

## Article

# Functional and Operational Requirements to Be Fulfilled by Conical Picks Regarding Their Wear Rate and Investment Costs

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**Abstract:** User's choices of conical picks currently involve specifying their material and geometric parameters (functional requirements), incorporating the place and conditions of their work (operational requirements). The selection is usually made based on solely one criterion, which is the price. Thus, at the stage of both purchase and operation, the quality of picks, as well as their matching for a specific machine, are not assessed. The problem of defining whether the producer has fulfilled the user's requirements arises only when the user questions the picks' quality. Analysis of this problem has resulted in developing assumptions, concepts and research procedures based on the cutting process requirements. The procedure allows conducting tests to determine the geometric parameters of a pick, the type of material of the pick body and WC-Co insert, as well as the pick wear rate (intensity). The C2 index describes the wear rate (intensity)—the smaller its value, the slower the pick's wear. Laboratory tests were carried out at the AGH University of Science and Technology in Kraków, Poland. Following the developed method and procedure, the quality of picks was precisely and unambiguously assessed. The C2 index, apart from testing the quality of picks, was also used to forecast their wear. Based on the C2 index, a method is proposed to estimate the wear rate of conical picks provided by different manufacturers and determine the acceptable unit price and operating costs. Thus, it is possible and reasonable to precisely define the investment requirements and appropriately select the pick. Relevant tests were carried out for eight different types of conical picks used in roadheaders, longwall shearers and shaft-boring roadheaders.

**Keywords:** underground mining; longwall shearers; roadheaders; conical picks; quality; costs



**Citation:** Krauze, K.; Mucha, K.; Wydro, T.; Pieczora, E. Functional and Operational Requirements to Be Fulfilled by Conical Picks Regarding Their Wear Rate and Investment Costs. *Energies* **2021**, *14*, 3696. <https://doi.org/10.3390/en14123696>

Academic Editors: Sergey Zhironkin and Maxim Tyulenev

Received: 4 May 2021

Accepted: 15 June 2021

Published: 21 June 2021

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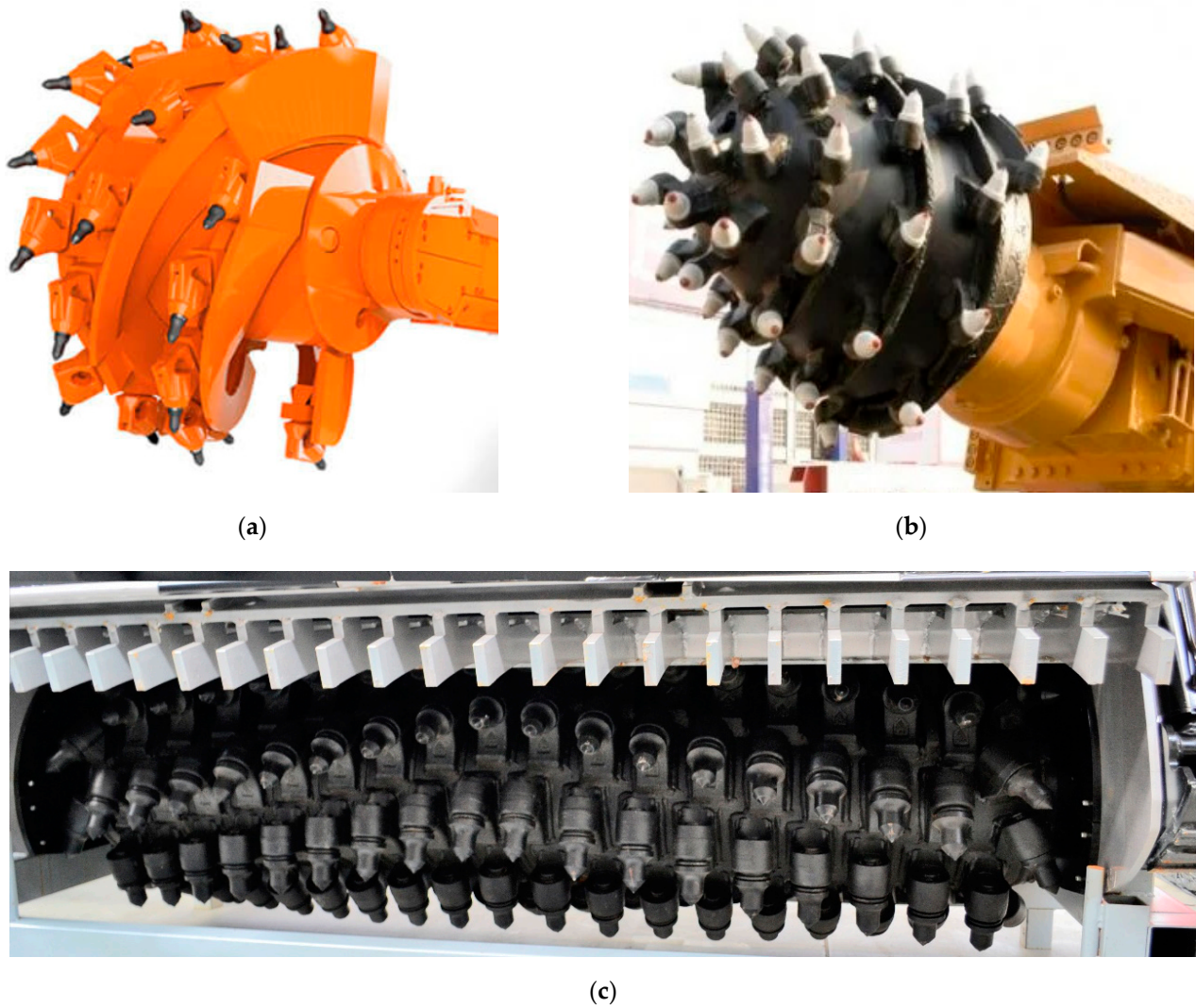


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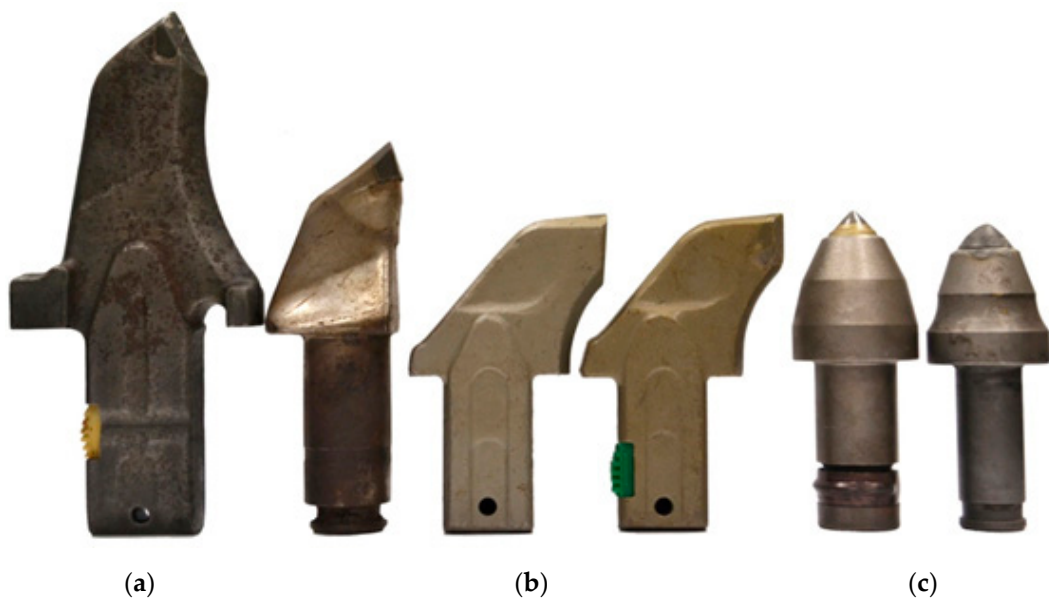
## 1. Introduction

Mining minerals consists of separating their parts from the whole using well-known mining methods, appropriate technology and machines. These methods can be divided into mechanical methods and blasting [1–3]. Milling, ploughing or drilling are widely used to extract minerals in underground mines [4–10], whereas digging and picking are open-pit technologies [11]. It is strictly borehole technologies that rely only on drilling, but in multi-step bits, conical picks are also used [6,12].

