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E-mail of Editorial Office: maszynygornicze@komag.eu

Editor–in–Chief: phone: +48322374600,
e-mail: dprostanski@komag.eu or maszynygornicze@komag.eu

Secretary of Editorial Office: phone: +48322374177,
e-mail: rzajac@komag.eu or maszynygornicze@komag.eu

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Dynamic analysis of thin-walled structures as energy absorbers

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Krzysztof Mazurek [1a], Marek Szyguła [1]

[1] KOMAG Institute of Mining Technology, Pszczyńska 37, 44-101 Gliwice, Poland

[a] e-mail: kmazurek@komag.eu

Keywords: numerical analysis, impact energy, energy dissipation, thin-walled structure

Słowa kluczowe: analiza numeryczna, energia uderzenia, rozpraszanie energii, struktura cienkościenna

Abstract:

In this work, a FEM dynamic analysis of the energy absorbing system was carried out on the example of a thin-walled column loaded with impact of mass. The results of the numerical analysis of the impact of the column cross-sectional shape and the notch on the amount of impact energy absorbed are presented. Modeling of phenomena occurring during impact is a very complex task, because it is necessary to analyze a complicated process in which geometric and physical nonlinearities and contact problems occur. Model preparation and calculation using the finite element method (FEM) is currently the most reliable method of modeling impacts. The results of numerical analyzes discussed in the paper were carried out using the special MSC.Software.

Streszczenie:

W niniejszej pracy przeprowadzona została analiza dynamiczna układu pochłaniającego energię na przykładzie cienkościennej kolumny, obciążonej udarem masy. Przedstawiono wyniki analizy numerycznej wpływu kształtu przekroju poprzecznego kolumny oraz karbu na wielkość pochłoniętej energii uderzenia. Modelowanie zjawisk zachodzących podczas uderzenia jest bardzo złożonym zadaniem, gdyż należy przeprowadzić analizę procesu, w którym następują nieliniowości geometryczne i fizyczne oraz problemy kontaktu. Przygotowanie modelu i przeprowadzenie obliczeń przy użyciu metody elementów skończonych (MES) jest aktualnie najbardziej wiarygodną metodą modelowania uderzeń. Omówione w pracy wyniki analiz numerycznych uzyskano przy wykorzystaniu specjalistycznego programowania firmy MSC.Software.

1. Introduction

Society is becoming increasingly aware of the need for designing the safe components and systems to reduce the tragic consequences arising in various types of car, airplane or natural disasters. In the second half of last century there was a significant development of the so-called impact engineering. Structural dynamics studies have contributed to a better understanding of the phenomenon of energy dissipation during impact. It was observed that thin-walled components such as plates, coatings, pipes, columns, etc., used in car assemblies, aircraft and ship hulls, during impact are usually subjected to compression and undergo large displacements, which may even exceed the permissible values twice. Therefore, many tests and computer simulations base on analysis of the systems consisting of thin-walled components [1, 2, 3].

It is obvious that, in the future, the transportation structures will be designed to withstand bumps and accidents. In the current trend for production of lightweight structures, weight of the components is reduced, while more tough requirements are put to designers as the standards for structures become more demanding. It is possible to design absorbers that will be able to dissipate energy in a safe way for people or load [4, 5].

The finite element method (FEM) is the most reliable method of modelling the impacts in which complex structures can be involved [4, 15]. Preparation of the model and calculations is time consuming, because it requires integration of a very large system of motion equations over time that

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can reach up to several hundred thousand degrees of freedom. However, computer simulations reduce the number of prototypes and thus reduce the cost of crash tests. In addition, when using FEM much more virtual tests can be carried out, which allows a better understanding and better designing of energy absorbers [8, 9].

In the discussed research work, MSC.Software, i.e. MSC.Dytran and MSC.Patran, was used, allowing relatively easy and quick modelling and analysis of mechanical systems absorbing the impact energy. Detailed information on the software used can be found in [10, 11, 12].

2. Energy absorption process

Energy during impact is absorbed by the absorber as kinetic energy is converted into other forms of energy. In energy absorbers, where large displacements occur, dissipation of energy is possible due to plastic flow of material, the formation of brittle cracks or friction. Then, the reversible, elastic part of the deformation energy is negligible [4, 7]. A typical relationship force-displacement, also known as crushing characteristics, in energy absorbing mechanical systems is shown in Fig. 1.

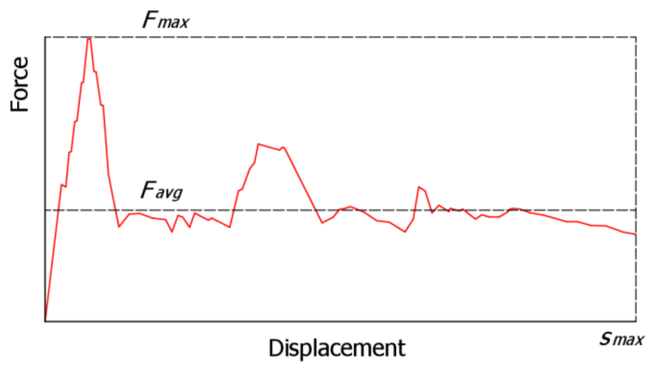

Fig. 1. Relationship between force and displacement (sample crushing characteristics)

The maximum force in the crushing process is marked as F_{max} [N], while the maximum permanent displacement as s_{max} [m]. Energy absorbed by the absorber in the Ω area (regardless of the type of processes involved) equals to the work of the external load:

$$W = \int_0^{s_{max}} F(s)ds = \int_{\Omega} E_{dys} d\Omega \tag{1}$$

Work of the external load W [J] can be expressed as:

$$W = F_{avg} s_{max} \tag{2}$$

where: F_{avg} [N] is an average crushing force.
Averaged absorbed energy is approximately equal to work of the external load:

$$E_{dyss} \approx W \tag{3}$$

3. Requirements put to energy absorbers

In the case of an impact between a moving object (with a given initial speed) and a rigid stationary wall creates forces, stresses and deformations resulting from this impact. Various types of tests and computer simulations lead to a possibility of controlling and routing the energy flow through the system [6, 13-19].

The test results enable to design structures meeting the following requirements:

- stable and controllable method for dissipation of kinetic energy impact,
- limited deformation of the protected volume for working people and equipment,
- limited accelerations and forces during impact – what is especially important when assessing the safety level for vehicles users [20, 21].

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These are the three main requirements, ranked according to the criterion of their importance for energy absorbers. To a large extent they are associated with the type of structures that they have to protect. If the first requirement is not met, it certainly leads to failure to meet the other two. Consequently, kinetic energy is not absorbed in the part of the structure intended for this, and thus with a very high probability there will be penetration into the protected zones, and the level of acceleration will exceed the allowable value [5].

4. Criteria for comparison of energy absorbers

The criteria presented below are used in comparison of different absorbers and assessment of their effectiveness. They describe in the best way the absorbers in which energy is absorbed through progressive axial compression [7, 22].

- Specific energy E_s [J/kg]

$$E_s = \frac{E_{dyss}}{m} \tag{4}$$

This is the ratio of dissipated energy E_{dyss} [J] to the absorber mass m [kg]. Only a part of the absorber involved in dissipation of energy is considered.

- Density of dissipated energy E_d [J/m^3]

$$E_d = \frac{E_{dyss}}{V_0} \tag{5}$$

This is the ratio of energy dissipated by the absorber E_{dyss} [J] to its initial volume V_0. If this coefficient is high it means that structure of the device is compact.

- Average crush intensity σ_{avg} [Pa]

$$\sigma_{avg} = \frac{F_{avg}}{A_0} \tag{6}$$

This is the ratio of average crushing force F_{avg} [N] to the initial surface area of the absorber A_0 [m^2].

- Crush force efficiency AE

$$AE = \frac{F_{max}}{F_{avg}} \tag{7}$$

This is the ratio of maximum crushing force F_{max} during energy dissipation process to the average crushing force do F_{avg}. If this ratio is close to 1, such absorbers have advantageous, flat crushing curve.

- Stroke efficiency SE

$$SE = \frac{s_{max}}{H_0} \tag{8}$$

This is the ratio of maximum displacement of the absorber s_{max} to its initial height H_0 [m].

Proper design of energy absorbers can significantly reduce the risk of injury or death, as deformations and accelerations are directly related to the type and operation of energy absorbers. In connection with the above, an additional comparative criterion for absorbers has been introduced in this paper, related to the probability of head injuries. These injuries are caused by the formation of linear or angular accelerations and by bending and stretching the spinal cord in the area of connection with the brain. The most commonly used criterion, which determines the probability of suffering head injuries, is HIC (head injury criterion). HIC exceeding 1000 is considered to be dangerous [5].

$$HIC = \left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a dt\right]^{2.5} (t_2 - t_1) \tag{9}$$

where:
t_1, t_2 – times determining the beginning and the end of the head's contact with the obstacle or the time interval for which the HIC value is the highest [s], a – acceleration acting on a head [ms^{-2}].

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5. Numerical tests

Modelling of phenomena occurring during an impact is a very complex task. Complicated process, in which there are geometrical and physical non-linearities and contact problems, has to be analysed. Model preparation and calculations using the Finite Element Method (FEM) is a complicated task, but it is currently the most reliable method for modelling the impacts [6, 7].

FEM dynamic analysis of the energy absorbing system was carried out on the example of a thin-walled column hitting a rigid wall. Based on the [2, 3, 14], a numerical task was developed in which a column, loaded with an additional mass of 300 kg, hits a rigid wall at an initial speed of 30 km/h. The diagram of the analysed system is shown in the Fig. 2.

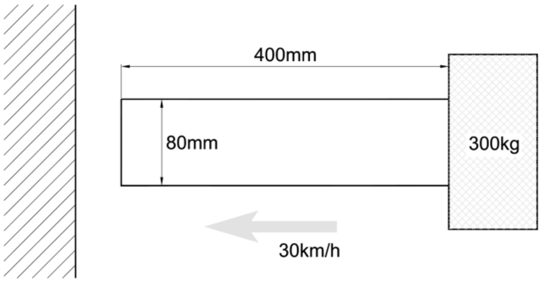

Fig. 2. Diagram of the analysed system column – wall

The column was modelled of aluminium AA 6063 T7 of the following parameters: *Young modulus* E=6.9E+10 Pa, density ρ=2720 kg/m^3 *Poisson* coefficient ν=0.3. Elastic-plastic material *ElasPlast (DMATEP)* with *True Stress vs Plastic Strain* model, available in *MSC.Dytran* was used. The method for defining the material properties is discussed in [21].

6. Impact of a column cross-section shape on amount of dissipated energy

To compare the impact of the cross-sectional shape of the structure on the amount of dissipated energy as a result of impact, the simulations were carried out on three column models. Model 1 is a square column (80 mm side), 2-circular model (ø80 mm) and 3-triangular model (equilateral triangle with 80 mm side). All columns have an equal wall thickness of 3 mm and a height of 400 mm. More information on the effect of column cross-section on the amount of energy dissipated can be found in [10]. Fig. 3, 4 and 5 present subsequent phases of deformation of the analysed models.

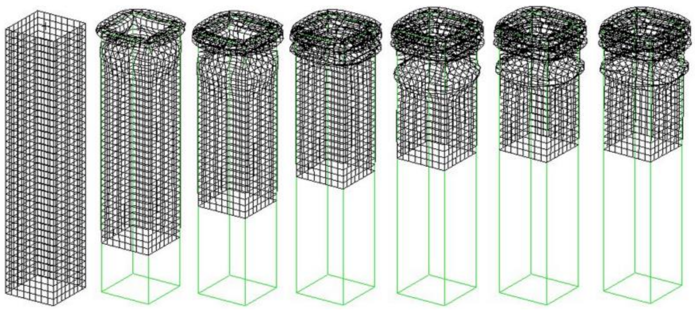

Fig. 3. Subsequent phases of deformation – model 1

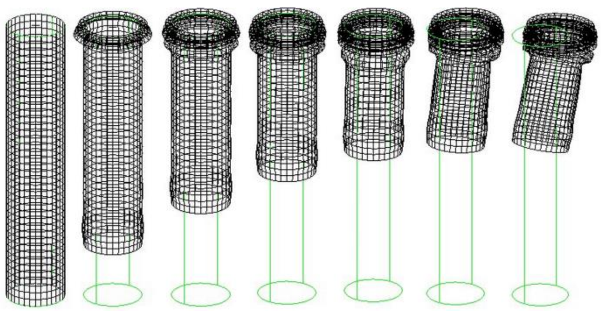

Fig. 4. Subsequent phases of deformation – model 2

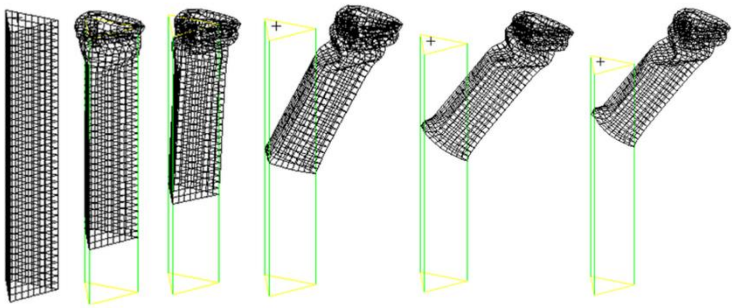

Fig. 5. Subsequent phases of deformation – model 3

In a result of column buckling - Model 3 (Fig. 5), the process of dissipation of impact energy is interrupted, while the crushing force and acceleration are small. The test proves that the column with triangular cross-section in comparison with other models is the least absorptive structure and the most susceptible to buckling. Therefore, model 3 will not be considered in further analyses.

To present the impact of shape on amount of dissipated energy, the following parameters were compared in models 1 and 2: crushing characteristics (Fig. 6) and acceleration in a function of time (Fig. 7).

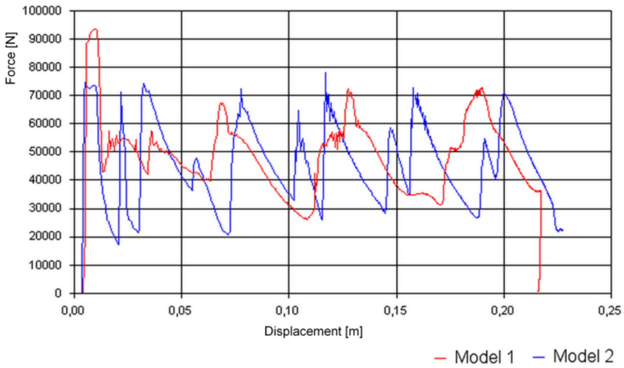

Fig. 6. Crushing characteristics in models 1 and 2

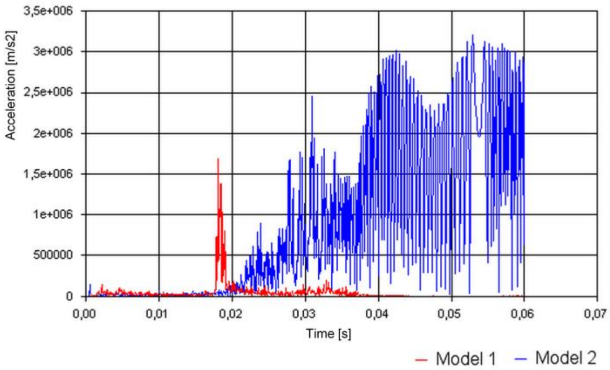

Fig. 7. Acceleration time process in models 1 and 2

Peak crushing force, shown in Fig. 6, indicate for the formation of subsequent impact waves in columns. Crushing force in model 1, at the moment of impact into the wall, was higher by 20 kN than in the model 2, however it was dissipated and dropped to 0. In Fig. 7, after 0.018 s, an increase in the acceleration can be observed in both models, probably due to the material strengthening, which in turn hindered the formation of another wave of column deformation. While in model 1 the deformation process is stable and the accelerations are close to 0, in the case of model 2 there is a gradual increase in acceleration, which is the result of column buckling.

Based on the averaged crushing force and maximum permanent displacement from the relationship (2), the work of the external load was calculated, which according to the relationship (3) is equal to the energy absorbed by the column. The results are presented in Table 1.

Table 1. Parameters characterizing the amount of dissipated energy

	Model 1	**Model 2**
$\mathbf{F_{avg}}$ [kN]	46.191	40.688
$\mathbf{s_{max}}$ [m]	0.215	0.261
$\mathbf{E_{dyss}}$ [kJ]	9.931	10.619

The analysis shows that model 1 (square column) in comparison with models 2 (column with cylindrical cross-section) and 3 (column with triangular cross-section) has the greatest ability to dissipate energy and is characterized by high stability of the deformation process. In addition, in model 1 there is less accidental acceleration, which, except for one dangerous impulse, gradually decreases to 0. So, further analysis was performed only on the square column model.

7. Impact of notches on the absorber surface on the amount of dissipated energy

To increase the energy dissipation capacity, notches were introduced on the absorber surfaces. Notches with dimensions 7 x R3.5 mm were placed on opposite walls of the column at a distance of 15 and 30 mm from the face. Three thin-walled prismatic columns were analysed: two with two notches (models 4 and 5) and one with four notches (model 6), Fig. 8. Column dimensions: cross-section 80 x 80 mm, height 400 mm, wall thickness 3 mm.

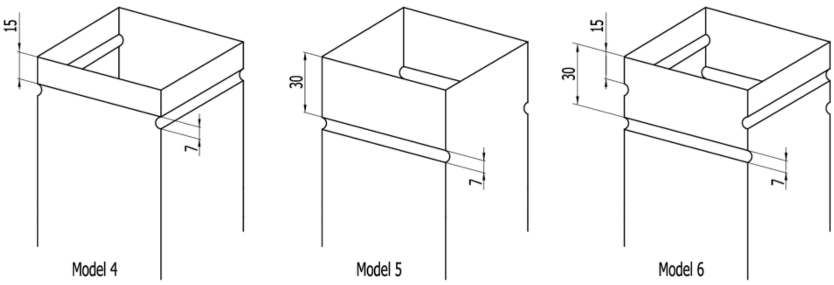

Fig. 8. Columns with notches (models 4, 5 and 6)

Fig. 9, 10 and 11 show the subsequent stages of deformation of models 4, 5 and 6, resulting from the columns hitting a stationary wall, in the selected time intervals (from 0 to 0.065 s). The process of deformation of columns 4 and 6, as in model 1, is stable. Introduction of a notch resulted in a significant increase in a deformation of the columns and thus had a positive effect on the amount of dissipated energy. However, too large distance of a notch (0.03 m) from the front surface of the column caused, in model 5, an unstable deformation process, and as a consequence the column buckled already in the first time interval of the analysis, interrupting the energy dissipation process. Therefore, model 5 will not be considered in further analysis.

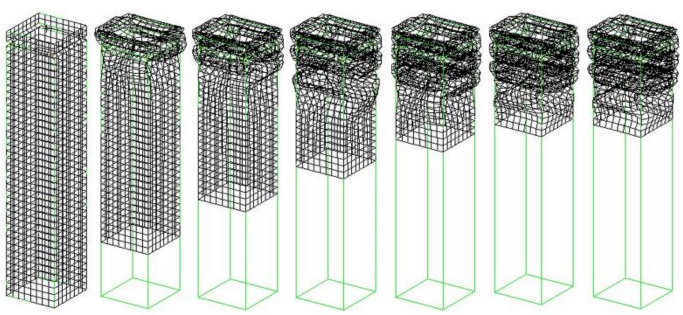

Fig. 9. Subsequent stages of deformation - model 4

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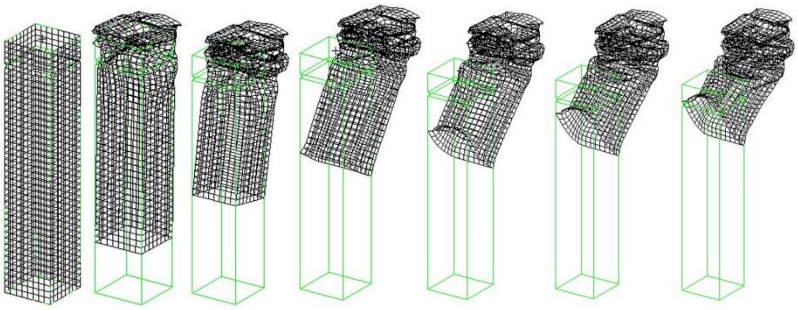

Fig. 10. Subsequent stages of deformation - model 5

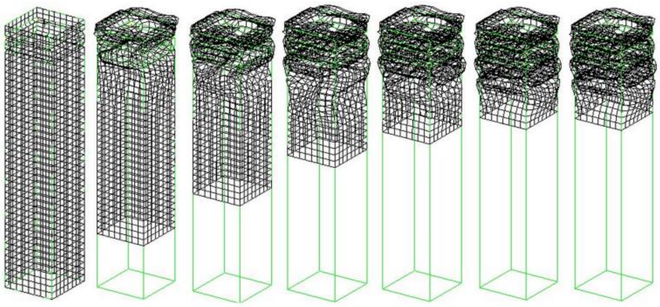

Fig. 11. Subsequent stages of deformation - model 6

For presentation of a notch impact on amount of dissipated energy, time processes of crushing force (Fig. 12), acceleration (Fig. 13) and kinetic energy (Fig. 14), in models 1, 4 and 5 were compared.

