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The photogrammetric approach in conical picks wear rate evaluation

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Abstract
The cutting tools in mining industry are especially prone to rapid wear, since most of the rocks exhibit aggressive abrasion attributes. A typical representative of fast wearing mining end-tools is a conical pick (also known as tangential-rotary cutter). In order to decrease the premature deterioration, the manufacturers and users tend to enhance the lifespan of the tool by wide range of approaches, namely heat treatment, chemical treatment, burnishing, hardfacing etc. In order to estimate the wear rate of a given pick one has to select appropriate procedure and method of evaluation. By this time, most commonly applied method is to estimate the wear rate basing on mass loss measurements of the tools being exploited with constant cutting parameters and fixed conditions. The Authors proposed also a new method of volumetric wear assessment, basing of three-dimensional photogrammetric scanning and compared the results with the outcome of traditional mass wear evaluation of the same sets of tools. Additionally, this paper contains recommendations regarding both approaches (volumetric and mass), especially focusing on the possibilities of the new method concerning measurements of the manufactured tool.

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1. Introduction

Most of the machines that are designed to deal with naturally occurring mineral materials (such as coal, sandstone, sand, gravel or rubble) or manufactured ones (bricks, airbricks or concrete) are prone to abrasive wear (Mucha, 2023). Such contact occurs during the sourcing or production of these materials (Jeong, 2023; Wang, 2022), their transport (Shi, 2017) or the processing process (Bembenek, 2023; Cleary, 2017). Although all parts may wear eventually, the cutting tools are especially vulnerable to abrasion since they are in direct contact with hard particles and are under constant load (Biały, 2016; Biały 2021). Such tools can have many different forms: radial picks, conical picks, disc cutters, core drills and mining drill bits, which are presented in Figure 1 (Biały, 2017; Dewangan, 2015; Kotwica, 2018; Su, 2020). All of them are fabricated using wear-resistant materials. The main body of the given tool is usually manufactured from heat-treated high-alloy steels (Bołoz, 2019; Bołoz, 2020), while the tool's tip is made out of sintered carbides in cobalt matrix WC-Co (Katiyar, 2016; Nahak, 2018) or some composites such as PCD – Policrystaline Diamond, MMC – Metal Matrix Composite or DEC – Diamond Enchanced Carbide (Johansson, 2019; Sundaramoorthy, 2017; Tsybulia, 2020). Heat treatment increases the material hardness and resistance to abrasive wear. If only the heat generated during the cutting operation is reasonably low, the wear resistance is usually considered plausible. However, if the heat outpaces the given steel's tempering level, the tool's body deteriorates rapidly (Bembenek, 2022; Katinas, 2023). If the pick's body wear exceeds the critical point and can no longer hold the carbide tip, which is often lost, the whole tool is rendered useless prematurely. It is the reason standing behind the manufacturer's tendency to apply an appropriate coating, which has anti-abrasion properties and can withstand high temperatures (Ahmed, 2019; Chinnasamy, 2023; Palaniappan, 2022). Another technique to enhance the lifespan of the tool is to enclose a cooling system for the whole cutting setup (usually with water or a coolant with special admixtures) (Prostański, 2012; Yang, 2019; Zhang, 2021), however any constructional enrichment of such a kind can increase the cost of the mining machine significantly (Krauze, 2020).

Fig. 1. Examples of cutting tools: a) conical picks, b) radial picks (Sandvik, 2023)

2. Research method

Having a large variety of conical picks (various shape, structural parameters) made using different technologies (various heat treating, hardfacing), an objective assessment of their durability and the associated purchase costs is required. It can only be done under laboratory conditions (Bołoz, 2023). A method and laboratory station have been developed to test and evaluate picks under the same conditions. The method involves the evaluation of the accuracy of tool manufacture, the properties of the body material and WC-Co insert, and the rate of wear during the grinding of an artificial rock sample through milling (Fig. 2), where the mass loss of picks after cutting is determined under specified and constant conditions (rotational speed, feed rate).