Machines and devices realising these processes are dedicated to each method and technology of exploitation (underground, open-pit, borehole). In underground mining, these are longwall shearers [3,10,13], roadheaders [2,5–7,14] and shaft shearers [15] or ploughs [9,10], whereas in road construction and open-pit mining, these are road milling machines, excavators and rippers [11]. The machines are equipped with cutting elements or units called cutting heads. The largest group of cutting heads are the milling heads (Figure 1) equipped with cutting picks, i.e., radial, tangent and conical picks (Figure 2). The latter are mainly applied in the mining of natural and artificial minerals [16–19]. They are widely used not only in underground or open-pit mining, but also in the construction industry.



**Figure 1.** Cutting heads of: (a) a longwall shearer; (b) a roadheader; and (c) a road milling machine [13,14,20].



**Figure 2.** Cutting picks: (a) tangent; (b) radial; (c) conical.

Conical picks are used in cutting heads due to their excellent durability, greater than radial or tangent picks. They have a specific structure, where the pick body is a solid of revolution, consisting of working and handle parts [21–23]. The working part is equipped with a WC-Co insert, which is a pick tip [24–27]. On the other hand, the pick holder's gripping part is equipped with a spring-ring, a spring sleeve or a Hert ring [23]. This prevents the pick from falling out of the holder during cutting.

The picks are installed in pick holders, furnished on the cutting head's lateral surface, and together form a system of picks. The rotary mounting of the picks in the holders enables their stochastic rotation and symmetrical wear [17,18,21] (Figure 3a,c). This process occurs if certain conditions related to the cutting angles are obtained [3,28–32]. Otherwise, the picks are blocked in the holders, and their wear is asymmetrical (Figure 3b). There is also the risk of the tip falling out (Figure 3d). This is why the selecting process of the design parameters of the picks and holders is so crucial, considering the geometrical and kinematic parameters of the cutterhead and the cutting machine [2,3,28]. Concurrently, mining and geological conditions must be considered, particularly the mineral's properties when being extracted (cutting resistance, abrasivity) [33–37]. Hence, the user should apply conical picks of the quality required for the premised cutting efficiency and costs [29].



**Figure 3.** Worn conical picks: (a) properly (symmetrical); (b) improperly (asymmetrical); (c) with the tip exposed; and (d) with the tip falling out [37].

The required quality of conical picks is related to their appropriate construction (cutting angles, dimensions), material parameters of the pick body (chemical composition, hardness, microstructure, steel grade), and the pick tip (dimensions, HV30 hardness, density, chemical composition—determination of the mass fraction of carbide phase (%WC), matrix (%Co) and WC grain size).

A better quality of pick increases the price. This translates into costs involved in purchasing picks and the costs associated with their replacements (operational costs) [29]. Therefore, the quality of picks should be relevant to the required design, material parameters and the rate of their wear. This becomes very important when a user is buying picks from various manufacturers and at different prices. Therefore, the user firstly should pinpoint their requirements and expectations concerning the design and material parameters of the picks. Secondly, a control method should be defined. Then, a decision, as to which picks meet the user's requirements and expectations, is required, with a price adequate to its quality and the assumed cutting efficiency. Hence, a method of determining the quality of conical picks and a procedure for their selection should be applied [28,29].

Based on this methodology and the procedures contained therein, different manufacturers' conical picks are tested to compare and assess the picks themselves. This is especially advisable when placing new conical pick designs or material solutions on the market.

For some time now, pick manufacturers have been using various forms of protection of the working part of the pick's surface [22,33,36] (Figure 4). This is often performed by hardfacing with various materials. Their hardness is higher than the native material used to make the body of the pick. In consequence, the abrasion resistance of the working part is better. However, this study revealed that the durability of picks with protected surfaces was not significantly increased compared to standard picks [37]. Hence, based on the research conducted thus far, it has been concluded that investigations need to be continued to find the most effective and cheapest protection and the technology for its implementation.



**Figure 4.** Options of additional protection of conical picks against abrasive wear: (a) standard pick; (b) welded picks; (c) pick with a ring made of WC-Co; (d) pick with two rings made of WC-Co; (e) pick with a lowered body and WC-Co insert in the CAP type [28].

For this purpose, the researchers obtained eight different types of conical picks used on the cutterheads of roadheaders, longwall shearers and shaft-boring roadheaders. These picks were tested according to the methodology described below, and the procedures contained therein (a measurement of constructional and material parameters, wear rate) to assess their quality and wear rate (durability).

## 2. Test Procedure for Conical Picks

The problem mentioned above related to assessing the quality of conical picks has been solved by developing a method and an appropriate procedure for experimentation [28, 29,36,37]. For the contemporary work of conical picks, the following elements have been considered:

- The measurement of geometric parameters of the whole pick;
- The measurement of geometric parameters and determining the shape of the pick tip in the form of a WC-Co insert;
- Testing of pick body material parameters;
- Testing of pick tip material parameters;
- Determination of the pick wear rate in laboratory conditions.

Therefore, the tests were carried out in three steps. The first step included measuring the geometric parameters; the second step was material testing; and the third step was measuring the wear rate of conical picks at a laboratory test stand.

The measuring of geometric parameters was conducted first for the whole pick. Next, the pick tip, in the form of a WC-Co insert fixed in the pick body by hard soldering, was obtained in the machining process. Then, it was possible to test the geometric parameters of the WC-Co insert.

The most essential linear and angular dimensions of a conical pick are (Figure 5):

- The length of the working part,  $L_n$ ;
- The total length,  $L_c$ ;
- The diameter or diameters of the holder part,  $d_u$ ,  $d_{u1}$ ;
- The diameter of thrust ring flange,  $d_k$ ;
- The angle of the pick tip,  $2\beta_u$ ;
- The height of the pick tip,  $h_w$ ;
- The diameter of the pick tip,  $d_w$ .

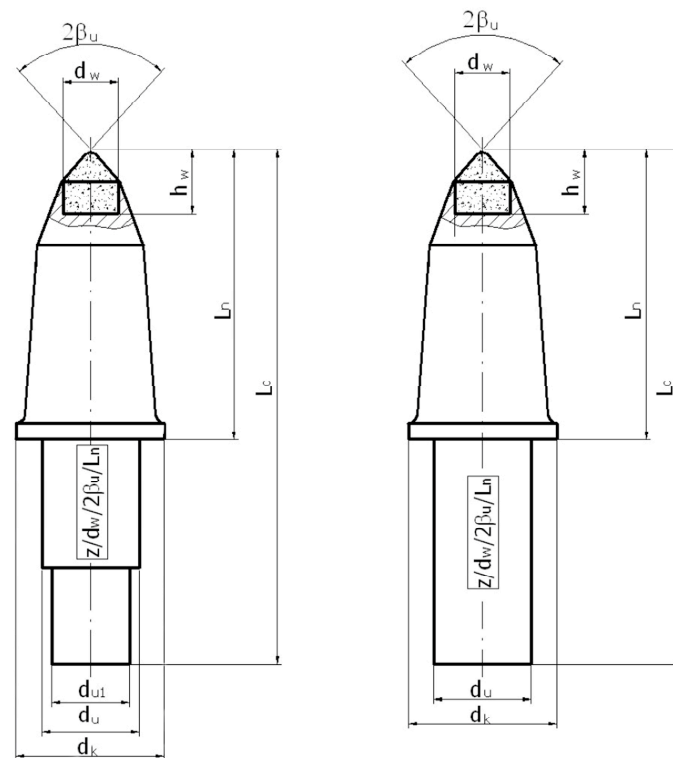
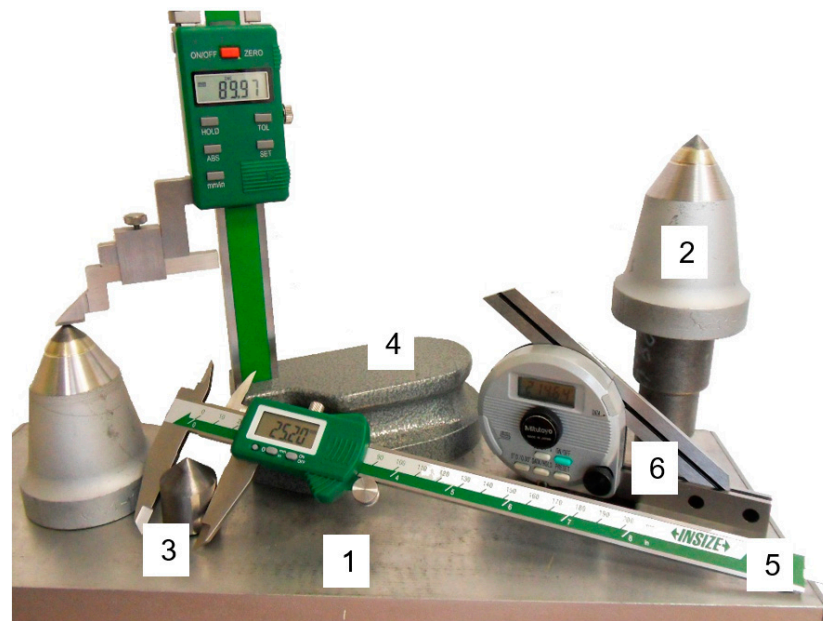


