INNOVATIVE SOLUTIONS APPLIED IN TOOLS FOR DETERMINING COAL MECHANICAL PROPRERTIES

Witold BIAŁY
Silesian University of Technology

Abstract:
Due to very specific conditions of work of machines and equipment used in coal mining industry, the manner of their selection, taking into account the changing working conditions, is very important. Appropriate selection influences the increased durability and reliability of machines and equipment, which translates into the economic effects achieved.
As the issue of measurement and evaluation of coal mechanical properties (including coal workability measurement) is of great importance, previously applied methods for coal workability evaluation have been shortly reviewed. The importance of the problem is confirmed by the number of methods developed in various research centres all over the world. The article presents new instruments for determining and evaluating the mechanical properties of coal material (workability). The instruments have been developed in Poland and the author of this article is their co-inventor. The construction, principle of operation and innovative character of solutions applied in the instruments have been presented.

Key words: workability, measurement instruments, measurement methods, experimental research

INTRODUCTION

In the broad meaning, workability can be defined as interactions between material being mined and the mining machine (tool). In its essence it is resistance offered by the material being mined (fined) against the mining part of the machine. For this reason workability is included in mechanical properties of a useful fossil mined (hard coal, brown coal, rocks).

It is practically impossible to unequivocally define workability as it is influenced by very many factors – among others the manner of mining.

Workability is also treated by some researchers as a technological property [12]. Depending on the mining technique, it can be defined as follows:
− in the process of drilling—drillability,
− in underground mining—workability, cuttability,
− in open-cast mining—rock breaking resistance.

In each of the above mining process an important factor is the technological process applied. The above mentioned processes are very loosely connected. For this reason, the results obtained in one mining process cannot be approximated for another process.

In the mining industry all over the world a number of methods for determining the workability of coal for the needs of mining mechanization are applied; they are defined and interpreted in different ways. These indicators [3, 5, 6, 9] reflect mechanical properties of a coal seam being mined. Hence, coal workability measurement allows the performance parameters of mining machines to be optimally selected and can be one of decisive factors for evaluating the possibility of effective exploitation of a particular

coal seam. This problem concerns coal mining by means of both the cutter-loader and plough.

PROPERTIES OF ROCKS

Mechanical properties of rocks depend on such factors as [8]:
− and origin of rocks,
− rock tectonics (faults, gaps, scratches, cracks, cleavage),
− porosity and humidity of rocks,
− size, shape and strength of grains,
− binder,
− force direction in relation to bedding.

Decisive mechanical properties of rocks include compressive strength, tensile strength, compactness and elasticity.

In practice different methods of workability measurement are applied. One of the simplest ways is measurement of the amount of work needed to separate and break up a unit of rock volume – it is expressed e.g. in J/m^3. Depending on equipment used to mine rocks, we can distinguish the following types of workability [2, 7, 9, 12]:
− shooting workability, expressed by the number of kilograms of explosive material used for mining 1 m^3 of rock,
− drilling workability, i.e. so-called drillability, measured by the amount of time (in minutes) needed to drill e.g. 1 running meter of an opening,
− mechanical workability, defined by workability (cuttability) rate A, A_ψ, WUB in kN/m.

Rock compactness depends on its composition, homogeneity, grain size and binder quality. Rock compactness is

not a characteristic which unequivocally defines rock strength; it does not define particular strength properties of rock, but it characterizes it in an indirect way. This property is taken into consideration when selecting the method of mining. The parameter (compactness) is described by means of so-called Protodiakonow compactness rate f. The higher the value of this indicator, the less workable the rock is.

Workability rate f defined by Protodiakonow method is still the most frequently applied rate to define workability in Poland. This indicator is also called a compactness rate. Table 1 presents a classification of rocks depending on the value of Protodiakonow rate f.

Table 1
Rock class depending on the value of f

Class	f rate	workability of rocks (coals)
I	< 0.4	very easily workable
II	0.4 – 0.8	easily workable
III	0.8 – 1.4	medium workable
IV	1.4 – 2.4	hardly workable
V	> 2.4	very hardly workable

In the 1970s a classification of coals depending on the value of workability rate determined by means of the POS-1 instrument was introduced in Poland. On the basis of conducted studies and analyses it was found that the initially adopted classification of Polish coals was excessively extended, as certain grades of coal did not occur in Poland. Hence, it was necessary to modify the classification of Polish coals. A new classification of Polish coals was proposed [3, 4, 7], consisting of three classes (Table 2).