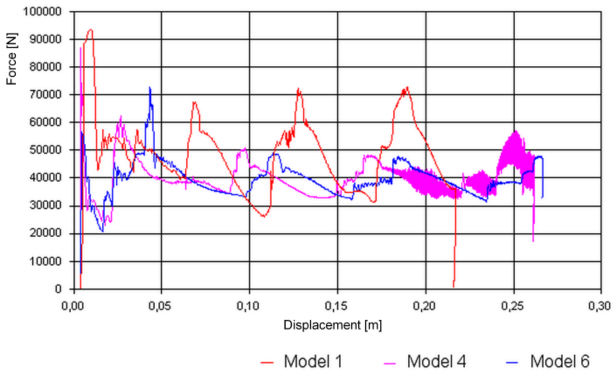

Fig. 12. Crushing characteristics in models 1, 4 and 6

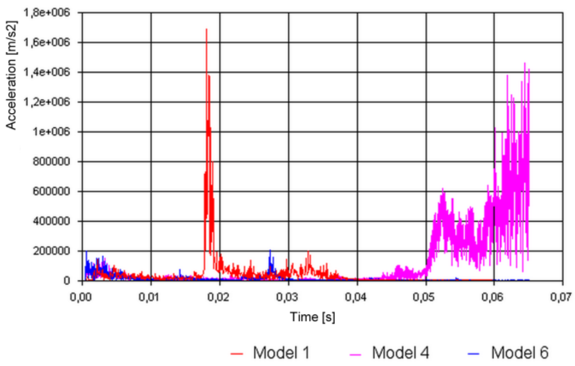

Fig. 13. Time processes of acceleration in models 1, 4 and 6

Analysis of time processes, presented in Fig. 12, 13 and 14, it clearly shows that the use of notches limits the forces and accelerations generated during a collision. However, in the case of model 4, in the final phase of deformation there were large force fluctuations, which resulted in a significant increase in acceleration in the column to values dangerous for the protected persons and structures. The introduction of the second notch in model 6 caused that both crushing force (Fig. 12) and acceleration (Fig. 13), compared to other models, were much lower.

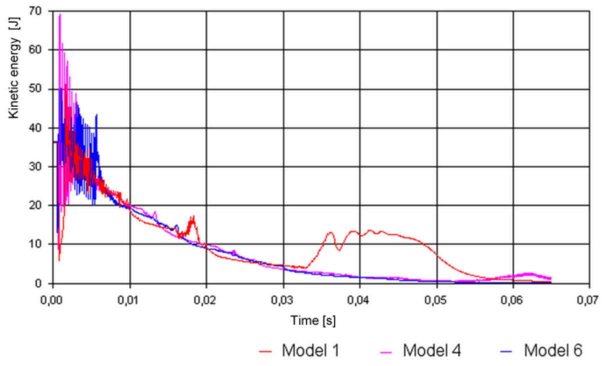

Fig. 14. Distribution of kinetic energy in time in models 1, 4 and 6

Distribution of kinetic energy in time in the discussed models, presented in Fig. 14, confirms advantageous impact of notches in energy dissipation process The column with two notches, model 6, was most advantageous also when analysing dissipation of kinetic energy.

Values of the characteristic parameters of the analysis, i.e. the average crushing force and the maximum permanent displacement, were used to calculate, from the relationship (2), the work of the external load, which according to the relationship (3) is equal to the energy absorbed by the column. The results from analysis of models 4 and 6 were compared with the results of model 1, as shown in Table 2.

Table 2. Parameters characterizing the amount of dissipated energy

	Model 1	**Model 4**	**Model 6**
F_{avg} [kN]	46.191	40.688	40.433
s_{max} [m]	0.215	0.261	0.268
E_{dyss} [kJ]	9.931	10.619	10.836

The criteria for assessing and comparing the effectiveness in dissipation of energy for models 1, 4 and 6 were determined. Results are given in Table 3.

Table 3. Energy absorbers comparison criteria

	Model 1	**Model 4**	**Model 6**
E_s [kJ/kg]	9.878	10.563	10.713
E_d [MJ/m^3]	26.840	28.548	29.286
σ_{avg} [MPa]	0.186	0.164	0.163
AE	2.042	2.135	1.800
SE	0.537	0.652	0.67

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In models 4 and 6, similar results were obtained (Tables 2 and 3), therefore, in order to justify the need of using two notches on the column surfaces, an additional criterion was introduced - the HIC (head injury criterion), calculated from the relationship (9). The *HIC* for models 1, 4 and 6 is given in the Table 4.

Table 4. *HIC* criterion

	Model 1	**Model 4**	**Model 6**
HIC	2.083E10	3.96E13	8.27E8

The analysis shows that the introduction of notches improves the energy absorption capacity of the presented models and limits forces and accelerations. Based on the results in Table 3, it can be seen that models 4 and 6 absorb almost 9% more of impact energy than model 1. This is due to greater deformation (shortening) of the columns equipped with notches. Comparison of displacement and deformation in columns 1 and 6 is shown in Fig. 15 and 16.

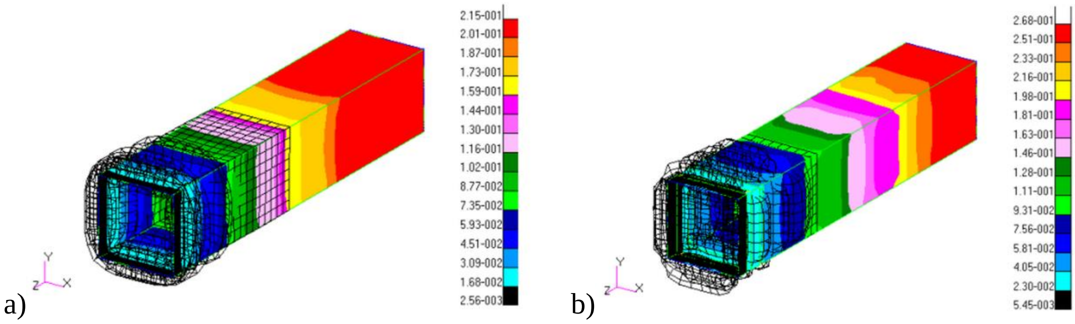

Fig. 15. Mapping of displacement: a) model 1, b) model 6

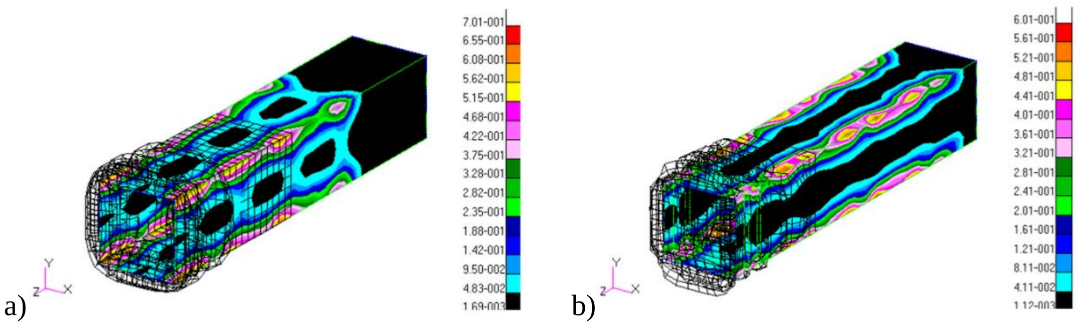

Fig. 16. Mapping of deformations: a) model 1, b) model 6

In addition, in notched columns the average crushing forces are about 12% lower than in the smooth column. The assessment of the effectiveness of the analysed models (Table 4) proved that model 6 shows the greatest energy dissipation capacity. Model 4 has slightly worse energy absorption properties. The use of an additional criterion, which is *HIC* (Table 4), allowed selecting the best solution among the analysed structures, which is model 6, which had the lowest *HIC* criterion.

8. Conclusions

Numerical analyses of the impact of the cross-sectional shape of the column and notches on the amount of dissipated energy from the hit of the column on a stationary wall as well as computer simulations allowed to draw the following conclusions:

- Shape of the structure cross-section significantly affects the amount of absorbed energy. Model 1 (square column) compared to models 2 (column cylindrical cross-section) and 3 (column with triangular cross-section) in collision with the wall shows the greatest ability to

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dissipate energy and is characterized by high stability of the deformation process. In addition, in model 1 there is less accidental acceleration, which, except for one dangerous impulse, gradually decreases to 0.

- The introduction of notches on the surface of the column significantly increases its ability to absorb energy and limits the acceleration and forces generated during impact. The results in Table 1 clearly show that models 4 and 6 (notched columns) absorb almost 9% more impact energy than model 1 (smooth column). In addition, in notched columns the average crushing forces reached about 12% lower value than in the smooth column. The assessment of the effectiveness of the analysed models (Table 3) confirmed the correctness of the use of notches, because models 4 and 6 obtain much better results than model 1. The application of the *HIC* criterion (Table 4) enabled the selection of the model with the highest absorption properties - model 6.

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Małgorzata Malec [1a], Lilianna Stańczak [1]

[1] KOMAG Institute of Mining Technology, Pszczyńska 37, 44-101 Gliwice, Poland

[a] e-mail: mmalec@komag.eu

Keywords: mining machines, technical documentation, longwall shearer, road-header, conveyor, winder, powered roof support, separator, jig

Słowa kluczowe: maszyny górnicze, dokumentacja techniczna, kombajn ścianowy, kombajn chodnikowy, przenośnik, maszyna wyciągowa, sekcja obudowy zmechanizowanej, separator, osadzarka

Abstract:

Some papers, presented at the 20th Jubilee Scientific and Technical Conference KOMTECH-IMTech 2019, are discussed in the article. Part 1 of the article, published in the Quarterly "Mining Machines" No. 1, concerned the role of coal in the global economy, the importance of the coal sector for the Polish economy, the security of energy supply as well as technical and technological achievements of the coal sector over the years 2011-2017. Special attention was paid to automation and digitalization in coal mines, health and safety issues, a protection of the environment, sustainable coal technologies and also to an improvement of the coal use. Part 1 was ended with a description of the KOMAG Institute's contribution to a development of the Polish mining industry in Sovereign Poland. Part 2 of the article concentrates on the role of the KOMAG Institute of Mining Technology in development processes of mining machines and equipment in Sovereign Poland. Over the period of nearly seventy years of the KOMAG scientific and technical activity more than 1100 technical documentations of mining machines and equipment for underground winning and for a beneficiation of coal were developed. The article also contains some information about Mine 4.0 in theory and practice.

Streszczenie:

W artykule omówiono wybrane referaty, zaprezentowane podczas XX Jubileuszowej Konferencji Naukowo-Technicznej KOMTECH-IMTech 2019. Część 1. artykułu, opublikowana w Kwartalniku „Mining Machines" nr 1, dotyczyła roli węgla w światowej gospodarce, znaczenia sektora węglowego dla polskiej gospodarki, bezpieczeństwa energetycznego oraz technicznych i technologicznych osiągnięć sektora węglowego w latach 2011-2017. Szczególną uwagę zwrócono na automatyzację i cyfryzację w kopalniach węgla, kwestie zdrowia i bezpieczeństwa, ochronę środowiska, zrównoważone technologie węglowe, a także doskonalenie sposobów wykorzystania węgla. Część 1. została zakończona opisem wkładu Instytutu KOMAG w rozwój polskiego przemysłu wydobywczego Niepodległej Polski. Część 2. artykułu koncentruje się na roli, jaką Instytut Techniki Górniczej KOMAG odgrywał i odgrywa w procesach rozwoju maszyn i urządzeń górniczych w Niepodległej Polsce. W ciągu prawie siedemdziesięciu lat działalności naukowo-technicznej Instytutu KOMAG opracowano ponad 1100 dokumentacji technicznych maszyn i urządzeń górniczych do podziemnego pozyskiwania i wzbogacania węgla. Artykuł zawiera także informacje na temat Kopalni 4.0 w teorii i praktyce.

1. Role of the KOMAG Institute of Mining Technology in development processes of mining machines and equipment in Sovereign Poland

The KOMAG Institute of Mining Technology dates back to 1950 [5]. Over the period of nearly seventy years it changed its name and organizational scheme, but it was always oriented onto designing, testing and implementing mining machines and equipment for winning and beneficiation of minerals, in particular hard coal. Since 1950 over 1100 technical designs of mining machinery, implemented in mines, have been developed [4]. An innovative character of technical and technological solutions is confirmed by 4400 patents and utility patents granted to KOMAG over the period of its scientific, research and technical activity [7].

In the fifties the WŁE-30ch heading coal-cutter (Fig. 1), the KW-1 cutter-shearer (Fig. 2) and the first KWB-3 longwall shearers (Fig. 3) started their operation.

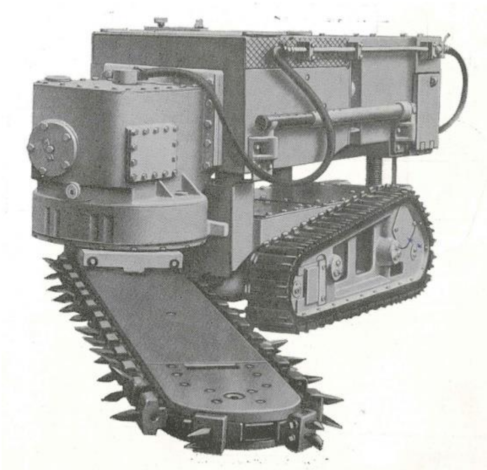

Fig. 1. WŁE-30ch heading coal-cutter [KOMAG]

WŁE-30ch heading coal-cutter (Fig. 1) was designed for cutting horizontal, vertical and askew bottom cuts in coal, coal and stone headings and shortwalls. It could make next-to-the floor cuts in the distance up to 500 mm and from 1200 mm to 1600 mm from the floor. The machine was mounted on a caterpillar chassis which enabled its operation in inclined workings [16].

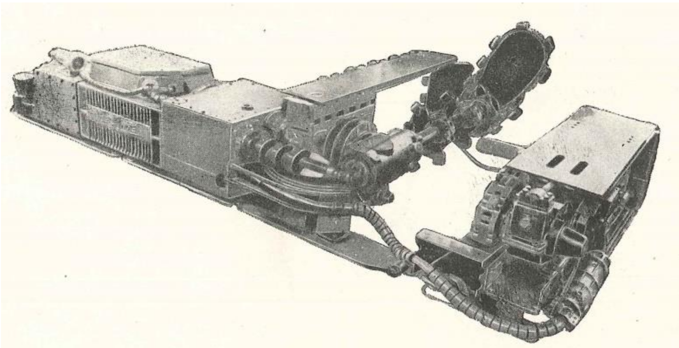

Fig. 2. KW-1 cutter-shearer [16]

KW-1 cutter-shearer (Fig. 2) was used for simultaneous coal cutting and loading to the conveyor in the longwall system. It was operated in the seams of the height from 0.9 to 1.8 m inclined up to 15^0 for cutting coal of medium hardness [16].

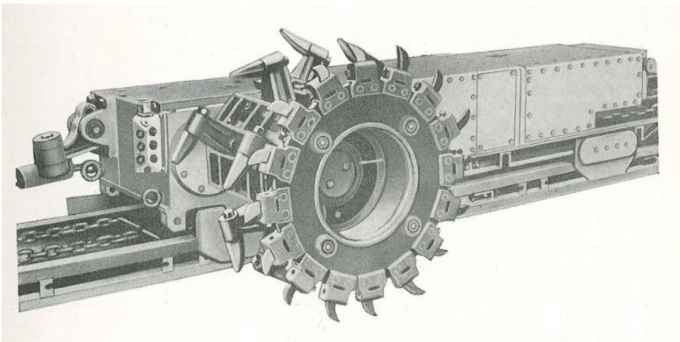

Fig. 3. KWB-3 longwall shearer [KOMAG]

KWB-3 longwall shearer (Fig. 3) was a single drum machine installed on a scraper conveyor of SAMSON type. It operated together with individual steel units or mechanized roof supports of OSM type. It was designed for longwall faces of the height from 1 m to 2 m. It could be used for cutting hard and difficult-to-be mined coal [1].

Apart from technical documentations of cutters and shearers also technical documentations of other machines were developed: ŁZK-5P overhead loaders (Fig. 4), ŁCh-2 shaft loaders (Fig. 5), SKAT scraper conveyor (Fig. 6), Koepe pulley winder of K-2500/Z type (Fig. 7) and double drum hoisting machine of BB-3000/B type (Fig. 8).

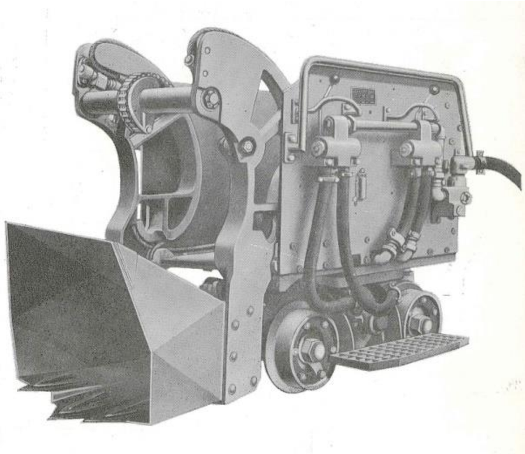

Fig. 4. ŁZK-5P overhead loader [KOMAG]

ŁZK-5P overhead loader (Fig. 4) was used for loading the run-of-mine in horizontal workings such as (headings, cross-cuts) of the height up to 2.2 m. It was equipped with two STG-9 pneumatic engines. It could also operate on the surface for loading stone, ore and debris.

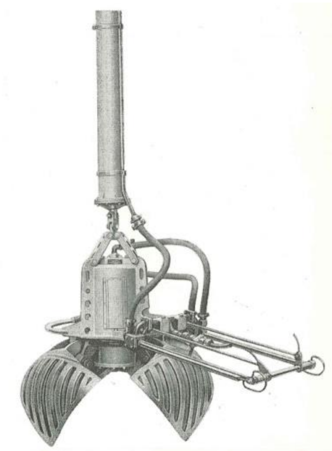

Fig. 5. ŁCh-2 shaft loader [KOMAG]

ŁCh-2 shaft loader (Fig. 5), equipped with pneumatic drive, was used for loading comminuted rock to buckets used at shaft sinking. It was easy to operate due to a simplified air circulation, an improved control of the grab movements and of the hoist as well as a relatively small weight.