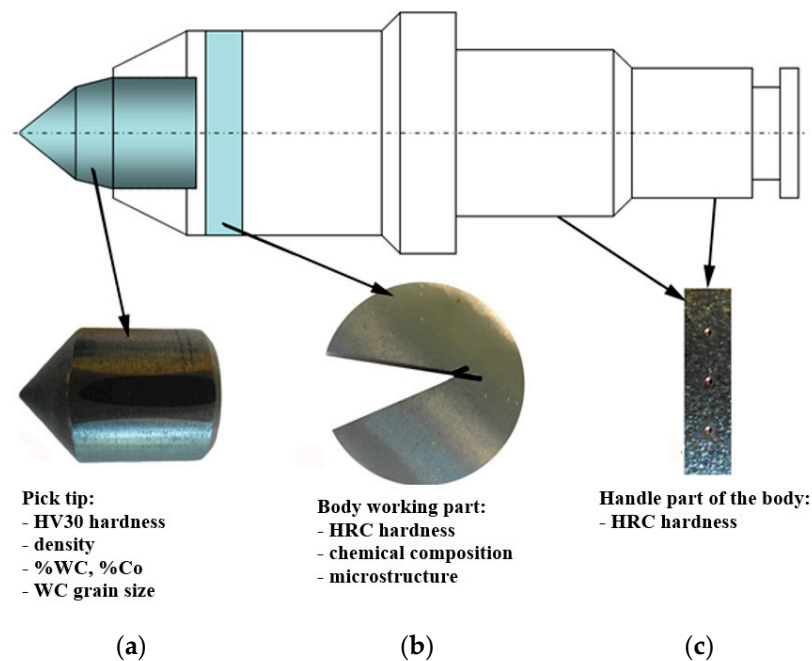
Figure 5. Two- and single-stage conical pick with its measured design parameters [28,29].

The linear dimensions were measured using an altimeter (maximum permissible error  $\pm 40 \mu\text{m}$ ) and a calliper (maximum error  $\pm 30 \mu\text{m}$ ), while the angles were measured with a protractor characterised by a maximum permissible error of  $\pm 2^\circ$ ). Figure 6 presents picks on this particular measuring base, equipped with an altimeter, calliper and protractor.



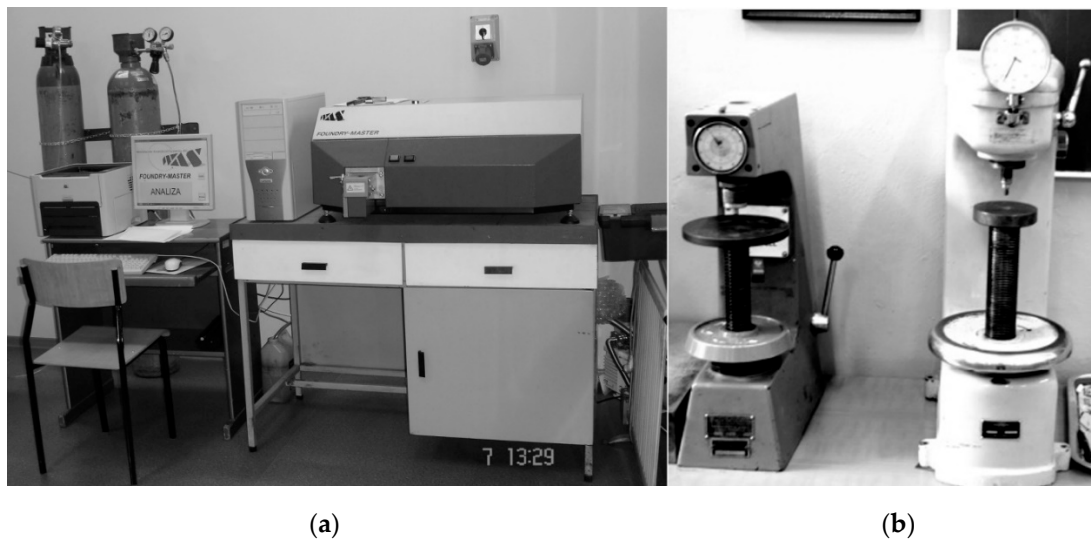
**Figure 6.** Instruments for measuring linear and angular dimensions: (1) surface plate; (2) conical pick; (3) WC-Co insert; (4) altimeter; (5) calliper; and (6) protractor [28,29].

The next part of the research procedure was material testing, which requires separating the tip from the steel body. Consequently, separate tests should be carried out for two different materials (Figure 7).



**Figure 7.** Conical pick with measurement points marked: (a) measurement of tip parameters; (b) measurement of working part parameters; and (c) measurement of gripping part parameters [28,29].

The chemical composition of the pick body material was analysed by the spark method using a Foundry Master device (Figure 8a), whereas the hardness measurement was carried out using the Rockwell method (Figure 8b), following the standard [38], on samples taken from the working part and the gripping part.



**Figure 8.** Instruments for metallographic measurements: (a) Foundry Master device; (b) hardness testers produced by Vickers and Rockwell [29].

WC-Co inserts (pick tips) have a particular chemical composition and mechanical properties primary for the cutting process [24–27]. However, measuring all the parameters of the WC-Co insert leads to a significant increase in research costs while being relatively insignificant for the valuation of the insert suitability for mining a specific rock. Therefore, considering the costs of the test and their subsequent application, it is recommended to perform a quantitative analysis of density and hardness for a mentioned WC-Co insert.

Quantitative analysis of the chemical composition of the WC-Co insert was performed by the X-ray method, using a Mini Pal4 EDXRF Analyser (Energy Dispersive X-ray Fluorescence), produced by Malvern Panalytical (Malvern, UK). The specific density was determined by the hydrostatic weighing method [39], and hardness by the Vickers method [40], using an HPO-250 hardness tester (Figure 8b).

Quantitative description of the WC-Co insert microstructure in the cobalt matrix was performed using the Met-Ilo automated image analysis computer software [41]. The microstructure images for analysis were captured with a DM 4000 light microscope, produced by Leica (Wetzlar, Germany), at 200- and 500-times magnification.

Measurement of the wear rate of conical picks leads to determining their durability. It must always be conducted under the same conditions so that the results are reliable, reproducible and comparable. This enables assessment of the pick durability, but it also allows comparing picks from different manufacturers.

To evaluate the conical picks' durability, their wear rate index was adopted for tests, as described by the C2 index, which is defined as the total loss of mass of the pick or picks concerning the volume of the mined rock obtained (Equation (1)).