A traditional manner of determining rock strength to one-direction compression Rc is subjecting a rock sample to compressive strength on a hydraulic press (BN-75/8704-07). This method involves loading a specimen in the form of a cylinder or rectangular prism with an increasing force until it is damaged. The test result is considerably influenced by so-called sample slenderness as well as friction between the sample and planes causing the pressure.

The conducted investigations into the resistance of rock samples in the shape of rectangular prisms having different dimensions and proportions to one-direction compression revealed that compressive strength is closely related to the course and number of planes with weakened cohesion, cracks, microcracks, pores in the examined sample [1, 2, 3, 8].

In Poland the rate of workability A, A_ψ, WUB, was determined by means of POS-1 instrument, whereas resistance to one-direction compression Rc is mainly determined by two methods:
- „traditional",
- ultrasound.

In the process of rock mining the key role is played by planes characterized by decreased cohesion (cleavage, bedding). In these planes rock is characterized by definitely lower values of mechanical properties (R_c, R_r), in relation to other planes.

The division of rocks, taking into consideration compressive strength R_c tested under conditions of normal humidity (dry air state) has been presented in Table 3.

Table 3
Division of rocks according to Rc

No.	Rock class	Value of R_c
1	very poor strength	< 15 MPa
2	poor strength	15 MPa ÷ 60 MPa
3	medium strength	60 MPa ÷ 120 MPa
4	high strength	120 MPa ÷ 200 MPa
5	very high strength	> 200 MPa

Rock tensile and bending strengths are much lower than compression strength. They reach the following values:
- tensile strength approximately 5 to 10% of R_c value,
- bending strength approximately 25 to 30% of R_c value.

The general classification of rocks in terms of workability (intuitive, taking into consideration hardness, brittleness and other mechanical features) is as follows:
1. Very hard,
2. Hard,
3. Brittle,
4. Soft,
5. Loose.

In underground hard-coal mining we most often deal with the first four types of rock, as loose rocks occur very seldom – practically they are not found.

INSTRUMENTS FOR DETERMINING WORKABILITY RESISTANCE – WORKABILITY RATE

In the last two years (2011, 2012), instruments for determining and evaluating the mechanical properties (workability) of coal material have been invented in Poland. These instruments, which are unique in the world, reproduce the work of a coal plough and a longwall shearer respectively. The first of the instruments was invented at the Central Mining Institute in Katowice, whereas the other one was developed at the Silesian University of Technology,

Table 2
Modified division of coals into categories according to the degree of workability

Workability rate $A \left[\dfrac{kN}{cm} \right]$	Side-crumble angle ψ [°]			Level of workability difficulty
	ψ > 70°	40° < ψ ≤ 70°	ψ ≤ 40°	
A ≤ 1.80	I	-	-	easily workable
1.81 < A ≤ 3.00	-	II	-	medium workable
A > 3.01	-	-	III	hardly workable
	brittle W_k	hard W_t	very hard W_{bt}	

in Production Engineering Institute. The instruments were based on state-of-the-art solutions in terms of construction as well as measurement and measured values recording. The instruments in question have ATEX **I M2 Ex ib I Mb** certificate, allowing their work in real conditions as devices intended for use in explosive atmospheres – in accordance with Directive 94/9/EC.

Instrument reproducing the work of a plough – GIG (Central Mining Institute) instrument

The instrument for measuring cutting forces, which reproduces the character of work of a coal plough, has been developed at GIG (Central Mining Institute) in Katowice (Fig. 1) [10, 11]. The instrument was invented as a result of team works, in which the author of this article took part.

The device enables making cuts with two turns – measurement of cutting resistance in seams having a thickness of 0.6 to 2.0 m, making a minimum of 10 measurement cuts with the device once mounted at one height, without having to shift it, which guarantees the precision of measurements. It allows uniform and stable feed-in of the measuring knife to the body of coal, ensures high precision of coal body preparation over a length of maximum 1 m and high precision of measurement cuts and measurements of parameters necessary to determine the rate of coal workability (cuttability). The device is easy to mount and use, which translates into low maintenance costs.