Publisher: KOMAG Institute of Mining Technology, Poland

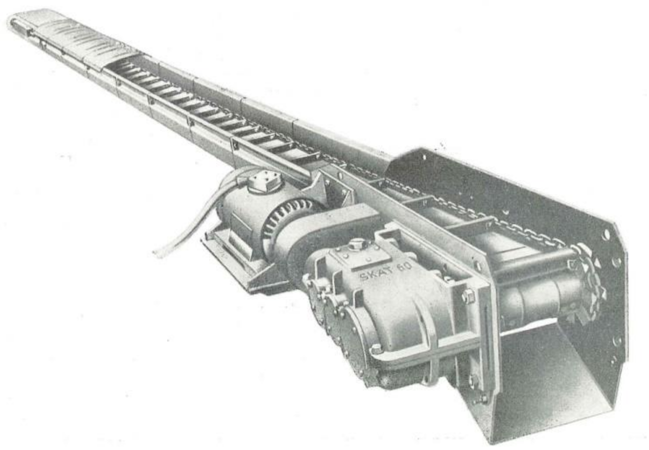

Fig. 6. SKAT-60 scraper conveyor [KOMAG]

SKAT-60 scraper conveyor (Fig. 6) was designed for haulage of the run-of-mine from headings, shortwalls and open-ends as well as from longwall faces inclined up to $\pm 18^0$. The conveyor was flexible $\pm 3^0$ in the horizontal plane (between two line pans) which enabled its operation on corrugated floors.

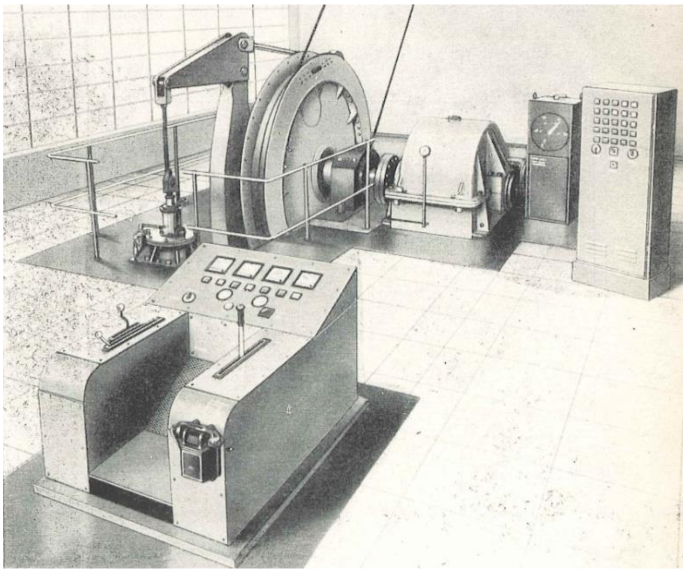

Fig. 7. Koepe pulley winder of K-2500/Z type [KOMAG]

Koepe pulley winder of K-2500/Z type (Fig. 7) was a single rope machine used for double and single cage with a counterweight installation. The machine could be installed over or next to the shaft both on the surface or underground. Control was performed from the control desk. It was equipped with a full protective system required in the case of hoisting men at the speed of 4 m/s. The brakes were controlled electro-pneumaticly.

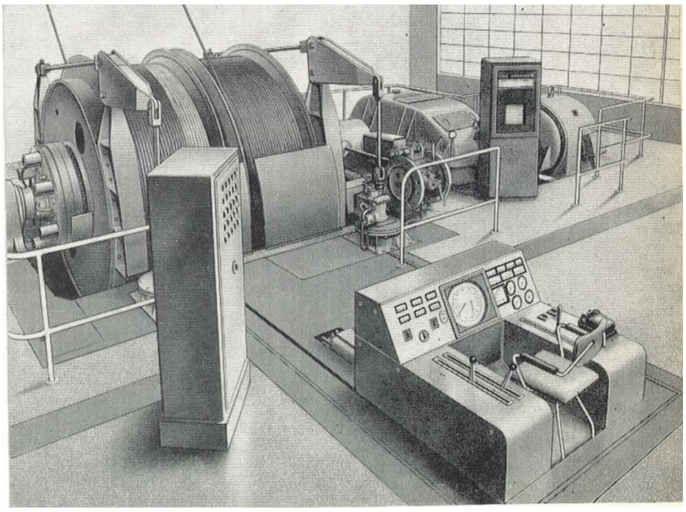

Fig. 8. Double drum winder of BB-3000/B type [KOMAG]

Double drum winder of BB-3000/B type (Fig. 8), equipped with an asynchronous drive, was used for double cage installations in the case of hoisting from different levels and for two-bucket systems used for shaft sinking at the speed of 6 m/s.

The machine was equipped with a reversible system of drums enabling an easy change of spacing between the winding zones of the drums according to spacing of the pulleys.

Powered roof supports of OSM type (Fig. 9) were developed together with specialists from the GIG Central Mining Institute (Katowice, Poland).

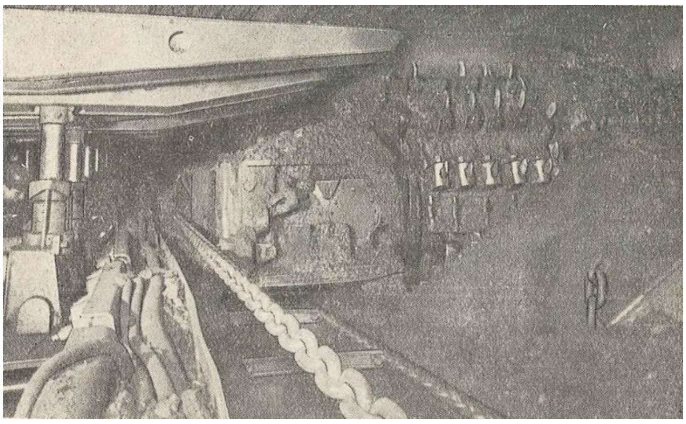

Fig. 9. OSM powered roof support [KOMAG]

In the sixties pillar supports in the frame (Fig. 10) and chock (Fig. 11) versions were designed.

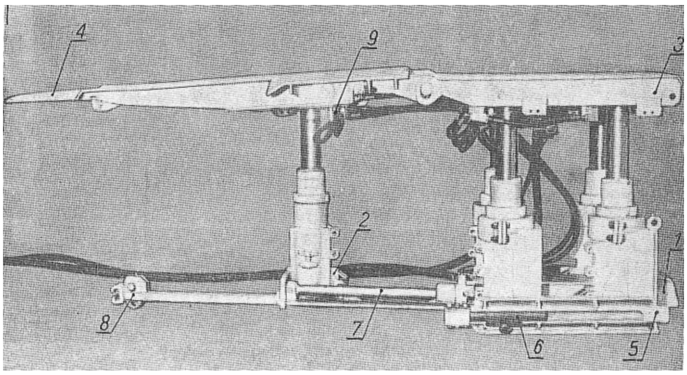

Fig. 10. KRAB-1 frame pillar support [2]

KRAB-1 frame pillar support [2] was designed for use in low seams from 0.8 to 1.3 m (horizontal and inclined up to 35^0), mined in the caving system. The numbers in Fig. 10 indicate as follows: 1 – frame base, 2 – separate plate, 3 – articulated frame canopy, 4 – additional canopy extended manually, 5 – conducting rod, 6 – sleeve, 7 – hydraulic advancing ram, 8 – advancing head and control manipulators.

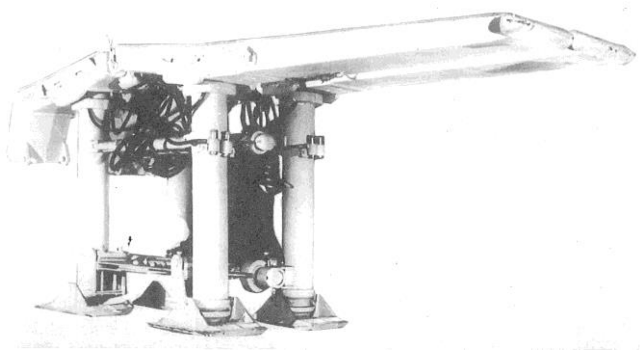

Fig. 11. FAZOS-70 chock pillar support [15]

The FAZOS Factory of Longwall Roof Supports produced the FAZOS-70 chock pillar supports (Fig. 11), designed for operation in medium-thickness seams inclined up to 35^0. There were two types of that design: FAZOS-12/23 Pz [15] for seams from 1.2 to 2.3 m thick and FAZOS-18/35 for seams from 1.8 to 3.5 m thick.

In that period of time technical documentations of the first pulsatory jigs, BOB-5500/630 bobin hoisting machine, WW-2Ms drilling jumbo, DEKO 75/100z winch and WL4-2000 four-rope hoisting machines (Fig. 12) were elaborated.

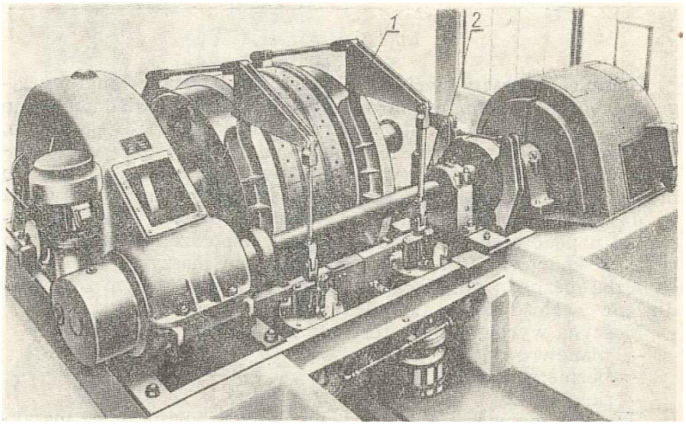

Fig. 12. WL4-2000 four rope hoisting machine [2]

WL4-2000 four rope hoisting machine (Fig. 12) was equipped with manoeuvre brakes (1) and emergency brake (2) which operated using the same shoes. Those brakes had independent drives and the control was carried out with use of relay mechanisms.

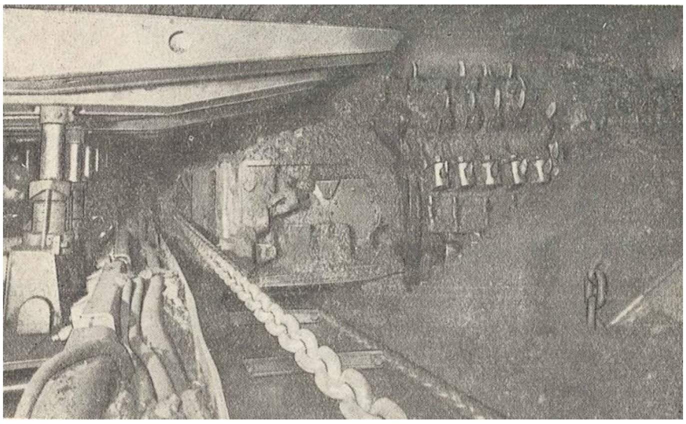

Fig. 13. OSM-1B powered roof support operating together with PZS – Samson conveyor and KWB-3 shearer [2]

The longwall system, shown in Fig. 13, enabled to reduce operational costs significantly due to an increase in production rates. Bumping seams could be mined without any hazard to miners because it was possible to use different control systems, including automatic ones.

In the seventies over 22000 of the FAZOS 12/28 Oz powered roof support units, designed at KOMAG, were produced. Presenting the information about the machines and equipment from that period KWB-6 two ranging arm shearer, SWP coal plough, SUPER SAMSON-NP face conveyor, SOW-80 TP longwall hanging support, equipment for mechanical dust control, AZZ-250A power pack, AW-3 water apparatus, EWA-15 drilling jumbo, AM-50 road-header, Gwarek 1200 and 1400 belt conveyors, KWB 3 RDUW drum shearer, in which the chain was replaced by the Polish chainless haulage system of POLTRAK II type, should be mentioned.

In the eighties research and development projects at KOMAG concentrated on the machines and equipment such as: KGS-160N longwall shearer, GLINIK-055/150zM shield support operating together with SWS-6N plough, RYBNIK 80 scraper conveyor with POLTRAK II haulage system, WPT-3 trapezoid vibratory feeder, KWB 3 RDUW/160 longwall shearer, SKAT/E/180 scraper conveyor, DISA-2 KU-3500P suspension separator, KGS-560 longwall shearer, B-2000 hoisting machine, WOW-1.5 dewatering vibrating centrifuge, PWP 1x3x6 and PWP2 2.4x4.5 vibratory screens, ZPP-ZZ scraper loader, KWM 780E longwall shearer, SKS-60 rail-mounted haulage unit and OG-800Ch roadway dust control installation.

In 1983 590 longwall shearers were in operation in the Polish hard coal mines and 564 of them were produced by the FAMUR Factory of Mining Machines (Fabryka Maszyn Górniczych), basing on the technical documentations developed at the KOMAG Institute [3].

In the nineties technical documentations of the machines, presented below were developed. KSE 344, 500, 700, 800/1000 longwall shearers were applied in longwall faces of high production concentration. KSE-1000, supplied with 6 kV, enabled to achieve daily output reaching 7500 tons. In Fig. 14 and in Fig. 15 KSE-500 and KSE-1000 shearers are shown respectively. KSE-500 was designed for an application in longwall faces of the height between 2.0 and 4.0 m, KSE-1000 – between 1.9 and 4.0 m [8].

Fig. 14. KSE-500 longwall shearer [KOMAG]

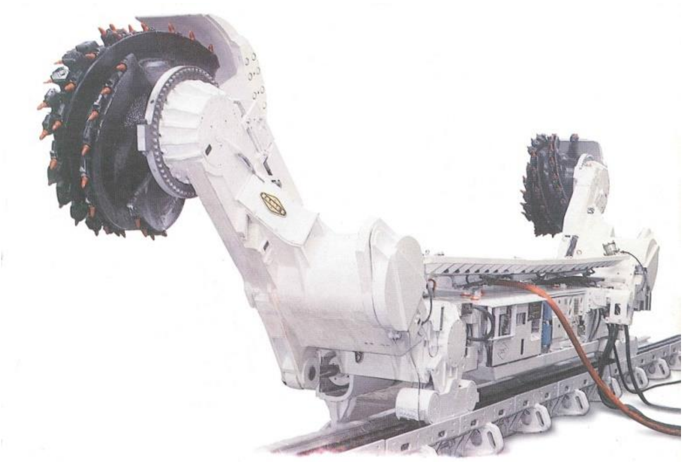

Fig. 15. KSE-1000 longwall shearer [KOMAG]

All the shearers of KSE type were equipped with AC motors controlled by frequency converters, located in road-headings. The control system enabled to automate the haulage speed, adapting the machine to the in-situ mining and geological conditions. This type shearers were equipped with chainless haulage and diagnostic systems enabling a current control of the motors' load as well as of the main assemblies' temperature. The hydraulic systems were used only for raising and lowering ranging arms as well as for releasing the parking brakes. Due to an implementation of narrow ranging arms it was possible to introduce stableless cutting systems. An efficient dust control was achieved due to an implementation of the internal water spraying system installed in the ranging arms [9, 12, 13].

Another interesting design solution, developed in the nineties, was the PSZ-750 scraper conveyor (Fig. 16).

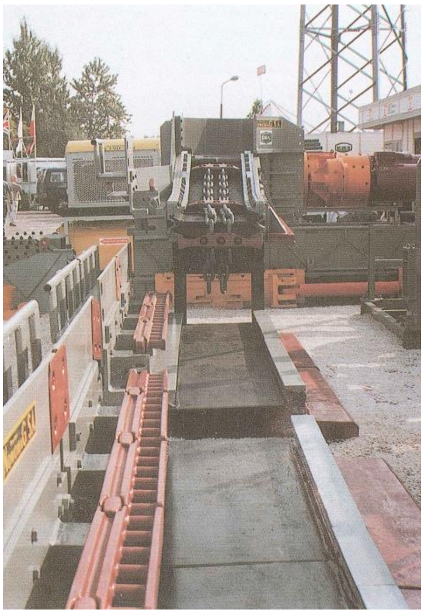

Fig. 16. PSZ-750 scraper conveyor [KOMAG]

PSZ-750 scraper conveyor, shown in Fig. 16, was produced by the NOWOMAG Factory of Mining Equipment. Its capacity reached 750 tons/hour and the power of drives was 200 kW. It was implemented in the following coal-mines: Gliwice, Dębieńsko, Mysłowice, Śląsk, Wesoła, Jastrzębie, Niwka-Modrzejów and Borynia.

In the same time intensive development projects were conducted on suspension separators and vibratory screens.

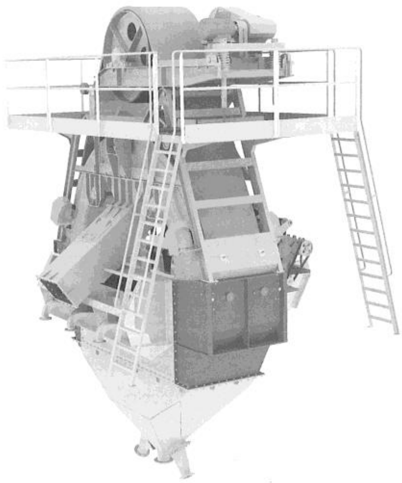

Fig. 17. DISA 2S suspension separator [10, 14]

DISA 2S suspension separator, shown in Fig. 17, was designed for a two-product beneficiation process. The feed was divided into two fractions: the floating one and the sinking one in the dense medium trough. The floating fraction moved along the dense medium current towards the overflow, where it was removed with a scraper. The sinking fraction, after having fallen down to the raising wheel, was directed to the chute.

The SKZ-81 rail-mounted toothed haulage unit (Fig. 18) should be mentioned as well due to its innovative character and many technical advantages.

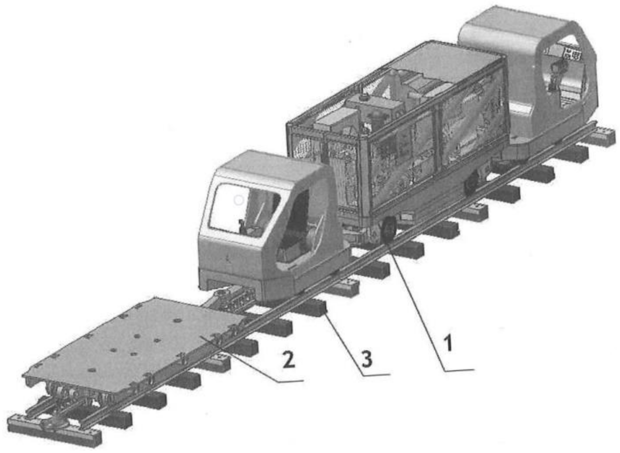

Fig. 18. SKZ-81 rail-mounted toothed haulage unit [KOMAG]

SKZ-81 haulage unit with a double drive system where 1 - haulage unit, 2 – platform, 3 – track was designed for an application in coal, salt or other minerals mines where the “a”, “b” and “c” methane explosion hazards and “A” and “B” classes of dust explosion hazard occur. Due to its construction it is possible to transport heavy assemblies from the shaft to the faces without any need of their unloading and reloading. It is equipped with a Volvo Penta D5AT engine which drives an assembly of hydraulic pumps which supplies hydraulic engines of the wheels or the engine of the toothed bar drive. The engine power is 81 kW and the maximal haulage force reaches 220 kN. It can be used for transporting components of 13500 kg weight.

After the year 2000 research and development projects at the KOMAG Institute of Mining Technology were also oriented on designing, testing and implementing new or modernized jigs, suspension separators, dust control installations and noise control systems. It is worth mentioning an innovative solution of a scraper conveyor with drives’ control system, WIG-200 engineering and geological drill rig, MWM-1 drilling jumbo, PCA-1 battery-driven suspended haulage unit, B-4300/DC hoisting machine, Lda-12K-EMA battery – driven locomotive for underground applications, KSW-750 E and KSW-950 E longwall shearers as successes of the KOMAG researchers and specialists playing an important and significant role in making mining operations safer and more profitable. Technical and scientific achievements in a development of preparation machinery should be highlighted. Over the years 1955-2018 technical documentations of 320 separators, including over 200 jigs, operating in Poland and abroad: in Brazil, China, India, Romania and Vietnam were elaborated. Their modified versions are used as classifiers of aggregates. Within recent years innovative designs of preparation plant machinery and equipment became a very important field of the KOMAG’s activity.