The *C2* index characterizing the tested tools' wear rate is defined as the ratio of the tool mass loss Δm product and the standard sample volume V_w to its initial mass m and the volume of the obtained debris V_u (1). It should be noted that the smaller the value of the *C2* index, the less wear the tool has and the greater its durability. As previously mentioned, the assessment of tool wear rate based on mass loss has been conducted for many years, and its detailed description can be found in the available literature (Krauze, 2017; Krauze, 2021). An attempt was also made to assess the tool wear rate based on volumetric loss using photogrammetry (scanning) (Collins, 2019; Dabove, 2019; Tavani 2020). It is a new method that allows for the evaluation of the tool wear rate based on volumetric loss and appears to reduce the influence of the difference in density between the WC-Co insert and the tool body (steel) on the *C2* index, which impacts the mass of the whole tool.

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

The volumetric wear index *C3* (2) is defined similarly as the product of the difference between the tool volume before and after testing ΔV and the standard sample volume V_w to the product of the tool volume before testing V and the volume of the obtained debris V_u. It should be noted that the smaller the value of the *C3* index, the less wear the tool has and, therefore, the more significant its durability. The only remaining task is determining these volumes (Krauze, 2023).

$$C3 = \frac{\Delta V}{V} * \frac{V_w}{V_u} \quad [-] \quad (2)$$

Fig. 2. A laboratory setup for studying the rock-cutting process using rotary milling or drilling head unit

The volumetric wear can be estimated using a photogrammetric approach, which involves scanning the object from different angles. To enable scanning, an appropriate setup had to be constructed and built (Fig. 3). The setup consists of a photographic camera (Fig. 3a) with a 12.2 MP Sony IMX333 sensor (Sony, Tokyo, Japan), a rigid photographic tent (Fig. 3b) with a built-in light source, and a stepper motor-driven turntable controlled by an Arduino Nano (Arduino, Somerville, USA) and a TMC2208 driver (Trinamic GmBH, Hamburg, Germany).

The rotation of the scanned tool was coupled with the trigger of the shutter, which captured an image of each tool 60 times (every 6 degrees). Additional geometric patterns on the turntable increased the number of characteristic points needed to reference the images, which were the input to the MeshRoom program (Alicevision Association, Paris, France, 2019). The light source in the form of an LED strip and the photographic camera lens were modified with a polarizing filter to eliminate reflections that would degrade the quality of the scan. The resulting 3D scan data was processed in MATLAB (Mathworks, Natick, USA) to find the symmetry axis of the tool model before and after use, fit them together, and calculate the volume difference (Fig. 4).

The consecutive steps for obtaining the tool volumes before and after the tests are shown in Figure 5. The method above requires checking and comparing the results with the currently used one (*C2*). In order to verify this method (volumetric wear, *C3* index), studies were conducted on the wear rate of various types of conical picks, and the *C3* and *C2* indexes (mass loss) were determined.

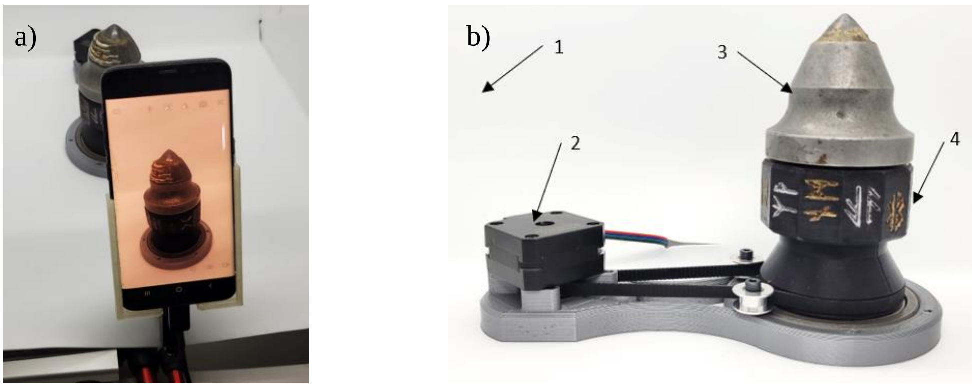

Fig. 3. View of the setup: a. camera position relative to the photographic tent and scanned object, b. the setup (background of tent 1, stepper motor-driven turntable 2, scanned tool 3, markers 4)

