C2_1}} \tag{21}$$

The dependence (21) indicates that a reduction in the volume of mined rock ΔV_u results mainly from the $C2_2 / C2_1$ ratio. The higher this ratio is than one, the higher ΔV_u.

If the unit price of mined rock in relation to its volume is C_{jur}, the financial losses K_{suv} are:

$$K_{suv} = \Delta V_u \cdot C_{jur} \tag{22}$$

It is similar in the case of mass:

$$K_{sum} = \gamma_w \cdot \Delta V_u \cdot C_{jum} \tag{23}$$

In the event K_{suv} or K_{sum} are higher than the cost of picks replacement – ΔK_n, n_{wz} picks should be used. Otherwise, when:

$$K_{suv} \; lub \; K_{sum} \le \Delta K_n \tag{24}$$

n_{sz} picks should be applied, if the unit price of n_{ws} picks is higher than

$$C_{n1}(C2_1) \ge \frac{\Delta V_u \cdot C_{jur}}{n} + C_{n2}(C2_2) \cdot \frac{C2_2}{C2_1} \tag{25}$$

or

$$C_{n1}(C2_1) \ge \frac{\gamma_w \cdot \Delta V_u \cdot C_{jum}}{n} + C_{n2}(C2_2) \cdot \frac{C2_2}{C2_1} \tag{26}$$

From inequalities (12) and (25) or (26) it is possible to estimate the maximum unit price of a pick which is worth paying to minimize losses resulting from different quality of picks. It can be easily noticed that inequality (12) takes into account only an increase in the wear of picks resulting from their quality (the $C2$ index), whereas inequality (25) or (26) also takes costs (losses) related to

reduced efficiency into consideration. Therefore, in most cases, better quality picks should be used (the lowest possible $C2$ index), and in the remaining cases, the condition is the price of better-quality picks, which is limited by the maximum value resulting from the $C2$ index and ΔV_u (dependencies 11, 25 and 26).

CONCLUSION

In the previously described method of assessing the quality of conical picks, a three-stage process of their testing was adopted. The process involves measuring geometric and material parameters as well as wear rate, expressed by the $C2$ index. This parameter, which indicates how resistant the pick is to abrasion, is determined under the same conditions for each pick. It was therefore assumed that it would also define the number of worn picks in relation to picks with the lowest value of the $C2$ index. As a result, it was possible to define various causes related to the $C2$ index and the pick price, as well as their replacement costs and a decrease in cutting efficiency. It was found that in most cases, picks of better quality (the lowest value of the $C2$ index) should be used without price restrictions. However, there are cases where the choice of a pick depends on its price and losses in processing.

It is therefore recommended that the method and procedure in question should be used for evaluating the quality of picks and their selection.

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Abstract: Currently, the user's choice of a conical pick involves specifying its geometric and material parameters, taking into account the place and conditions of its work. The selection is then made, usually on the basis of solely one criterion, which is the price. Thus, at the stage of both purchase and operation, the quality of picks and their suitability for a specific machine and the processed mineral are not assessed. Therefore, a method was developed to enable conducting tests that determine the geometric parameters of a pick, the types of materials of the pick body and WC insert as well as the pick wear rate (intensity) in a laboratory workstation. The wear rate (intensity) is described by the $C2$ index – the smaller is its value, the slower is the pick's wear. The $C2$ index has been used to forecast the wear of picks and to determine their unit price and operating costs. This allows for precise determination of investment requirements and a proper selection of the pick.

Keywords: underground mining, rocks cutting, conical picks, costs