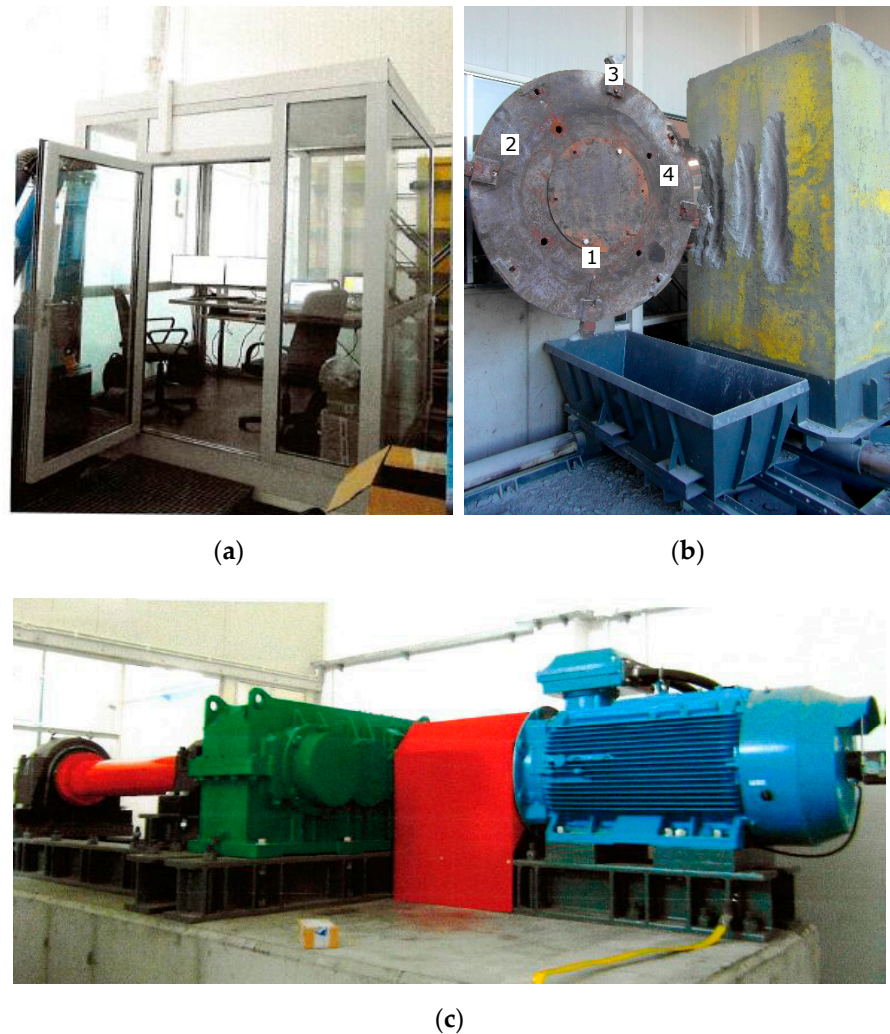
$$C2 = \frac{\Delta m}{m} \cdot \frac{V_w}{V_{un}} [-] \quad (1)$$

where C2 is the pick wear rate index based on mass,  $\Delta m$  is the loss of pick mass during tests (body with the tip) [g],  $m$  is the pick mass before tests [g],  $V_w$  is the sample standard volume [m<sup>3</sup>], and  $V_{un}$  is the volume of sample mined during tests [m<sup>3</sup>].

The definitions of the above parameters and the requirements for testing the wear rate of conical picks necessitate the use of the following test methodology:

- Cutting an artificial cement–sand sample with almost-isotropic properties;
- Mining by cutting in laboratory conditions;
- Measurement pick's mass before and after the cutting process;
- Measurement of the volume of rock cut.

Laboratory tests need to be conducted in a unique test stand that meets the adopted test methodology requirements. Therefore, the tests were carried out at a unique laboratory test stand for testing the cutting process with single cutting tools or heads belonging to the AGH University of Science and Technology, Kraków, Poland (Figure 9).



**Figure 9.** Laboratory test stand for testing by cutting or rotary drilling with single cutting tools or heads: (a) operator's cab; (b) concrete sample as well as a test cutting head; (c) head drive [29,37].

The test stand consists of two units: a cutting head drive and a block advance system intended for mining. The working element is a unique drum with commercial holders of single-stage and two-stage conical picks.

The rotations of the head and the rectilinear, reciprocating motion of the rock sample in the horizontal plane, allowed the cutting process within a particular area. The hydraulic advance mechanism enabled the base to be moved together with the rock block. The engine revolutions were regulated by the control system located in the control cabinet, while a hydraulic power unit regulated the value of advance rate mining and sumping.

A sample could be placed on the advance mechanism base. In the case of testing the wear rate of conical picks, it is advisable to cut artificial rock (cement–sand sample), which has strong abrasive properties. The test stand was equipped with a measuring system: comprising a torque meter, pressure transducers, distance transducers, and measuring computer. These measured the load of the cutting element, the speed and pressure in the advance system, and, consequently, determined the resistance or energy consumption of the cutting process.



Four picks mounted in holders of the testing drum were used (Figure 10) to calculate their wear rate. Before testing, each pick had to be marked to enable accurate identification after the tests (position on the test drum).

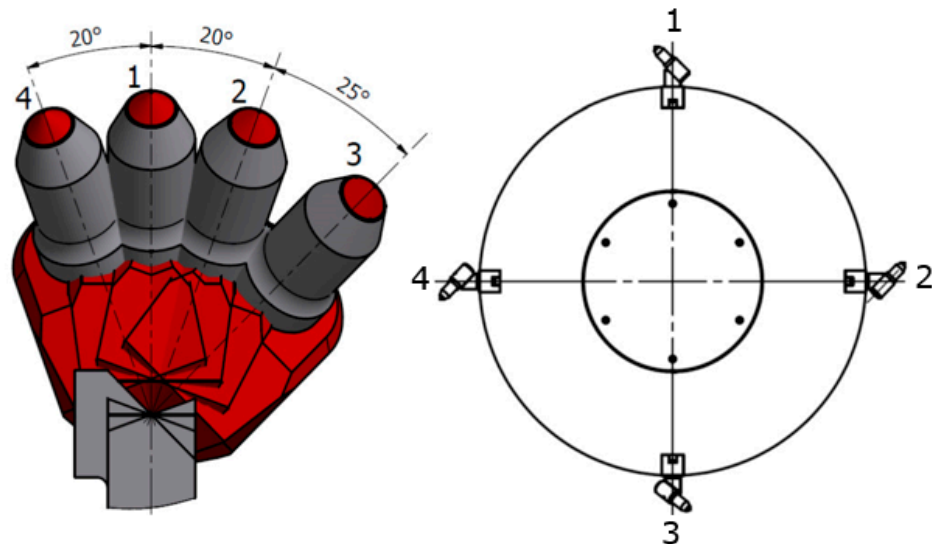


Figure 10. Diagram of the applied pick system with the marking of picks' numbers [21,28,29,37].

Picks were weighed both before and after tests with a certificated laboratory scale (verification scale interval 1 g). The obtained weight loss and the excavated rock sample volume were used to calculate the C2 index. It should be emphasised that the smaller the value of the C2 index, the smaller the pick wear. In this case, laboratory tests are particularly recommended, but most importantly, they need to be carried out at a unique test stand that meets the adopted test methodology requirements.

### 3. Price of the Conical Pick and Its Wear Rate versus Cutting Efficiency

The previously described method and its implementation allow for checking the geometric and material parameters of the conical pick body and the tip, as well as the wear rate index, C2.

Therefore, it is reasonable to establish the correlation of the C2 index with the number of worn picks and the cutting efficiency. The dependency (1) shows that the higher the C2 index value, the faster the pick wears out; thus, it has a lower quality. Using these picks on the cutting drum results in faster wear and a decrease in cutting efficiency. This is caused by a more frequent change of picks and downtime of the mining machine (milling machine). In [29], dependency (2) was given, which indicated when slower wearing and more expensive picks could be used without increasing the purchase costs of picks (3). This condition makes it possible to set the maximum price of a better-quality pick, which results in savings in terms of investment and operation (the cost of purchasing picks, transport, and replacement).