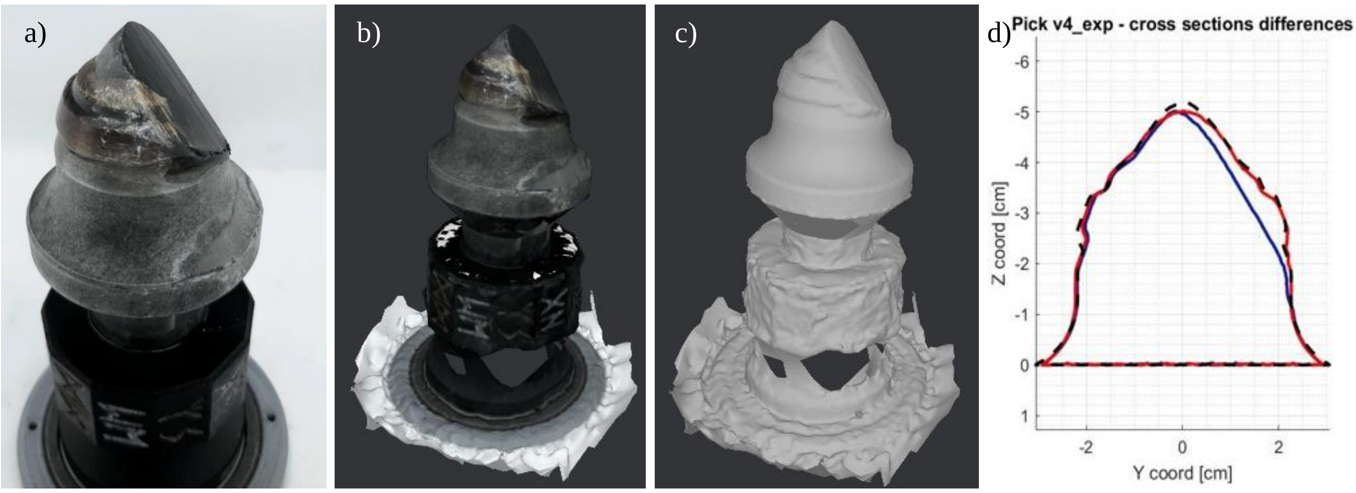

Fig. 4. An example of acquiring the geometry of a pick: a. a projection of the tool captured by the camera, b. a view of the digital reconstruction, c. a view of the filtered stereolithographic geometry, d. a view of projecting the largest and smallest cross-section onto a common plane

3. Assessment of the wear rate of conical picks

The study of wear rate was conducted for three types of picks. Their bodies (working parts) were hardfaced with various materials designed to increase their durability. The pick manufacturers chose the surfacing types (chemical composition, hardness). All tested picks were conical picks intended for underground roadheaders with a working part length of 65- or 70 mm. Conical picks with a 70 mm working part length, surfaced with a coating of WC-Co (sintered carbide) inserts with a diameter of ϕ22 mm and a tip angle of $2\beta u = 105°$ in a quantity of four pieces, were marked as N1 (Fig. 6a). The same picks with a different coating were marked as N2 (Fig. 6b). Conical picks with a 65 mm working part length, surfaced with a coating of WC-Co (sintered carbide) inserts with a diameter of ϕ25mm and a tip angle of $2\beta u = 95°$ in a quantity of four pieces were marked as N3 (Fig. 6c).