The device for determining coal workability rate consists of four main elements (Fig. 1):
1. Guideway 1 fixed to hydraulic props 2,
2. Car 3 driven by hydraulic motor 4,
3. Chain wheels 5 and chain 9,
4. Coal body feed-in set 6.

On two hydraulic props 2 (Fig. 1) is mounted guideway 1 with car 3, driven by hydraulic motor 4, equipped with a handle for mounting interchangeably:
- levelling knife (head) 7,
- planing-measuring knife 8,
- head with scanner 11.

Power is transmitted by chain 9, mounted on chain wheels 5. The device has a coal body feed-in set 6, which consists of two consoles connected with hydraulic props 2 by means of clamping rings 10.

The adopted methodology of measurements provides for making minimum three measurement grooves on one level in the seam.

The use of the scanning head provides a possibility to precisely measure the groove formed after making a measurement cut. Thus, we can compare the recorded shapes of coal body surface before and after making a groove and determine the volume of coal (rock) mined. On the basis of recorded values of cutting resistance (forces) and the calculated volume of coal mined, its workability (cuttability) from the following dependency [10, 11] is calculated:

$$A_{Bi} = \frac{F_B}{V_B} \left[\frac{kN}{cm^3} \right] \tag{1}$$

where:
F_B – average value of the force recorded on the measurement knife when making a measurement cut
V_B – volume of coal (rock) mined.

Originality of solutions applied in GIG instrument results from:
- possibility of mounting three different measuring-recording devices on one car (3),
- use of the innovative laser scanning technique both before and after making a measurement cut, which allows detailed mapping of the geometric parameters of the groove,
- easy in use.

Instrument reproducing the cutter-loader's work– POU-BW/01-WAP

POU-BW/01-WAP instrument (whose main creator is the author of this article), mounted and ready for work, has been presented in Fig. 2 [13].

The instrument is a mobile device which enables taking measurements both in real and laboratory conditions, reproducing the real character of work performed by the mining machine – drum-type longwall shearer. It consists of the following elements: mechanical, hydraulic and electrical.
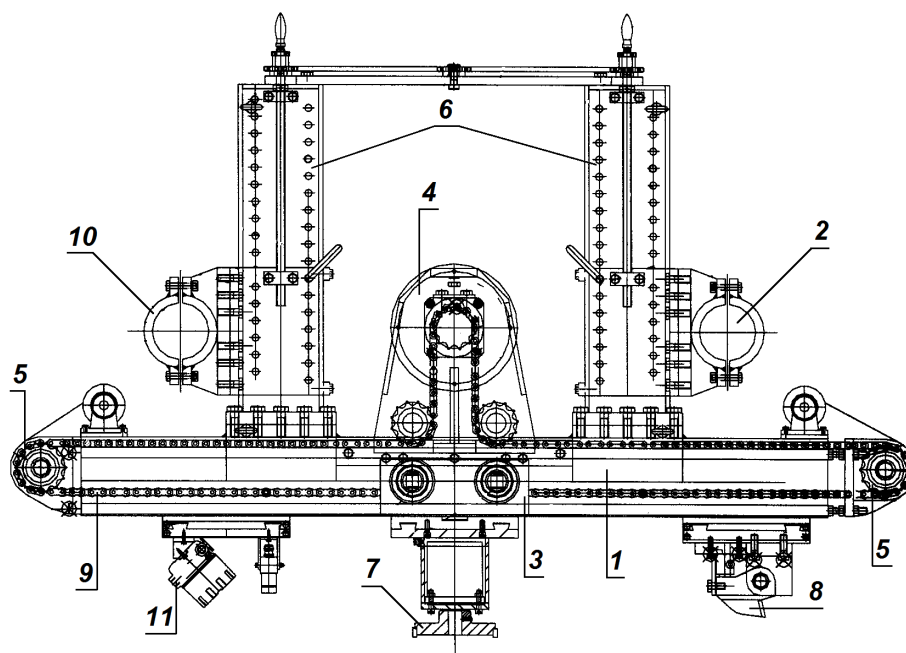