Assuming that the price of a lower-quality pick  $C_{n2}$  is equal to PLN 80 (approx. EUR 20) per piece and the  $C_{22}:C_{21}$  ratio is equal to 1.5, the price for a better-quality pick  $C_{n1}$  ( $C_{21}$ ) cannot exceed PLN 120 (approx. EUR 30). However, the  $C_{22}:C_{21}$  ratio may assume different values depending on the C2 index values for individual picks obtained through empirical tests. The ratio is always higher than one when  $C_{22}$  is higher than  $C_{21}$ .

$$C_{21} < C_{22}; \frac{C_{21}}{C_{22}} < 1 \quad (2)$$

$$C_{n1}(C_{21}) < C_{n2}(C_{22}) \cdot \frac{C_{22}}{C_{21}} \quad (3)$$

Similarly, from Equations (4) and (5), it is possible to determine the maximum price of a better-quality pick concerning the possible decrease in the cutting efficiency for lower-quality and cheaper picks.

$$C_{n1}(C2_1) \geq \frac{\Delta V_u \cdot C_{jur}}{n} + C_{n2}(C2_2) \cdot \frac{C2_2}{C2_1} \quad (4)$$

or

$$C_{n1}(C2_1) \geq \frac{\gamma_w \cdot \Delta V_u \cdot C_{jum}}{n} + C_{n2}(C2_2) \cdot \frac{C2_2}{C2_1} \quad (5)$$

where  $\Delta V_u$  is the volume of mined rock [ $\text{m}^3$ ],  $\gamma_w$  is the density of mined rock [ $\text{kg}/\text{m}^3$ ],  $C_{jur}$  is the unit price of mined rock in relation to its volume [ $\text{PLN}/\text{m}^3$ ],  $C_{jum}$  is the unit price of mined rock in relation to its mass [ $\text{PLN}/\text{kg}$ ], and  $n$  is the number of picks to be replaced after one cutting cycle [pcs].

Bearing in mind the above dependencies, in most cases, better-quality picks should be used [29].

#### 4. Research Material

Five pieces of each type of conical pick were assigned for testing. One pick was intended for material tests, and the other four were for measuring the design parameters and the wear rate. The pick's bodies were made of various grades of steel and reinforced with various cemented carbide (WC-Co) inserts. The surface of the working part of the pick body was protected with various padding welds—reinforced picks (Figure 11b–f)—or was not protected—standard picks (Figure 11a,c,g,h). The following picks were used for testing:

1. Commercial picks for roadheaders—five pcs (Figure 11a);
2. Hardfaced picks for roadheaders—five pcs (Figure 11b);
3. Commercial picks for roadheaders—five pcs (Figure 11c);
4. Commercial picks for shaft-boring roadheaders—five pcs (Figure 11d);
5. Commercial picks for shaft-boring roadheaders—five pcs (Figure 11e);
6. Commercial picks for shaft-boring roadheaders—five pcs (Figure 11f);
7. Commercial picks for longwall shearers—five pcs (Figure 11g);
8. Commercial picks for longwall shearers—five pcs (Figure 11h).

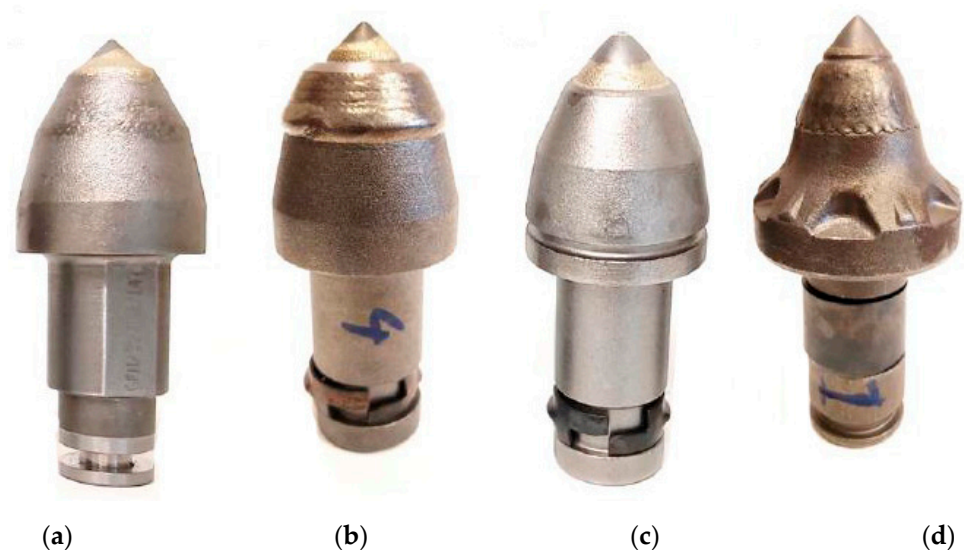
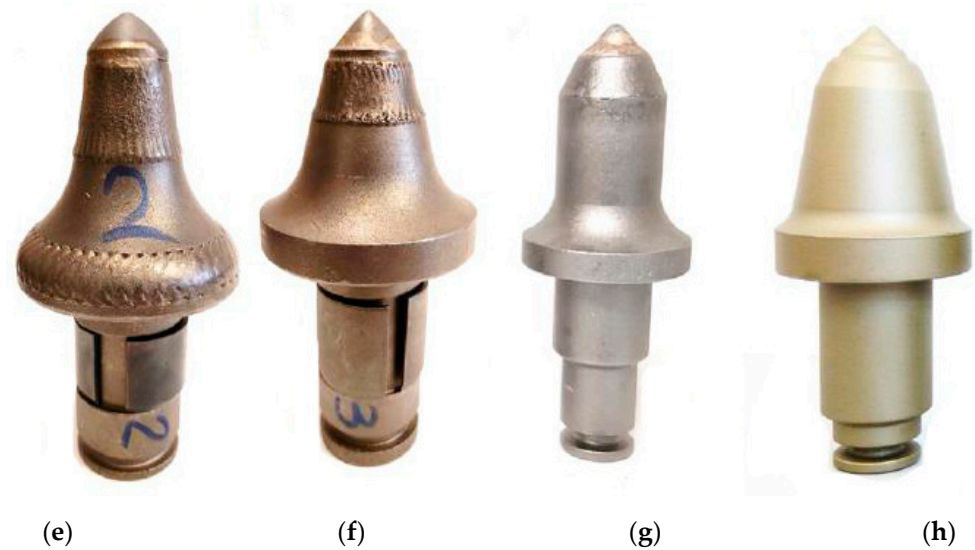


Figure 11. Cont.



**Figure 11.** Types of conical picks for tests: (a–c) picks for roadheaders; (d–f) picks for shaft-boring roadheaders; (g,h) picks for longwall shearers.

### 5. Conical Pick Testing Results and Discussion

The selected conical picks were tested in accordance with the previously described procedure. The obtained results allowed for evaluating the picks and formulating conclusions regarding their design and material parameters as well as the wear rates.

