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## Directions for the Development of Research on Selected Parameters of Conical Picks

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### Abstract:

The paper presents an analysis of directions for developing research on selected parameters of conical picks used in mechanical rock cutting. These tools constitute the basic equipment for the cutting drums of mining and road machines, and their durability and efficiency depend on geometric and material properties, as well as on wear resistance. Based on a review of the literature and current research methods, limitations in determining cemented carbide grain size and assessing material wear resistance were identified. Low repeatability of WC grain-size measurements was observed despite the use of standardised methods. The study also indicates a lack of laboratory methods that enable the reliable reproduction of wear conditions encountered during actual rock cutting. Standard tribological tests do not fully reflect the complex nature of material degradation, while testing complete tools is costly and time-consuming. Therefore, a new research method based on a modified pin-on-drum approach is proposed to evaluate the wear rates of materials and coatings under conditions similar to those in real operating conditions. A concept for a test rig is presented, and the ranges of key process parameters, such as cutting speed, normal load, and counter-sample properties, are defined. The proposed approach enables rapid, comparative testing of numerous material variants, serving as an intermediate stage between tribological testing and testing of finished tools. The results indicate the need for further work on more repeatable methods for WC grain size determination and on test rigs that enable better reproduction of the real operating conditions of cutting tools.

Keywords: conical picks, rock cutting, WC grain size, tool wear, research methods

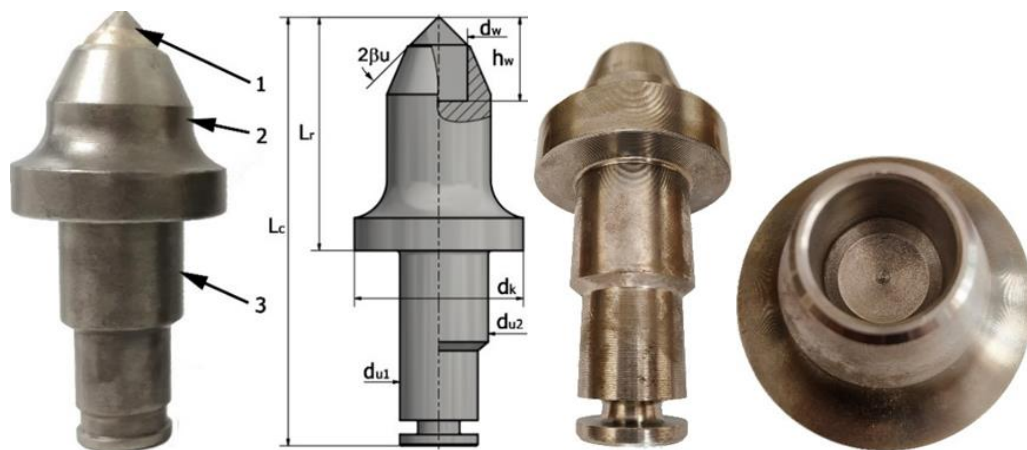


## 1. Introduction

Mechanical rock cutting is a key process in raw material extraction, excavation, and road surface milling, and is used in underground and surface mining, road construction, and tunnelling. This process is performed using various machines, such as longwall shearers and roadheaders, road and floor milling machines, and tunnel boring machines.

The working elements of these machines are cutting drums equipped with cutting tools or disc tools, with the largest share being cutting drums on longwall shearers and roadheaders fitted with conical picks. These tools are directly involved in the rock-cutting process. The materials being cut may include hard and lignite coal, metal ores, rock salt and potash salt, concrete, asphalt mixtures, and various rocks such as sandstones, shales, clays, gypsum, and dolomites [1].

Currently, conical picks are the most commonly used tools. A standard conical pick consists of a body comprising a shank part (3) and a working part (2), in which the tip (1) is located (Fig. 1).



**Fig. 1.** Construction and basic dimensions of a conical pick:  
a) pick construction; b) basic pick dimensions; c) pick body; d) pick holder socket

The shank part consists of a cylindrical, single- or double-stage shaft. The working part of the pick is a rotational body tapering towards the tip, of various shapes, reinforced with a cutting tip in the form of a cemented carbide insert [2]. Various shapes and sizes of working parts and flanges of conical picks are available.

The fundamental principle of operation of a conical pick is its ability to rotate freely and randomly about its own axis during cutting, ensuring uniform wear and maintaining a tip shape close to its original shape.

Such rotation depends on an appropriate distribution of forces acting on the pick. The pick must be pressed into the holder along its axis; otherwise, bending leads to jamming and asymmetric wear [3, 4].

Cutting drums may be equipped with several to over two hundred picks. The smallest number of picks is used on small adapter drums or milling attachments. Standard cutting drums of longwall shearers and roadheaders are equipped with several dozen picks, whereas the largest numbers are used in continuous miners and several types of floor milling machines. Picks used for cutting rock salt, potash, or gypsum exhibit minimal wear. Higher wear is observed when cutting coal seams, while the highest wear occurs when cutting surrounding rocks with high silica content, especially metal ores.

Picks are subjected to various tests that allow the determination of their geometric and material parameters as well as those describing their durability. These methods are well known and applied in practice [1, 5, 6].

One of the key parameters of cemented carbide tips is grain size. Despite the use of standardised methods, they do not yield repeatable, reproducible results; therefore, modifications to existing methods or the development of new ones are required.

Another important operational parameter is the wear rate of materials used for the body and the tip. Currently applied tribological methods do not adequately reproduce the wear process occurring during rock cutting and do not provide reliable results. In turn, methods that test complete tools require manufacturing finished picks and conducting costly test-rig experiments. As a result, there is a lack of systematic comparative studies on the wear resistance of various materials, coatings, and carbides, and on the influence of manufacturing process parameters.

Therefore, this paper analyses the current state of knowledge, demonstrating the need to develop a method for determining the grain size of cemented carbides, as well as a method and a test rig for evaluating the suitability of materials for mining tools. The study aims to develop a method and test rig concept enabling the laboratory evaluation of the wear resistance of materials used in conical picks, with the most faithful reproduction of mechanical rock-cutting conditions. The study includes an analysis of existing research methods, identification of their limitations, and the proposal of a new research approach, along with assumptions for the test rig.

