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Diagnostic methods and ways of testing the workability of coal - a review

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Abstract
The need to classify rocks in terms of workability stems primarily from the need to choose the appropriate, most effective diagnostic method (DM) and way of mining the given rock. Studying and measuring the workability of rocks is extremely difficult due to the fact that workability depends on many various factors. There are many DM for determining the workability of rocks, but none of them take into account the influence of all factors, hence the obtained results are only indicative. In the article, many DM and ways of determining the cutting resistance with the use of various devices are presented and characterized. The principles of their operations are presented, as well as the DM of measuring the cutting resistance and its utilitarian usefulness in forecasting the selection of mining machines on the basis of cutting for specific mining and geological conditions. The core of the problem is confirmed by the number of covered DM and tools in various research centers around the world. In the article, new tools measuring and evaluating the mechanical properties of the coal solid, all created in Poland, are presented. Their structure, principles of their operation, as well as the innovation of these solutions, are all presented. In this article, their ad-vantages and disadvantages are highlighted, as well as showing the DM which best represents the way of work of the winning machine. Therefore, the results achieved through the aforementioned DM can be understood as representative values.

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1. Introduction

The mining industry, including coal mining, is characterized by the complexity and specificity of the problems related to usage of technical means used in the industry. These problems arise during designing, constructing, and producing machines made to cut coal seams, accumulating with the usage of those machines (Biały and Fries 2019; Sapietova 2012).

One of the very important technical issues in the coal mining industry is the selection of machines (devices) which will consider the specific (incomparable to other branches of the industry) conditions of its usage (Pivarciova, 2019). This especially applies to the selection and work conditions of machines cutting the coal seams. The most representative machines are drum longwall shearer and coal plough. These machines exploit the resources through the cutting process. The issue of properly choosing a shearer plough to the specific coal wall, including the specifications of the process, is incredibly important, especially with an increasing mining concentration.

The operation of cutting, realised by a shearer plough, through a cutting head, consists of separating bits of the rock or solid in a mechanical manner with the help of cutting tools, placed on the flaps or the shield of the cutting head. In the case of a drum shearer, the cutting stems from the combination of two movements of the cutting head – rotational and translational. We assume, that the main movement is the rotational movement expressed in cutting velocity, whereas the translational movement of the whole shearer is merely a helping movement. In the case of a coal plough, separating bits from the coal solid, the main motion is a translational motion.

The issues with the most noticeable impact on decision-making in this field are:

- the mining and geological conditions of the chosen seam,
- the coal mining method,

- the properties of the coal solid.

One of the very important factor defining the ability to apply a certain winning machine in certain conditions, as well as achieving the assumed production goals with mi-nimal costs (economic effect) is the susceptibility of coal to cutting, which is a property of the coal solid (Baron and Głapman 1969; Krauze, 2000; Jonak, 2002; Biały, 2009; Biały, 2017).

One of the basic index characterizing the correct selection of the machine for specific conditions is the energy consumption, defined as the relation of force (work) needed to separate (that is, to cut) the coal from the coal solid to the volume of the worked coal (Gliński, 1998; Davies and McManus, 1990; Vostova et al., 2008; Biały, 2009; Biały, 2013). Defining the value of mining energy consumption by a drum longwall shearer in real conditions and defining its correlation with the properties of the coal solid (its susceptibility to cutting) is imperative in order to properly choose a machine for the given conditions.

When it comes to the workability of rocks, planes with reduced cohesiveness (cleavability, cleavage, rock jointing, stratification) are of great importance. In these planes, the rock is characterized by much smaller indexes of mechanical properties (R_c, R_r), in relation to other planes. This parameter influences the DM of mining (Özbek et al., 2018; He et al., 2019; Dinc et al., 2011).

In recent world literature there are sparse descriptions of research on coal workability DMs (Krauze, 2000; Jonak, 2002; Biały, 2009; Biały, 2013; Kozioł, Machniak, 2010; Biały, 2014; Biały, 2016). However, there are some publications, which concern a broader issue, where the topic of research on coal workability methods is an essential, key element (Biały, 2016; Bołoz and Midor 2019; Bołoz, 2020).

2. Workability

Workability can be broadly defined as the interactions between the worked material and the mining machine (the tool). The workability is the force of resistance, being put up by the worked (fragmented) material onto the cutting head of the machine. That is why workability is one of the mechanical properties of the worked useful minerals (hard coal, lignite, rock).

Mechanical rock mining involves many DMs such as boring, cutting, and planing. These DMs use the processes of cutting, undercutting (chipping), impact cutting, or static pressure cutting. Over the years, unconventional methods such as thermal, electrohydrau-lic, water jet, laser, and other mining methods have also been tested (Vogt, 2016; Bilgin et al., 2018; Stoxreiter et al., 2018; Bołoz and Kalukiewicz, 2020; Zhang et al., 2020; Kotwica, 2021).

It is practically impossible to define workability in an indisputable way, as there are many factors at play – including the cutting method.

Workability is also treated as a technological property by some researchers (Vostova et al., 2008; Biały 2009; Biały 2017; Bilgin et al., 2018). Depending on the cutting technique, it can also be described as:

- in the case of drilling – drillability,
- in the case of deep mining – workability, cuttability,
- in the case open-cast mining – breaking resistance.

In each of the above-mentioned mining processes, the technological process at play is of utmost importance.

The dependencies amongst the above processes are mostly undefined. Which is why the results acquired through one process cannot be approximated to another.

The winning process can be categorized as either active or passive. The influence of the mined material on the ear of the tool used to complete said process is regarded as active workability.

Passive workability covers all parameters that influence the depth the cutting head delves into and the breaking off of parts separated from the seam.