As mentioned before, the durability (wear rate) of conical picks is assessed through empirical research, which involves determining the mass loss of the pick before and after cutting under specific and constant conditions. Similarly, the wear rate of the exact pick can be determined based on the volumetric loss using photogrammetry (scanning). In both cases, conducting the same empirical research (milling) is necessary using a specialized workstation provided by the Department of Machinery Engineering and Transport at AGH University of Science and Technology in Krakow. The mass and volume of the pick are then determined before and after the tests, followed by the calculation of the mass and volumetric loss. Of course, the research capabilities of this workstation are more significant as it allows for the examination of the cutting process through milling or drilling using individual cutting tools or organs.

The research implementation is carried out on a test rig that meets the requirements of the adopted research methodology. It is used to conduct comprehensive laboratory research on the broadly understood process of cutting rocks. The research mentioned above enables the realization of the milling process with a specific cutting tool on an artificial or natural rock sample under laboratory conditions. In this case, the picks are mounted on the test disk, creating a pick system, the diagram of which is shown in Figure 7. The picks are distributed around the circumference every 90°. Each set of picks is mounted in numbered (1 to 4) holders installed on the disk

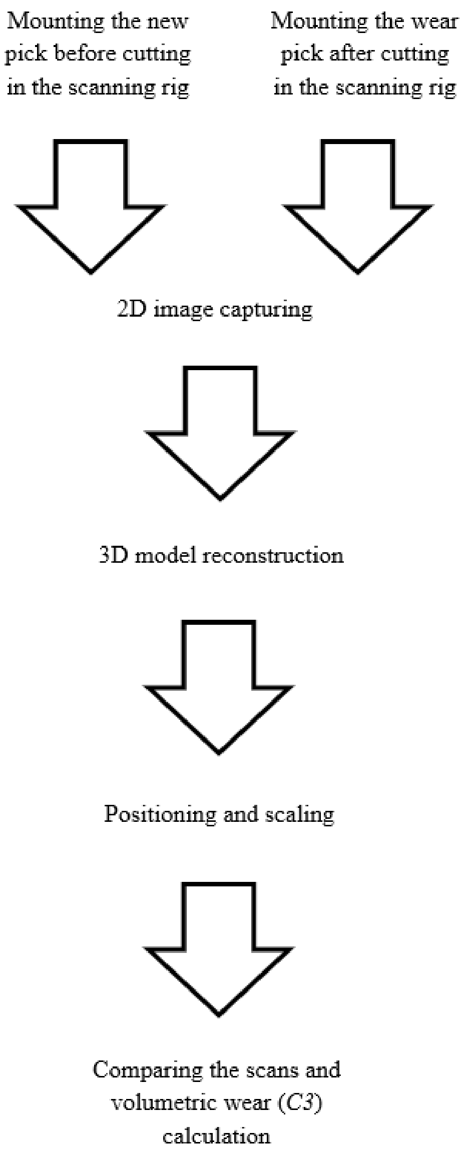

Fig. 5. Scheme of the algorithm for determining the volume of picks and their difference