## 2. Testing of Conical Pick Parameters

Cutting tools should be characterised by a long service life, and the durability of picks depends on many factors. Methods are used to evaluate [1, 5, 6]:

- geometric parameters of the body and the tip,
- material parameters of the body and the tip,
- wear rate indicator,
- non-invasive measurement of tip size.

These methods are applied both in research and in the evaluation of tender picks and in quality control [1, 5, 6].

Testing of geometric parameters involves determining selected linear and angular dimensions of the pick and comparing the results with user requirements and manufacturer documentation.

Material testing involves determining the type and properties of materials from which the conical pick is made. Material testing requires separating the steel body from the cemented carbide tip. The material analysis of the body includes determining the chemical composition of the steel, the hardness of the shank and working parts, and the heat treatment. In contrast, the analysis of the cemented carbide tip includes determining its composition, density, and hardness.

Under laboratory conditions, the durability of picks is defined as the amount of material (mass or volume) that can be cut before replacement is required. The method for determining the wear rate of conical picks involves milling a rock sample with four identical picks. The wear rate indicator is then calculated based on the mass loss of the tested picks and the volume of material removed. All tests are carried out on the same sample and under identical conditions, enabling comparison of different picks and selection of the best one in terms of durability.



Direct measurement of the tip (diameter and height) in a finished pick is not possible. Therefore, the tip is removed by brazing to verify its geometry. This method is costly, time consuming, requires specialised stationary equipment, and prevents further use of the tested pick. The dimensions of the tip are very important, especially its height, which has a decisive influence on the service life. The need for such verification has led to the development of new non-invasive methods for assessing tip size [1].

The above methods for testing selected parameters of picks are well established and provide comparable and reliable results. Similarly, for determining WC grain size and assessing the wear resistance of materials used in mining tools, the development of appropriate research methods is necessary.

### 3. Determination of Cemented Carbide Grain Size

The mechanical properties of tips used in mining tools made of cemented carbides determine their suitability for rock-cutting. The tip must be characterised by sufficient strength to prevent chipping and fracture, while maintaining the highest possible resistance to abrasive wear. The key parameters are the WC (tungsten carbide) content and the WC grain size. These parameters determine the properties of cemented carbides, such as compressive strength, bending strength, hardness, toughness, and other characteristics describing susceptibility to cracking and brittle fracture.

These properties and parameters are determined using appropriate standards [7]. One of the key parameters of cemented carbides is the WC grain size, which significantly affects the properties of the entire tip. However, despite the use of standardised methods, the obtained results are not repeatable. Various classifications of cemented carbides according to grain size are known [8, 9]. According to PN EN ISO 4499 2:2021 (Hardmetals — Metallographic determination of microstructure — Part 2: Measurement of tungsten carbide grain size [10]) and its Polish interpretation [7] cemented carbides are classified by WC grain size dWC from nano fine-grained (below 0.2  $\mu\text{m}$ ) to super coarse-grained (above 6.0  $\mu\text{m}$ ). The influence of Co binder phase content and WC grain size on the mechanical properties of sintered materials is well known and confirmed by numerous studies [8, 9, 11–14]. Increased WC content results in higher strength and hardness, and thus higher resistance to abrasive wear, but at the expense of toughness. In contrast, increasing WC grain size reduces abrasion resistance, hardness, and bending strength, but increases resistance to cracking and toughness. Examples of relationships between selected parameters and WC grain size in cemented carbides are presented in Fig. 2, where the red frame indicates the range of cobalt content in typical grades used for rock cutting. The variability in mechanical properties with grain size and cobalt content requires consideration of operating conditions and expected tool performance. There is no universally optimal cemented carbide for rock cutting.

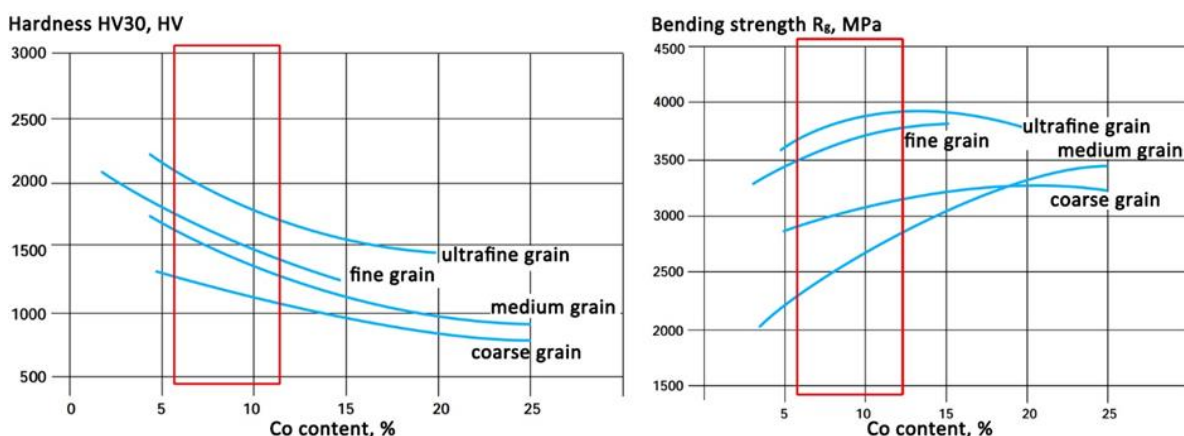


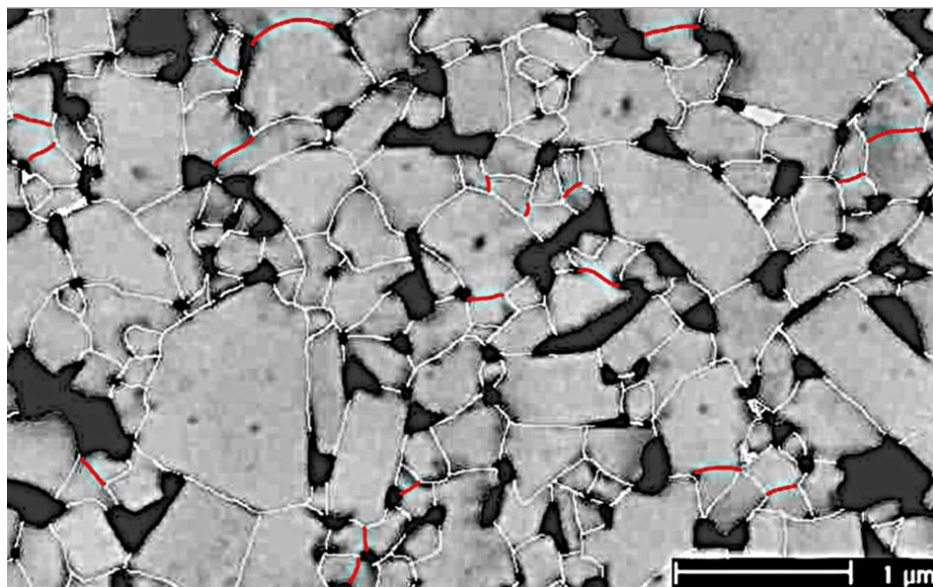
Fig. 2. Influence of Co content and WC grain size on selected mechanical properties of cemented carbides (based on [14]): a) Vickers hardness; b) bending strength