The relations (dependence) between active and passive workability can be established on the basis of chosen properties of the mineral. These properties influence both workability values.

The cutting process, which takes part in natural conditions, making use of specific technology is a complex process, more often it greatly varies from the adopted model. The complexity of this process has been presented on Figure 1.

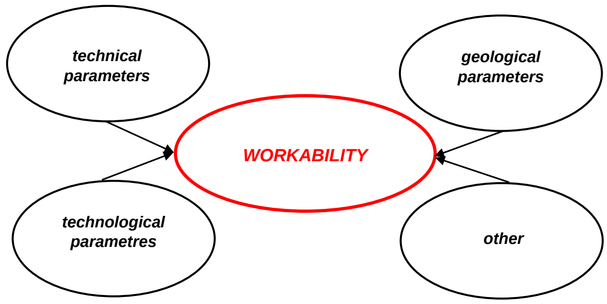

Fig. 1. Parameters influencing the workability

Geological parameters can be designated as a collection of physical, mechanical, and petrographic properties. From a workability standpoint, the most important mechanical property would be compressive strength (Nasseria et al., 2003; Ozcelik et al., 2011).

Technical parameters are specific properties of the work tool, which is strictly connected with the given cutting technology (Biały, 2009; Biały, 2017; Bołoz and Midor, 2019). The geometry of the blade and its mate-rial are examples of such properties.

Technological parameters are defined by technical parameters of the winning machine. The rotational speed of the cutting head, the speed of the advancing movement, which are technological parameters, define the size of the cut furrow, and efficiency. Even in the case of full automation, the human factor also influences the mining process.

Other (the last group of parameters), which influence the cutting process is hard to predict. An example of such a parameter is the tension in the proximity of the cutting machine, its size, as well as the changing petrographic composition and the temperature of the minerals.

Therefore, it is impossible to objectively establish the workability without considering the aforementioned factors. Which is why every cutting technology requires a different method of assessing the workability. Therefore, the workability assessment methods must vary greatly between each other. In practice, different methods of assessing the workability can be (and are) used in the lab (on the test bench), as well as "in situ".

One of the simplest methods is the measurements of the work needed to detach and crush a unit of volume of rock, which is expressed in e.g. J/m^3. In accordance with the applied rock-cutting methods one can distinguish different types of workability (Gliński, 1998; Biały, 2009; Vostova et al., 2008; Kozioł and Machniak, 2010):

- firing workability, expressed through the kg of explosive material used to exploit 1 m^3 of rock,
- drilling workability, or the so-called drillability, measured in the amount of time (in min) needed to drill e.g., a 1 mb opening.
- mechanical workability, described by a workability index (cutability) A, Aψ, WUB in N/cm.

3. The Mechanical Properties of Rocks

The mechanical properties of rocks vary depending on factors such as:

- the type of rock and its origin,
- the tectonics of the rock (faults, fissures, cracks, cracks, cleavage),
- the porosity and moisture of the rock,
- grain size, shape and strength,
- binders (adhesives),
- the direction of the force in relation to the stratification (Bołoz, 2020).

Resistance against compression, stretching, compactness, hardness, and elasticity are some decisive mechanical properties of rocks.

The compactness of a rock is a trait determining its resistance against separating parts of said rock from the solid with the use of tools. Its workability is strongly connected with this property. As the compactness index grows, so does the workability – the rocks are harder to cut. The workability of a rock is its susceptibility to breaking with mining met-hods, i.e., with the use of cutting machines or explosives.

4. Review and Analysis of Applied Methods of Researching Workability Worldwide

In order to establish properties of the coal solid which will in turn establish the susceptibility of coal to cutting with drum longwall shearers working on the basis of cutting, it is imperative to introduce research methods which will establish the sum of resistance forces posed by the mined material (coal) when separating its parts from the coal solid, and will establish the so-called coal workability. In the process of coal cutting, the seam's continuity is destroyed, expressed by changes in volume and size of the cut coal. The coal cutting and grinding process is strongly connected with the dynamic action of the force, which is also why the method of establishing workability must depend on the type of work of the cutting machine and must consider the fact that the workability of coal in each place is greatly influenced by such properties of coal as (Pozin, 1972; Kidybiński, 1979; Biały, 2009; Biały, 2017):

- the type of coal material (type of coal),
- the state of stress in the work zone of the cutting head,
- the variability of the cutting force within the bounds of the seam's thickness,
- the occurrence and location of planes of weakened cohesion,
- coal bands.

A general classification of rock depending on their workability (intuitive, taking hardness, brittleness, and other mechanical characteristics into account) presents itself as follows:

- loose,
- soft,
- fragile,
- hard,
- very hard.

In deep coal mining we mostly must deal with four types of rock, as loose rocks occur very sporadically, if at all – those practically do not occur.

In worldwide mining a variety of coal workability defining methods, for the needs of mechanization, are used, which are defined by different methods and interpreted differently. Those indexes (of which there are many) (Paschedag and Schwolow, 1991; Krauze, 2000; Biały, 2005; Biały, 2009) differently reflect the mechanical properties of the cut coal seam, they also can be separated into the following groups:

1 – laboratory methods of defining the workability of coal,
2 – registering drilling parameters in the seam,
3 – crushability measurements,
4 – the measurement of cutting forces from a pick or group of picks.

In the article, the DMs which have found the widest application in the selection and location of longwall winning machines operating on the principle of cutting, have been discussed.

4.1. The laboratory methods of defining the workability of coal (rocks)

To this group belong methods such as:

I – the Protodyakonow method of establishing the workability index *f*, by mashing coal samples (BN-77/8704-12). The rule of establishing is based on mashing a certain amount of black coal, its coal band or accompanying rocks, after which calculating the volume of the acquired grains under 0.5 mm. On this basis, the workability index f is calculated.