N1 N2 N3

Fig. 6. Picks before testing

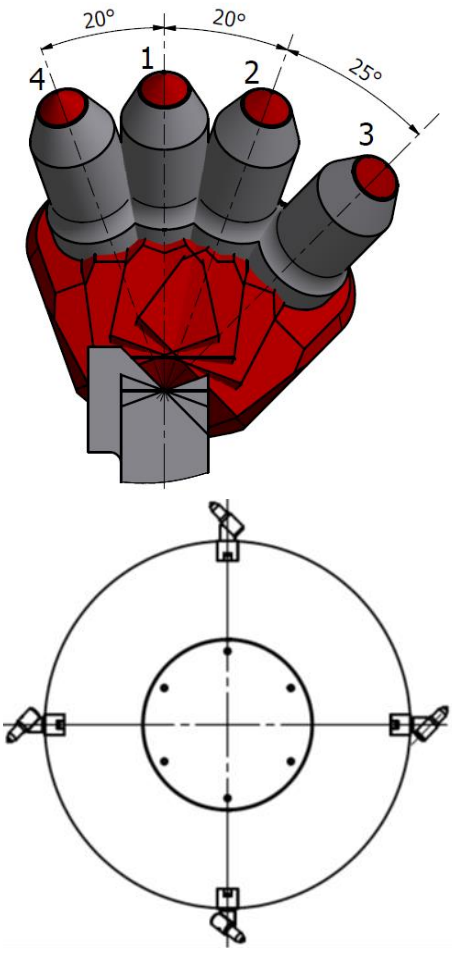

Fig. 7. Diagram of the used picks system with the picks enumerated (Krauze, 2017)

According to the previously described method and procedure, tests were conducted on cement-sand samples using conical picks, where the working parts were protected with overlays. Each batch of picks (four pieces) mounted on the disc was first weighed and scanned. Then, they were used to cut the limestone at the same feed rate v_p and rotation speed n. Afterwards, the picks were photographed (Fig. 8), weighed, and scanned again after cooling and cleaning (Fig. 9). This allowed for the essential part of the research, which is determining the mass loss (Tab. 1) and volume loss (Tab. 2) of the picks. The calculated values of the *C2* index for the tested picks were compared in Table 3, and the *C3* index in Table 4.

picks N1

picks N2

picks N3

Fig. 8. View of selected picks after the tests prepared for measuring mass and volume

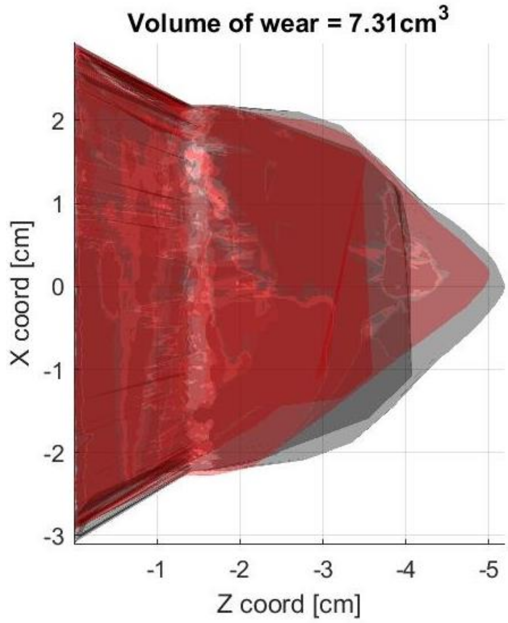

Fig. 9. Scan of the geometry of the N4 pick in position 4 before (grey colour) and after (red colour) testing

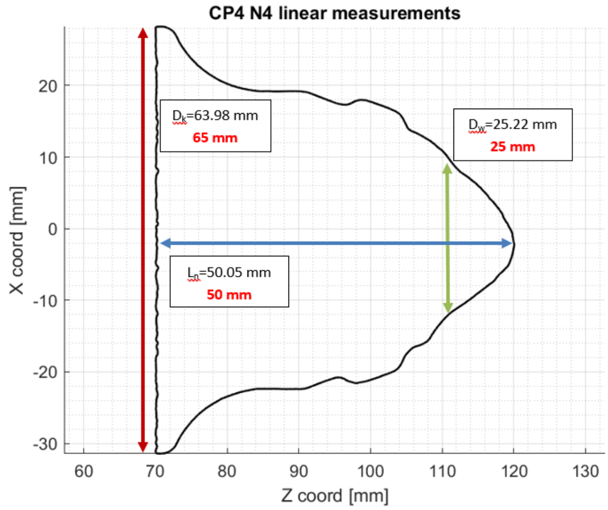

Fig. 10. Scan of the geometry of the N1 pick in position 1 before testing with dimensions from the scan (black) and measured dimensions (red). The L_n dimension lacks 15 mm of its real length due to manual scan clipping