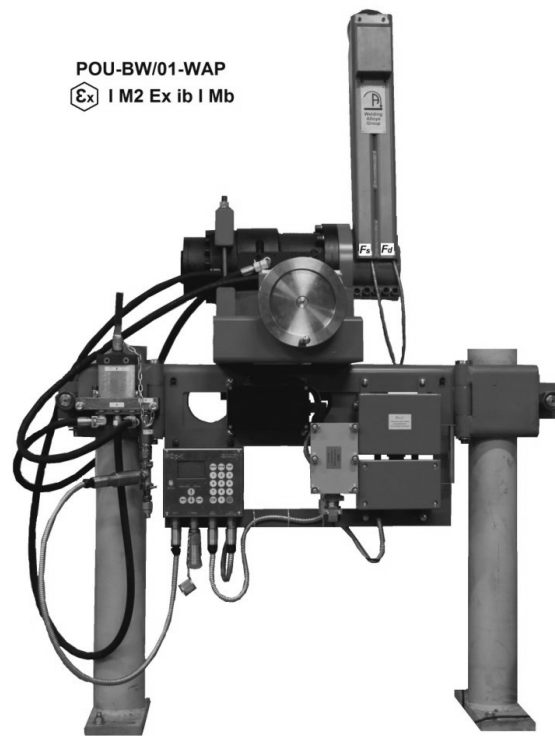*Fig. 1 The GIG device for measuring the cutting forces*

Management Systems in Production Engineering 4(20)/2015
W. BIAŁY - Innovative solutions applied in tools for determining coal mechanical proprerties

205

POU-BW/01-WAP
⟨Ex⟩ I M2 Ex ib I Mb

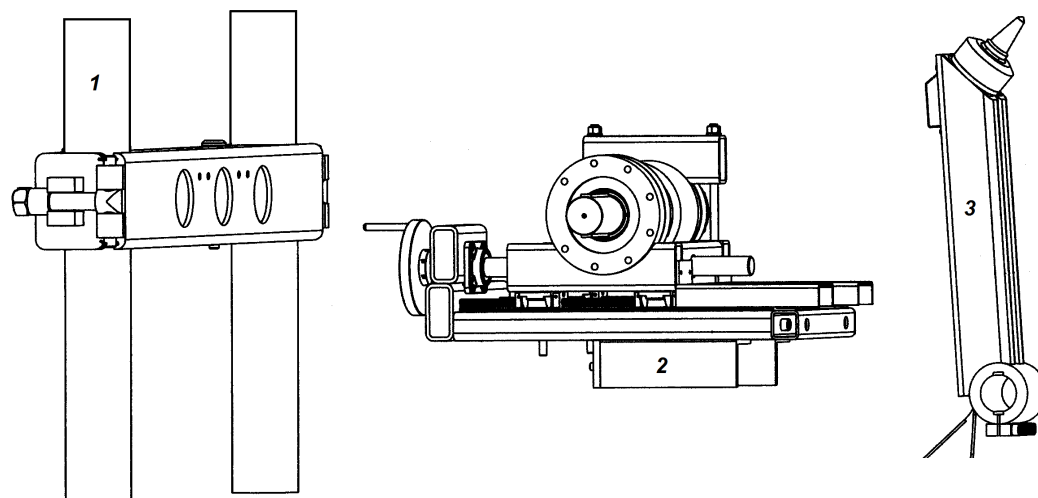*Fig. 2 The POU-BW/01-WAP device*

Fig. 3 Mechanical components device

Mechanical elements include (Fig. 3):
− load-carrying beam for SHC/SHI props 1,
− support with a car and actuator 2,
− arm with a cutting head and measuring knife 3.
Hydraulic elements of the instrument include:
− actuator,
− separator – control box,
− manometer,
− set of hydraulic lines.
Electrical devices of POU-BW/01-WAP instrument include a set of elements for *Coal Cutting Force Measurement* (CCFM).

The POU-BW/01-WAP instrument enables cutting in a vertical plane (perpendicular to the roof and floor), with two mining turns.

The instrument reproduces the real character of drum-type cutter-loader's work, as the measurement cut has a changeable direction of cutting, starting approximately from the horizontal one, to the vertical and horizontal, but with an opposite turn at the end.