In mining applications, standard WC–Co cemented carbides are predominantly used, where the specified Co content and mean WC grain size are decisive. However, the properties of cemented carbides are also influenced by the use of other binders, including nickel (Ni) or iron (Fe), as well as additives such as titanium carbide (TiC) or tantalum carbide (TaC), and the production of materials with graded microstructure [9, 15, 16].

Numerous methods are available for determining grain parameters, including grain size. Cemented carbides are at least two-phase materials; only selected methods are applicable [17, 18]. Grain size determination is based on images of metallographic specimens obtained by optical microscopy, scanning electron microscopy (SEM), or electron backscatter diffraction (EBSD). It is also performed using a scanning microscope. Grain size is determined from two-dimensional images [19, 20].

In practice, the most commonly used methods are the linear intercept method and the area-based method. Several studies have compared these methods [21, 22, 23], also depending on whether images were obtained using SEM or EBSD [24, 25]. This issue is often analysed for very fine WC fractions, significantly below 1  $\mu\text{m}$  [26, 27]. One study proposed a new method for determining grain size with accuracy comparable to EBSD [28]. Other studies compared EBSD-derived grain sizes with those obtained for powders using laser diffraction [29, 30]. The EBSD method yielded errors of 3.4% to approximately 12%, indicating limited accuracy; however, the extent of WC grain growth during sintering was not specified.

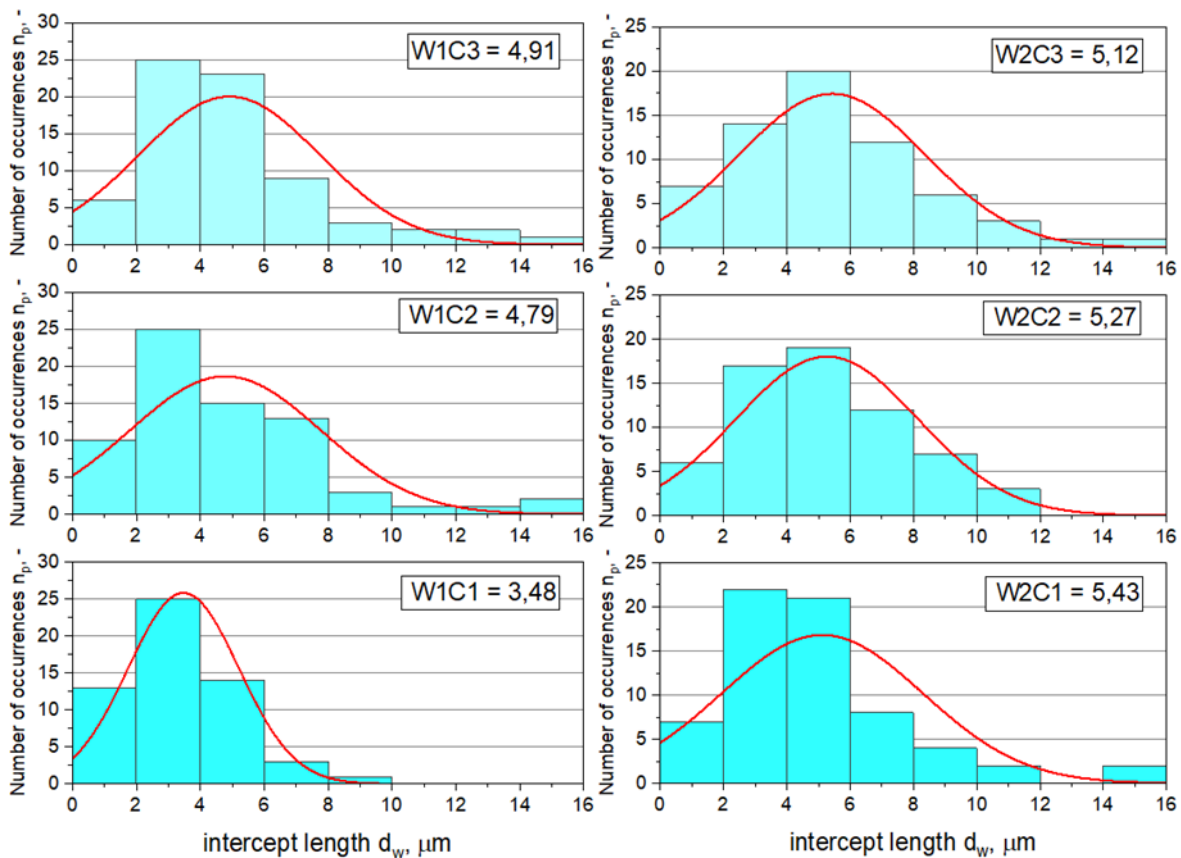
The most widely used method is the linear-intercept method described in PN EN ISO 4499-2:2021 [10]. This standard specifies the procedure for determining the average tungsten carbide grain size. The method involves calculating the average segment length between grain boundaries by drawing intercept lines on a properly prepared metallographic specimen. Due to the lack of well-defined grain boundaries, operator interpretation is required, which introduces significant error and leads to poor reproducibility. Despite proper etching, grain boundaries are not always clearly visible and unambiguous. Fig. 2a shows an example microstructure of a fine-grained cemented carbide. In this image, the operator, based on experience, identified the grain boundaries used for grain-size determination [27]. The same image was later analysed by an experienced operator from AGH, who added missing grain boundaries (red lines). This example clearly illustrates the problem of subjective interpretation. In Fig. 2b intercept lines were drawn according to the standard requirements.