At present in 18 hard coal mines 40 preparation plants are in operation. Among them 33 plants beneficiate steam coal and 7-coking coal. The machines and equipment, used in these processes, include: pulsatory jigs, screens, crushers, heavy-medium separators, Reichert spirals, heavy-medium cyclones, hydrocyclones, flotation machines, vibrating screens and vibrating centrifuges, screen-sedimentation centrifuges, belt presses, filtration presses, pressure filters and disc vacuum filters [6, 11]. At present these technological nodes are automated and visualized.

Several research and development projects, realized at the KOMAG Institute within the recent decade, were oriented onto jigs.

In Fig. 19 OS 18 medium-size grain jig, installed in the modernized Preparation Plant of the Budryk Mine, is shown. The beneficiation node consists of 6 medium-size grain jigs of OS 18 type (70-2 mm), of 2 fines jigs OM 20 type (12-0 mm) (Fig. 20) and of 14 bucket conveyors of B-1000 type (Fig. 21).

Fig. 19. OS 18 medium-size grain jig [KOMAG]

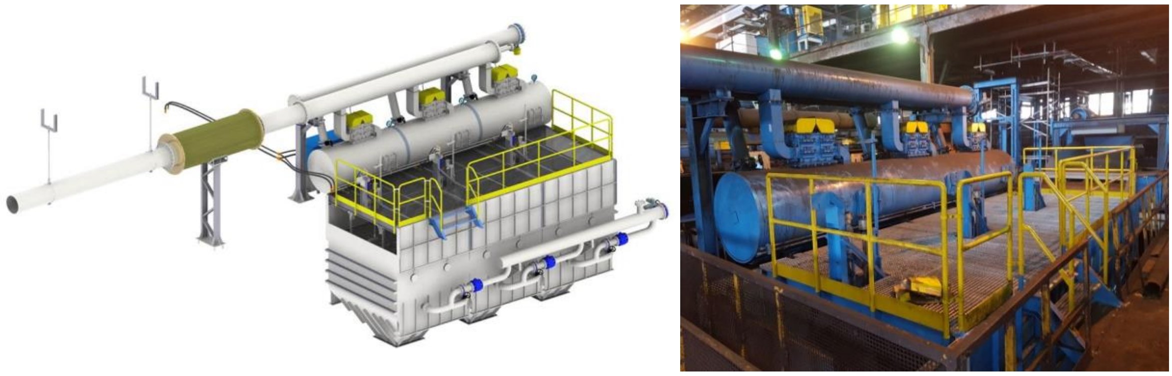

Fig. 20. OM 20 fines jig [KOMAG]

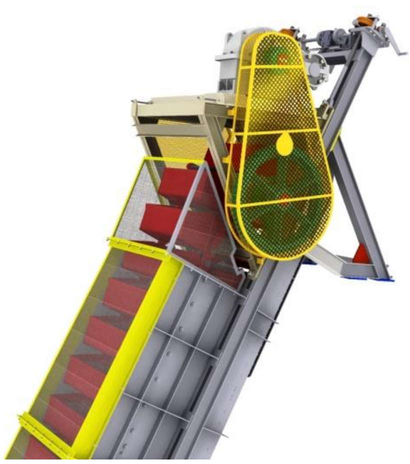

Fig. 21. B-1000 bucket conveyor

The jig node is controlled by the KOGASTER system developed at KOMAG. Due to a modernization of the Budryk Preparation Plant it is possible to beneficiate coal of two types: 34 and 35, using two independent systems.

In the development strategy of the KOMAG Institute of Mining Technology the activities oriented onto an increase of producers' competitiveness due to an implementation of innovative products and technologies play an extremely important role. Market achievements can be measured by a successful operation of mining machines and equipment and significant improvements in the scope of miners' work safety. These activities are realized by KOMAG researchers, designers and specialists working in the accredited laboratories and in the Certifying Body of Products. The KOMAG Institute of Mining Technology is a EU notified body in the scope of three directives: Machinery, ATEX and Safety of Toys.

Publisher: KOMAG Institute of Mining Technology, Poland

2. Mine 4.0 in theory and practice

At present Mine 4.0 seems to be a commonly used term although there are some opinion differences among experts, so it was very interesting to find out what Dr. Jacek Korski from the FAMUR Factory intended to say, presenting the paper on Mine 4.0 – in theory and practice. He described characteristic features of industrial revolutions. In the case of Industry 1.0 – it was a steam engine, in the case of Industry 2.0 – use of electric energy, in the case of Industry 3.0 – teleinformation systems, integrated circuits and robots. Industry 4.0 is characterized by a computerization of processes and by autonomous decisions taken by machines. It can be described as the age of a barrier decay between people and machines. It takes advantage of the Internet of People, the Internet of Things, the Internet of Services and the Internet of Data. The key technologies for Industry 4.0 include data storage (sensors), data transmission and communication (RFID), data storage and processing, including data flow, processing in the cloud, group processing in computer networks and also transaction registers of operations instead of a status register, advanced analytics incorporating analyses of Big Data and Artificial Intelligence, as well as a visualization of information using Virtual Reality (VR) and Augmented Reality (AR). As regards the hardware smart robots, drones, wearable devices e.g. smart watches and autonomous vehicles, 3D print in manufacturing processes (AM – Additive Manufacturing) will be used.

The Komatsu/Joy Company has elaborated a map of remote longwall management, which can be treated as a step towards Mine 4.0.

It includes the following components:

- Basic automation of the longwall face containing Faceboss RS20s system, longwall control system and cutting with a memory of cut.
- Monitoring of the longwall operation in the semi-automatic system requiring advanced automation of the shearer, an automation of drives, fast Ethernet network, LASC system of keeping rectilinearity, remote monitoring of the longwall operation and Joy Smarts solutions.
- Remote monitoring in the fully automated system enabling to obtain exact information about the conditions in the longwall face, a visualization of the longwall face, seam management and checking the geometry. Personal proximity sensors and remote management centre are required.
- Remote management in the semi-automatic system requires an advanced control of the armoured face conveyor.

3. Conclusions

- The 20th Jubilee Scientific and Technical Conference KOMTECH-IMTech 2019 enabled an exchange of knowledge as well as scientific and professional experience among representatives of academia, research institutes, producers of mining machinery and end-users from mines.
- After having analyzed a development of mining machinery and equipment over the period of recent seventy years, it can be stated that KOMAG played and still plays the leading role in the process of designing, testing and implementing innovative solutions of these machines.
- A contribution of the KOMAG Institute of Mining Technology to a development of the Polish mining industry in Sovereign Poland was highlighted.
- Some information about Mine 4.0 against the characteristic features of Industry 4.0 was given.
- Bearing in mind a development of mining machinery and equipment, it can be concluded that at present scientists and researchers are oriented on projects reflecting the needs of Mine 4.0.

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Testing the equipment used in ventilation of mine workings

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Michał Olejnik

Affiliation: KOMAG Institute of Mining Technology, Pszczyńska 37, 44-101 Gliwice, Poland

e-mail: molejnik@komag.eu

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Słowa kluczowe: badania, urządzenia odpylające, wentylatory lutniowe, lutnie wirowe

Abstract

The article gives a short presentation of three basic test types of equipment used in ventilation of mine workings, such as dust collectors, fans and vortex ventubes.
The procedure for measurements preparation and tests realization as well as how to present the test results, is given. In addition, the article contains information on the regulations to be met for proper tests realization. The mentioned tests concern equipment operating in the forced or sucking-forced ventilation systems. Furthermore, the article presents the design and layouts of measuring stands used in KOMAG. It also specifies the parameters to be measured along with their read out places.

Streszczenie

Artykuł zawiera krótką prezentację trzech podstawowych rodzajów badań urządzeń wykorzystywanych przy przewietrzaniu i odpylaniu wyrobisk kopalnianych, jakimi są: odpylacze, wentylatory i lutnie wirowe.
W opracowaniu określono zasadnicze cele poszczególnych badań, zaprezentowano procedurę przygotowania pomiarów, tok postępowania podczas badań oraz sposób przedstawiania wyników. Dodatkowo zostały w nim zawarte informacje dotyczące przepisów do jakich należy się dostosować w celu prawidłowego przeprowadzenia danych pomiarów. Wymienione w artykule badania dotyczą urządzeń pracujących w najczęściej stosowanych na kopalniach układach przewietrzania tj. w układzie wentylacji ssącej lub ssąco tłoczącej. Ponadto w publikacji przedstawiono budowę oraz schematy stanowisk pomiarowych wykorzystywanych do badań w ITG KOMAG, a także zostały określone parametry jakie należy mierzyć wraz z miejscem ich sczytywania.

1. Introduction

Currently, mining the hard coal seams using the state-of the-art technologies causes generation of coal dust, what has a negative impact on miners health and poses serious threat of coal dust explosion. Hazards related to the explosive properties of coal dust in underground mine workings belong to the earliest identified and most dangerous ones and are listed as one of the primary hazards identified in hard coal mines both in Europe and in the USA [1, 2]. There are the following main sources of dust: longwall coal mining, including advance of powered roof supports, development of roadways by roadheaders, using the blasting method as well as run-of-mine transportation and crushing [3]. Also, technological processes in coal processing plants can be a source of dust, posing a threat to health and explosion hazard [4].

In this case the following equipment may be a source of dust emissions:

- machines - point and surface sources,
- containers - surface sources,
- transportation routes - line sources.

Therefore, it is important to eliminate these hazards by applying appropriate technical measures.

Depending on the characteristics of the technological lines, three types of dust control installations can be used:

- local - limited to one source of emission,

- technological – covering the whole technological line or its bigger part,
- structural - covering entire buildings or rooms.

Regardless of the type of technological or structural dust control method used, there will always be places of increased dust concentration [5].

Vortex ventubes as well as dust collectors have been used for several years in hard coal mines for dust control and roadways ventilation. In accordance with additional restrictions applicable in the Polish mining industry regarding work safety and environmental protection, use of these devices in a roadway which is under development by a roadheader is mandatory [6].

The equipment placed on the market meet the requirements of the regulations, both in terms of meeting the requirements for ventilation, as well as air quality and formal requirements, covering the devices operating in underground mines. Research and development work is constantly being carried out to improve the operational reliability of the ventilation and dust control systems in mine workings as well as to ensure proper conditions of work safety [7].

These devices are certified for compliance with the general requirements of the directives [8, 9], as well as the requirements of the applicable standards, specifying the requirements and scope of tests for dust collectors and vortex ventubes.

The test results confirm compliance of the required parameters of the devices with the requirements and their effectiveness, what allows their use in combined, sucking and forcing ventilation systems in the hard coal mines underground. At the same time, the universal nature of the equipment, in particular dust collecting devices, allows to broaden the spectrum of their use, e.g. for dust collecting in coal processing plants or in other industries [6].

2. Procedures for testing the equipment used for mine workings ventilation

For each of the discussed devices, the measurements have to verify their operational parameters specific to the given type of device, to check compliance with the requirements for safe use and to test the structure strength.

- during dust collector tests, the primary objective is to determine the dust collection efficiency using the dust meter (including the respirable fraction), in which the ventube pipeline conditions are simulated and a sample is taken to check the device efficiency.
- measurements of ventubes operation have to check if they do not exceed the permissible operational parameters and to determine the proper range of their operation.
- during tests of vortex ventubes, adjustment of the device and determination of output of air flowing through the ventube, is the main objective.

Problems of the research projects on testing the devices used in ventilation of mine workings, carried out at the KOMAG Institute of Mining Technology are presented on the example of testing the dust collectors, ventubes and vortex ventubes.

2.1 Tests of dust collecting equipment

The dust collector's testing process includes mainly checking the functionality of each unit and their components, as well as determining the efficiency of dust control.

Due to the fact that the dust collector's testing process was not standardized at both global and European level, the PN-G-52002:2009 Polish Standard was developed in the Polish Committee for Standardization, which regulates the principles of testing in this case. The test stand built at KOMAG meets the requirements specified in the Polish Standard [10].

The constructed stand is used for testing wet type dust collectors. The basic operating parameters are as follows:

- flow rate range from 120 to 1000 m^3/min,
- measuring ventube diameter ∅ 630, ∅800, ∅1000 mm.

The main part of the stand is the measuring ventube in which the tested air flows. Additionally, devices used to induce the air flow, such as:

- auxiliary fans,
- airborne dust blowing fans,

are installed within the stand.

The test stand consists of the following components:

- dosing scale,
- inlet cone,
- tested dust controlling device,
- fan,
- measuring ventube,
- gravimetric dust meter.

General outline of the test stand is presented in Figure 1.

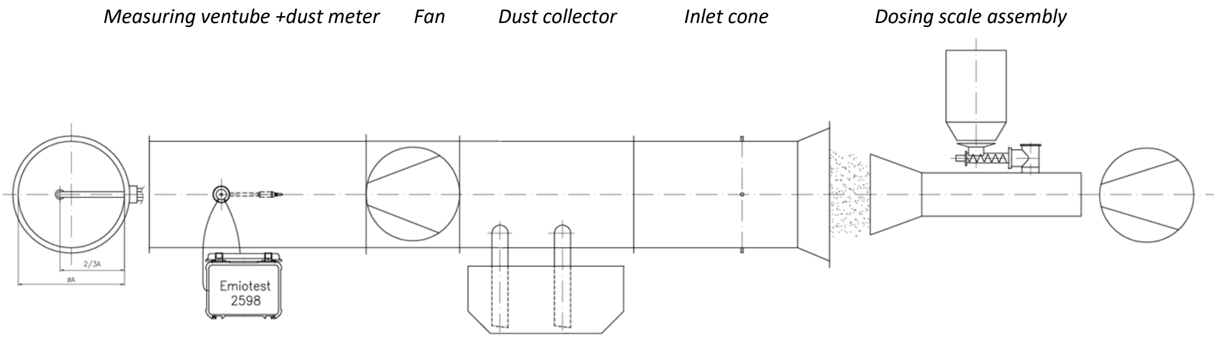

Fig. 1. Schematic diagram of the stand for testing dust collecting equipment

The scope of testing the dust collector

During dust collector tests, the most important issue is to define dust collection efficiency as the basic parameter. Before starting the tests it is necessary to determine the following initial parameters:

- water system efficiency,
- efficiency of transported air,

with active water supply system.

Efficiency of the water system

To measure the efficiency of the water system, it is necessary to assembly a measuring system consisting of a nozzle (nozzle assembly or water distributor), pump and connection hoses, and then measure the time required to fill up the tank of known volume.

The volume of water stream flowing through the water system is calculated using the following formula:

$$\dot{V}_w = \frac{V_{zp}}{t_n} \tag{1}$$

where:

$\dot{V}_w$ – volume of water stream flowing through the water system, m^3/s
V_{zp} – volume measured in the measuring tank, m^3
t_n – average time of filling the tank to the volume V_{zp}, s

In turn, the mass of water flowing through the water system is calculated in relation to the density of water at temperature at which the measurement was made.

Output of air flowing through the dust collecting device

To determine the efficiency of the air flowing through the dust collecting device, a system, in which inlet cone is installed at to the device entry according to ISO 5221:1984 [11], is used.

After assembling the system, it is necessary to determine the fan lowest and the highest point of operation, at those points fan output should be determined. For that purpose, after switching on the driving system of the device or the fan, under the load of water, it is important to throttle the dust control device at the outlet by the gate valve until the fan enters the pumping state, in which its operation is irregular and with power variability.

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Parameters for the lowest point of fan operation at which the minimum flowrate should be determined should be close to the pumping point, but without entering this state, and the parameters for the highest point of operation refer to the maximum flowrate obtained in the device.

After determining the operational parameters, it is important to measure the power of the nozzle or drive assembly motor and check if it does not exceed the rated value, when the water load is too high.

The parameters listed in Table 1, read from the scale of the measuring instruments are the input data for calculations.

Table 1. Parameters to be measured for calculation of air volume flowing through the dust collecting device

Parameter	Symbol	Unit	Measuring instrument
Barometric pressure	b_{at}	[Pa]	barometer
Relative humidity	φ	[%]	hygrometer
Temperature	t_1	[°C]	thermometer
Pressure drop on Venturi tube (differential pressure)	Δp	[Pa] (inlet cone ISO)	micromanometer

Stream of fed dust mass

At first, to determine mass of dust fed to the system, output of air flowing through the system should be determined and then dust concentration in flowing air. It was assumed that dust concentration in air is c_p = 500 mg/m^3, and mass of dust fed to the system is calculated according to the following formula:

$$\dot{m}_p = c_p \cdot \dot{V} \tag{2}$$

where:

c_p – dust concentration in flowing air, kg/m^3

$\dot{V}$ – output of air flowing through the system, m^3/h

$\dot{m}_p$ – stream of fed dust mass, kg/h

Measuring instruments and testing procedure

Automatic dust meter, configured according to the needs, was the basic component included in the stand for testing the dust control devices. Disposable filters are used for measurements, the type of which depends on the filtration method. For internal filtration, so-called thimbles, mini-bags or flat paper filters are used. After drying in a desiccator, the filter is weighed just before the test with an accuracy of 0.001 mg on a laboratory scale. Then the filter is placed in the dust separator (Fig. 2a) and then the dust removal device tests are carried out. After completion, the filter is again dried for 24 hours in a desiccator and weighed "dry". The filter masses before testing the dust control device (i.e. without dust) and after the test (with caught dust) are used to determine the dust control efficiency of the device.

Fig. 2a. Separator and dust filter prepared for installation

Fig. 2b. Measuring probe with the filter installed in the tested ventube pipeline

The air-dust mixture was prepared in the dosing scale assembly and blown by an auxiliary fan to the tested dust control device. After passing through the dust collector, the gas stream flows through to the aspiration probe being a part of the dust meter. The probe should be installed in the appropriate socket of the measuring ventube section (Fig. 2b) so that the dust separator with the aspiration end, where dust particles are caught on the measuring filter, is in the axis of the flowing air stream in 2/3 of the channel diameter.

Dust control efficiency

The following parameters should be determined for calculation of dust control efficiency:

- m_0 [mg]– initial mass of dried filter,
- m_k[mg] – final mass of dried filter after the test,
- m_p[mg] – mass of dust collected on the filter,
- τ [min]– duration of measurement,
- Vv [m^3/h] – air flowrate through dust separator

Dust control efficiency is determined according the following formula:

$$\eta = \frac{C_p - C_k}{C_k} \cdot 100[\%] \tag{3}$$

where:

C_p – initial concentration, mg/m^3
C_k – final concentration, mg/m^3

$$C_k = \frac{m_p}{\tau \cdot V_V} \tag{4}$$

Assuming that big dust particles are completely removed and only respirable fraction of size from 0 to 5μm passes the device, we can determine dust control efficiency of this fraction as not less than:

$$\eta_{5-0} = \frac{x_{5-0} - (100 - \eta)}{x_{5-0}} \cdot 100[\%] \tag{5}$$

where:

$\eta_{5\text{-}0}$ – dust control efficiency of respirable fraction of size from 0 to 5 μm, %
η – total dust control efficiency, %
$x_{5\text{-}0}$ – share of fraction from 0 to 5 μm, %

When interpreting the results of dust collector tests, the following factors should be borne in mind:

- dust control efficiencies should be compared using the same inlet concentration of particles in the gas.
- change in concentration of solid particles at the inlet to the dust collector has negligible impact on change in flow resistance through the device.
- dust control efficiency is the same for dust collectors of the same energy consumption and increases with pressure drop, especially for pressures above 2500 Pa [12].

Additional tests and measurements

In addition to the tests related to the dust control process, the noise emitted by the device (especially the drive unit or fan) was measured.

In the case of devices containing components that operate in a pulsating manner, the vibrations produced during the operation of the device should be tested additionally.

If necessary, also check the rotor rotational speed**.**

2.2 Testing the ventube fans

Ventube fan tests are carried out according to the procedure given in the EN ISO 5801:2017-12 standard [13], and the result is the relationship between the fan capacity $\dot{V}$ [m^3/min] and:

- ram effect ΔP_F [Pa], recalculated for air density ρ_0 = 1.2 kg/m^3,
- electric power in [kW] recalculated for air density ρ_0 = 1.2 kg/m,

- total efficiency of the fan set η_e [%].