Table 2. A summary of the average values of the *C2* index for each batch of four picks N1, N2 and N3

Position of the pick on the disk	Pick N1	Pick N2	Pick N3
1	54.14	56.28	74.60
2	50.35	60.28	49.65
3	0.85	5.58	0.54
4	5.11	40.64	15.11
C2 average value:	27.61	40.70	34.97

Table 4. A summary of the average values of the *C3* index for each batch of four picks N1, N2 and N3

Position of the pick on the disk	Pick N1	Pick N2	Pick N3
1	84.0	105.70	180.60
2	89.7	111.20	100.10
3	0	39.30	0
4	12.60	74.80	55.30
C3 average value	46.60	82.80	84.00

The *C3* values for tool number 3 in N1 and N3 batches (Table 4.) are "0" because the scanning process resolution was too low to detect such miniscule differences. Comparing it to the mass loss at 0.54÷0.85 g, this level of measurement error can be accepted.

4. Discussion

Based on the conducted research and obtained results, it is possible to assess individual picks' durability and protective layers' influence on their durability. It should be clearly emphasized that the tested picks, according to the research plan and methodology, always worked in the same conditions (cutting speed and feed rate, pick arrangement, rock sample), and the measure of their wear rate is the *C2* index. The value of this parameter indicates the speed of pick wear, and the smaller the parameter, the higher the durability of the pick. Table 5 presents the values of *C2* and *C3* indexes for picks N1, N2, and N3 as a function of their position on the disc and the average value of these parameters.

The lowest average value of *C2* = 27.614, and thus the lowest wear rate, was obtained for picks N1 with reinforced working part of the tool using automatic welding. Picks N3, with an imitation of a steel ring on the tool's working part, achieved a slightly higher average value of *C2* = 34.972 (an increase of 26% compared to picks N1). Picks N2, with an additional manually welded overlay, ranked third (*C2* = 40.695 - an increase of 47% compared to picks N1). As for the volumetric loss rate *C3*, similar to the mass loss rate, it can be observed that pick N1 had the lowest rate of wear. The remaining picks, N2 and N3, have comparable *C3* rates. It deviates somewhat from the gradation of wear rates of picks described by the *C2* index.

It is also necessary to consider the position of the pick on the tool, as the cutting resistance is different. It can be seen from the values of the *C2* index, whose value for all types of picks in position 3 is the lowest. A similar situation can be observed for picks in position 1, where again, for two cases, the picks in this position have the highest value of *C2* (N2, N3). The exception is pick N2, where the pick in position 2 had the highest value of *C2*.

In general, pick N1 with a factory-made bead obtained the lowest average values of *C2* and *C3*, and any in-situ fabricated hardfacing overlay decreased the pick's resistance to abrasive wear. For the remaining picks, *C2* and *C3* values indicate that pick N2 has the highest *C2* value (mass loss), while according to volumetric wear, it is pick N3. Therefore, there is a need for further improvement of the volumetric wear method to achieve full compliance with the mass loss method. Similar conclusions can be drawn for linear dimension measurements (Tab. 6).

The differences in *C2* and *C3* values and linear measurements are caused by scanning process discrepancies. Each tool was scanned with a focal length fixed on the upper part of the pick's working surface, which had most of the characteristic points crucial for generating the output 3D geometry. The measurement of the diameter of WC-Co inserts has the most significant discrepancies, caused by the visible solder that makes identification of inserts borders harder. Enhancing the precision of scans by using stereometric matrices for image acquisition is possible.

5. Conclusion

The carried-out tests of the wear rate of the picks during the mining of the artificial sample showed a significant impact on the durability of the protective layer of the working part of the pick and its position on the disc. The protective layer protects the pick if it is appropriately selected and made. N1 picks obtained the lowest value of the *C2* index with factory-made (automatically) overlay. Making an additional overlay on factory tools may increase their durability. However, the research showed that these tools' wear rate was higher.