The measurement knife used in the instrument is a knife installed in drum-type cutter-loaders (tangential-rotary), which causes that the influence of knife geometry on measurement results does not have to be taken into consideration in the process of results preparation.

The dimensions of the instrument, assembled and ready for work, has been presented in Fig. 4.

The support with a car and actuator (Fig. 5) has been mounted on the upper part of the beam by means of screws in one of possible positions – the actuator's shaft should be located on the right side of the instrument.

An original solution applied in the instrument is the actuator, used for transmitting the drive from the piston onto the measurement arm of the instrument. The piston travel is converted to rotation of the arm. This happens owing to the helical tooth of the piston as piston travel is transmitted onto the shaft and converted into rotation.
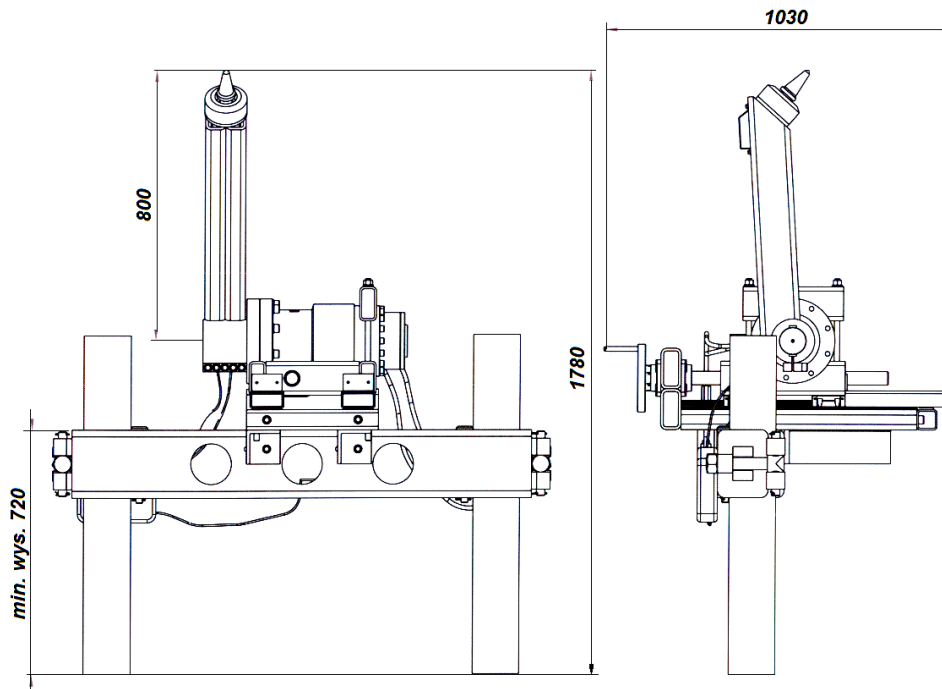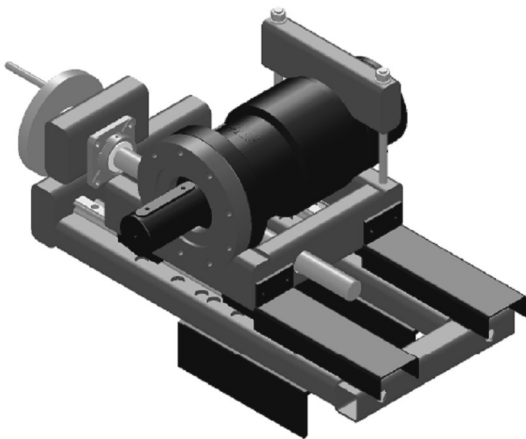
Fig. 4 Dimensions of POU-BW/01-WAP instrument

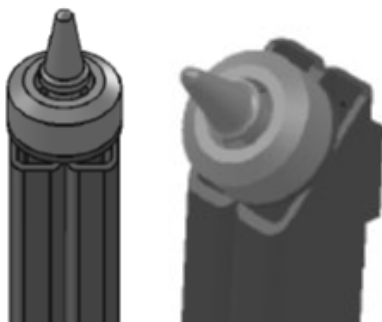

Fig. 5 Support of trolley actuator

Fig. 6 The measuring arm with knife

The last element of the instrument is the arm, at the end of which a measurement knife has been mounted (Fig. 6). The knife of the arm should be directed towards the seam mined (side wall).