The workability index *f* established through the Protodyakonow method that is the most commonly used (to this day), index to establish the workability. This index is also called the brevity index. The brevity of the rock depends on its composition, unity, size of grains, quality of binder. This trait is included when considering cutting DM. This para-meter, brevity, is described by a so called Protodyakonov brevity index *f*. The higher the value of the index, the harder it is to work or cut the rock.

Table 1 shows the classification of rocks depending on the value of the Protodyakonow index *f*.

The brevity of rocks is not a trait unequivocally defining the strength of the rock, but it does inexplicitly define the rock.

Table 1. Class of rocks in relation to value *f*

Class	*f* index	workability of rocks (coal)
I	< 0.4	very easy to cut
II	0.4 – 0.8	easy to cut
III	0.8 – 1.4	of medium workability
IV	1.4 – 2.4	hard to cut
V	> 2.4	very hard to cut

II – the energy method of establishing the workability index "*U*", defined by the static pressing of irregular clumps in a press while measuring simultaneously the critical deformations.

This method also approximately shows the strength properties of the worked rocks.

III – coal compressive strength R_c (BN-75/8704-07). The method establishing the coal compressive strength against uniaxial (unidirectional) compression in laboratory conditions relies on loading a cylinder- or cuboid-shaped sample with an increasing force until the moment of strength failure. The result of the study is strongly influenced by the so-called smoothness of the sample, as well as the friction between the sample and the surfaces applying the pressure. By studies of coal samples of an irregular shape it is proposed to use paper between the sample and surface to determine a real contact area and to take this contact area into account when determining the compressive strength.

The strength established through this DM is usually twice as large as the strength es-tablished on samples of a regular shape.

The R_c value established this way remains closely connected with (Bęben, 1992; Krauze, 2000; Jonak, 2002; Biały, 2009):
- the size of the given sample,
- the direction of compression in relation to its stratification.

The classification of rocks after taking into account the compressive strength R_c, measured in the state of average humidity (dry air), has been shown in Table 2.

Table 2. Classification of rocks based on R_c

No.	Class of rocks	value of R_c
1	very weak compressive strength	< 15 MPa
2	weak compressive strength	15 MPa ÷ 60 MPa
3	medium compressive strength	60 MPa ÷ 120 MPa
4	large compressive strength	120 MPa ÷ 200 MPa
5	very large compressive strength	> 200 MPa

The strength of rocks against stretching and bending are much lower than the compressive strength. Those reach values of:
- stretching strength from around 5% to 10% of the R_c,
- bending strength from around 25% to 30% of the R_c.

The studies done on the compressive strength of cuboid-shaped rock samples of different sizes and proportions against unidirectional compression have shown that the compressive strength is closely related to the course of action and number of planes of weakened cohesion, cracks, microfissures, and pores in the tested sample.

IV. It is also worth to note the studies done at the Istanbul Technical University, which have the recommendation of the International Society for Rock Mechanics, as the norm for the laboratory measurement of workability. In these studies, workability is described by the SE index. This index is calculated as the ratio of the force (FN) acting on the cutting pick along the length of the cut to the volume of the cut rock (Q) (Burneau of mines 1981).

$$SE = FN/Q \ [MJ/m^3] \quad (1)$$

This parameter has a decisive influence on the durability, installed power and size of the cutting machine, and thus influencing the costs of purchase and exploitation. Therefore, the coal workability measurement allows for the optimal choice of operating parameters of mining machines. This issue concerns both coal winning with the shearer technique and with the plow technique.

The above index can be one of the decisive factors of assessing the possibilities of an effective exploitation of a given area or seam.

4.2. Registering drilling parameters in the seam

The method using the SDM device (Fig. 2) belongs to the second group, used mainly in Russia (Baron and Głapman, 1969; Pozin, 1972).

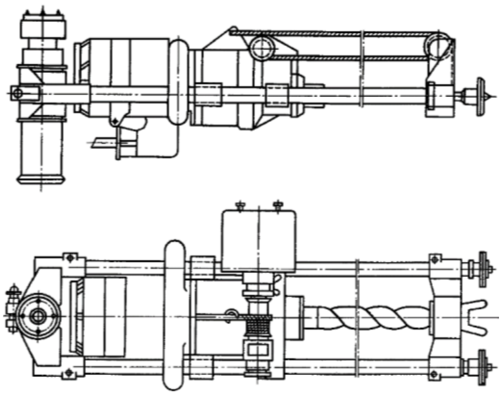

Fig. 2. Device SDM

The workability index in this method is established on the basis of the torque on the rod during the drilling of the hole in the face of the excavation.

Because of the unique character and direction of the measuring cut of the SDM device as well as other machines working on the principle of cutting, the results acquired through this method cannot form a basis of establishing the resistance forces of cutting with the use of drum longwall shearers.

4.3. Crushability measurement

One of the most widely used DMs of defining the crushability of coal, and therefore indirectly defining the workability index, is the method created in Mitsui Miike Machinery Co., Ltd (Biały, 2005; Biały, 2009). The samples for the tests are collected from measurement points on the face of the wall. In every measurement point, two samples of coal are collected from the same stratigraphic section. Next, those samples are ground and placed in a special chest above a steel plate, where, as a result of opening the bottom of the chest rapidly, they fall onto a metal plate, becoming fragmented. The percentage of grain classes is established, on the basis of which the percentages of certain classes are defined, as well as the reference index.

Crushability, marked as FD, is designated as the difference between the total percentage share and the sum of the products of the percentage shares of certain classes and reference indexes. This method reflects the properties of the coal solid, however there is no connection between the work order of the winning machines with the principle of cutting and the susceptibility to cutting.