**Fig. 2.** Fine-grained microstructure of WC from SEM with added grain boundaries, magnification 2000 $\times$  (based on [27])

ISO 4499 also refers to ASTM E112 – 13 (Standard Test Methods for Determining Average Grain Size [31]), which describes a circular (planimetric) method for determining grain size. This method is based on a circle of known area and counting grains fully or partially within it. The ISO standard highlights key requirements allowing measurement error below 10%. It also states that the method is not intended for determining grain-size distribution or grain shape, which requires further investigation.

Fig. 4 presents grain-size distributions determined using the ISO 4499 method for three intercept lines on a single specimen for two cemented carbides. Each graph includes the mean grain size value. The distributions differ significantly, confirming the limitations indicated in the standard. Mean values between individual intercept lines also differ considerably, with differences exceeding 40%.



**Fig. 4.** Results for two cemented carbides for three intercept lines:  
a) carbide W1; b) carbide W2

For example, Tab. 1 presents results obtained by two independent laboratories for three cemented carbides. Differences between results obtained under the same standard can reach up to 39%. These tests were conducted at the request of a cemented carbide manufacturer to meet tender requirements. Despite producing carbides from WC powder with an appropriate grain size, standardised measurements may indicate non-compliance. A mining company specified minimum mean WC grain sizes ( $d_{WC}$ ) of 2.5  $\mu\text{m}$  or 6.0  $\mu\text{m}$ , depending on the pick type [32]. For the carbide labelled No. 2, the tender would have been rejected by laboratory 1 and accepted by laboratory 2.

**Table 1.** Example results of WC grain size dWC determination [1]

Carbide No.	Mean grain size dWC, $\mu\text{m}$		Relative difference, %
	Lab 1	Lab 2	
1	6.27	8.70	38.87
2	5.79	7.90	36.44
3	7.07	8.80	24.56

The large variation in grain-size determination results constitutes both research and a practical problem, particularly when specific grain sizes are required. Therefore, it is justified to develop new methods or refine existing ones. The primary objective is to achieve high repeatability and reproducibility, ensuring that results across laboratories and operators remain within acceptable limits. An automated method is desirable, as it eliminates operator interpretation and improves reproducibility.

The method should also ensure consistency with the grain-size values determined for WC powders before sintering, while accounting for microstructural changes that occur during manufacturing. During sintering, WC grains grow via mechanisms such as Ostwald ripening [9, 33, 34]. Therefore, grain size measured on metallographic specimens cannot be directly compared with that of powder. One possible validation approach is to produce special sintered materials in which grain growth is suppressed.

#### 4. Research on Materials for Mining Tools

Rock-cutting tools are subjected to various tests to determine the parameters that influence their durability. Such studies are conducted at research centres worldwide [35]. The applied methods can generally be divided into:

- testing of finished tools under laboratory conditions,
- testing of finished tools under real operating conditions,
- determination of material wear rate using mechanical engineering methods.

Testing finished tools is an effective approach; however, it is costly and time-consuming because it requires manufacturing complete tools and testing under conditions that reflect real operation. For this reason, such tests are used to a limited extent, mainly for selected solutions of different geometries, materials, or coatings. Testing under real conditions, despite its advantages, cannot serve as a standard research method due to rock heterogeneity and anisotropy, natural hazards, and changing operating conditions. In addition, such tests interfere with normal mining operations. Therefore, they are mainly applied at the final stage to verify selected tool designs.

The last group includes abrasion tests widely used in mechanical engineering, which are well-suited for evaluating construction materials and coatings. However, in these tests, the wear process is mainly confined to the surface and reflects conditions typical of standard tribological systems. The PN EN ISO 28080:2021 standard defines three methods for evaluating the abrasion resistance of cemented carbides. Each method is based on static wear of a specimen in contact with an abrasive material and does not account for the dynamic character of operation [36].

Standard methods are not suitable for testing materials and coatings intended for mining tools, since the wear process in such applications involves not only surface interactions but also dynamic effects. For example, tests of the wear rate of conical picks with titanium nitride coatings did not demonstrate improved resistance [37]. In contrast, TiN coatings significantly increase durability in conventional tribological applications, such as machining tools [38, 39].



Wear resistance is commonly determined using test rigs such as tribotesters or tribometers. Numerous configurations exist, allowing simulation of specific wear mechanisms and measurement of key parameters, such as the coefficient of friction. These tests are based on measuring the mass loss of a specimen due to frictional interaction, typically involving relative motion between the specimen and a counter-sample or an abrasive. Common configurations include pin-on-disc, ball-on-disc, disc-on-disc, and pin-on-drum systems [8, 40, 41, 42].

The wide variety of methods and test rigs results from the diversity of tribological conditions. Even rigs based on the same principle may differ in parameters, abrasives used, or operating conditions (dry or wet). Consequently, modified or newly developed methods are often introduced to simulate specific operating conditions characteristic of particular industries [8, 43, 44, 45, 46]. In such studies, either modified setups were used, or parameters were selected to ensure results matched the wear observed during actual operation.

Research findings indicate the need to develop and modify experimental methods and test rigs to reproduce real processes better. It is essential to simulate operating conditions using parameter values that provide results consistent with engineering practice [40].

During rock cutting, abrasive wear occurs through processes such as micro-cutting, scratching, micro-ploughing, shearing, detachment of asperities, and chipping due to cracking. Despite the use of water spray systems, tools operate at elevated temperatures. Methods used in tribological testing also simulate these phenomena across a range of process parameters, which explains their diversity [8].

Similarly, in testing rock abrasivity, which is intended to predict tool wear, existing methods often fail to account for key factors that influence results. Despite the availability of many methods, there is a recognised need to develop new approaches that account for the specific nature of mechanical rock cutting [47].

The same conclusions are drawn from comparative studies of the abrasion resistance of different materials conducted using several test rigs. Results were compared with wear observed in field tests under mining conditions. Only some laboratory methods produce results consistent with real wear. It was also noted that even well-selected methods are mainly useful for eliminating less resistant materials rather than identifying optimal ones [48, 49].

To address this, a new method and test rig were proposed for testing materials and coatings. Based on an analysis of existing methods, it was concluded that a modified pin-on-drum arrangement can reproduce conditions similar to those in rock cutting.