After mechanical elements have been assembled, the hydraulic system is linked by means of pipes and supply from the water-oil main in the mine is connected to the sockets and control box (the instrument can also be supplied by a pump).

The CCFM (coal cutting force measurement) instrument makes it possible to measure and record the two forces which take part in the cutting process, i.e. cutting force (F_s) and the force of pressure (F_d) against the coal body mined (Fig. 7).

The CCFM instrument consists of the following electrical devices:

- *Operator's panel (Pop-1)* – a parent driver functioning as an operator's interface, enabling the results of measurement to be monitored on the display. A *Portable Memory Module* is connected to the control desk socket, the task of which is to gather measurement data. This data, recorded in the form of files and used for analysis and visualisation in the form of tables and charts, is transferred to an overground PC.
- *Analogue-Digital Converter KAD/CAN* – transforms the analogue signal from two tensometric bridge sensors of analogue-digital conversion and sends measurement data to the operator's panel via a CAN serial bus.
- *Tensometric Sensor of Cutting Force (F_s)* – enables an indirect measurement of the cutting force by changing the tensometers' resistance, which is proportional to physical deformations caused by mechanical forces.
- *Tensometric Sensor of Pressure Force (F_d)* – enables an indirect measurement of the knife's pressure force to coal body by changing the tensometers' resistance, which is proportional to physical deformations caused by mechanical forces.
- *Analogue Pressure Transducer (PAC-1)* – enables measurement of medium pressure in the hydraulic system in the coal cutting force measurement system.
- *Intrinsically Safe Power Supply (ZIM-BX/H/12-1)* – for supplying electrical devices used in the coal cutting measurement system with intrinsically safe voltage of 12V DC.
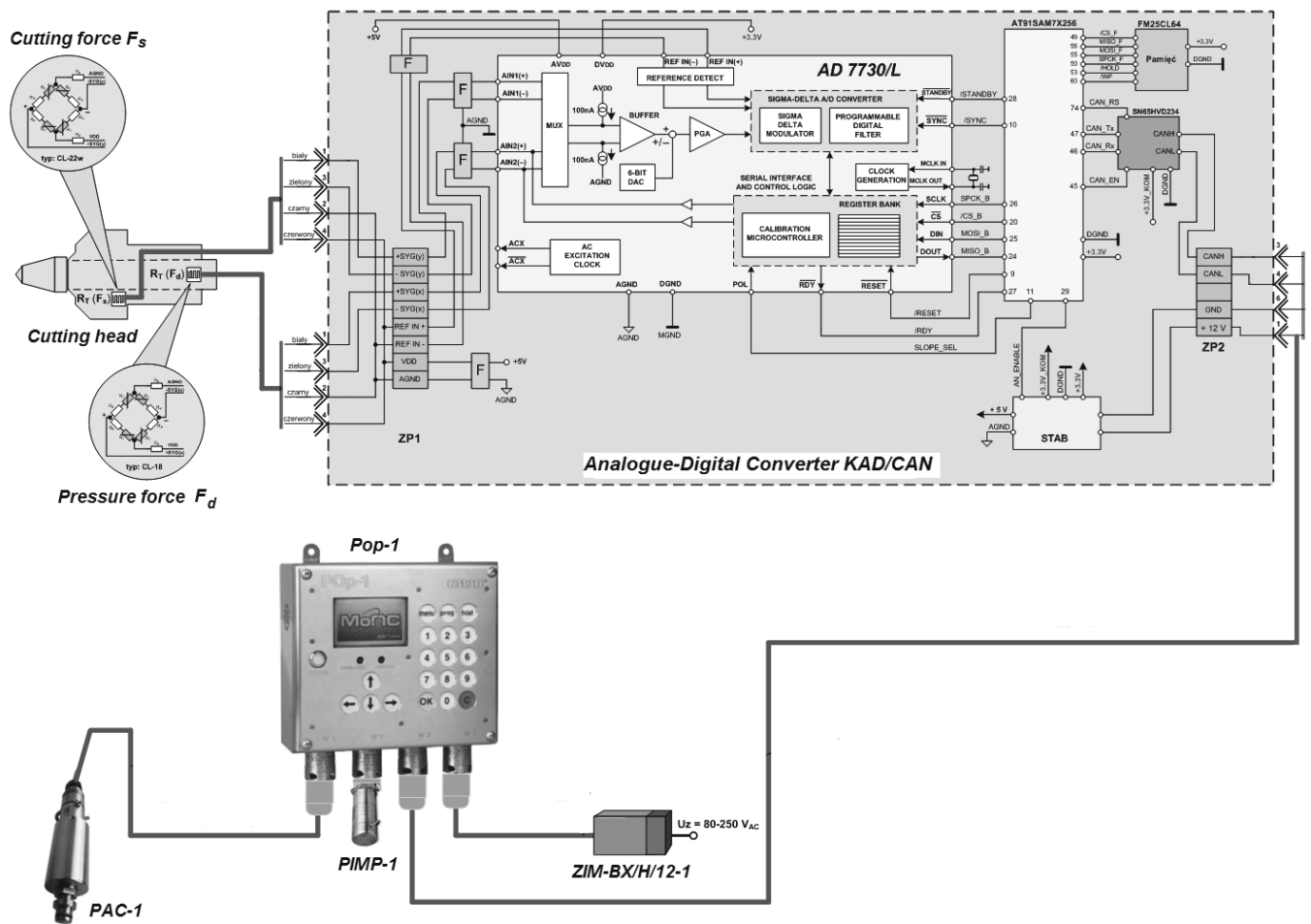
Management Systems in Production Engineering 4(20)/2015
W. BIAŁY - Innovative solutions applied in tools for determining coal mechanical proprerties