In addition, it is necessary to check if the recalculated electric power of the tested ventube motor does not exceed the permissible power calculated according to information from the motor's nameplate.

The standard presents testing procedures for four types of measuring channels:

- type A – free inlet and free outlet,
- type B – free inlet and a channel at the outlet side,
- type C – channel at the inlet side and free outlet,
- type D – channel at the inlet side and channel at the outlet side.

The most popular operating system for ventubes used in mines are relevant to the C-type stand with the measuring channel at the inlet side and the free outlet, the design of which is schematically shown in Fig. 3.

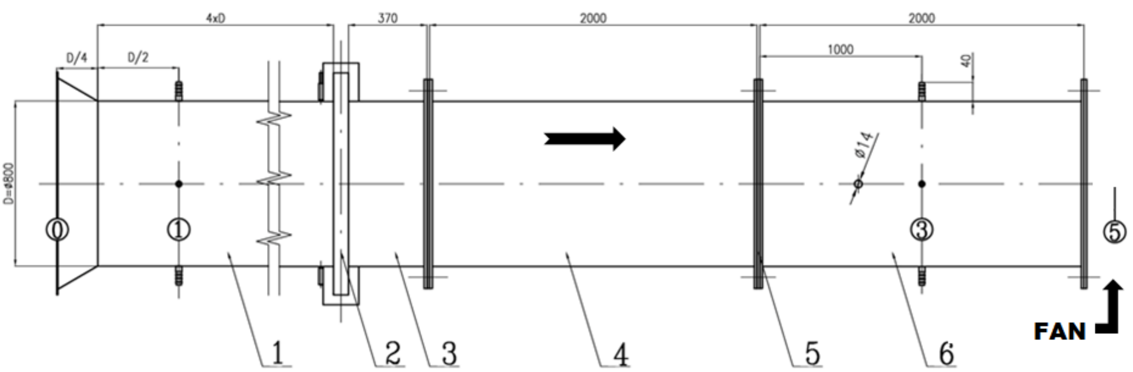

Fig. 3. Diagram of the testing facility type C

Explanations:

1. Inlet cone ∅800* with four measuring ends ∅11.
2. Mesh gland.
3. Stream straightener.
4. Spacer ventube ∅800x2000.
5. Gaskets ∅810x∅900 2 pcs.
6. Measuring ventube ∅800x2000 with four measuring ends ∅11 and opening ∅14.

Measuring cross-sections acc. to PN-EN ISO 5801:2017-12 were marked as follows:

0 – inlet (environment parameters),
1 – stream contraction zone,
3 – measuring cross-section in the channel at the side of fan inlet,
5 – fan outlet.

* *other measuring cones can be used e.g. ∅630, ∅320 mm.*

The tested ventube fan is connected to the outlet of the measuring channel and draws in air through this channel. The air flows first through the inflow cone (position 1), creating a difference between the negative pressure caused by air stream contraction and the surrounding pressure. On this basis, the air flow rate through the fan is determined. In the further part of the test stand, using a mesh gland (position 2), the resistances of the network cooperating with the fan are simulated. This unit is equipped with a perforated metal sheet, on which throttling nets of the standard mesh sizes are placed one on another to create air flow resistance. In this way, by reading out the below mentioned parameters for each number of nets, the fan characteristic points are obtained. The air then flows through the cell straightener of air stream (position 3). Next, the air flows through the distance ventube (position 4) to stabilize the air stream and then through the measuring ventube (position 6), where the vacuum generated by the fan connected to the measuring ventube outlet as well as air stream temperature are measured. Each test stand assembly is flange connected using gaskets (position 5).

Testing and test results

According to the calculation procedure, the following parameters should be measured and recorded on the measurements sheet:

- ambient temperature t_0 [°C] – ahead of the measuring inlet,
- ambient humidity φ_0 [%] - ahead of the measuring inlet,

- atmospheric pressure P_b [%] – around the measuring inlet,
- pressure drop on inlet in relation to atmospheric pressure h_1 [mm H_2O],
- temperature in the measuring channel t_3 [°C],
- pressure drop in the measuring channel h_3 [mm H_2O],
- air stream temperature on the fan outlet or behind the noise dumpers and diffusor (if the fan has such equipment) t_5 [°C],
- motor (or motors) power N_1 (N_2) kW.

The measurement results and the results of calculations are presented in tabular form and in graphical form in the form of graphs of fan characteristics (Fig. 4), showing the relationships of total ram effect, electrical power and total efficiency in a function of fan output. It is also important to interpret the measurement results regarding the correct fan operation, i.e. whether the mechanical power limit for the motor is not exceeded and to determine the scope of correct operation and a pumping range.

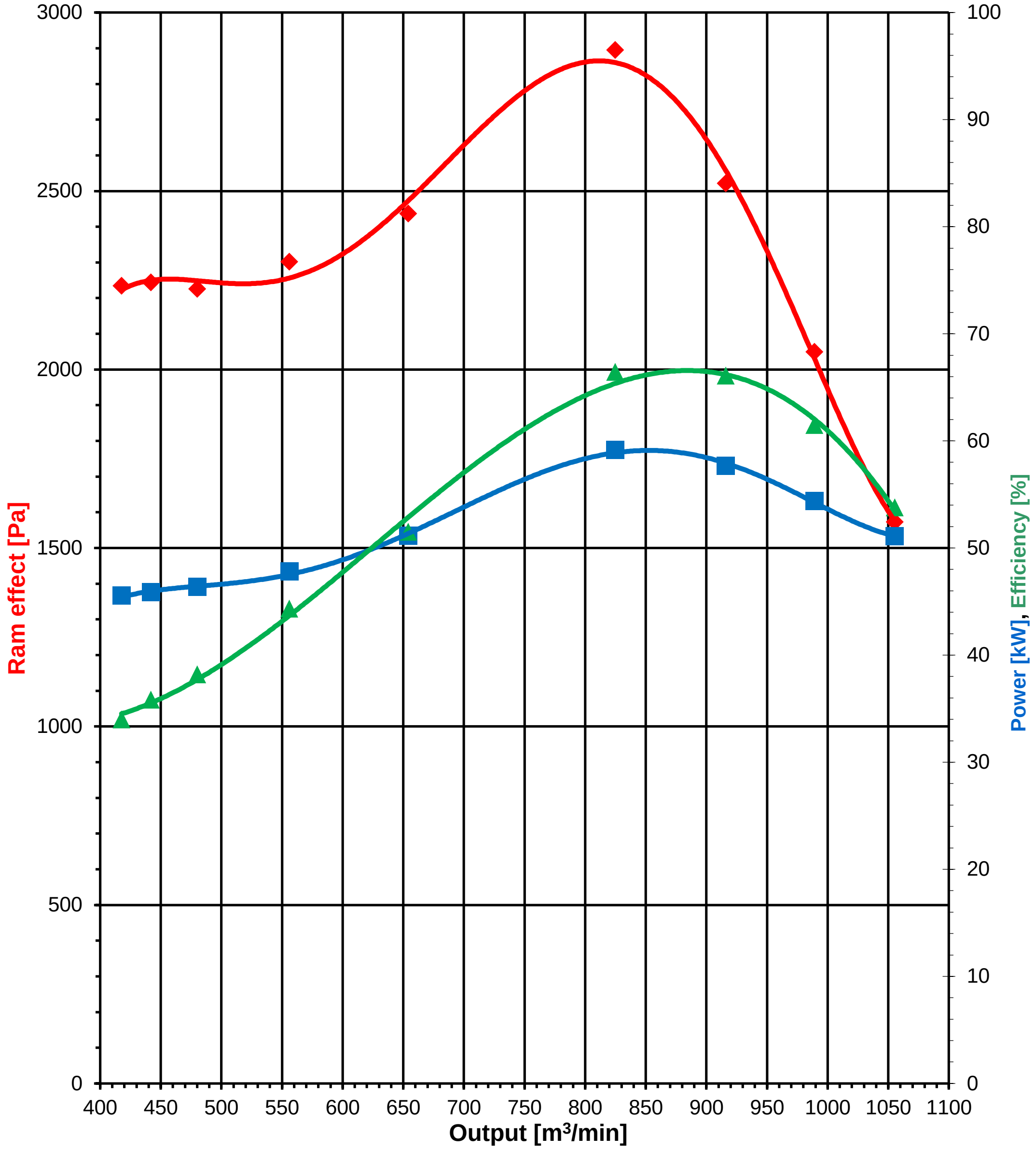

Fig. 4. Sample fan characteristics for air density 1.2 kg/m^3

Additional tests and measurements

Apart of the basic tests, the tests of noise and vibrations were conducted and the calculated electric power was recalculated for other air densities, i.e. ρ_o = 1.3 kg/m^3 or ρ_o= 1.4 kg/m^3 to determine the device ability to operate in tough (not typical) conditions.

2.3 Testing the vortex ventubes

Vortex ventube is another device subjected to testing in the KOMAG laboratories for analysis of effectiveness of air vortices generation.

Similarly as in the case of dust collectors, the testing methodology for the mentioned devices was not standardized at European and at global level, therefore in Poland the national standard PN-G 43042: 2011 [14] is the basis for the uniform testing methodology. This standard specifies the requirements, as well as the types and methods for testing the vortex ventubes intended for use in underground roadways drilled with roadheaders in hard coal and other minerals mines.

Testing the vortex ventubes covers the following procedures:

- determination of output of air flowing through the ventube,
- measurements of distribution of air outflow rates from the ventube gaps,
- adjustment of ventube gaps width,
- measurements of the driving motor power.

Test stand structure and characteristics

Structure of the test stand together with measured parameters is schematically presented in Figure 5. The KOMAG stand for testing the vortex ventubes consists of the following components:

1. an inflow cone,
2. a ventube fan,
3. a vortex ventube driving unit,
4. segments of tested vortex ventube, where total length of the ventube gap should be 10 m,
5. a flap.

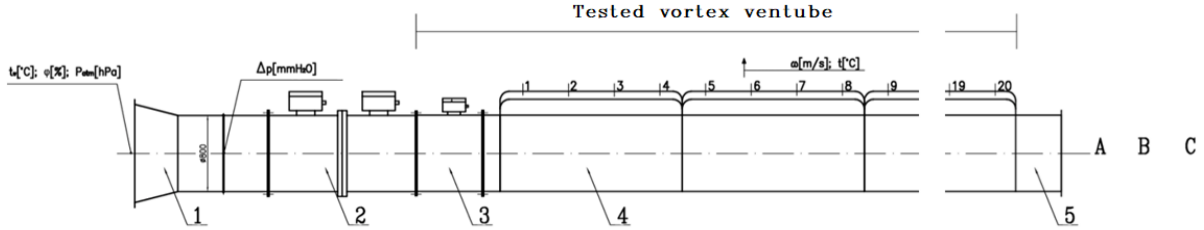

Fig. 5. Schematic diagram of the stand for testing the vortex ventubes together with the tested device

According to the testing procedure, 20 measuring points are evenly deployed on vortex ventube segments along the outlet gap. According to Figure 3, the following parameters are measured in points A, B, C:

- in point A – air flowrate in the ventube axis in a distance of 30 cm from the outlet,
- in point B – air flowrate in the ventube axis in a distance of 60 cm from the outlet,
- in point C – air flowrate in the ventube axis in a distance of 100 cm from the outlet.

The tested vortex ventube is connected from the inlet side to a measuring system constructed according to ISO 5221: 1984 [11], consisting of an ISO inflow cone (position 1) and to a ventube fan (position 2), whose task is to force gas flow through the test stand. In the inflow cone, the air flow rate through the entire vortex ventube (and the test stand) is determined on the basis of readout of the gas stream pressure drop (Δp). Then, in the case of non-flap vortex ventubes, the air flows through the vortex ventube driving unit (position 3), causing a gas outflow from the ventube segments gaps (position 4), where the gas outflow rate and temperature are measured at the specified points 1 - 20. In the case of a flap vortex ventubes, the flow through the vortex gaps is forced by completely closing the flap located at the outlet from the last ventube segment (position 5).

Testing procedure and test results

The vortex ventube air output is determined in the same way as in the case of the fan tests, while the outlet gap width is adjusted with screws for the maximum possible lifting up the control ribbons as in Fig. 6 and the smallest possible air outflow rate from the ventube's outlet.

Fig. 6. Correctly adjusted vortex ventube

Distribution of output air flow rate from a vortex ventube's gap

The air flow rate ω and temperature *t* should be tested with a thermo-hygrometer, whose measurement error does not exceed 5%, at a distance of not more than 5 cm from the edge of the outlet gap, at least at 20 points, deployed evenly along the length of the outlet gap.

The measurement results should be tabulated and interpreted graphically using a polynomial curve from 2 to 6 degrees selecting the curve for which the coefficient of concordance is closest to one. Examples are shown in Fig. 7.

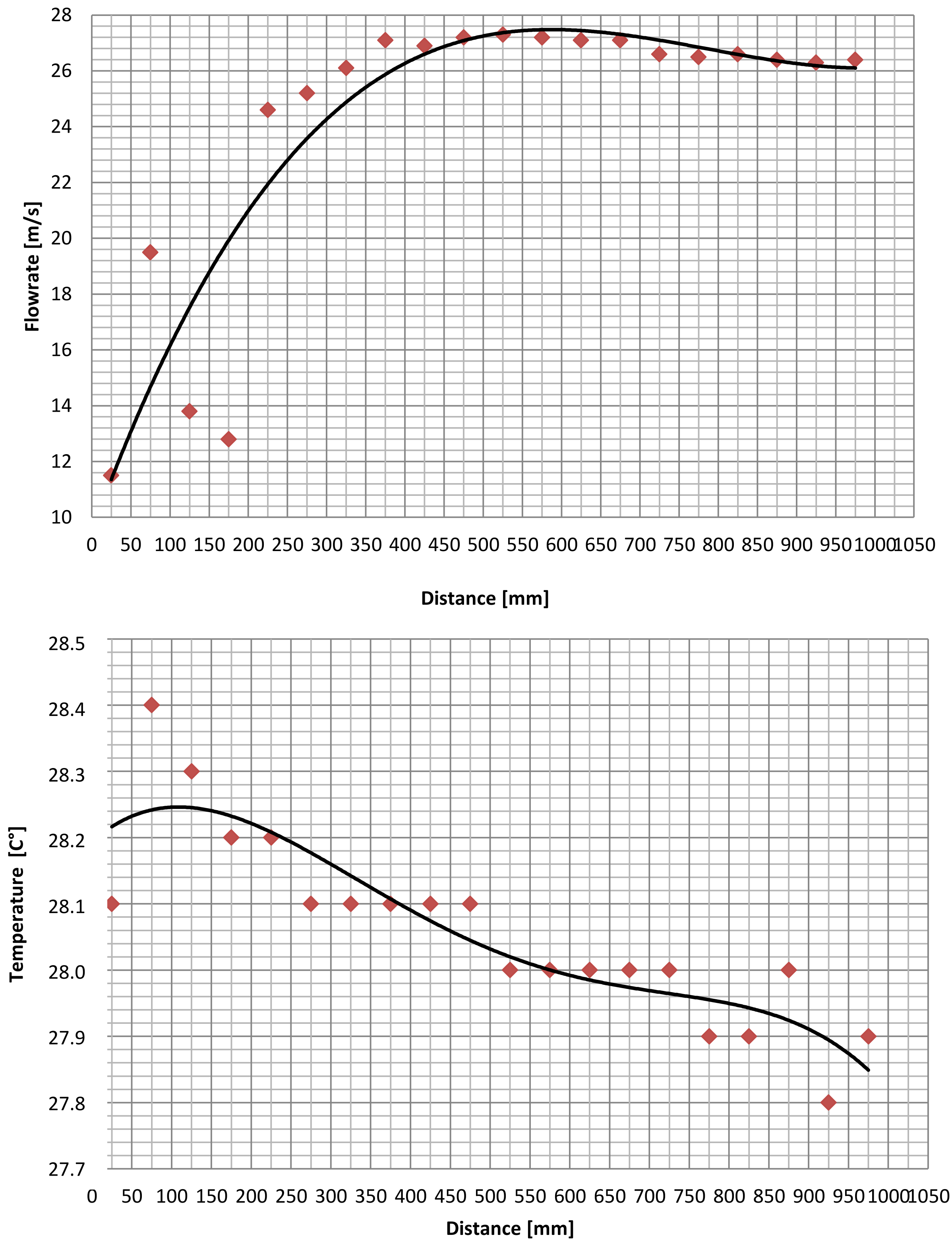

Fig 7. Graphical presentation of flowrate and temperature measurement results in a function of distance

Additional tests and measurements

In addition, compliance with the requirements for operation in potentially explosive atmospheres was tested on the basis of certificates and declarations of compliance for materials and devices, as well as the working media consumption (e.g. compressed air) was measured with instruments which measurement error does not exceed 5%.

Additionally, a continuous operation test can be conducted by turning on all ventube's sub-assemblies, in the gap air flow mode, for at least 20 min checking the correctness of the vortex ventube operation.

3. Summary

Dust control equipment and ventilation devices used in the mining industry enables eliminating the dust particles (coal dust, rock dust) significantly reducing dust hazard during solid coal mining. Due to the increasing expansion of mine networks there is a subsequent increase in ventilation network size and complexity, making fresh air distribution and management of the ventilation network challenging and energy intensive [15] Selection or designing the devices for dust control depends on many factors, first of all on local conditions and characteristics of dust source and dust itself [16]. Conducted tests enable gaining information on parameters, the scope of use and usability of the devices operating in mine ventilation and dust control systems. This knowledge is especially important for potential purchasers to decide about selecting the devices best suited for their needs.

Sample tests discussed in this article are based on guidelines given in the standards relevant to a given type of equipment. Knowledge about the most characteristic parameters and principles of the safe use of tested devices, is the tests result. In the case of dust collectors it is dust control efficiency, in the case of fans, it is very important to check if the power recalculated for air density of 1.2 kg/m^3 does not exceed the permissible power and to gain knowledge on their operational characteristics. Determination of effectiveness of the air vortex process in the vortex ventube was the objective of the vortex ventube tests.

It should also be noticed that for all tests the same principles of safe operation of the test stand apply, where special attention should be paid to the following:

- noise (exposure to mechanical vibrations of fan components and its motor as well as aerodynamic vibrations of the pumped gas),
- power supply (possibility of electric shock),
- air stream (possibility of entering the air stream of high flowrate),
- mechanical hazard (moving parts of the fan).

Information gained during the tests is very important not only as it concerns equipment used in hazardous conditions but also health and even life of people working in underground workings which depend on their reliable operation. In addition, expert opinions based on data collected during tests are the documents required for granting the certificate of compliance with the ATEX directive.

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Tests of neodymium content in selected materials

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Paweł Friebe

KOMAG Institute of Mining Technology, Pszczyńska 37, 44-101 Gliwice, Poland

e-mail: pfriebe@komag.eu

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Słowa kluczowe: pierwiastki ziem rzadkich, REE, przeróbka mechaniczna, separacja, nowe technologie

Abstract:

Rare earth elements are recognized as Critical Raw Materials (CRMs) due to their wide range of applications in the glass, steel, chemical and electronic industries. Often rare earth elements are referred to as a single group, but in practice each element has individual technical applications. Therefore, the demand varies for each element. Demand for rare earth elements is likely to increase in the future due to use of NdFeB magnets, especially in vehicles with electric motors and wind turbines. This publication presents research results aimed at finding raw material or waste that can be used to obtain neodymium at economical profit. This publication presents tests aimed at an identification of the raw material from which neodymium can be obtained. Research began with an identification of materials that could potentially become an economically viable source of neodymium extraction. The following materials were selected: natural aggregates, fine-grained raw materials of magma origin as well as coal sludge and fine-grained waste after hard coal enrichment. These raw materials were subject to content analysis by mass spectrometry, with ionization in inductively compressed plasma (ICP-MS).