The classical pin on drum method is well known and described in the literature [50]. In this method, a rotating specimen moves along the surface of a rotating drum, pressed against an abrasive surface. The drum has a diameter of 0.509 m and a length of 0.610 m, rotates at 1.7 rpm (linear speed 2.7 m/min), while the specimen rotates at 17 rpm.

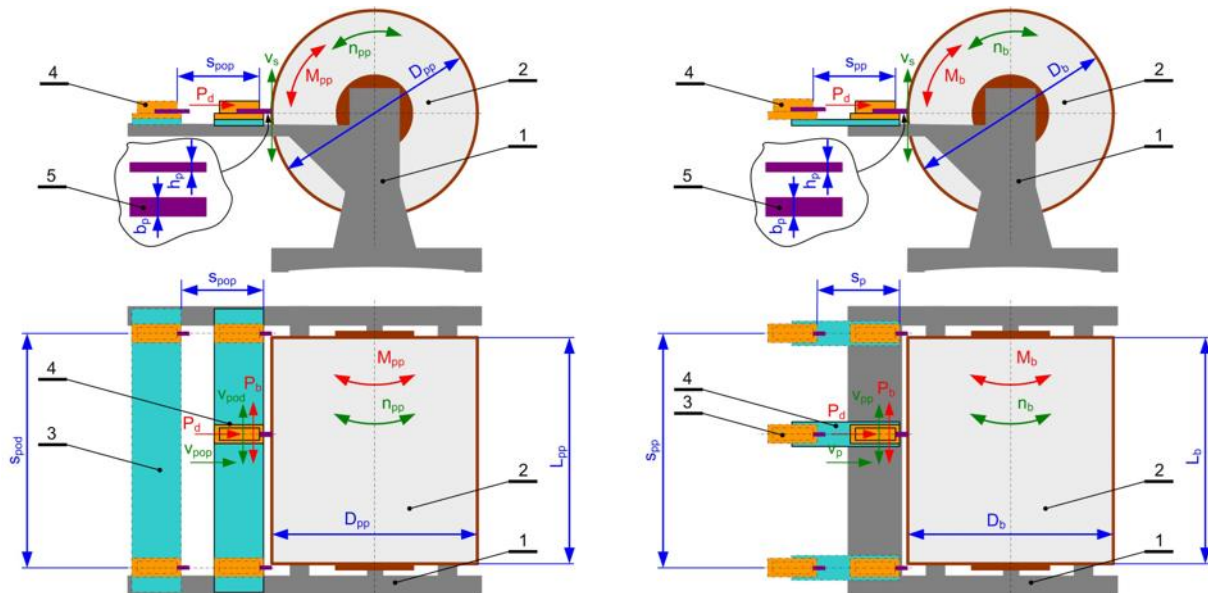
Pin on drum test rigs are still widely used. It is estimated that properly conducted tests can reduce measurement error to  $\pm 0.5\%$  [51]. These rigs are used in both original and modified forms, for example, for testing coatings on steel substrates [52] or composites [53, 54], as well as in modified configurations including vibration loading for heavy industry machines [46].

The proposed method assumes the use of small, simple-geometry specimens. Specimens made from different materials, coatings, or subjected to specific treatments (e.g., thermochemical processes) should be compared. Tests are conducted on artificial samples, such as concrete with controlled properties. This approach allows rapid and cost-effective testing of numerous material and process variants. A key aspect is defining appropriate ranges of process parameters based on real operating



conditions. Some parameters must be determined experimentally and validated by comparison with practical observations; a sufficiently wide parameter range must be considered.

Based on the pin on drum concept, a schematic diagram of the proposed test rig was developed. Fig. 5 shows a simplified concept comprising a frame (1), a counter-sample (2), a transverse carriage (3), a longitudinal carriage (4), and a specimen (5). Unlike in the classical configuration, the specimen does not rotate. The figure shows two variants of the test rig design.



**Fig. 3.** Schematic of the two variants of the proposed test rig

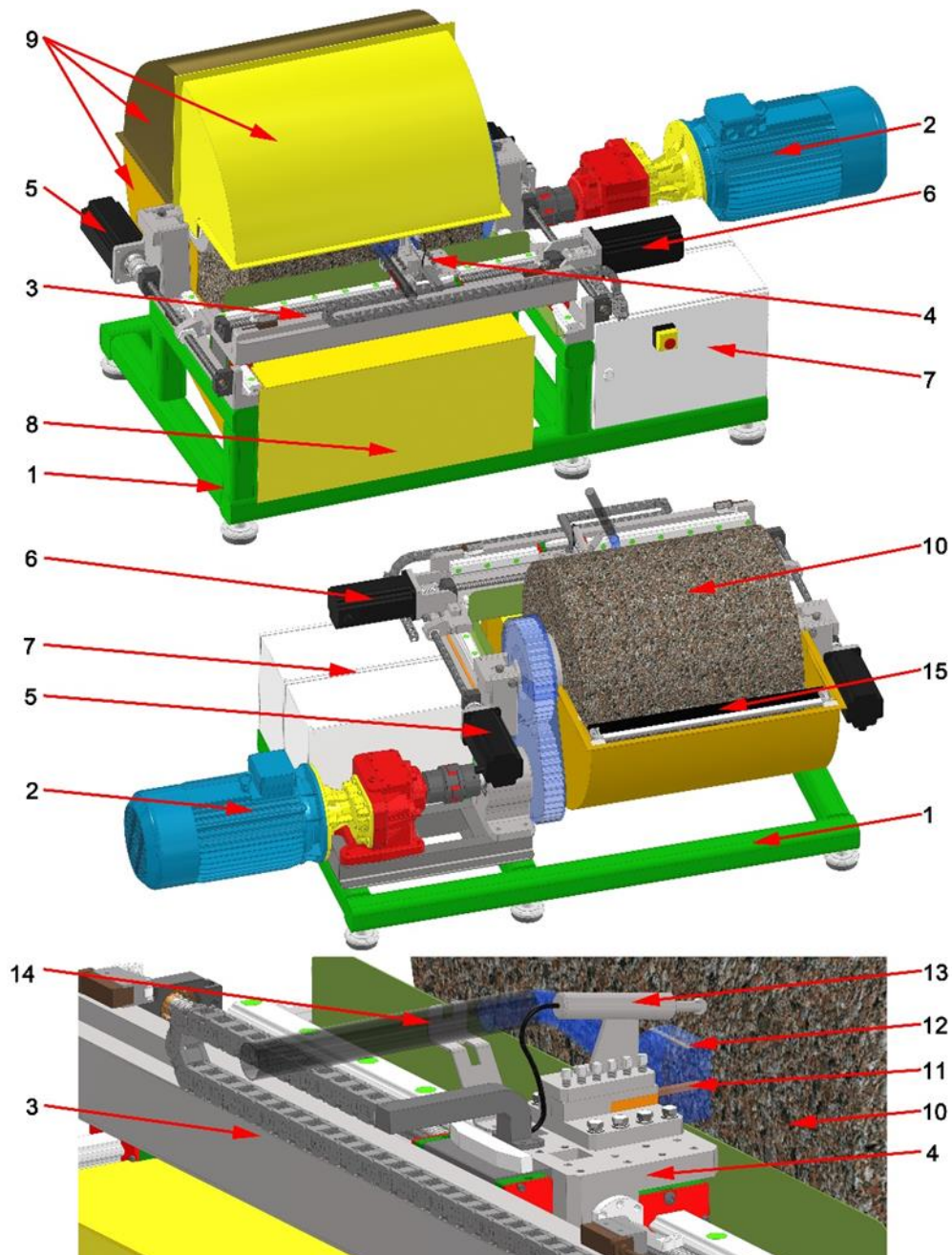
1 – frame, 2 – counter-sample, 3 – transverse carriage, 4 – longitudinal carriage, 5 – specimen