The measurement of cutting forces from a pick or group of picks

The measurement of cutting forces from a pick (or group of picks – that is the fourth group) is done with the use of special tools (Baron and Głapman, 1969; Pozin, 1972).

This method does not include factors such as: the state of stress in the work are of the cutting head, the variability of the cutting force within the bounds of the seam's thickness, the occurrence and location of planes of weakened cohesion and coal bands.

I. PKS, DKS, Lubimowa, UD (Russia) (Pozin, 1972). All the aforementioned tools are defined by the complexity of their structure, effortfulness needed to make the measurements, as well as the need to make special cavities or holes.

Fig. 3 shows the perfected version of the DKS, DKS-4 device.

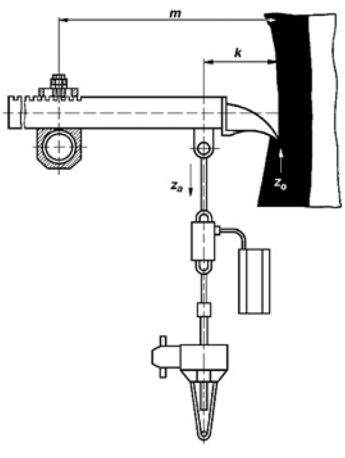

Fig. 3. Device DKS-4

The measurements of cutting resistance forces were made only in the plane parallel to the floor, which does not correspond to the work order of the drum longwall shearer.

Another rule of operation was visible in the UD-2 device (Fig. 4) (Pozin, 1972). The cutting force was measured along previously prepared openings in the coal seam. The length of the openings was between 8 and 10 m, the measurement was made along these openings. The measurements acquired this way included, among others, the tension in the strata, cleavability, stratifications.

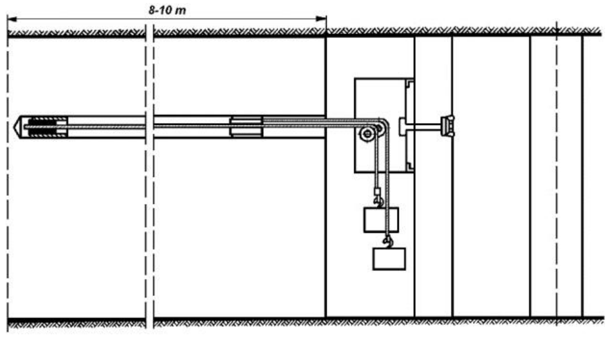

Fig. 4. Device UD-2

The measurements were made only in planes parallel to the floor, which does not correspond to the work order of the drum longwall shearer. This device eliminated measurements in seams with many or creased "inserts" of layers of different mechanical properties.

II. DMT created in Deutsche Montan Technologie in Essen (Germany) (Paschedag and Schwolow, 1991), a device used mainly to locate coal ploughs (Fig. 5).

Fig. 5. Device DMT

The principle of measurement depends on registering the force of cutting with the pick placed on the cutting head while making a 2 cm deep cut.

Therefore, this method cannot be used for the location of drum longwall shearers, as the work order is different.

III. IN-SEAM TESTER (USA) (Burneau 1981) which works based on the tensometric measurement of forces acting on the cutting pick.

The measurements made with the use of this device are effortful, however, the results give us the properties of the worked coal solid quite accurately.

IV. CERCHAR (France) (Cerchar, 1986; Plinningera et al., 2003). One of the stages of the method, created in the Center for Studies and Research of the Charbonnages de France (Cerchar), in collaboration with Mines Paris, is measurement of cutting forces with a single pick in laboratory conditions. The measurements of cutting forces were made on models of cutting heads in 1:6 scale, after which they were made in 1:1 scale, as well as on actual objects in mines in the Lorraine area. A measurement of component forces influencing the cut rock was made, specifically: the tangential component force called the cutting force F_s as well as the normal F_d force called the pressing force.

Based on these measurements, the cutting force has been established, which quite loosely characterizes the coal workability.

V. ZP-1 (The Czech Republic) (Biały, 2005; Biały, 2009). This method depends on the measurement of the cutting force with a test pick in a specific excavating location, on the basis of which the susceptibility of coal to cutting is determined, which is represented by the workability index B (Fig. 6).

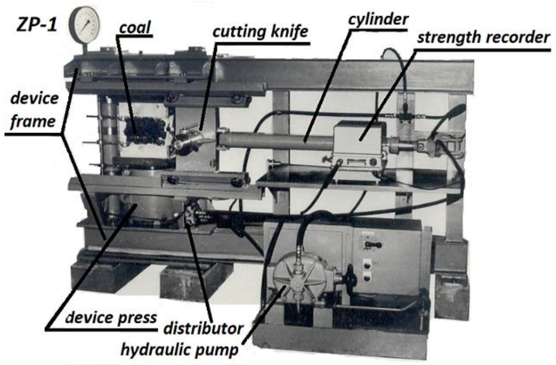

Fig. 6. Device ZP-1

The inability to make vertical cuts with this device disables the use of this method for the attestation of drum longwall shearers.

5. Methods of Assessing Coal Workability in Poland

5.1. The Sikora device

The essence of this DM lies in the measurement of the cutting force on the sidewalls of the openings with a diameter of 100 mm and length of 1 m, drilled in the seam in a di-rection parallel to the face (Sikora and Kidybiński, 1965). This DM adapts the ratio of the average test pick-cutting force to the depth of the cut as its workability index. This device (Fig. 7), was equipped with a rectangular cutting pick 7 set on an arm 5, with the ability to change the depth of the cut. The shift of the pick could be made with the help of a tension device with a gear 3 and crank 4.