On the other hand, the case of measuring the picks' durability using the volumetric loss method (*C3* index) and measuring the linear dimensions of the pick looks promising. However, it requires refinement and full compliance with the mass loss method (*C2* index) and the traditional measurement of pick dimensions using linear measuring instruments. In addition, when determining the *C3* index, differences in the specific density of the material of the pick body and the WC-Co tip should be considered.

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Appendix

Table 1. Comparison of mass loss results and *C2* index values for N1 picks

Pick N1				Reference volume of the sample $V_w = 5$ m^3	
Pick's position on the disk	Mass of the pick: before testing m [g]	Mass of the pick: after testing m_p [g]	Mass loss of the pick $\Delta m = m - m_p$ [g]	Volume of the output V_u [m^3]	*C2* [–]
1	1534.59	1335.18	199.41	0.012	54.14
2	1533.80	1348.44	185.36		50.35
3	1527.27	1524.15	3.12		0.85
4	1539.10	1520.24	18.86		5.11
The average value of the pick's relative weight loss *C2* index				*C2*: 27.61	

Table 3. Comparison of the results of the volumetric loss and the value of the *C3* index for N1 picks

Pick N1				Reference volume of the sample $V_w = 5$ m^3	
Pick's position on the disk	Volume of the pick: before testing V [cm^3]	Volume of the pick: after testing V_p [cm^3]	Volume loss of the pick $\Delta V = V - V_p$ [cm^3]	Volume of the output V_u [m^3]	*C3* [–]
1	110.39	88.14	22.25	0.012	84.00
2	117.98	92.57	25.41		89.70
3	108.77	108.77	0		0
4	116.74	113.22	3.52		12.60
The average value of the pick's relative volume loss *C3* index				*C3*: 46.60	

Table 5. A summary of the average values of the *C2* and *C3* indexes for each batch of four picks N1, N2 and N3

No.	Position of the pick on the disk	Pick N1		Pick N2		Pick N3	
		C2	*C3*	*C2*	*C3*	*C2*	*C3*
1	1	54.14	84.00	56.28	105.70	74.60	180.60
2	2	50.35	89.7	60.28	111.20	49.65	100.10
3	3	0.85	0	5.58	39.30	0.54	0
4	4	5.10	12.60	40.64	74.80	15.11	55.30
Average value		27.61	46.60	40.70	82.80	34.97	84.00

Table 6. Average values of linear dimension measurements for N1, N2 and N3 tools, made with calliper ("measurements" column) and performed on the digital scan ("scan" column)

Pick dimension	Pick N1			Pick N2			Pick N3		
	Measurement	Scan	Difference	Measurement	Scan	Difference	Measurement	Scan	Difference
L_n	70.00	69.45	-0.55	70.00	69.12	-0.88	65.00	63.98	-1.02
D_k	58.00	57.42	-0.58	58.00	57.07	-0.93	65.00	64.21	-0.79
D_w	22.00	23.14	+1.14	22.00	22.85	+0.85	25.00	25.81	+0.81

圆锥齿磨损速率评估中的摄影测量方法

關鍵詞
矿业
岩石切割
圆锥齿
质量磨损
体积磨损

摘要
矿业中的切削工具尤其容易迅速磨损，因为大多数岩石表现出激烈的磨损特性。矿业快速磨损末端工具的典型代表是圆锥齿（又称切割圆锥）。为了减少过早的磨损，制造商和用户倾向于通过一系列方法来提高工具的寿命，包括热处理、化学处理、抛光、堆焊等。为了估算给定齿的磨损速率，需要选择适当的程序和评估方法。目前，最常用的方法是根据工具在恒定切割参数和固定条件下的质量损失测量来估算磨损速率。作者还提出了一种新的三维摄影测量法来评估体积磨损，并将其与同一组工具的传统质量磨损评估结果进行了比较。此外，本文还包括有关这两种方法（体积和质量）的建议，特别关注新方法在制造工具测量方面的可能性