The counter-sample, in the form of a concrete ring cast on a pipe, is mounted on a shaft and driven by an electric motor through a gearbox. Both carriages are driven independently, and the transverse carriage may be pressed against the counter-sample with a constant force. The longitudinal carriage holds the specimen and may be replaced with a fixture holding multiple specimens. Controlled parameters include rotational speed and diameter of the counter-sample, as well as the positions of both carriages.

The recommended development procedure for new tools includes:

1. testing multiple material variants on the proposed test rig,
2. laboratory testing of finished tools to select the best solution [1],
3. validation under real operating conditions.

Such an approach significantly expands research capabilities and allows ongoing evaluation of new materials, coatings, and manufacturing processes. A 3D model of the proposed test rig is shown in Fig. 4. The modular design enables easy reconfiguration and further expansion, e.g., for force measurement or testing multiple specimens simultaneously.



**Fig. 4.** 3D model of the test rig for evaluating wear rate of materials used in mining tools [1]:

- 1 – frame, 2 – drive system of counter-sample, 3 – transverse carriage, 4 – longitudinal carriage, 5 – transverse drive system, 6 – longitudinal drive system, 7 – electrical cabinet, 8 – debris container, 9 – protective housing, 10 – counter-sample, 11 – specimen, 12 – specimen shield, 13 – radius sensor, 14 – dust extraction system, 15 – cleaning system of the counter-sample

## 5. Conclusions

High demand for certain mineral resources, combined with the ongoing drive to increase efficiency and reduce operating costs, is driving the development of mechanical rock cutting. This process involves direct interaction between the cutting tool and the rock mass and is most commonly carried out by milling using various types of mining machines. Currently, conical picks are the standard for

equipping cutting drums, while radial picks and discs are used less frequently. Regardless of the cutting method, the key factors are the tool itself and the cutting process.

Methods for testing conical picks allow evaluation of their quality by analysing geometric and material parameters as well as wear rate. From the user's perspective, the most important parameter determining tool durability is the wear rate indicator, which can be determined in laboratory tests using test rigs that allow evaluation of individual tools and entire cutting drums.

Determining cemented carbide grain size remains a significant challenge. Research results confirm the low repeatability of measurements despite the use of standardised methods. This indicates the need to modify existing methods or develop new approaches, which should be validated while considering WC powder characteristics and changes that occur during sintering.

Wear and durability testing using full-scale conical picks is costly and organisationally demanding, which makes systematic studies of the influence of materials, coatings, and process parameters difficult. There is a lack of a test rig capable of reproducing real wear conditions in a laboratory setting. Therefore, a concept of a new method based on a modified pin-on-drum arrangement and corresponding test rig assumptions has been developed.

The novelty of the study includes identifying the limitations of standard methods for WC grain-size determination, identifying the gap between tribological testing and testing of finished tools, and developing a concept for a modified test method that enables the evaluation of materials under conditions similar to real operating conditions.

The proposed approach serves as a basis for the construction of a test rig enabling more reliable evaluation of wear resistance. It may help reduce research costs and shorten the development time of new cutting tools. Future work will include the construction and validation of the test rig, as well as the comparison of laboratory and field test results.

## References

- [1] Bołoz Ł.: Narzędzia Organów Urabiających Skały. Dobór i Projektowanie, Badania i Eksploatacja. Wydawnictwa AGH: Kraków, 2025.
- [2] Bołoz Ł.: Conical Picks for Underground Mining. *New Trends in Production Engineering* 2020, 3, 221–230, DOI:10.2478/ntpe-2020-0018.
- [3] Rożenek Z.: Teoria obrotu noża styczo-obrotowego. *Przegląd Górniczy* 2018, 74, 7–12.
- [4] Kotwica K.: Zagrożenia generowane podczas mechanicznego urabiania skał zwięzłych – możliwości ich eliminacji lub ograniczenia. *Napędy i Sterowanie* 2018, 20, 74–83.
- [5] Bołoz Ł.: Mass and Volume Wear Rates of Conical Picks. *Management Systems in Production Engineering* 2025, 33, 494–501, DOI:10.2478/mspe-2025-0049.
- [6] Bołoz Ł.: Methods for Quantitative Assessment of Conical Pick's Wear Rates. *Production Engineering Archives* 2025, 31, 448–454, DOI:10.30657/pea.2025.31.41.
- [7] Tomiczek B., Matula G., Gołombek K.: Metodyka badań mikrostruktury i podstawowych własności węglików spiekanych. *LAB - Laboratoria, Aparatura, Badania* 2020, 25, 26–30.
- [8] Ścieszka S.F., Filipowicz K.: Materiały na narzędzia górnicze: nowe trendy w technice badań; Wydawnictwo Politechniki Śląskiej: Gliwice, 2001.
- [9] García J., Collado Ciprés V., Blomqvist A., Kaplan B.: Cemented Carbide Microstructures: A Review. *International Journal of Refractory Metals and Hard Materials* 2019, 80, 40–68, DOI:10.1016/j.ijrmhm.2018.12.004.