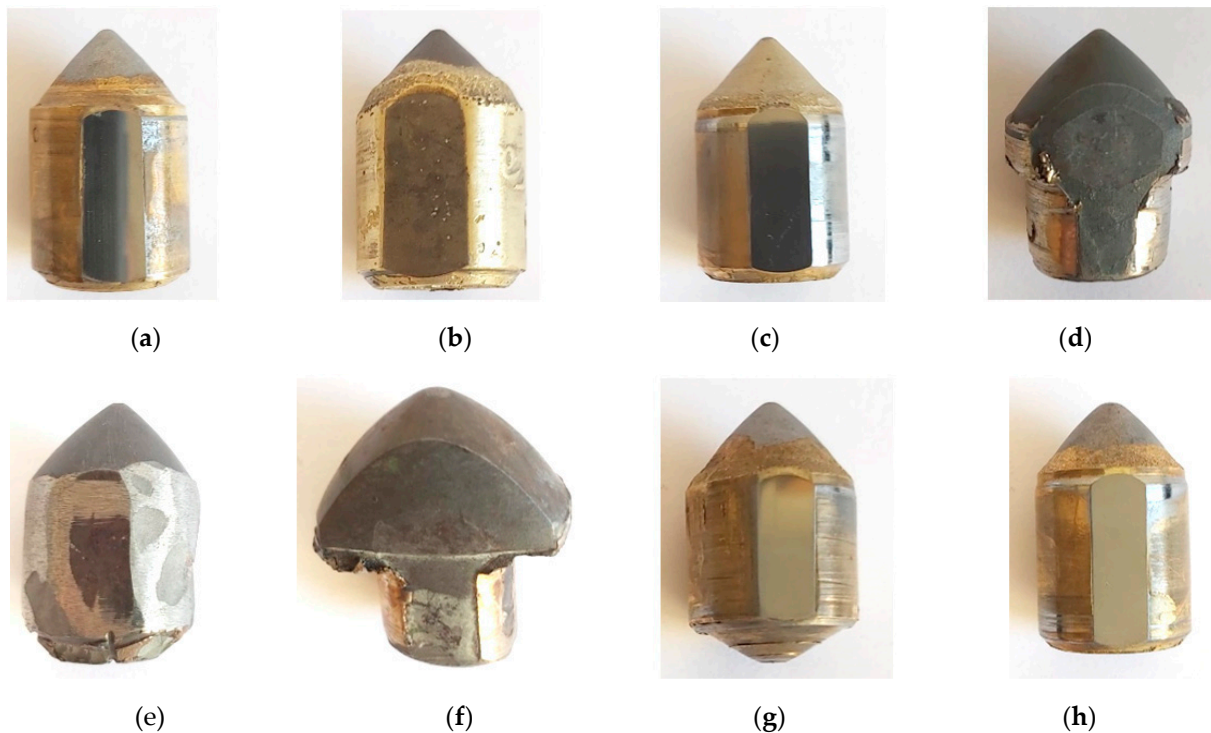
#### 5.1. Determination of Design Parameters

The parameters obtained from the measurements of construction dimensions' average values are summarised for each pick in Table 1. The designations of individual parameters in the table are consistent with the designations in Figure 6. Measurement of the dimensions of the tips in the form of sintered carbide (WC-Co) inserts was possible only for one of the five picks, which was intended for material testing. For this purpose, the insert was extruded from the pick body (Figure 12). At the same time, the body of the same pick was subjected to material tests.

The results of measurements of conical picks' construction dimensions indicate that the obtained cutting angles are correct. Therefore, the rate of the picks' wear can be tested at a laboratory test stand. However, notably, the tips of two picks for shaft-boring roadheaders had a different shape (Figure 12d,f). In both cases, they were mushroom-shaped, unlike the others, which were cylindrical–conical.

**Table 1.** Summary of linear and angular dimensions of the tested picks.

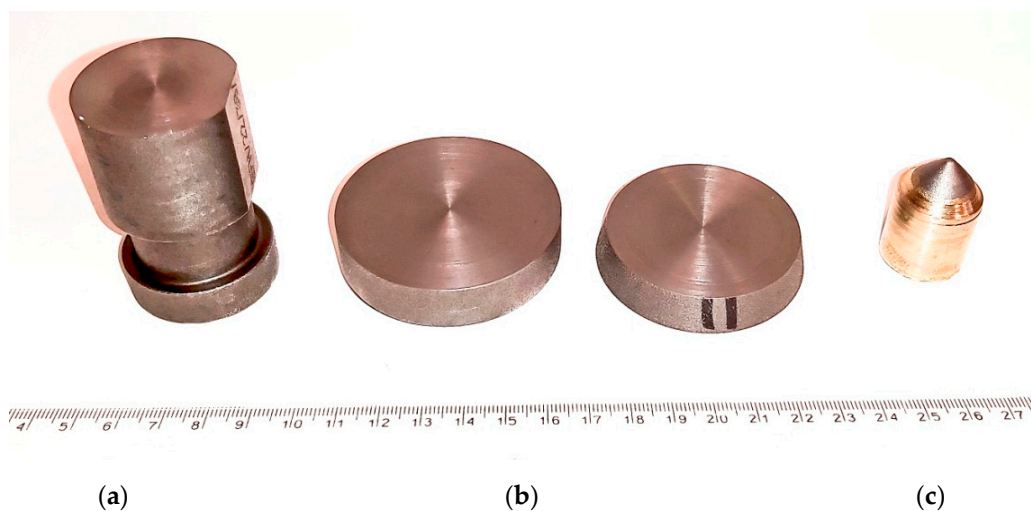
No.	Pick	Geometrical Parameters									
		$L_c$ (mm)	$L_n$ (mm)	$L_u$ (mm)	$h_k$ (mm)	$2\beta_u$ (°)	$d_k$ (mm)	$d_u$ (mm)	$d_{u1}$ (mm)	$d_w$ (mm)	$h_w$ (mm)
1	Figure 11a	146.30	70.80	75.50	16.77	93.00	58.10	37.88	–	22.00	34.89
2	Figure 11b	146.37	70.82	75.55	16.82	93.00	58.17	37.98	–	22.04	34.87
3	Figure 11c	147.20	71.00	76.20	15.15	–	57.70	37.98	–	25.28	35.46
4	Figure 11d	155.13	77.53	77.60	15.13	94.45	80.08	41.99	–	22.11/ 17.85	29.11
5	Figure 11e	167.64	90.67	76.97	–	–	80.00	41.88	–	22.04	33.84
6	Figure 11f	156.63	76.69	79.94	14.10	93.30	80.00	41.82	–	22.04/ 15.06	29.92
7	Figure 11g	165.22	90.25	74.97	12.22	92.97	58.00	37.80	29.89	22.05	35.20
8	Figure 11h	165.44	90.30	75.14	16.32	93.00	64.88	37.89	–	22.12	34.86



**Figure 12.** Tips in the form of WC-Co inserts, obtained by extruding from the tested picks: (a) pick for roadheaders (Figure 11a); (b) hardfaced pick for roadheaders (Figure 11b); (c) pick for roadheaders (Figure 11c); (d) pick for shaft-boring roadheaders (Figure 11d); (e) pick for shaft-boring roadheaders (Figure 11e); (f) pick for shaft-boring roadheaders (Figure 11f); (g) pick for longwall shearers (Figure 11g); (h) pick for longwall shearers (Figure 11h).

### 5.2. Determination of Material Parameters

As mentioned before, one pick from each batch of picks was intended for material testing. For this purpose, samples from the steel body of each pick were obtained in the process of machining (Figure 13a,b), and tips in the form of sintered carbide inserts (Figure 13c) were obtained.



**Figure 13.** Examples of samples from a conical pick for material testing: (a) gripping part; (b) working part; (c) WC-Co insert.

The results of measurements of the tested picks' material parameters have been provided in tables, i.e., Tables 2–6, where the results of measurements for the pick used in

roadheaders are presented (Figure 11a). The tables contain information on the hardness of the working and gripping parts, the chemical composition of the steel comprising the tested pick's body, as well as the hardness of the WC-Co insert and the value of its density. Based on this, the grade of steel used to make the bodies of the tested picks [42] and the types of carbides used to make their tips were determined. The type (symbol) of sintered carbide was determined using the PN-88/H-89500 polish standard [43], classifying sintered carbides based on WC and Co percentages, density, HV30 hardness and other mechanical parameters, and also indicates the place of their application. In the case of picks reinforced with padding weld, their hardness was additionally measured (Figure 14). The results of material tests for individual picks are given in Table 7.