The size of the cutting force was measured with the help of a spring dynamometer, which was embedded in the head of the device. The cutting force value was transferred to the drum, which recorded the force in the function of the knife path. The device was fixed in the excavation using toothed struts 1 equipped with limiters 2. In order to capture the influence of the direction of the cleavability, a set of 3 holes was drilled at each measurement point in the following directions: - 45°, 0°, + 45°, relative to the face (the holes were located in parallel planes). Then, using the device, 5 measuring cuts with a depth of 1-4 mm were made in each hole (the depth of the cut was measured on the basis of the furrow's imprint in plasticine). The results of the measurement of cutting forces and the depth of cut for a given measurement location were averaged.

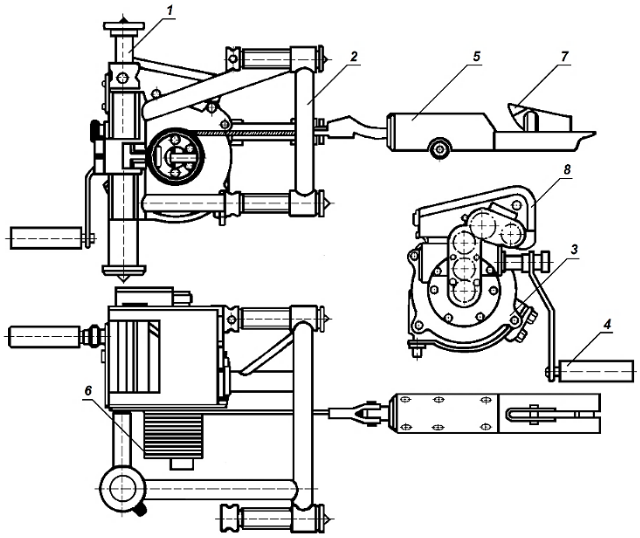

Fig. 7 Device Sikora

The measurement was characterized by the noticeable effortfulness of creating an entire grid of holes and a small cross-section of the measuring cut in relation to the cross-sections of cuts made by the picks of the winning machines. This method took the influence of cleavability into account, but only in a minor way, which made this method not very accurate.

5.2. Coal workability establishing method using the Potępski device

The method of establishing coal workability using the Potępski device used to rely on the measurement of coal cutting forces in the seam with the use of a measuring pick (Biały, 2005; Biały, 2009). The establishment of the device in the place of measurement was carried out by anchoring the device in front of the researched face. The measuring cut along the smoothed face of the face was created through drive from a hand crank, a worm gear with a rope wound on a drum. The measuring pick is embedded in a support, which cooperates with the guides attached to the frame of the device. The possibility of moving the guides of the support against the body allowed for making measuring cuts according to the desired distance between them. The design of the device also allowed for the depth of cut to be adjusted.

The measure of workability K_s is, according to this DM, the proportion of the cutting work to the volume of the cut, or the ratio of the average cutting force to the cross-section of the furrow.

The main flaws of this DM are:

- *test cuts were made in a seam layer which was derived of stress,*
- *the small depth of the measuring cut.*

5.3. The AGH method

The method of determining the workability index of coal *A*, created at the Department of Mining, Processing and Transport Machines, AGH University of Science and Technology, relies on the measurement of cutting resistance forces directly in the coal face while making the straight cuts (Bołoz and Midor, 2018). Those measurement cuts are made with a standard pick on a smoothed surface, which moves along the face of a coal face. The straight movement of the pick is forced through appropriate guidance, which is part of the workability measuring device (Fig. 8).

On the basis of the measurement and registering pressure during cutting with a standard pick at the depth of 2 cm, after proper processing of the measurement signal, one can obtain the average value of cutting force *P*.

The ratio of the average cutting force *P* to the depth of the cut gs is defined by the index of workability *A*.

According to the ITG KOMAG classification, coal with an angle smaller than 60° is classified as compact, while coal with an angle larger than 60° is classified as brittle coal.

On the basis of the workability index A and the coal breakage azimuth ψ one can, using the classification of Polish coals also created by ITG KOMAG, the method determine the type and category of the given coal, thereby choose the proper cutting technique.

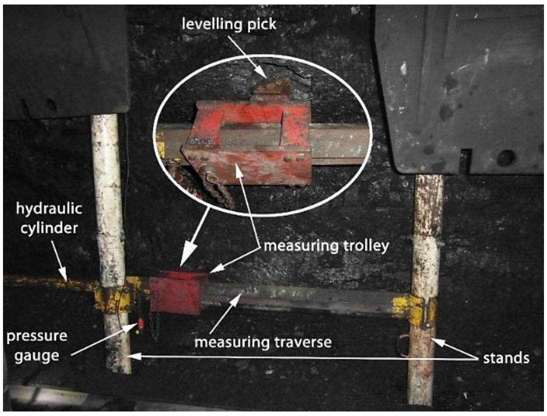

Fig. 8. Device AGH

This index (A), which is determined with the help of the presented device, allows for the comparison of the cutting difficulties for different coal seams. The higher its numerical value, the more difficult it is to work a given seam. The inability to make horizontal cuts with this device disables the use of this method for the attestation of longwall plows.

5.4. Method of determining the coal workability through drilling resistance

To determine the coal workability through measuring the drilling resistance, an electric drill is used. The essence of this method is to use the dependence of the power used during drilling the opening with the electric drill as a function of the speed of drilling progress at the assumed constant rotational speed of the drill. This dependence is, within some limits, a linear one, as long as the resistance of removing drill cuttings from the opening is very small in comparison to the cutting resistance of the drill blade.