Streszczenie:

Pierwiastki ziem rzadkich zostały uznane w ostatnich czasach jako surowce krytyczne ze względu na ich szeroki zakres zastosowań w przemysłach: szklarskim, stalowym, chemicznym i elektronice. Często pierwiastki ziem rzadkich łączone są w jedną grupę, jednakże w praktyce każdy pojedynczy pierwiastek posiada odrębne zastosowania, dlatego popyt na każdy pierwiastek jest inny. Prognozy wskazują na prawdopodobny wzrost zapotrzebowania na pierwiastki ziem rzadkich, co może być związane między innymi ze zwiększenia stosowania magnesów NdFeB, szczególnie w pojazdach hybrydowych i elektrycznych oraz turbinach wiatrowych. W niniejszej publikacji przedstawiono badania mające na celu zidentyfikowanie surowca, z którego będzie można pozyskać neodym. Badania rozpoczęto od wskazania materiałów, które potencjalnie mogą stać się ekonomicznie uzasadnionym źródłem pozyskiwania neodymu. Wytypowane zostały: kruszywa naturalne, drobnoziarniste surowce pochodzenia magmowego oraz muły węglowe i drobnoziarniste odpady po wzbogacaniu węgla kamiennego. Surowce te zostały poddane analizie zawartości neodymu metodą spektrometrii mas, z jonizacją w plazmie indukcyjnie sprężonej (ICP-MS).

1. Introduction

A big interest in rare earth elements (REE) results from their specific and required properties. They have a wide application in state-of-the-art technologies and industries: glass-making, steel, chemical and electronic. In recent years rare earth elements became an object of many research and development projects. A development of new technologies causes a systematic increase in the demand of these elements.

One of the key elements of rare earth, used in the industry, is neodymium. This element is used for a production of strongest permanent magnets, which are applied in electric motors of electric and hybrid cars, in some electric energy generators, hard disks and professional playing equipment.

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Materials with a small neodymium content are used in lasers for generating laser beams of big power and in infrared spectrum. Besides, neodymium is used in the glass making industry, also for a production of hard disks, audio equipment as well as for conducting magnetic resonance. Due to a development of the latest technologies forecasts indicate a probable increase in demand of neodymium and of its price.

The biggest difficulty in obtaining rare earth elements is their small concentration in mineral resources. Present projects of the KOMAG Preparation systems Division, connected with the subject-matter of separating rare earth elements, are in the stage of searching appropriate materials. REE do not occur in the nature as pure elements. Most often they occur in a form of chemical compounds such as oxides, phosphates, silicates, carbonates and halides [1]. More than 250 minerals, among others such as e. g. allannite, apatite, bastnasite, xenotime or monazite, are known.

The content of rare earth elements in them, expressed as oxides, can reach even up to 70-74 %[2]. The chemical compounds and minerals, mentioned before, occur as mixes in many rocks such as: basalt, granite, gneiss, shale and silicate rocks.

At present Poland does not possess its own recognized raw materials resources which could constitute an economical source of obtaining REE. Their occurrence, in a form of poor deposits, is reduced to the region of Szklarska Poręba, the Sudeten Mountains, somewhere Białystok way and sand on the Baltic Sea beaches. The waste heaps from the phosphogypsum industry and ashes from the power plants burning and co-burning coal are rare earth elements. These wastes can be an essential source of regaining rare earth elements.

The objective of research work, undertaken by KOMAG, consisted in testing of selected groups of materials which, subject to proper separation process, will be a source of obtaining neodymium. The work in this scope included: obtaining of materials and their preparation for tests, tests of REE content using mass spectrometry which ionization in inductively compressed plasma (ICP-MS) and an analysis of obtained results.

Different materials were used for tests. The resources from sedimentary deposits were used: raw material from sand deposit, and fine-grained fall through the classifier sieves for washing aggregates. Besides, the test incorporated coal sludge and fine-grained waste after the coal enrichment. The resources from magma deposits: fine-grained granite aggregate and fine-grained basalt aggregate were used as well. In the further part of this article the most important sources of getting minerals, containing REE, are presented.

2. Sources of gaining rare earth elements

Neodymium, as well as other REE, do not occur in a pure form in the nature. It can only be found as a component of minerals, presented below. So far more than 250 minerals, containing REE, have been recognized, however at present an exploitation of deposits containing only some minerals, among others such as: bastnasite, monazite, xenotime and laterite clay (China) [1, 2] is economic in a commercial scale. Neodymium occurs in the earth's crust in the amount of 38 ppm [3].

The biggest producers of REE raw materials mainly exploit seams of three types of original ores: bastnasite (USA, China), monazite (Brazil, India, Malaysia, Sri Lanka, Thailand) and laterite clay (China). Besides, the REE are obtained as co-products during an exploitation of seams of xenotime or loparite ores as well as apatite and phosphorite ores (Russia), uranium ores (USA), iron ores (Bayan Obo, China) and ilmenite with monazite ores (Australia) [2].

Bastnasite is a fluorocarbonate of the chemical formula (Ce, La, Y)CO_3F. It occurs in pegmatites, granites and metamorphic rocks in the zones, where a contact metamorphism plays a dominating role [4]. The cerium element is replaced by lanthanum, yttrium or other light rare earth elements. Bastnasite usually co-occurs with other minerals such as allannite, fluocerite and others containing REE [5].

Monazite is a phosphate mineral of the chemical formula (Ce, La, Nd, Th)(PO_4). It usually occurs in a form of grains of small sizes as an accessory mineral in magnetic rocks or metamorphic ores such as granite, pegmatite, basalt, shale and gneiss [6, 7, 8, 9]. Monazite grains are resistant to an impact of the atmosphere. Bed-rocks are subject to weathering and to erosion which cause a transport of monazite grains and their accumulation in valleys of rivers and streams. Accumulations of grains of a certain size form a chipping seam which can be exploited for obtaining heavy elements, including rare earth elements and thorium [10]. A general chemical formula of monazite shows an exchangeability of cerium, lanthanum, neodymium and thorium in the mineral structure.

Deposits of laterite clay, containing rare earth elements, are generated in the result of weathering of magmatic rocks (usually granite), which contain compounds of rare earth elements. Due to weathering rocks are subject to a decomposition – among others a ionization of the compounds of rare earth elements occurs. Then the rare earth elements are adsorbed by clay minerals [11]. Laterite clays are a very important source of heavy rare earth elements (HREE). Due to their nature clays require a physical beneficiation only to a small extent or to no extent at all. They are directly processed with use of hydrometallurgical methods due to a big content of rare earth elements [12].

Xenotime is a phosphate mineral of a chemical formula YPO_4 and of properties similar to monazite. The main features of xenotime are: high yttrium content (above 50%), low content of light rare earth elements (LREE), significantly lower content of thorium than monazite [13]. Xenotime is a rare mineral which similarly to monazite occurs as accessory mineral in veins of magmatic rocks. A process of creating chipping deposits of xenotime develops in convergence with monazite [14]. This mineral can contain radioactive elements such as uranium or thorium and the element such as tungsten. In some deposits the content of tungsten was detected [15].

Xenotime, monazite and bastnasite are minerals which can occur in the rocks such as granite, basalt, pegmatite and others mentioned above. The materials, used for tests, are characterized below.

Granite is an abyssal magmatic rock of evidently crystalline structure. The rock is generated due to a slow crystallization of magma under the Earth surface. The main minerals of granite are: orthoclase, plagioclase, quartz and biotite. The content of rare earth elements in this rock depends on the content of accessory minerals. A part of granite accessory minerals contains REE. They include among others: monazite, xenotime, allannite, titanite and anatase [16, 17].

Basalt is a basic, soiled outflow (volcanic) rock of very fine-grain structure (cryptocrystalline) or afanite, sometimes porphyry. The main minerals of this rock are: pyroxenes, plagioclase, mica, amphibole. A presence of rare earth elements in basalt rocks is shown in many research projects [18, 19, 20]. The presence of rare earth elements also in these rocks is connected with the content of accessory minerals [21].

The presence of rare earth elements was detected not only in the rocks and minerals of magmatic origin, but also in coal and in the rocks accompanying coal. The Polish coal mining industry produces significant amounts of wastes, which are generated in the result of hard coal exploitation and preparation. Clay minerals are an original carrier of rare earth elements in coal and coal wastes [22, 23]. They are mainly sedimentary rocks occurring in roofs and floors as well as in interlayers of coal seams. The rocks, accompanying coal, are treated as waste in the hard coal beneficiation process. The following wastes can be distinguished:

- coarse-grained wastes e. g. from heavy-medium separators of grain sizes 200-20 mm,
- fine-grained wastes e. g. from jigs of grain sizes 20-0,5 mm,
- very-fine grained wastes e. g. from flotation beneficiation <1 mm.

Generated wastes contain vestigial elements including rare earth elements. A concentration of rare earth elements in the rocks, accompanying hard coal seams, depends on a number and kind of clay minerals due to their higher ability of ion exchange and sorptive properties [23]. The best sorptive properties have the minerals such as montmorillonite and illite [24] due to their structure and this is the reason why coal wastes, containing these minerals, will be a potentially better carrier of rare earth elements (REE).

A process of separating rare earth minerals embraces preparation processes with use of the devices characterized in the publication [25].

3. Rare earth elements on the market, demand and price of neodymium

Rare earth elements are more and more commonly used, in particular in high-tech industries, what has a significant impact on their price. Each branch of industry has different requirements as regards the purity, so they occur in different forms on the market. These elements are in a form of concentrates:

- bastnasite concentrate (60-85% REO – Rare Earth Ore, rare earth oxides),

- monazite concentrate (55-60% REO),
- xenotime concentrate (>25% REO),
- bastnasite-and-monazite concentrate (30%, 60% or 71% REO).

Apart from that these elements also occur on the market as processed raw materials, having a form of:

- mixed metal (98-99% of rare earth elements),
- ferrocerium (74% of mixed metal),
- individual elements of 96-99.9999% purity,
- compounds such as carbonates, chlorides, fluorides, nitrates and others [26].

Changes in demand and price of the most desirable rare earth elements on the market, together with a forecast for the years 2022 and 2025, are presented in Tables 1. and 2. Starting from the year 2015, a demand for presented elements increases continuously till the year 2025, but the biggest increase occurs in the case of neodymium and the lowest one – in the case of lanthanum and yttrium. As regards the price a continuous increase is achieved only by neodymium and the other elements experience increases and decreases of prices.

Table 1. Tabulation of demand of five most desirable rare earth elements on the market over the years 2015–2025 [27]

	Neodymium	**Lanthanum**	**Cerium**	**Praseodymium**	**Yttrium**
Years	**[Mg]**				
2015	11 647	11 578	8 114	4 342	2 810
2019	18 452 ↑ 58%	12 627 ↑ 9%	9 067 ↑ 12%	5 999 ↑ 38%	3 065 ↑ 9%
2022	21 620 ↑ 17%	13 476 ↑ 7%	9 677 ↑ 7%	6 716 ↑ 12%	3 271 ↑ 7%
2025	23 073 ↑ 7%	14 382 ↑ 7%	10 327 ↑ 7%	7 168 ↑ 7%	3 491 ↑ 7%

Table 2. Tabulation of five most desirable elements of purity min. 99% (yttrium min. 99.9999%) on the market over the years 2015–2025 [27]

	Neodymium	**Lanthanum**	**Cerium**	**Praseodymium**	**Yttrium**
Years	**[USD/Mg]**				**[USD/kg]**
2015	68 543	6 955	6 411	119 963	21
2019	108 786 ↑ 58%	7 033 ↑ 1%	4 197 ↓ 34%	119 103 ↓ 1%	41 ↑ 95%
2022	123 355 ↑ 13%	6 558 ↓ 7%	3 248 ↓ 22%	113 105 ↓ 5%	35 ↓ 14%
2025	148 444 ↑ 20%	6 932 ↑ 6%	3 308 ↑ 2%	119 093 ↑ 5%	38 ↑ 9%

A significant demand increase for neodymium as well as its price increase in comparison with previous years can be caused by a use increase of magnets made of neodymium, iron and boron alloy in the industry. Due to using these magnets in hybrid and electric cars their drives enable to achieve the highest possible efficiency and profitability. These magnets are also used in generators of very big off-shore wind turbines, reaching an increased efficiency in comparison with a conventional generator with a mechanical gear. Motors, using the above mentioned magnets which enable to achieve smaller dimensions and a smaller weight in comparison to the motors using ferrite magnets, are used in the aviation industry as well. Advantages, resulting from using rare earth elements in technology, contribute to their more and more frequent use in the industry, replacing other solutions.

4. Tests of neodymium content in selected materials

Research work, undertaken at the KOMAG Institute, started from choosing materials which potentially can contain rare earth elements. The following materials were selected: material aggregates – sands, fine-grained raw materials of magmatic origin, coal silts and fine-grained wastes after hard coal beneficiation. The selected raw materials were subject to an analysis of the content using the mass spectrometry method with ionization in inductively compressed plasma (ICP-MS). The tests were directed towards a determination of neodymium element content.

4.1. Testing material

The following materials were used for tests:

- Sand – Sand Mine 1

The Sand Mine 1 exploits a deposit, whose main mineral is back-filling sand and the accompanying mineral is a sand-and-gravel mix. The deposit is mined with use of a dredger excavator. Then the material is transported to the Preparation Plant, where it is subject to rinsing, classification and drying processes. Commercial products are: construction sands, rinsed and dried sands as well as gravels. The deposit is divided into two exploitational slopes having the material of different characteristics. One sample of raw material from each slope was taken. The sample material was taken by KOMAG employees.

- Sand – Mine 2

The Sand Mine 2 exploits a Quaternary deposit of a river origin. This mine conducts a deposit exploitation from under the water surface using a sucking dredger. Then the material is transported to the Preparation Plant using among others a wheel dewaterer, screens and a classifier. This Plant produces aggregate of the following sizing: 16-8 mm and 8-2 mm. The material, used for tests, is the material which passed through the bottom sieves (slot 2 mm) of the pulsatory classifier. A pulsatory classifier is a device, in which a separation of the material, according to density, takes place. The material is positioned in layers – at the top there are layers of the smallest density, and at the bottom-layers of biggest density. Therefore, if the feed to the device contains grains of minerals of big density (including minerals containing REE), these grains will leave the device through the bottom sieves. The material samples were taken by the Mine staff.

- Coal sludge – Hard Coal Mine 1

96% of commercial reserves of the Hard Coal Mine 1 contain coal of types: 34 and 35. The Preparation Plant beneficiates hard coal in grain classes 200-20 mm and 20-0 mm. The Plant technology includes a system of crushing and preclassification of raw coal to obtain the grain class 200-0 mm, which is then separated into grain classes 200-20 mm and 20-0 mm. In the successive step the class 200-20 mm is beneficiated in heavy medium separators and the class 20-0 mm is beneficiated gravitationally. Dewatering screens (class 200-20 mm) and dewatering centrifugal screens as well as dewatering screens (class 20-0 mm) are used for dewatering beneficiation products. Desludging of technological water is conducted with use of a radial concentrator. Coal sludge, used for tests, came from the radial concentrator. The material samples were taken by the Mine staff.

- Coal sludge – Hard Coal Mine 2

The Mine produces coal of type 31.2. The Preparation Plant beneficiates hard coal in grain classes 200-80 mm and 80-16 mm. The Plant technology includes a system of crushing and preclassification to obtain the grain class 200-0 mm. The obtained material, in the following step, is separated into grain classes 200-80 mm, 80-16 mm and 20-0 mm. Classes 200-80 mm and 80-16 mm are beneficiated in heavy medium separators, and class 20-0 mm is directed to mixes after screening class 6-0 mm. Technological water is clarified in a radial concentrator. Desludging of technological water takes place in radial concentrators. Dewatering of beneficiation and desludging products takes place in vibratory screens, dewatering centrifugal sieves, sedimentation centrifuges and filtration presses. Coal sludge, used for tests, comes from the radial concentrator. The material sample was taken by the Mine staff.

- Floatation waste – Hard Coal Mine 3

This Mine produces coal type 34.2 and steam coal. The Preparation Plant beneficiates hard coal in grain classes: 65-10 mm, 10-0 mm and 1-0 mm. The Plant technology includes crushing and preclassification system to obtain the grain class 65-0 mm. Then the material is subject to a classification for grain classes: 65-10 mm and class 10-0 mm. The grain class 65-10 mm is directed to a three-product gravitational beneficiation process and class 10-0 mm is a commercial product - steam coal. Middlings from the gravitational beneficiation process are subject to the crushing stage and to classification to the grain size 10-0 mm, and then secondarily it is gravitationally beneficiated. Desludging of technological water takes place in radial concentrators. Coal sludge, obtained from the radial concentrator, is directed to flotation machines where they are beneficiated. Dewatering of beneficiation products takes place on dewatering screens, in radial concentrators, centrifuges, centrifugal sieves and chamber presses. The flotation waste, used for tests, comes from the chamber press. The material sample was taken by the Mine staff.

- Flotation waste – Hard Coal Mine 4

This Mine produces hard coal of type 35.1. The Preparation Plant beneficiates hard coal in grain classes: 150-20 mm, 20-0 mm and 0.315-0 mm. The Plant technology includes the preclassification system to the grain sizes 150-0 mm. Then the material is subjected to the classification for grain classes: 150-20 mm and 20-0 mm. The grain class 150-20 mm is directed to a beneficiation in heavy medium, and class 20-0 mm is beneficiated gravitationally. Desludging of technological water takes place in radial concentrators. In the next step flotation beneficiation of coal sludge in the scope of grain size 0.315-0 mm is conducted. Dewatering of beneficiation products takes place on vibratory screens, in bucket conveyors, radial concentrators and filtrating presses. The flotation waste, used for tests, comes from the filtrating press. The material sample was collected by the Mine staff.

- Fine-grained basalt aggregate 2-0 mm – Basalt Mine 1

This Mine produces basalt aggregates of many graining sizes. The Mine deposit is exploited with use of drilling-and-blasting technology. The technology includes multi-stage crushing and classification. Fine-grained basalt aggregate 2-0 mm, used for tests, was taken by the Mine staff.

- Fine-grained basalt aggregate – Basalt Mine 2

This Mine produces basalt aggregates of many types of graining. The technology includes multi-stage crushing and classification. Fine-grained basalt aggregate 2-0 mm, used for tests, was taken by the Mine staff.

- Fine-grained granite aggregate 2-0 mm – Granite Mine 1

This Mine produces granite aggregates of many types of graining. The technology includes multi-stage crushing and classification. Fine-grained granite aggregate 2-0 mm, used for tests, was taken by the Mine staff.

4.2. Preparation of materials

This stage was oriented onto obtaining representative samples of sands, coal sludges, flotation wastes, fine-grained granite and basalt aggregates of 1 kg weight. The weight of samples was determined by the KOMAG Laboratory of Material Engineering and Environment. Standard tools of the Minerals Processing Laboratory were used for a preparation of samples.

The samples of sand, granite and basalt were separated with use of the Jones's splitter. Each material sample weighed 1 kg. The samples were put into a string bag and then they were delivered to the laboratory.

Flotation wastes as well as coal sludges are materials of big humidity. They were placed in plastic cuvettes; samples, which were used for a determination of the REE content in raw material, were separated from each sludge and flotation waste. The materials were dried in the laboratory drier, which caused a strong conglomeration of fine grains of flotation wastes and sludges into thick agglomerates, which afterwards were comminuted in disk mill adjusted for the smallest distance between the mill disks.

In the following step the second part of samples of flotation wastes and coal sludges was separated. It served for testing the REE content in the ash which was left after burning these materials. Similarly to the previous case, the materials were placed in cuvettes, from which the samples were separated and then they were dried in the laboratory drier and ground in the disk mill. The Standard PN-ISO 1171:2002 – Solid fuels – Determination of ash was used in the process of obtaining ash. The laboratory muffle furnace was used for burning materials. According to the Standard mentioned above 1-2 g of material were prepared for a crucible, in total:

- Hard Coal Mine 1 – about 20 g of coal sludge,
- Hard Coal Mine 2 – about 24 g of coal sludge,
- Hard Coal Mine 3 – about 23 g of flotation wastes,
- Hard Coal Mine 4 – about 22 g of flotation wastes.