**Table 2.** Results of measurements of HRC hardness of the gripping part of the pick for roadheaders (Figure 11a).

No.	Measurement Site Number										Average
	1	2	3	4	5	6	7	8	9	10	
1	40	40	41	41	42	42	41	41	40	40	41

**Table 3.** Results of measurements of HRC hardness of the working part of the pick for roadheaders (Figure 11a).

No.	Distance from the Surface, mm	Measurement Site Number			
		1	2	3	4
1	1	35	35	35	35
2	3	36	34	36	35
3	10	35	30	37	36

**Table 4.** Chemical composition of the material (steel) of the conical pick for roadheaders (Figure 11a).

Chemical Element, wt.%									Steel Grade
C	Mn	Si	S	P	Cr	Ni	Mo	V	
0.336↓	0.860↓	1.19↑	0.0092	0.0154	1.14↓	0.0766	0.0262	0.002	100CrMn6
Al	Cu	Ti	W	Pb	As	Co	Fe	—	
0.0196	0.173	0.002	0.015	0.025	0.01	0.0092	96.1	—	

The chemical elements, the content of which is underestimated or overestimated in relation to the standard, are marked in red.

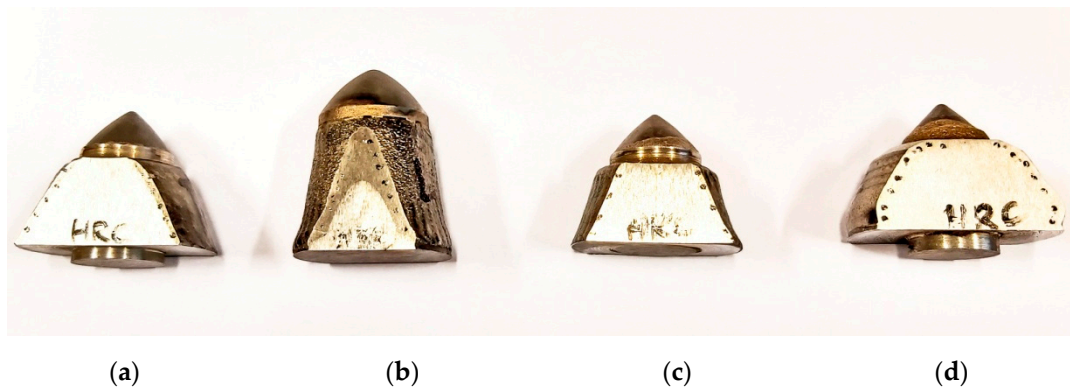
**Table 5.** Results of measurements of HV30 hardness of the sintered carbide insert of the pick for roadheaders (Figure 12a).

No.	Measurement Site Number										Average
	1	2	3	4	5	6	7	8	9	10	
1	1076	1034	1041	1075	1111	1071	1057	1081	1125	1135	1081

**Table 6.** Results of measurements of the density of the sintered carbide insert of the pick for roadheaders (Figure 12a).

No.	Temperature of Water Used for Weighing, °C	Water Density, g/cm <sup>3</sup>	Carbide Mass in Air, g	Carbide Mass in Water, g	Insert Density, g/cm <sup>3</sup>
1	21	0.9975	149.1258	138.9177	14.572

Based on Tables 5 and 6 and the standard [43]—carbide type B45.



**Figure 14.** Examples of samples prepared for padding weld hardness tests from tested picks: (a) pick for shaft-boring roadheaders (Figure 11d); (b) pick for shaft-boring roadheaders (Figure 11e); (c) pick for shaft-boring roadheaders (Figure 11f); (d) hardfaced pick for roadheaders (Figure 11b).

**Table 7.** Summary of the results of material tests for individual picks.

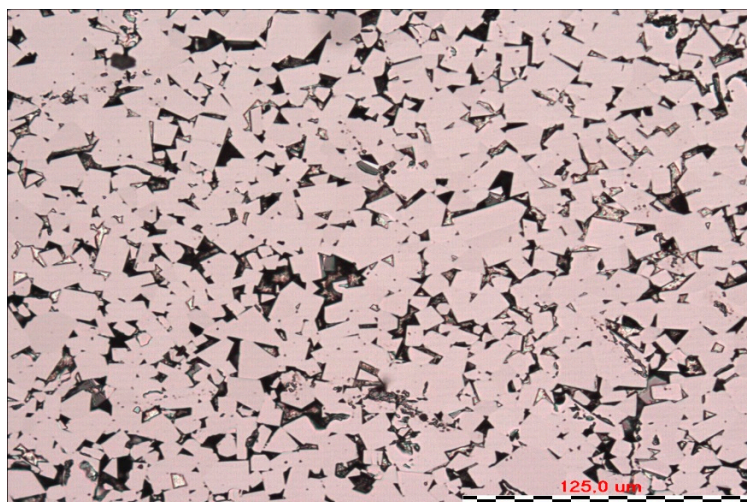
List of Picks								
No.	Pick	HRC of the Gripping Part	HRC of the Working Part	Steel Grade	HV30 of the Carbide	Carbide Density	Type of Carbide	HRC of the Padding Weld
1	Figure 11a	41	35	100CrMn6	1081	14,572	B45	–
2	Figure 11b	45	35	100CrMn6	1127	14,408	B45	62
3	Figure 11c	40	43	100CrMn6	1143	14,378	B40	–
4	Figure 11d	46	46	36Mn5	1326	13,959	G15	56
5	Figure 11e	44	47	36Mn5	1168	14,629	B23	65 * 59 **
6	Figure 11f	47	43	100CrMn6	1158	14,197	G30	51
7	Figure 11g	38	38	100CrMn6	1155	14,821	B23	–
8	Figure 11h	41	44	100CrMn6	1124	14,483	B40	–

\* Padding weld on the carbide. \*\* Padding weld on the working part flange.

The test results contained therein show that, with the exception of picks 5 and 6 whose bodies were made of manganese alloy steel (36Mn6), the remaining picks were made of chrome–manganese (100CrMn6) steel. The hardness of the working part of the picks was mostly above 40 HRC; its value was lower—38 HRC only in the case of pick No. 8. A similar situation was observed in the case of the tested picks' gripping parts. The hardness values of the gripping parts of picks 1 and 2 (35 HRC) were lower than that of the working parts (over 40 HRC), which is an advantage because the pick-holder sockets are not knocked out. On the other hand, the values of padding welds hardness were much higher, exceeding 60 HRC.

Measurements of the hardness and density of the WC-Co inserts allowed for determining their grade. B23 cemented carbide inserts are recommended for cross-bits and drills (picks 6, 8). The properties of these carbides were intermediate, between those of B2 and B45 carbides. B40 carbides are intended for reinforcing the tips of radial tools and rotary drilling tools (drill bits, multi-step bits, picks 3 and 8), whereas B45 carbides are used to reinforce the tips of conical picks, cross-bits and drills (picks 1, 2). G15 (pick 5) and G30 (pick 7) carbides are recommended for insert bits and discs [17,19,34,44].

For WC-Co cemented carbide inserts, quantitative analysis of the WC carbide phase was also performed. For this purpose, the test specimens were prepared by the traditional method of grinding and polishing metallographic specimens using polish suspensions with a diamond grain, with coarseness values of 3  $\mu\text{m}$ , 1  $\mu\text{m}$  and 0.25  $\mu\text{m}$ . The prepared specimens were subjected to chemical etching in order to reveal the boundaries of WC carbide grains (Figure 15) [45].



**Figure 15.** Microstructure of the tip made of sintered tungsten carbide–cobalt (WC-Co) of the conical pick for roadheaders (Figure 11a).

WC grains were measured for all tested WC-Co inserts. The average WC particle size ranged from 4.78  $\mu\text{m}$  to 6.15  $\mu\text{m}$ , and the cobalt content from 8.4% to 9.5%.