The measurements were made with an electric drill, the characteristic $P_u = f(P_o)$ of which is known, P_u being the different speeds of the drilling progress. During drilling, the power consumption of the drill was registered – after taking the efficiency of the drill into account, the average power usage during drilling the opening, P_u, is determined.

In order to make measurements using this method, it was necessary to maintain an unchanged voltage of the electril drill. The changing shares of resistance forces of removing drilling cuttings (especially of soft coals), in general of drilling resistance forces and varying depending on the coal, did not guarantee a comparability of results of the workability index in different coal seams.

The coal workability index V_s *determined through this method properly reflected the situation by cutting with heading machines.*

5.5. Method of determining the coal workability with the POS-1 device

In the early seventies of the last century, in the then ZKMPW (currently ITG KOMAG), the development of a new device was undertaken, one that would determine the cutting resistance. Developing the new DM, it was assumed, that it should allow for proper location of drum longwall shearers, which is why it should fulfill the below requirements:

- be based on workability of the coal lying directly in the seam, analogously to the real cutting head of the working machines. This assumption removes any defects and imperfections of methods, which depend on drilling the coal or require conversion factors,
- make coal workability measurements in planes of working props, both in faces of coal walls as well as in the full depth of the shearer's burden,
- enable coal workability research in lab conditions on the lab bench, in all possible states of tension and deformation, which can occur on the face of the wall.

The coal workability determining DM created by ITG KOMAG fulfills all those requirements, whereas the methodology of making those measurements was created together by ITG KOMAG and the Department of Mining Mechanization of the Silesian University of Technology. The methodology of those measurements was described in detail in the works (Biały, 2005; Biały, 2009).

The development of those workability index A measurement DMs ITG KOMAG have allowed for the building of a classification system of Polish coal according to the A factor. Ipso facto, allowing for the practical use of workability resistance forces with one cutting tool.

Based on this DM, the commonly used in Poland POS-1 device was used to determine the cutting resistance forces, constructed by ITG KOMAG (Fig. 9).

The DM of defining coal workability with the help of a POS-1 device is based on measuring the resistance of coal cutting with the help of a ploughing device, with a constant depth of the cut in the plane with an arbitrary slope to excavation floor.

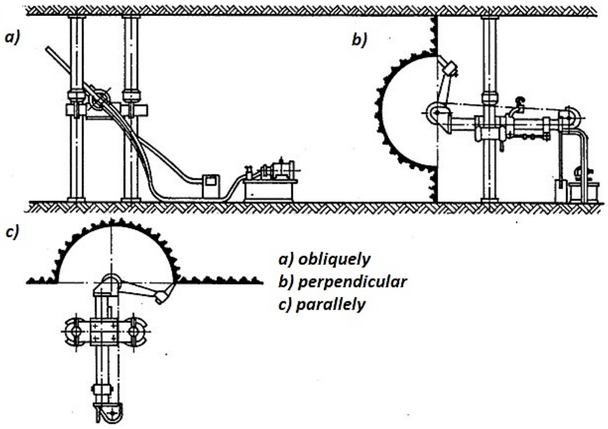

Fig. 9. Device POS-1

The device's construction allowed to widen the measuring furrow in the cutting plane in order to avoid measurement error, caused by possible friction of the measuring pick holder on the coal during the pick's penetration. The construction enabled one to freely situate the tool in the heading. This tool corresponded to the way of work of real tools installed in cutting heads with its cutting technique, whereby the main direction and sense of cutting remains the same.

Determining the cutting resistance forces with the POS-1 device depends on measurement of the cutting force *P* with a constant depth of cut *g*, in an arbitrarily sloped plane in proportion to the excavation floor.

The POS-1 device (Fig. 10) is built from a double-sided ram 1, which powers the arm together with measuring pick 3 through a ladder chain 2. The ram is powered by hydraulic unit 4, consisting of a PZ-25T pump with a performance of 0.045 m^3/min and maximum pressure of 1500 Pa, powered by an electric motor (air motor).

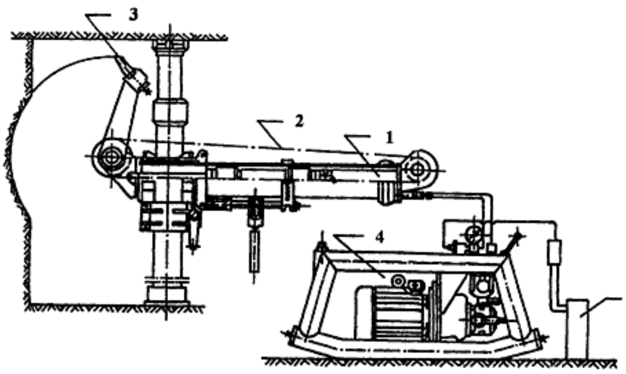

Fig. 10. Device POS-1 – structure, principle of operation

Measurements of cutting force on a cutting knife are made indirectly through measuring the pressure of the medium in the ram. The size of the pressure in the ram is measured with a strain gauge manometer installed in the ram's power supply. The impulses of the pressure changes are strengthened in the strengthener and saved as a chart on the recorder tape 5. The construction of the device enables its arbitrary positioning at the height of the excavation.

Thanks to its mining technique, this device corresponds to the methods of drum longwall shearer picks and imitates the operation of real tools installed in the cutting heads, while the main direction and direction of cutting remains the same. It can only be used for the location of longwall shearers.

6. Innovative Devices to Establish the Cutting Resistance

6.1. Device imitating the work of a plough

The device to measure the cutting force, which imitates the nature of a coal plough's work, was created in GIG in Katowice in 2010 (Prusek et al., 2011; Prusek et al., 2011a).