207

Fig. 7 Elements of the instrument for measuring coal cutting forces (CCFM)

Component forces taking part in the cutting process can be determined by means of two independent measuring blocks, which are tensometric sensors of: cutting force (F_s) knife pressure force (F_d) – (Fig. 8).
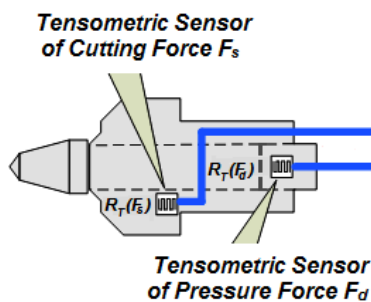

Fig. 8 Cutting head with tensometric bridges

Using the tensometric sensor built in the power supply circuit, we can determine the instantaneous power of coal body (rock surrounding the deposit) mining.

When the measurements have been taken, the results noted by recording devices are subject to further processing by means of a special computer programme, which is an integral part of the device.

Based on the recorded values determined by means of the POU-BW/01-WAP device, we can determine the rate of workability A:

$$A = \frac{F_{sr}}{g}\left[\frac{kN}{m}\right] \qquad (2)$$

or power workability rate AE:

$$AE = \frac{F_{sr} \cdot l}{Q}\left[\frac{MJ}{m^3}\right] \qquad (3)$$

where:
F_{sr} – average cutting force over the cut length,
g – depth of cut,
l – length of cut groove,
Q – volume of coal (rock) mined.
Originality of solutions applied in the POU-BW/01-WAP instrument results from:
− measurement of two component forces taking part in the cutting process (F_s and F_d),
− two independent sources of measurement – possibility of verifying the obtained results,
− possibility of determining the instantaneous mining power,
− application of an actuator for the cutting arm drive,
− power supply from the water-oil main in the mine – there is no additional power generator,
− simple construction (three elements), easy operation, small weight (ca 250 kg),

SUMMARY

In Polish coal mining industry coal is extracted mainly in longwall systems, by means of mining machines the operation of which is based on cutting. Therefore, one of the essential areas of mines' activity is proper selection of machines and equipment needed to ensure the continuity of the mining process. An important element in the process of

mining equipment design and construction is experimental research, which takes into consideration the character of a machine's work. These investigations are aimed at examining the highest possible number of parameters and their effect on the work of a machine (its elements) in difficult geological and mining conditions.