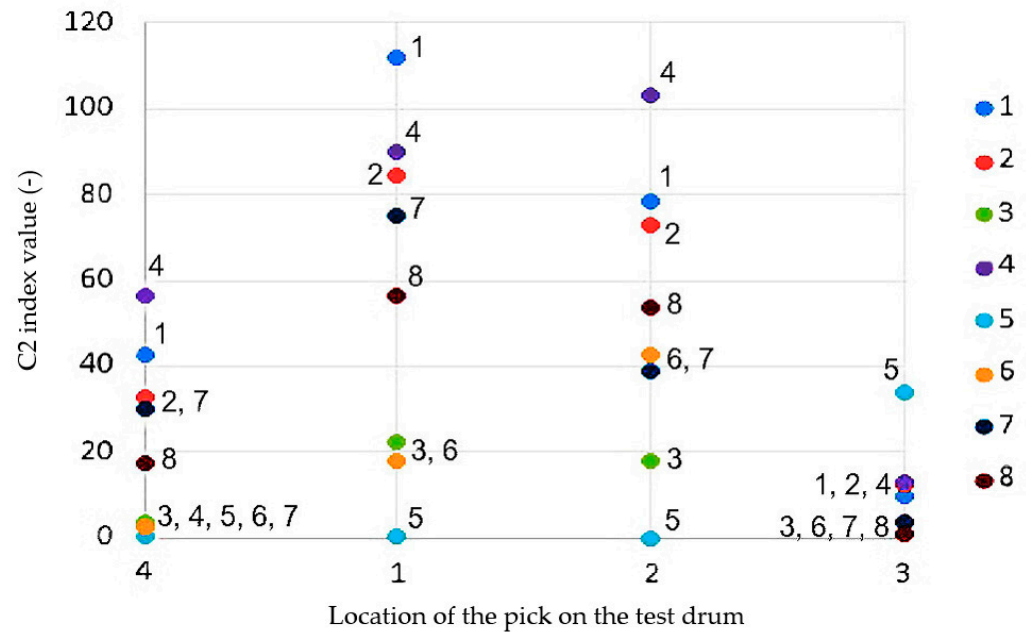
Analytical and empirical studies have shown that the best properties of WC-Co inserts for mining tools are 9% cobalt content (hardness, impact toughness). The size of the WC grains is also important. Based on the literature [24] and our previous work, the average grain size should be above 3  $\mu\text{m}$ .

### 5.3. Determination of the Rate (Intensity) of Wear

To determine the rate (intensity) of wear of the tested picks, first, the values of their mass before and after the test were determined. Next, the cutting parameters (advance speed, revolutions) were set, and efforts were made to ensure the same conditions for each set of picks. On the same sand–cement sample with uniaxial compressive strength equal to 35 MPa, all picks were tested. The results of the tests and the determined values of the C2 index for individual picks are summarised in Table 8. Based on these results, a table of C2 index values was prepared depending on the pick's location in the test drum (Figure 10, Table 8). Similarly, Figure 16 shows the C2 index point values for individual picks as a function of the test drum's location.

**Table 8.** Summary of C2 index values for the tested picks depending on the location on the test drum.

No.	Pick	Location of the Pick on the Test Drum			
		4	1	2	3
1	Figure 11a	41.958	112.020	78.657	9.486
2	Figure 11b	32.150	84.470	72.652	12.317
3	Figure 11c	3.148	22.155	17.946	0.965
4	Figure 11d	55.756	89.902	103.275	13.029
5	Figure 11e	0.055	0.254	0.038	33.744
6	Figure 11f	2.241	18.187	42.907	3.832
7	Figure 11g	29.350	74.907	38.679	3.831
8	Figure 11h	17.050	56.395	53.592	1.082
	Average value	18.515	46.881	41623	8.165



**Figure 16.** C2 index values for individual picks and their locations on the test drum.

The above comparisons clearly show a strong correlation between the pick's wear rate and their position on the test drum. The wear rate was the fastest for picks in position one and two, followed by picks in position four, whereas picks in position three wore the most slowly. It can also be observed that a specific pick wears differently depending on the position on the test drum, as already mentioned, although this wear expressed by C2 index correlated with its quality.

The average values for individual picks are summarised in Table 9 (C2, the presence of padding weld, type of cemented carbide insert, and the hardness of the working part).

**Table 9.** Summary of the results of average values for individual picks.

List of Picks					
No.	Pick	C2 Index	Padding Weld	Type of Carbide	HRC of the Working Part
5	Pick for shaft-boring roadheaders (Figure 11e)	8.513	padding weld	B23	44
3	Pick for roadheaders (Figure 11c)	11.054	missing	B40	40
6	Pick for shaft-boring roadheaders (Figure 11f)	16.792	padding weld	G30	47
8	Pick for longwall shearers (Figure 11h)	32.030	missing	B40	41
7	Pick for longwall shearers (Figure 11g)	36.692	missing	B23	38
2	Pick for roadheaders (Figure 11b)	50.397	padding weld	B45	41
1	Pick for roadheaders (Figure 11a)	60.530	missing	B45	45
4	Pick for shaft-boring roadheaders (Figure 11d)	65.490	padding weld	G15	46

It can be observed that the tested picks considerably differed in their wear rate, which is puzzling and does not depend or depends only to a minimal extent on the protective layer of the working part (padding weld). The lowest wear (C2 index) was observed in the case of the pick in position 1 (Table 9). The next pick in the table had a 30% higher C2 index value. In contrast, the C2 index value of the third pick was twice as high. The C2 index values for the fourth and fifth pick were almost four times higher. The C2 index value for the sixth pick was six times higher, and for the seventh and eighth pick, this rose



to eight times higher. It is also worth noting that the padding weld and carbide grade do not determine the wear rate of the pick, as with the hardness of the working part.

Generally, it is possible to use the C2 index to assess the pick's wear resistance. The lower the C2 index value, the longer the pick should cut while meeting the cutting process requirements. As a result, it is possible to forecast the value of picks' wear and, consequently, their purchase cost. In this case, it is easy to determine the maximum price of a pick with a lower C2 index value by referring it to the price of picks with a higher C2 index value. It is enough to multiply the prices of the picks by the ratio of their C2 index values.

## 6. Conclusions

In the presented method of assessing the quality of conical picks, a three-stage testing process was adopted, consisting of measuring geometric and material parameters and the wear rate, expressed by the C2 index. The tests carried out on eight types of conical picks from different manufacturers have shown that their geometric and material parameters are in accordance with the manufacturers' declarations and users' requirements. However, based on these data, it is only possible to assess the correctness of their manufacture, not their quality. Only when a complete procedure is carried out can the quality of the pick be assessed.

This strategy was confirmed by comparing two picks for shaft-boring roadheaders (Figures 11d and 12e). Both picks were made of the same 36Mn5 steel, their working part hardness was the same, and both were welded, although the pick for the shaft-boring roadheader in Figure 11d had a C2 index value as much as eight times greater than the pick for shaft-boring roadheaders in Figure 11e, which means that its quality is eight times lower.

It follows that particular attention should be paid to the C2 index because, as a result of this research, it does illustrate the wear rate of the pick and thus its durability (quality). However, carrying out a complete procedure also allows conclusions in the future and indicates further research directions to improve the quality of conical picks. For example, it was noticed that further attention should be paid to the correlations between the hardness of the working part and padding weld and the value of the C2 index.

Determining the C2 index, it can also be observed that the position of the pick on the test drum and, presumably, the sequence of entering the cut have a significant influence on the pick wear process. Moreover, the C2 index enables defining various causes related to the value and the price of the picks, as well as the costs of their replacement and reduced cutting efficiency. In most cases, it has been established that picks of better quality (the lowest value of the C2 index) should be used regardless of the price. However, there are cases where a pick's choice depends on its price and losses in cutting.

The C2 index is the parameter that best describes the quality of the pick; therefore, it is recommended that the proposed method and procedure should be used to evaluate picks both when placing orders and to file complaints, but also in other cases, whenever cutting tools need to be selected.

**Author Contributions:** Conceptualization, K.K.; methodology, K.K.; software, T.W.; validation, K.K. and K.M.; formal analysis, K.K. and K.M.; investigation, K.K., K.M. and T.W.; resources, K.K.; data curation, K.M.; writing—original draft preparation, K.K. and K.M.; writing—review and editing, K.M.; visualization, K.M. and T.W.; supervision, K.K. and E.P.; project administration, K.M.; funding acquisition, K.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** The research was funded by AGH University of Science and Technology, Kraków, Poland.

**Data Availability Statement:** Data presented in the article are original and not inappropriately selected, manipulated, enhanced, or fabricated.

**Conflicts of Interest:** The authors declare no conflict of interest.

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