It enabled one to evenly and stably move the measuring pick to the coal solid, ensuring a high accuracy of preparing the coal solid at a maximum length of 1 m and a high accuracy of making measurement cuts in it and taking measurements of parameters, necessary to calculate the workability index of the rock. This device enables one to make cuts in two directions, measure the cutting resistance force in seams from 0.6 to 2.0 m in thickness, making at least 10 measuring cuts from one device setting at one height, with no need to move it, which influences the accuracy of the cuts. The device it easy to mount, easy to use, which results in low exploitation costs.

The rock workability calculating device is made of four main elements (Fig. 11):
1. linkage l mounted to hydraulic props 2,
2. cart 3 driven by a hydraulic motor 4,
3. sprockets 5 and chain 9,
4. unit to move the device 6 to the coal solid.

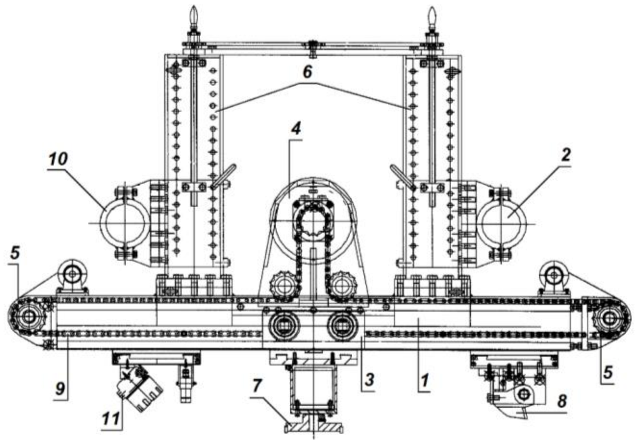

Fig. 11. Device GIG

Two hydraulic stands 2 (Fig. 11) are fitted with a guide 1 with a trolley 3 equipped with a holder for the interchangeable mounting of a leveling pick (head) 7, or a planning and measuring pick 8, driven by a hydraulic motor 4. The drive is transmitted through a chain 9 mounted on chain wheels 5.

The device is equipped with an infeed unit for the coal solid 6, which consists of two consoles connected with the hydraulic props with clamps 10.

Measurement of cutting forces happens in the following four stages:

- stage I – before measuring the cutting forces, we smooth the surface of the coal solid. The smoothing is carried with the help of a smoothing head with a built-in no.7 hydraulic engine,
- stage II – constituting the smoothing head with a head equipped with an 11 scanner in order to scan the smoothed surface,
- stage III – installing a head with a no.8 ploughing-measuring pick in order to make a measurement through registering the cutting resistance forces.
- stage IV – after making the measurements, the ploughing-measuring pick is constituted by a scanning head in order to scan the acquired furrow.

Based on the registered values of cutting resistance forces and the calculated volume of the cut coal, its cutability index is calculated. In order to create next furrows at the same height, the shown course of action should be repeated. It is expected to create at least three furrows at one level in the seam.

The originality of the applied solutions in the GIG device:
- *the possibility of mounting three (3) different measuring and recording devices on one car,*
- *the use of an innovative laser-scanning technique both before and after making the measuring scan, which allows for a detailed reproduction of the geometric parameters of the furrow,*
- *ease of use.*

6.2. The device replicating the work of a longwall shearer

The POU-BW/01-WAP device, the concept, and design and development objectives of which were developed in the Faculty of Production Organization of the Silesian University of Technology (Biały 2013; Biały 2014). The device mimics the work of a shearer in its way of work. The device was created in Poland, financed by the Technical University of Ostrava. The device assembled and ready for work has been presented on Fig. 12 (Welding 2012; Biały 2017a).

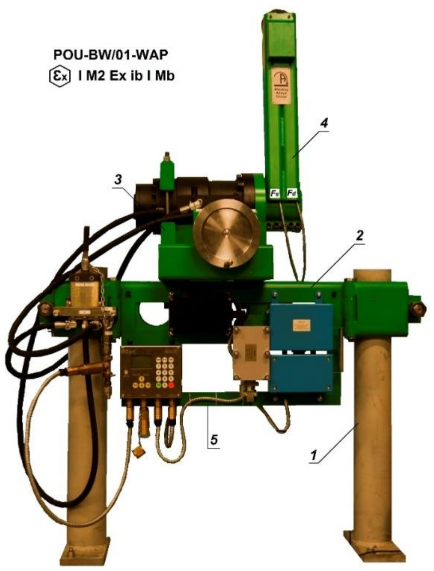

Fig. 12. Device POU-BW/01_WAP

It consists of:
- a supporting beam 2, to be mounted on the SHC/SHI prop 1,
- support of the actuator cart 3,
- an arm with a measuring pick 4,
- power supply, control, and recording device 5.

The coal workability assessing device POU-BW/01-WAP enables cutting in a vertical plane (perpendicular to the ceiling and floor), with two directions. During the work, the real work order of drum longwall shearers is recreated, because the measuring cut has a varying cutting direction, starting more or less from horizontal through vertical to horizontal, but with the opposite direction at the end. This device (POU-BW/01-WAP) enables one to evenly and stably move the measuring knife to the coal solid by means of the support 2 fixed to the frame 1. The support's construction guarantees a high accuracy of coal seam preparation, as well as similarly high accuracy of making cuts in it and making measurements necessary to determine the coal workability index. In the device, a real pick applied in drum shearers (a round shank cutter bit) is used as a measuring pick, which results in not having to include the geometry of the pick as a factor in the results. In the devices used so far, measuring picks with a geometry similar to real picks was used, which caused the need to consider the influence of the pick's geometry on the value of the cutting force.

A pressure regulator is built-in in the circuit, designed to prevent the pressure value from exceeding the acceptable value (21 MPa per device), which can happen in the mine power main. The current pressure value can be checked with the manometer attached to the device.