- [10] PN-EN ISO 4499-2:2021 PN-EN ISO 4499-2:2021-02. Węgliki Spiekane. Metalograficzna Ocena Mikrostruktury. Część 2: Pomiar Wielkości Ziarna Węglików Wolframu; 2021.
- [11] Pirso J., Letunovič S., Viljus M.: Friction and Wear Behaviour of Cemented Carbides. *Wear* 2004, 257, 257–265, DOI:10.1016/j.wear.2003.12.014.
- [12] Saito H., Iwabuchi A., Shimizu T.: Effects of Co Content and WC Grain Size on Wear of WC Cemented Carbide. *Wear* 2006, 261, 126–132, DOI:10.1016/j.wear.2005.09.034.
- [13] Armstrong R.W.: The Hardness and Strength Properties of WC-Co Composites. *Materials* 2011, 4, 1287–1308, doi:10.3390/ma4071287.
- [14] Boehlerit: Węgliki Spiekane. Ochrona Przed Zużyciem i Półfabrykaty. Katalog PDF. Available online: [https://www.boehlerit.com/fileadmin/user\\_upload/PDF/Wegliki\\_spiekane\\_Tvrdokov.pdf](https://www.boehlerit.com/fileadmin/user_upload/PDF/Wegliki_spiekane_Tvrdokov.pdf) (accessed on 6 February 2025).
- [15] Konyashin I., Ries B., Lachmann F., Fry A.T.: Gradient WC-Co Hardmetals: Theory and Practice. *International Journal of Refractory Metals and Hard Materials* 2013, 36, 10–21, DOI:10.1016/j.ijrmhm.2011.12.010.
- [16] Qian C., Li K., Liu Y., Zhang X., Zhang S., Zhang J., Jiang L., Cheng H.: Wear Behavior of Functionally Graded Cemented Carbides with CoNiFeCr Multi-Principal-Element Alloy Binder. *Journal of Materials Science & Technology* 2025, 217, 245–267, DOI:10.1016/j.jmst.2024.08.003.
- [17] Ryś J.: *Stereologia materiałów*; Fotobit-Design, 1995; ISBN 978-83-901450-5-1.
- [18] Grabowski G.: *Mikrostruktura Jako Podstawa Modelowania Numerycznego Właściwości Tworzyw Ceramicznych*; Wydawnictwo Naukowe AKAPIT: Kraków, 2022; ISBN 978-83-65955-54-8.
- [19] Brown C.U., Alkan Donmez: *Microstructure Analysis for Additive Manufacturing: A Review of Existing Standards*. Raport NIST AMS 100-3.; National Institute of Standards and Technology: Washington, 2016.
- [20] Farooq M.U., Klement U.: EBSD Characterization of Carbide–Carbide Boundaries in WC–Co Composites. *Journal of Microscopy* 2004, 213, 306–312, DOI:10.1111/j.0022-2720.2004.01313.x.
- [21] Roebuck B., Phatak C., Birks-Agnew I.: A Comparison of the Linear Intercept and Equivalent Circle Methods for Grain Size Measurement in WC/Co Hardmetals. Raport NPL Report MATC(A)149.; National Physical Laboratory: Teddington, 2004.
- [22] Mucha K., Augustyn-Nadzieja J., Szczotok A., Krauze K.: An Improved Procedure for the Quality Control of Sintered Carbide Tips for Mining Applications, Based on Quantitative Image Analysis of the Microstructure. *Materials* 2021, 14, 1236, DOI:10.3390/ma14051236.
- [23] Pesin V.A., Vasilyeva M.V., Osmakov A.S.: Osobiennosti Miedoda Siekuszczich, Ispolzujemogo Dla Opriedielenija Razmiera Ziernaw Splawach WC-Co. *Izviestija Wuzow. Izv. VUZ. Poroshk. Met.* 2024, 18, 28–37, DOI:10.17073/1997-308X-2024-3-28-37.
- [24] Mingard K.P., Roebuck B., Bennett E.G., Gee M.G., Nordenstrom H., Sweetman G., Chan P.: Comparison of EBSD and Conventional Methods of Grain Size Measurement of Hardmetals. *International Journal of Refractory Metals and Hard Materials* 2009, 27, 213–223, DOI:10.1016/j.ijrmhm.2008.06.009.
- [25] Mingard K.P., Roebuck B.: Interlaboratory Measurements of Contiguity in WC-Co Hardmetals. *Metals* 2019, 9, 328, DOI:10.3390/met9030328.