The furnace was heated to the temperature of 500ºC within 60 minutes and this temperature was kept for 30 minutes. After that time period, within the following 50 minutes the temperature inside the furnace was increased to 815ºC. In this temperature the samples were heated for 60 minutes. Then they cooled down for a few hours. Cool samples were placed in the exsiccator. After weighing the samples on the analytical scales the following results were obtained:

- Hard Coal Mine 1 – about 6 g of ash,
- Hard Coal Mine 2 – about 11 g of ash,
- Hard Coal Mine 3 – about 15 g of ash,
- Hard Coal Mine 4 – about 18 g of ash.

The testing material, prepared in such a way, was conveyed to the KOMAG Laboratory of Material Engineering and Environment.

4.3. Tests of rare earth elements' contents

Tests of REE contents were conducted in the way presented below. Laboratory samples of sand, coal sludges, flotation wastes and ashes were tested from the point of view of dry mass. Their mineralization was also conducted. The samples were mineralized in the closed-loop dry system, using the microwave mineralizer. The quality of pulping the samples under testing was subject to a visual assessment. In the result of such an approach a colourless and clean solution was obtained for the majority of the samples. Tests of neodymium content were conducted with use of mass spectrometry, with ionization inductively coupled plasma (ICP-MS). The results of tests are presented in Tables 3, 4 and 5.

Table 3. Tabulation of neodymium content in aggregates

Identification of samples		Nd content [ppm]
Sand Mine 1, top slope of deposit	Sand	<5
Sand Mine 1, bottom slope of deposit	Sand	<5
Sand Mine 2	Sand	<5
Basalt Mine 1	Fine-granulated basalt aggregate	38.2
Basalt Mine 2	Fine-granulated basalt aggregate	21.7
Granite Mine 3	Fine-granulated granite aggregate	13.5

Table 4. Tabulation of neodymium content in coal sludge and ashes after burning the sludge

Identification of samples		Nd content [ppm]
Hard Coal Mine 1	Coal sludge	6.5
	Ash after burning sludge	33.5
Hard Coal Mine 1	Coal sludge	11.3
	Ash after burning sludge	13.8

Table 5. Tabulation of neodymium content in coal wastes and ashes after burning the waste

Identification of samples		Nd content [ppm]
Hard Coal Mine 1	Wastes from flotation beneficiation of coal	<5
	Ash after burning flotation wastes	15.2
Hard Coal Mine 1	Wastes from flotation beneficiation of coal	7.0
	Ash after burning flotation wastes	24.0

5. Summary and direction of further research work

Tests of the material taken from the top slope and from the bottom slope of the deposit in the Sand Mine 1 showed the contents of neodymium < 5 ppm. Similarly, the mineral taken from the bottom sieves of the classifier (fallen through) in the Sand Mine 2 contained <5 ppm of neodymium. The highest amount of the neodymium element, among fine-granulated basalt aggregates contained <5 ppm of neodymium.

The highest amount of the neodymium element, among fine-granulated basalt aggregates contained the aggregate from Basalt Mine 1 – 38.3 ppm. This content is comparable with the average content of this element in the earth's crust. The material from the Basalt Mine 2 contained 21.7 ppm.
Coal sludge from the Hard Coal Mine 1 contained 6.5 ppm of neodymium. The burning process of the material led to a multiple increase of the element content, to the amount of 33.5 ppm. The content of neodymium in the coal sludge from the Hard Coal Mine 2 before its burning was 11.3 ppm and after burning – 13.8 ppm. Before burning the sludge from the Hard Coal Mine 1 was characterized by a higher neodymium content, among coal sludges, and after burning the bigger content was reached by the Hard Coal Mine 2. Therefore it can be stated that a searched element content increased by 415% in the case of the material from the Hard Coal Mine 1 and by 22% – in the case of the material from the Hard Coal Mine 2.

An analysis of the neodymium content in the waste from the flotation process, before burning, from the Hard Coal Mine 3 gave the result <5 ppm. Burning of this material caused an increase in the neodymium content in the flotation waste from the Hard Coal Mine 4, before burning, it was 7.0 ppm and after burning – 24.0 ppm. The material from the Hard Coal Mine 4 is characterized by a bigger neodymium content both before burning as well as after burning. An increase by 242% of the searched element content in the wastes of the Hard Coal Mine 4 was observed.

The conducted tests enabled to draw a series of conclusions concerning a usability of the tested materials for gaining one of the rare earth elements- neodymium. The obtained results, concerning the neodymium content in sand deposits can indicate lack of the searched element in the material. Therefore, these materials are not useful for gaining neodymium. The determined neodymium contents in granite and basalt aggregates enabled to conclude that these materials contain neodymium compounds in small quantities, up to 38.2 ppm. A separation method, chosen correctly, will enable to increase the neodymium content in the obtained product. Basing on the obtained results of the tested element content in coal sludges and flotation wastes, it can be stated that the neodymium compounds occur in them in very small quantities, up to 11.3 ppm. An incineration of coal sludges and flotation wastes led to a concentration increase (e. g. from 6.5 ppm to 33.5 ppm). At present it cannot be excluded that a part of the particles, containing neodymium, is lost irretrievably. A loss of a part of these particles can happen during their burning, during their transport together with escaping gases. These gases are collected through the exhaust hole in the muffle furnace. In the future a method, enabling to exclude or confirm such a phenomenon, will be elaborated.

Future research work will include further analyses of the materials used in this work as well. It is planned to conduct analyses of granulometric contents of granite and basalt aggregates. An application of the sieves, having the following mesh sizes: 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm and 0.063 mm, will enable to gain narrow grain classes. As it can be concluded from the information presented in the literature, it is expected to obtain a higher REE concentration in the finest-grained classes. Then tests of rare earth elements contents in the obtained grain classes will be conducted. These tests are indispensable for a rejection of these grain classes which have a small REE content at the very beginning, before this material is directed to the separation process.

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Innovative solutions need an innovative approach – 3D printing technology, example of use and conclusion from implementation in an organization

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Dariusz Michalak [1a], **Juan Alfonso Gómez Herrero** [2b]

[1] KOMAG Institute of Mining Technology, Pszczyńska 37, 44-101 Gliwice, Poland,

[2] Instituto de Biomecánica de Valencia, Universitat Politècnica de Valencia, Camino de Vera s/n, Edificio 9C, 46022 Valencia, Spain

[a] e-mail: dmichalak@komag.eu

[b] e-mail: juan.gomez@ibv.org

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Słowa kluczowe: druk 3D, FDM, szybkie prototypowanie, inżynieria mechaniczna, innowacje, projektowanie

Abstract:

3D printing is a very popular technology for rapid production and prototyping. The rapid development of various 3D printing techniques began at the beginning of the 21st century. The concepts of rapid manufacturing and prototyping have gained new meaning due to unlimited shaping possibilities and the wide range of printing materials available. The possibility of obtaining a material object in accordance with the documentation relatively quickly, redefined the production process, especially in the case of a unit or small-lot production. One of the variants of 3D printing - FDM (Fused Deposition Modelling) technology has become the most popular, thanks to the wide possibilities of hardware modification and the low price of printing devices. 3D printing is used in almost all industries. The article presents examples of 3D printing applications in various areas of engineering activities, including medical applications. An example of an approach to implementing 3D printing technology in an organization was also presented. A description of the developed training resources is provided to quickly train all process participants - the people responsible for the 3D printing process itself and potential recipients. The implementation of 3D printing technology in an organization is not only associated with the purchase of appropriate equipment, but it is also necessary to ensure an appropriate level of knowledge, which avoids confusion and makes the expectations of potential technology recipients real.

Streszczenie:

Druk 3D to bardzo popularna technologia szybkiego wytwarzania i prototypowania. Szybki rozwój różnych technik druku 3D rozpoczął się z początkiem XXI wieku. Dzięki praktycznie nieograniczonym możliwościom kształtowania i dostępnej szerokiej gamie materiałów do druku, pojęcia szybkiego wytwarzania i prototypowania nabrały nowego znaczenia. Możliwość stosunkowo szybkiego uzyskania obiektu materialnego zgodnego z projektem, przedefiniowała proces produkcyjny zwłaszcza w przypadku produkcji jednostkowej czy małoseryjnej. Dzięki szerokim możliwościom modyfikacji oraz niskiej cenie urządzeń drukujących jedna z odmian druku 3D - technologia FDM (Fused Deposition Modelling) stała się najbardziej rozpowszechniona. Druk 3D znajduje zastosowanie praktycznie w każdej gałęzi przemysłu. W artykule przestawiono przykłady zastosowań druku 3D w różnych obszarach działalności inżynierskiej, w tym w zastosowaniach medycznych. Przedstawiono także przykład podejścia powalającego na wdrożenie technologii druku 3D w organizacji. Przedstawiono opis opracowanych zasobów szkoleniowych pozwalających w szybki sposób przeszkolić wszystkich uczestników procesu - osoby odpowiedzialne za realizację samego procesu wydruku 3D jak i potencjalnych odbiorców. Wdrożenie technologii druku 3D w organizacji, nie wiąże się jedynie z zakupem odpowiedniego sprzętu, konieczne jest zapewnienie odpowiedniego poziomu wiedzy, co pozwala uniknąć nieporozumień i urealnia oczekiwania potencjalnych odbiorców w zakresie rzeczywistych parametrów wydruków 3D.

1. Introduction

Computer-aided design is currently a standard. In certain cases, projects of new solutions of technical means, technologies, or complex mechanization systems can be created without the need for experimental tests or constructing the physical prototypes. Computer support can begin at the stage of concept creation and ends at the stage of creating technical documentation - necessary to produce the first unit of the machine. But in fact, such an approach is possible to implement only in certain situations, mostly in the case when data from real tests carried out earlier, are available. Experiences from testing similar design solutions that have been developed using a standard approach, based on bench tests and physical prototype tests, are still important aspects of the development of the new solutions. Another important aspect is access to experience from exploitation in real conditions, that allow the identification of criterion states [1], which cannot be predicted in a virtual environment. Additionally, in systems operated by humans, several additional factors should be taken into account to prove the safety [2], usability of designed structures [3] and properly shaping the user training process [4]. Typical engineering activities like the assessment of structural strength – is simulated by FEM (Finite Element Method), analysis of the interaction of system components – may be assessed by MBS (Multi-Body Simulation), ergonomics aspects may be tested using the parametric 3D model of the human body (for testing the field of view, reachability, and comfort of use of the analysed object) are possible to simulate in a fully virtual environment. In case of new product testing engaging end-user, or testing the new idea concepts, the real prototype is more usable than even the most advanced simulation. It shows, that physical prototyping is still an important aspect of design activities. We can say that nowadays the physical prototypes are built only to test the precisely selected group of features or functionalities, see Fig.1.

Fig. 1. Remote controller prototype – prototype including only external features of the device, with buttons mock-up - for testing the product comfort of use [5]

Delivering innovative products and technologies is the biggest challenge for designers [6]. Innovativeness is defined as a process that delivering the new method, technology, or product (depending on the area of implementation) which is better than already used for the same purpose. The development of innovative solutions is not only associated with the need to solve new problems but also with finding new (cheaper, faster, easier to apply) solutions to known problems. This approach requires using the techniques that will allow testing selected featured of newly developed products in a short time with minimum investment (without incurring the costs of having to build full-size prototypes with the parameters of the final product). Utilizing 3D printing technology [7], as an element of rapid prototyping workflow may shortening the whole product development process giving possibilities to test various design variants proposed by the team of designers. Currently, practical implementation of prototyping is a fusion of virtual and real testing methods incorporating advanced simulation methods and rapid prototyping technologies in a proportion defined by the possibilities and needs of an organization [8]. In the article, the KOMAG's and the 3DSPEC project partner experiences of implementation of the 3D printing technology will be presented.

2. Own 3D printing facility as the basis for rapid prototyping of new design solutions

The high costs of producing the fully functional machine prototypes, which are particularly evident in the case of large-size machines designed to work in special conditions, have forced a change in the approach to prototyping. Currently, the physical prototyping is limited, mostly to completely new construction nodes or technologies, and is used to confirm theses whose verification is impossible or difficult employing computer simulation. Most often the first copy of the machine (prototype), after passing the test procedure, becomes a fully functional product.

With the popularization of 3D printing technology, the possibilities for rapid prototyping have significantly expanded, and the prototyping process itself has changed dramatically. The price reduction of 3D printers and the constantly growing range of available materials for printing make this technology affordable not only for producing elements for testing but also as a technology to produce the final product. In some cases, 3D printing technology is the only way to produce e.g. complicated patterns of the internal cooling system, or impossible to produce by CNC technology object internals shapes. In 2015, the KOMAG Institute of Mining Technology began work on including additive technology into the design process. The FDM (Fused Deposition Modelling) additive technology was selected as the most affordable and cost-effective one. A relatively low level of investment to start the process and the construction simplicity of 3D printers used in the FDM method was the key benefit. The 3D printing facility built-in 2017 covers the internal demand, and provide services to external clients, Fig. 2. shows the equipment included in the 3D printing facility.

Fig. 2. 3D printing facility equipment

The equipment was selected to cover as wide as possible range of 3D printouts size, and a possibility to use all available on the market materials. Currently, available devices allow printing elements up to 500mmx500mmx500mm size, from materials such as ABS, PLA, Nylon, as well as water dissolve support material and two-colour printouts. Each of six, 3D printers have different features and ensures optimal printing quality in a different range of dimensions and accuracy. This allows for optimal adjustment of the printing process to the expected results. After testing the mechanical properties of 3D printouts made in FDM technology, this workflow is also used to produce prototypes that are subjected to perform the functional tests similar to real conditions. Supplementing the KOMAG's research facilities with new manufacturing capabilities, significantly reduced the duration from concept to prototype (in a situation where a material prototype and tests are required and limitations of the FDM technology are acceptable).

3. A different scenario of using 3D printing technology in own 3D printing facility

3D printing is used at every design stage - from concept to marketing activities related to the presentation of the new product. It allows presenting initial concepts in the form of the easy-to-understand form (this is especially important for people who cannot read standard technical drawings, and thanks to 3D prints the concept becomes clear to everyone). Using hi durability filaments gives a possibility to produce prototypes of system components, and machine parts which may be as real parts (typically made from steel). In a typical way, the process of productions the metal parts engaged the external manufacturer, by using own 3D printing facility the whole process may be realized internally by an organization's workforces. Even in the mining machinery industry is possible to use simple FDM technology to prototype system elements, to test in environments similar to real conditions.

3.1. The use of 3D printing to test new construction concepts

3D printing technology is characterized by potentially unlimited possibilities in the field of shaping, there is no need to take into account the specific conditions associated with the production technology, e.g. CNC. At the conceptual stage, a designer can focus only on solving a specific problem. A good example of using 3D prints is quick testing of new design concepts for spraying nozzles, see Fig. 3.

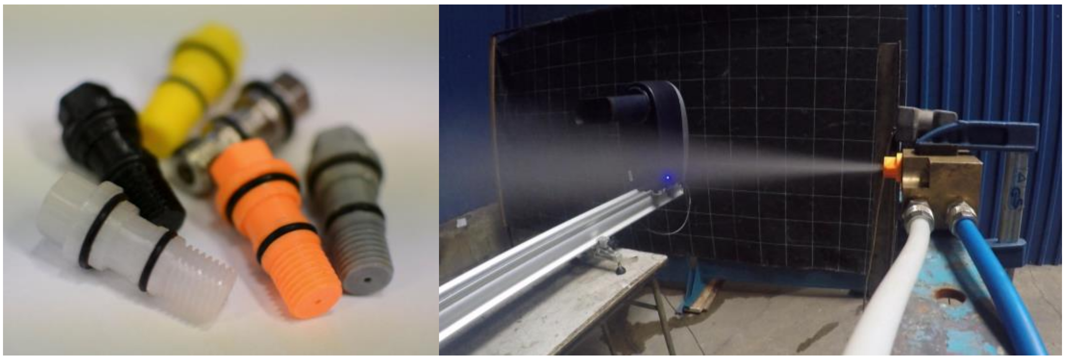

Fig. 3. Material prototypes of spraying nozzles made in FDM technology, view of the test stand [9]

With the appropriate testing facilities, it is possible to conduct a full test cycle - using the test bench - in one day. The model printed in FDM technology has lower material properties than that produced from the target material, however, its strength allows conducting preliminary tests to determine further directions of action. The development of innovative construction solutions may require verification not only of the construction form but also verification of physical phenomena that cannot be simulated without specialized knowledge and computer software. An example of such an application is the verification of the magnetic coupling. the operation being developed at the KOMAG Institute, where the test system was designed and 3D printed for the verification of theoretical assumptions, Fig. 4.

Fig. 4. 3D printout of the magnetic coupling, view of the test stand [10]

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The mechanical properties of the 3D printed prototype allowed for positive verification of theoretical construction assumptions and determine the directions for further research in this area. If the material properties of 3D printed implemented in FDM technology are not sufficient to carry out the full test procedure, it is possible to use additional supporting elements (e.g. reinforcing bars) to increase strength, without affecting the external geometric features of the printout. The prototype can also be made as a modification of an existing solution, by adding 3D printed elements to change the shapes/profiles of the examined objects. An example of such an application can be printouts for the purposes of carrying out research procedures of the new design of high-performance fans, Fig. 5.

Fig. 5. 3D printouts of fan blades with space for reinforcing bars, the fan modified by adding prints changing the shape of the blades [11]

The construction of custom design solutions and the implementation of complex test procedures requires the use of specially designed auxiliary elements, in this area 3D printing technology works perfectly well and allows the rapid production of support elements, holders, housings, for the purposes of carrying out research procedures, Fig. 6.

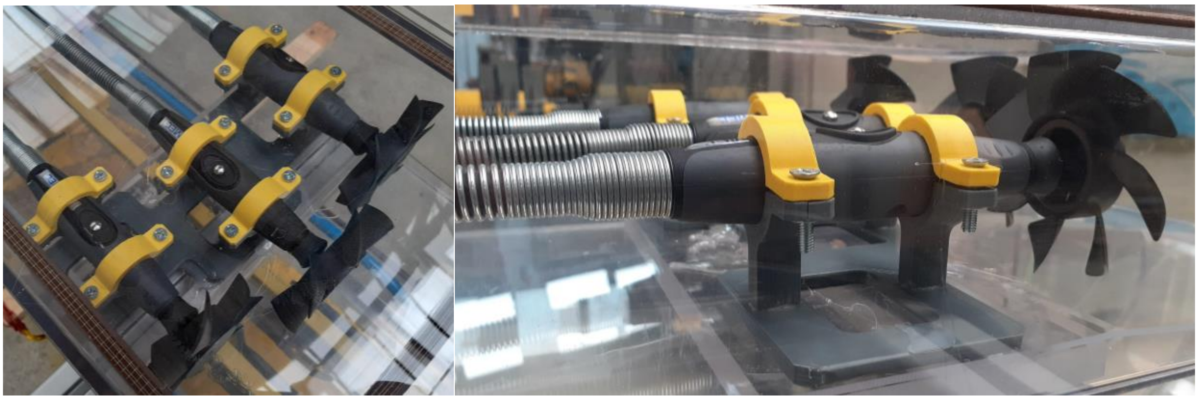

Fig. 6. 3D printed support brackets for the construction of the test stand

Such implementation is highly recommended for producing elements that do not carry high loads.

3.2. The use of 3D printing for special applications

3D printing technology is used in various areas of life, including health care. Due to the fact that materials used for creation implants must be certificated, and its composition is closely monitored throughout the production process, simple 3D printing technologies can only be used as an intermediate element, supporting the formation of the final product. For example for the purpose of mould making foundry, from which the final product is cast using the target material. Figure 7. Presenting example of using rapid manufacturing technology such as stereolithography used for manufacturing the cranial implant positive mould.