The originality of the solutions applied in the POU-BW/01-WAP device are:
- *measurement of two contributing forces taking part in the cutting process: cutting force F_s, as well as the pressure of applying the pick to the coal solid F_d,*
- *two independent sources of measurement - possibility of verification of the acquired results,*
- *the possibility of determining the momentary force of cutting,*
- *applying the actuator to the drive of the cutting tool,*
- *power supply from the central water-oil main in the mine – lack of another supply unit,*
- *the simplicity of the structure (three elements), simplicity of use, small weight (around 250 kg).*

7. Summary

The importance of the issue of measurement and assessment of coal workability (of stone), is confirmed by the number of different methods of its measurement, developed in different places around the world.

From the research and analyses conducted so far, it is known that the magnitude of the indicator has a significant impact on the power, efficiency, and durability of the cutting equipment. Therefore, this parameter has a deciding influence on the energy consumption, the installed power, and the size of the cutting machine, therefore influencing the cost of purchase and exploitation. Large power settings installed on cutting machines increase the size of those machines, as well as the risk of a climactic threat, disruptions in the air flow, methane hazard, or the necessity to make mining excavations with larger cross-sections.

Which is why the measurement of coal workability allows for an optimal selection of exploitative parameters and can be one of the decisive factors in an assessment of effective exploitation possibilities of the given lot or coal seam. This issue applies to both the planers technique and shearer technique of coal mining.

The tools developed so far enable one to principally measure one force, as a resultant force of three component cutting forces. The POU-BW/01-WAP is an exception, with the help of which one can measure two component forces (the force of cutting F_s and the pressing force of the knife to the coal solid F_d).

New, innovative tools, which were developed in Poland during the recent years, have an ATEX certificate allowing work to be done in real conditions. These are devices allocated for use in spaces with a risk of explosion - in accordance with directive 94/9/EC.

The newest tools, made in Poland (GIG, POU-BW/01-WAP), have been recognized worldwide for their innovative solutions. During the annual International Innovation Exhibition – INNOVA, taking place in Brussels, Belgium, in November, devices received the following awards:

- GIG device in 2011 – GOLD MEDAL,
- POU-BW/01-WAP device in 2012 – SILVER MEDAL.

Moreover, in 2013 the device POU-BW/01-WAP received awards at exhibitions taking place in:

• Taiwan,
• Japan,
• Romania.

8. Future Directions

There are a number of diagnostic method in various areas of development e.g. (Nikitin et al., 2020; Trefilov et al., 2021; Nikitin et al., 2022). Despite a wide variety of available methods, not every fulfills its purpose due to technical and organizational limitations of working in a coal mine. A good research method, one useful in coal mining, must fulfill a variety of requirements, such as:

- low costs,
- high availability,
- short test-completion and result-receiving time,
- real-time execution,
- analysis accuracy.

Moreover, the applied DM shall not disturb the exploitation process. The aforemen-tioned limitations eliminate some solutions, as well as limit the possibilities of other solu-tions. In the near future, one must expect quick developments of DMs, the use of which will not collide with mining exploitation.

In the near future, one must expect quick developments of methods, the use of which will not collide with mining exploitation.

The possibility of measuring all three compound forces that occur in the mining process (coal cutting) is very important from the point of view of cutting tools and machine load, that is:

1. the force of cutting F_s,
2. the pressing force of the pick to the coal solid, F_d,
3. the lateral force (resistance) F_b.

Nowadays, there is no such tool which would register all forces engaged in the cutting process during the process itself.

Moreover, it is the goal to create a compact solution, one able to be easily transferred to the measuring site, and that is defined by the mass of the device. Nowadays, the devices are too heavy to be transported by one person.

Another important, expected trait of the tool is the ability to use different cutting he-ads. From the standpoint of the research DM and building a deposit workability database it is imperative to use one, identical tool in all conditions. However, in practice, different picks are used to cut different minerals. The ability to install a real tool allows to precisely assess the power requirement for one specific, chosen, cutting head. The tools known cur-rently only use one cutting head.

Another solution worth consideration is the usage of a mechanism for moving the tool laterally. Such a motion simulates the successive cuts in the given cutting pitch.

Thanks to such a solution, it would be possible to make different types of cuts from one tool setting, especially open and semi-open ones. Open and semi-open cuts are realized by consecutive picks on the cutting head, its sequence resulting from the design of the pick setting. Depending on the cutting pitch, we acquire different cutting resistance forces. The ability to do research on different pitches will allow us to acquire more information on cutting resistance forces.

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诊断煤炭的方法和测试可行性的途径 – 一项综述

關鍵詞
机械性能 岩石
工具
力量的组成部分
实验研究
测量

摘要
将岩石按可加工性进行分类的需求主要源于选择适当、最有效的诊断方法（DM）和采矿方式的需要。由于可加工性取决于许多不同因素，研究和测量岩石的可加工性非常困难。有许多 DM 可用于确定岩石的可加工性，但它们没有考虑到所有因素的影响，因此所得结果仅供参考。本文介绍和描述了许多用各种设备测定切割阻力的 DM 和方法。介绍了它们的操作原理，以及测量切割阻力和根据具体采矿和地质条件预测选矿机选择的 DM 的实用价值。这个问题的核心得到了世界各地各个研究中心所涉及的 DM 和工具数量的证实。本文介绍了在波兰开发的用于测量和评估煤炭固体机械性能的新工具。介绍了它们的结构、操作原理以及这些解决方案的创新性。文章突出了它们的优点和缺点，并展示了最能代表采矿机工作方式的 DM。因此，通过上述 DM 获得的结果可以理解为代表性数值。