- [26] Wachowicz J., Chlebiej K., Zieliński R.: Influence of WC Grain Size on the Properties of WCCo Cemented Carbides Obtained by the Method of Pulse-Plasma Sintering SPS. *Materiały Ceramiczne /Ceramic Materials/* 2019, 71, 195–203.
- [27] Park S.J., Cowan K., Johnson J.L.: German, R.M. Grain Size Measurement Methods and Models for Nanograined WC–Co. *International Journal of Refractory Metals and Hard Materials* 2008, 26, 152–163, DOI:10.1016/j.ijrmhm.2007.05.010.
- [28] Mueller D., Konyashin I., Farag S., Ries B.: A Novel Express Method for Determining WC Grain Sizes and Its Use for Updating Dependencies of Coercivity and Hardness on WC Mean Grain Size in Hardmetals. *International Journal of Refractory Metals and Hard Materials* 2023, 117, 106416, DOI:10.1016/j.ijrmhm.2023.106416.
- [29] Josefsson F.: Development of a Quantitative Method for Grain Size Measurement Using EBSD & Comparison of WC-Co Materials Produced with Different Milling Processes. [Praca Dyplomowa], Royal Institute of Technology: Stockholm, 2012.
- [30] Tomach P.: The Influence of the Grinding Media Diameter on Grinding Efficiency in a Vibratory Ball Mill. *Materials* 2024, 17, 2924, DOI:10.3390/ma17122924.
- [31] ASTM E112 – 13 ASTM E112 – 13 Standard Test Methods for Determining Average Grain Size; 2021.
- [32] JSW przetarg 125/PM/24 Dostawy Do Kopalń JSW S.A. Noży Kombajnowych z Terminem Realizacji 12 Miesiący Od Daty Zawarcia Umowy. [Dostęp 01.02.2025] 2024.
- [33] Müller D., Konyashin I., Farag S., Ries B., Zaitsev A.A., Loginov P.A.: WC Coarsening in Cemented Carbides during Sintering. Part I: The Influence of WC Grain Size and Grain Size Distribution. *International Journal of Refractory Metals and Hard Materials* 2022, 102, 105714, DOI:10.1016/j.ijrmhm.2021.105714.
- [34] Konyashin I., Nazari N., Mueller D., Farag S., Ries B., Bondarev A., Meledin A.: WC Coarsening in Cemented Carbides during Sintering. Part II: Mechanisms of the Influence of Different Grain Growth Inhibitors. *International Journal of Refractory Metals and Hard Materials* 2025, 128, 107087, DOI:10.1016/j.ijrmhm.2025.107087.
- [35] Bołoz Ł., Biały W.: Methods and Test Benches for Cutting Tools Testing - A Review. *Energies* 2023, 16, 1–17, DOI:10.3390/en16010445.
- [36] PN-EN ISO 28080:2021:08 PN-EN ISO 28080:2021:08. Węgliki Spiekane - Badania Ścierania Węglików Spiekanych.; 2021.
- [37] Krauze K., Bołoz Ł., Wydro T., Mucha K.: Durability Testing of Tangential-Rotary Picks Made of Different Materials. *MIAG* 2017, 1 (529), 68, doi:10.7494/miag.2017.1.529.68.
- [38] Trento C.: Benefits of Titanium Nitride Coating for Cutting Tools Available online: <https://www.samaterials.com/content/benefits-of-titanium-nitride-coating-for-cutting-tools.html> (accessed on 11 February 2025).
- [39] Kucharska B., Czarniak P., Kulikowski K., Krawczyńska A., Roźniatowski K., Kubacki J., Szymanowski K., Panjan P., Sobiecki J.R.: Comparison Study of PVD Coatings: TiN/AlTiN, TiN and TiAlSiN Used in Wood Machining. *Materials* 2022, 15, 7159, doi:10.3390/ma15207159.
- [40] Dukhnenko Y.: Study of Materials Test Methods for Wear Resistance in Oil and Mining Industry. *International Journal of Mechanical Engineering and Technology* 2019, 10, 1781–1791.



- [41] Mikołajczyk J.: Tribotestery. Budowa i przeznaczenie; Wydawnictwo Państwowej Wyższej Szkoły Zawodowej im. Stanisława Staszica w Pile: Piła, 2019.
- [42] Valdes M.J., Ardila Marín J.G., Rodriguez-Cabal M.A., Betancur J.D.: TRIBOMETRY: How Is Friction Research Quantified? A Review. *International Journal of Engineering Research and Technology* 2020, 13, 2596–2610, doi:10.37624/IJERT/13.10.2020.2596-2610.
- [43] Ojala N.: Application Oriented Wear Testing of Wear Resistant Steels in Mining Industry; Tampere University of Technology: Tampere, 2017; ISBN 978-952-15-3936-7.
- [44] Filipowicz K., Ścieszka S.F.: Badania materiałów dla systemów transportu i przeróbki węgla. *Zeszyty naukowe Politechniki Śląskiej* 1995, 223, 19–36.
- [45] Valtonen K., Keltamäki K., Kuokkala V.-T.: High-Stress Abrasion of Wear Resistant Steels in the Cutting Edges of Loader Buckets. *Tribology International* 2018, 119, 707–720, DOI:10.1016/j.triboint.2017.12.013.
- [46] Kandeve-Ivanova M., Vencl A., Karastoyanov D.: Advanced Tribological Coatings for Heavy-Duty Applications: Case Studies; Prof. Marin Drinov Publishing House of Bulgarian Academy of Sciences: Sofia, 2016.
- [47] Hamzaban M.-T., Rostami J., Dahl F., Macias F.J., Jakobsen P.D.: Wear of Cutting Tools in Hard Rock Excavation Process: A Critical Review of Rock Abrasiveness Testing Methods. *Rock Mech Rock Eng* 2023, 56, 1843–1882, DOI:10.1007/s00603-022-03187-x.
- [48] Blickensderfer R., Tylczak J.: Evaluation of the Planar Array Field Wear Test. *Wear of Materials* 1991. 1991, 1, 339–344.
- [49] Tylczak J.H., Hawk J.A., Wilson R.D.: A Comparison of Laboratory Abrasion and Field Wear Results. *Wear* 1999, 225–229, 1059–1069, doi:10.1016/S0043-1648(99)00043-5.
- [50] Blickensderfer R.: Tylczak J.: Laboratory Tests of Spalling, Breaking, and Abrasion of Wear-Resistant Alloys Used in Mining and Mineral Processing; U.S. Department of the Interior. Bureau of Mines: Washington, 1985.
- [51] Blickensderfer R., Laird G.: A Pin-on-Drum Abrasive Wear Test and Comparison with Other Pin Tests. *Journal of Testing and Evaluation* 1988, 16, 516–526, DOI:10.1520/JTE11270J.
- [52] Teixeira M.F., Pacheco J.T., Da Silva L.J., Rabelo A., Pereira M., Niño C.E.: Laser Cladding of Metco 1040® (Fe-V-Mn-C) on Hadfield Steel: Effect of Processing Parameters on Microstructure and Wear Resistance. *Optics & Laser Technology* 2021, 142, 107219, DOI:10.1016/j.optlastec.2021.107219.
- [53] Muthukumar S., Mathiyalagan P.: Evaluation of Wear Behavior of Al-Sic p Composite Under Dry Sliding Wear Tests. *International Journal of Applied Engineering Research* 2015, 10, 403-411.
- [54] Nakamura K., Minegishi M., Kanno H., Ishii S., Moribayashi T., Takase T.: Comparison of Micro- and Macro-Tribological Properties of Carbon Composites Reinforced by Vapor-Grown Carbon Fibers. *Materials Letters* 2024, 354, 135359, DOI:10.1016/j.matlet.2023.135359.