For this reason, measurement of coal workability, allowing an optimal selection of the performance parameters of mining machines is so important and can become one of the decisive factors evaluating the possibility of effective exploitation. This problem concerns mining by means of a plough as well as a cutter-loader.

Measurement results can be used to determine the class of coal (classify according to mining difficulty), and, in consequence, the projected power of the plough/longwall drum-type shearer working in particular mining-geological conditions.

The innovative solutions applied in the devices have been appreciated in the world. At the International Exhibition of Innovation, held annually in November, the devices were granted the following awards respectively:
  − 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.

This device received in 2013 and 2014 a diploma of the Minister of Science and Higher Education.

The article is the result of the registered work with symbol BK-223/ROZ-3/2015 entitled "The importance of the production engineering in the innovative development of products and services" carried out in theInstitute of the Production Engineering, Department of Organization and Management at Silesian University of Technology.

REFERENCES

[1] L.J. Baron, L.B. Głapman. Wznios instrumenta pri rjezani gornych porod. Moskwa: Hedba, 1969.

[2] A. Bęben. Technika wiertnicza w odkrywkowym górnictwie skalnym. Katowice: Śląskie Wydawnictwo Techniczne, 1992.

[3] W. Biały. „Empiryczne prognozowanie mocy ścianowych kombajnów bębnowych". Zeszyty Naukowe Politechniki Śląskiej, seria Górnictwo, no. 262, 2005.

[4] W. Biały. „Nowa klasyfikacja urabialności pokładów węgla Zagłębia Górnośląskiego", Przegląd Górniczy, no. 9, 2003, p. 26-32.

[5] W. Biały. „The selection of optimal method determining mechanical properties of coal layers". Management Systems in Production Engineering, no. 2, 2011, p. 26-30.

[6] W. Biały. „The side-crumble angle ψ of coal and the energy consumption of the mining process as a function of the vertical component σ_z of exploitation pressure", Archiwum Górnictwa, vol. 47, no. 3, 2002, p. 361-384.

Management Systems in Production Engineering 4(20)/2015
W. BIAŁY - Innovative solutions applied in tools for determining coal mechanical proprerties

209

[7] W. Biały. „Volba dobývacích kombajnů na základě výzkumů rozpojitelnosti uhlí". VŠB-Technická univerzita Ostrava, Monografie, Fakulta strojní Ostrava, 2009.

[8] J. Jonak. Urabianie skał głowicami wielonarzędziowymi. Katowice: Śląskie Wydawnictwo Naukowe, 2002.

[9] K. Krauze. Urabianie skał kombajnami ścianowymi. Katowice: Śląskie Wydawnictwo Naukowe, 2000.

[10] S. Prusek, S. Rajwa, A. Wrana, A. Walentek. „Ocena skrawalności pokładów węgla i skał otaczających w warunkach dołowych z wykorzystaniem przyrządu opracowanego w GIG". International Mining Forum Nowe spojrzenie na technikę i technologię eksploatacji cienkich pokładów węgla kamiennego, Nov. 24-26,2011. LW Bogdanka SA. p. 123-131.

[11] S. Prusek, S. Rajwa, A. Wrana, A. Walentek. „Wykorzystanie nowoczesnych technik pomiarowych do oceny parametru skrawalności węgla i skał w warunkach in situ". Górnictwo i Środowisko, no. 1, Katowice: Główny Instytut Górnictwa, 2011. p. 302-307.

[12] V. Voštova, T. Křemen, J. Fries, D. Sládková, J. Jurman. Progresivní technika v technologiích zemních prací. Praha: Wydawnictwo České Vysoké Učení Technické, 2008.

[13] Welding Alloys Polska sp. z o.o. Gliwice Dokumentacja Techniczno-Ruchowa Przyrządu POU-BW/01-WAP. 2012.

dr hab. inż. Witold Biały
Silesian University of Technology, Faculty of Organization and Management
Institute of Production Engineering
ul. Roosevelta 26, 41-800 Zabrze, POLAND
e-mail: wbialy@polsl.pl

[7] W. Biały. „Volba dobývacích kombajnů na základě výzkumů rozpojitelnosti uhlí". VŠB-Technická univerzita Ostrava, Monografie, Fakulta strojní Ostrava, 2009.