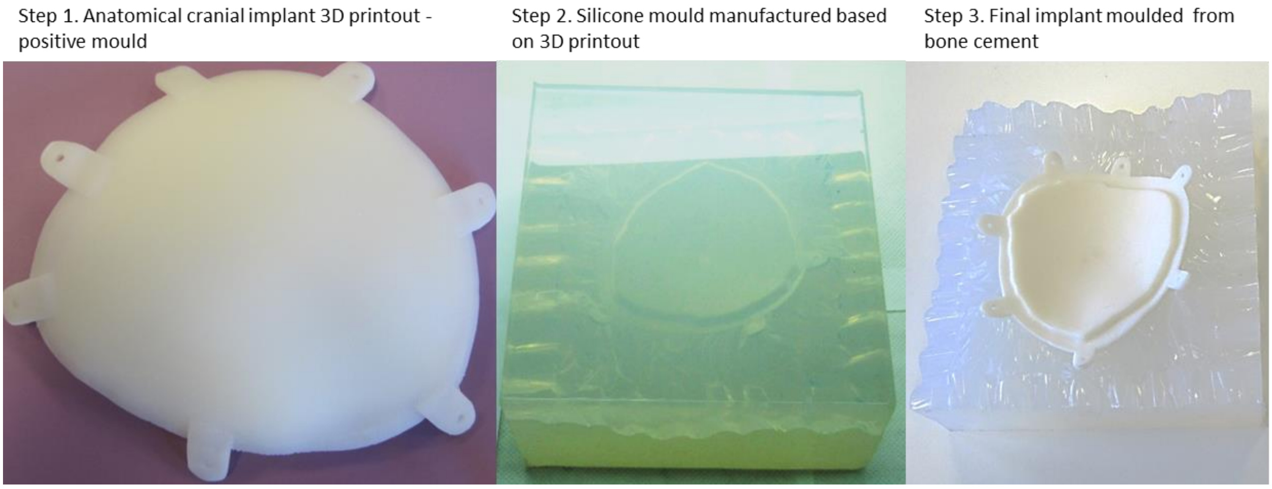

Fig. 7. Implementation of 3D printing technology to produce a positive mould for cranial implant manufacturing [12]

It is also possible to use 3D printouts made in FDM technology to support therapeutic activities in the treatment of complicated bone fractures. 3D printing technologies are used to produce personalized splints, tailored to the specific patient. In this case, 3D prints replace the standard stiffening using plaster casts, and due to the low weight and openwork structure significantly improve wearing comfort and accelerate the treatment process itself. The leader in the practical application of 3D printing for fracture treatment is the EXOVITE company, which has implemented an innovative manufacturing process in which a personalized splint is produced based on scans of the limb undergoing treatment.

3.3. The use of 3D printing as a medium for presenting new construction solutions

One of the most common applications of 3D printing is the preparation of advertising printouts, keyrings, figurines, etc. This approach may be applied also in the area of mechanical engineering marketing activities. It is possible to use 3D printouts as a form of presentation of innovative construction nodes, elements distinguishing a given construction solution, or presentation of the cooperation of entire systems. The possibility of presenting a new design takes on special significance when presenting large size machines, where 3D printing made on a scale, in some cases is the only possible form of product presentation. 3D models printed based on manufacturing documentation, are characterized by mapping accuracy consistent with the original. By adding the miniature drives and control systems, it is possible to map the ranges of motion of individual elements and to present the principle of operation of the machine. In Fig. 8 a scale model is presented. The model, in addition to mapping the external geometric features of the machine, thanks to the use of a control system (based on the Arduino module), allows us to present the range of movements and basic machine functionalities. The model is equipped with a control panel that allows selecting one of the developed demonstration programs covering various motion sequences characteristic of specific work activities.

Fig. 8. Scale model presenting the principle of operations of new construction solution

4. The conclusions from the implementation of the 3D printing technology in the organization

Implementation of the new solutions in an organization requires proper preparation on both the hardware and organizational side. Since the development of hardware infrastructure is most often associated with significant costs resulting from the need of the equipment purchase (3D printers, instrumentation, tools, and filaments), it is necessary to analyse potential areas of application (internal use only or commercial offer, small series or multiple printouts of single part), expectations regarding the accuracy and maximum dimensions of the expected 3D printed parts (analysis of the available printer's working area versus the cost of the 3D printing machine), as well as materials that can be used (testing the mechanical parameters of printouts made from various materials). All such considerations should be made before the process of 3D printing technology begin. It is necessary to analyse the market in terms of the purchase costs of specific printing devices, which should take into account not only the cost of equipment, but also the cost of consumables, and the possibility of possible independent repairs or replacement of components that may be damaged during operation. In the field of typical engineering applications including functional tests and marketing demonstration, FDM technology gives relatively the best results at a low cost of equipment purchase. In addition, due to the high popularity of FDM technology, consumables are easily available, in a wide range of achievable mechanical parameters and colours. Due to the simplicity of the design of the printing device itself, service operations can be performed without the need for external companies, which additionally affects the overall cost of a single printout.

An important aspect of using new technologies is to familiarize the design teams (i.e. potential internal customers) with the possibilities, potential benefits, and, what is most important, the limitations of the used technology. It is a mistake to assume that the technology well known and widespread on the market is also well known to all persons involved in a given process. 3D printing technology is a good example of this, although it has been developed since the 1980s, and the first 3D printer solutions available to private customers appeared at the beginning of the 21st century, and more precisely in 2001, many understatements arose around its possibilities. Because the majority of potential 3D print users shape their knowledge, about the possibilities and limitations, based on marketing presentation, their expectations usually exceed real possibilities. As it results from practical observations, most often after the first contact with technology, when it turns out that in practice the printing time is very long (printing times of complex elements may exceed 48 hours at a working field of 200mmx200mmx200mm), and the quality of the print depends not only on the material used but also on the shape of the printed object (large variations in the thickness of the printed object walls may cause internal stresses, and then deformations of the final product), recipients recognize that the technology does not meet their expectations. It is important to ensure an adequate level of knowledge in the organization at the beginning of the implementation process. Organizing information meetings and workshops that allow learning about the real possibilities of hardware facilities available on-site in the company, significantly speed up the implementation process Fig. 9.

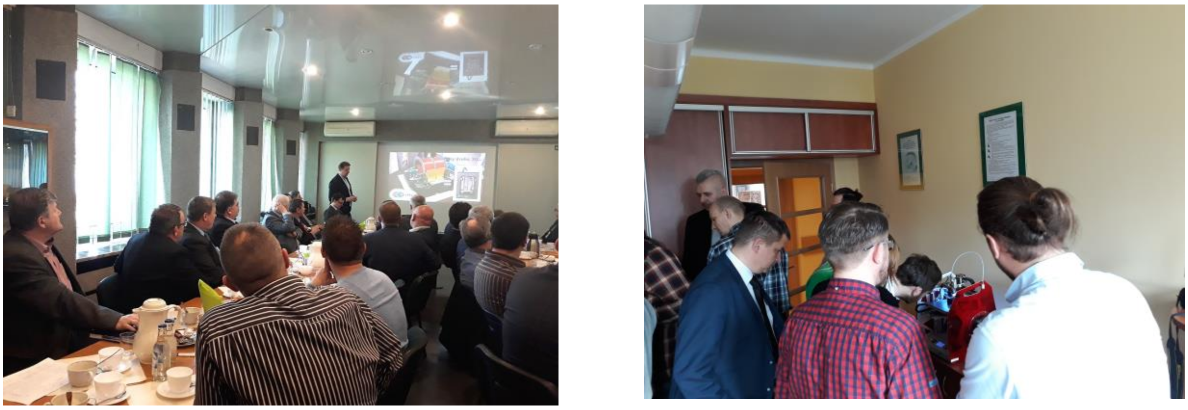

Fig. 9. Information meetings combined with a workshop part organized to disseminate information on the possibilities of using 3D printing with the FDM method in engineering practice - a meeting organized at ITG KOMAG as part of the 3DSPEC project [13]

At the KOMAG Institute, the implementation of 3D printing technology was carried out comprehensively. The process of selecting and bought of the 3D printers devices was performed simultaneously with the development of the knowledge resources to train all participants of the 3D printing process. The training materials describing the possibilities of available 3D printers, guidelines describing the requirements for the preparation of 3D models for the printing process, potential problems, and examples of applications from various fields are compiled in a form of e-learning course, see Fig. 10.

Fig. 10. Specialist in 3D printing - specialized training in the application of 3D printing - e-learning course [12]

Activities related to the development of training materials for 3D printing technology were implemented as part of the 3DSPEC project, realized in an international consortium, consisting of representatives of various areas of application of 3D printing, which allowed the development of comprehensive materials covering various areas of implementation, along with specific guidelines for the preparation of 3D models for the needs of 3D printing [12]. The training materials are available free on the elearning.komag.eu platform and contain the following modules:

- Module 1. Introduction: General view of the 3D printing technology - In this module, a trainee will be provided with structured knowledge that describes the basics of 3D printing technology, will become aware of how the whole process works, and will learn the advantages and disadvantages of different solutions,
- Module 2. Preparing the input file for 3D printer - In this part of the course, a trainee will learn how to prepare an input file for a 3D printer. Different ways of preparing a computer 3D model of an object are presented. Also examples of how to adjust models obtained e.g. from 3D scanning process to make 3D printouts. Work in specialist software dedicated for preparing input files for 3D printers (files in GCODE format) is described,
- Module 3. Materials used in 3D printing - Use of proper material for 3D printing is very important in terms of future use of a 3D printed object. In this module physical properties of most often used materials will be presented. Results of research that characterize the strength properties of 3D printouts will be also shown,
- Module 4. Examples of the use of 3D printing in activities conducted in your profession - Examples of application of 3D printing in a trainee's area/s of operation and relevant theory (if necessary) is presented in the module. Procedures to be followed to produce a given, sample 3D printout are presented. In each topic, a trainee gains access to downloadable additional materials – 3D models of an object.
- Module 5. Self-designing and assembling of 3D printers - After a description of 3D printers in terms of their features and possible use, exemplary cases presenting how to build and improve your 3D printers are presented. Materials present step-by-step how to connect any DIY (do-it-yourself) open-source-based 3D printers to the network and also ideas on how to design your own 3D printer are presented.

Despite the fact that many different 3D printing methods have developed over the years, the knowledge of a real 3D printer parameters, possibilities and costs resulting from the use of 3D printing is still at an unsatisfactory level, which raises a number of problems associated with excessive expectations may be a barrier in implementation. Therefore, it is important to ensure the same level of knowledge for all participants in the process. The training resources provided by ITG KOMAG can be a great source of knowledge and inspiration both at the stage of implementing 3D printing technology in an organization as well as at the stage of analysing available solutions and selecting printing technology that fulfils the specific requirements of the organization.

5. Summary

3D printing is used at every design stage - from concept to marketing activities related to the presentation of the finished product. It gives the opportunity to present initial concepts in the form of easy-to-understand printouts (this is especially important for people who cannot read standard technical drawings, and thanks to 3D prints the concept becomes clear to everyone). However, in order to fully utilize the possibilities of this technology, one must become familiar with both the possibilities and limitations of individual variants of 3D printing technology. The article presents a proposal for an approach to the implementation of 3D printing technology in the organization. Due to several understatements and misleading marketing messages, expectations for 3D prints are very high and do not match current print parameters. High expectations combined with a lack of basic knowledge, about how to form the final product, may affect the limited scope of technology application in the organization. The provision of appropriate knowledge resources, with specific examples of applications, and a set of guidelines on how to prepare 3D models for 3D printing are the basis for optimal use of all the possibilities of this technology.

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Mechatronic systems developed at the KOMAG

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Krzysztof Stankiewicz

KOMAG Institute of Mining Technology, Pszczyńska 37, 44-101 Gliwice, Poland

e-mail: kstankiewicz@komag.eu

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Słowa kluczowe: systemy mechatroniczne, algorytmy sterowania, systemy elektryczne, systemy komunikacyjne

Abstract:

Intelligent control and automation systems, capable for adaptation and learning, are expanding their area of application in industrial practice. Particularly, due to the necessity of continuous improvement of work safety, as well as the need to increase production efficiency and work reliability, the group of users of intelligent systems, which are currently implemented in many important branches of Polish industry, including mining, is constantly growing. The KOMAG Institute of Mining Technology develops modern, intelligent and distributed mechatronic systems which increase work safety and reduce energy consumption of technological processes. Innovative solutions of distributed control and power supply systems, focused on improvement of selected technological processes are presented in this article. Assumptions of IIoT (Industrial Internet of Things) and direct machine communication M2M (Machine to Machine) have a large impact on the structure and functionality of control systems, shaping the ideas of Industry 4.0. All control systems, compatible with IIoT, use communication networks, often of high complexity, combining various components, modules, actuators and sensors. KOMAG researchers have noticed and proposed a solution to the problem of self-organized communication paths in a complex sensor network. In order to create and optimize the communication structure, the SA class algorithm (Swarm Algorithm) was proposed. As an example of a distributed control system, the KOGASTER control system using the CAN communication bus was described. Another innovative solution, presented in the article, is Shield Support Monitoring System (SSMS), which allows monitoring the condition of the powered roof support in real time by monitoring its operating parameters (such as geometry, hydraulic pressure parameters and tip to face distance). SSMS provides data for the Longwall Mining Conditions Prediction System (LMCPS) in order to forecast the risk of a dike and generate information on necessary corrective actions. The projects developed at the KOMAG perfectly fit into the current development trends of mechanization and automation systems for the industry, including the mining industry.

Streszczenie:

Inteligentne systemy sterowania i automatyki, zdolne do adaptacji i uczenia się, zyskują coraz szersze grono użytkowników i powiększają obszar zastosowań w praktyce przemysłowej. Jest to szczególnie uwarunkowane potrzebami ciągłego polepszania bezpieczeństwa pracy, a także zwiększaniem wydajności produkcji i ciągłości pracy w wielu ważnych gałęziach polskiego przemysłu, w tym w górnictwie. Instytut Techniki Górniczej KOMAG rozwija nowoczesne, inteligentne i rozproszone systemy mechatroniczne, które wychodzą naprzeciw tym oczekiwaniom jednocześnie zmniejszając energochłonność procesów technologicznych. W artykule przedstawiono innowacyjne rozwiązania rozproszonych systemów sterowania i zasilania, ukierunkowane na usprawnienie wybranych procesów technologicznych. Założenia IIoT (Industrial Internet of Things) i bezpośredniej komunikacji maszyn M2M (Machine to Machine) mają duży wpływ na strukturę i funkcjonalność układów sterowania maszyn, kształtując przy tym idee Przemysłu 4.0. Wszystkie systemy sterowania, kompatybilne z IIoT wykorzystują sieci komunikacyjne, często o dużej złożoności, łączące różne komponenty, moduły, siłowniki i czujniki. Specjaliści ITG KOMAG dostrzegli i zaproponowali rozwiązanie problemu samoorganizacji ścieżek komunikacyjnych w złożonej sieci czujników. W celu stworzenia i optymalizacji struktury komunikacyjnej zaproponowano algorytm klasy SA (ang. Swarm Algorithm). Jako przykład rozproszonego systemu sterowania opisano system sterowania KOGASTER wykorzystujący magistralę

komunikacyjną CAN. Innym nowatorskim rozwiązaniem, przedstawionym w artykule, jest System Monitorowania Zmechanizowanej Obudowy Ścianowej (SSMS, ang. Shield Support Monitoring System), który pozwala na monitorowanie jej stanu w czasie rzeczywistym poprzez monitorowanie wybranych parametrów (takich jak geometria, ciśnienia hydrauliczne i odległość od czoła ściany). SSMS dostarcza dane do Systemu Predykcji Warunków Wydobycia LMCPS (ang. Longwall Mining Conditions Prediction System), w celu prognozowania ryzyka zawału stropu i generowania informacji o koniecznych działaniach naprawczych. Projekty opracowane w ITG KOMAG doskonale wpisują się w aktualne trendy rozwoju systemów mechanizacji i automatyzacji przemysłu, w tym górnictwa.

1. Introduction

Mechatronics includes elements of Mechanics, Electronics, Control and Information Technology and it is used, among others, for designing of state-of-the-art automated and robotized machines and equipment, including industrial robots. According to the definition (approved by the International Federation for the Theory of Machines and Mechanisms), Mechatronics is "a synergic combination of Fine Mechanics, Electronic Control and Systematic Thinking while designing products and production processes" [1, 2].

Products of mechatronics and mechatronic systems should be characterized by multifunctionality, flexibility and a possibility of an easy configuration, as well as by an adaptation ability and operational simplicity. It can be stated explicitly, that in fact this subject-matter has been developed for a dozen or so years by scientists and manufacturers of products working for the mining industry, which will be illustrated with some examples in a further part of this paper. A confirmation of the fact that mechatronics in the mining industry already has an established position, is a requirement of knowledge and education, being one of the professional qualifications indispensable for a person performing activities in the supervision of underground mining operations in the scope of machines and equipment as regards their mechanical part.

KOMAG, with regard to the necessity of increasing the safety of mining crews and improving the efficiency of coal mining, transport and processing, implements a number of research projects aimed at implementing state-of-the-art control and communication systems. Among others, a state-of-the-art, self-organizing and wireless sensor network is being developed. The wireless sensor network can operate in connection with control systems or operate independently. Currently, one system of wireless distributed sensors is introduced in the mining market [3, 4]. Meanwhile, in order to become more competitive, the mining industry has to invest in further solutions of this type, especially in the area of equipment for mine roadways, e.g. belt conveyors for the transport of the extracted coal, with lengths ranging from hundreds of metres to several kilometres. This is a result of fast changes in the configuration of machines resulting from the progress of mining works and activities aimed at automation and autonomy of mineral excavation technologies.

Development of self-organizing, distributed, wireless sensor networks and control systems requires the development of an alternative method of powering their elements by recovering waste energy available in their surroundings, e.g. energy of mechanical vibrations, thermal energy [5, 6], as well as energy of rotary motion or electromagnetic radiation. The development of electronic systems with low power demand and the development of low power radio data transmission standards makes it easier to use wireless sensors [1, 7]. Self-powered sensors are often used in ventilation or air conditioning systems.

Artificial intelligence methods are increasingly used in communication between machines used in mining. They are particularly used for monitoring and diagnostics of subassemblies and component wearing [8, 9, 10, 11] and in machine control systems and mechanisation systems [12, 13]. According to KOMAG's experience, the three hardware and software components of the discussed solutions are of the greatest importance for operational reliability: self-powered sensors, distributed control systems and self-organized communication network binding these components into one system.

2. KOGASTER - distributed control and diagnostics system

Distributed control systems are a class of systems in which the controllers are physically separated over a certain area covering a monitored or controlled object. It is different from a centralized control system in the absence of a structure that clearly focuses control functions in one device. In a distributed control system (DCS), each component, each machine or device is managed by a dedicated controller. A DCS consists of a large number of local controllers, located in different zones of the installation/machine area, which are connected via an efficient communication network. Research and development projects carried out at KOMAG have become the basis for the development of distributed control system modules offered under the name KOGASTER. This system is a good example of an installation covering potentially large areas (up to 1 km in diameter), in which sensors, actuators, control units are located and connected by wired or wireless communication network. In addition, KOGASTER can be implemented in a mining environment. It is designed for use in machines operating in difficult conditions, especially in potentially explosive atmosphere, where the use of explosion-proof automation systems is required. The KOGASTER system has been certified under the ATEX Directive. The system has been designed to ensure a high level of safety (switching off the power supply in case of an explosive atmosphere, as well as in difficult working conditions, in particular due to its improper use and in case of changes in environmental conditions). The components making up the KOGASTER system are classified in the 1st explosion Group. The open structure of the communication protocol enables connecting KOGASTER system elements with elements (transmitters, sensors) from other manufacturers. KOGASTER elements can be used in machines equipped with both intrinsically safe and extrinsically safe circuits.

The KOGASTER system is a distributed system that operates using the CAN bus and CANopen protocol for communication [14, 15]. It is intended primarily to control mining machines and equipment [6, 16, 17, 18, 19]. The implementation of the CAN bus and the CANopen protocol enabled the construction of a system with open architecture. The main characteristics of the KOGASTER control system are as follows:

- distributed structure [20],
- intrinsically safe and redundant CAN bus [21],
- intrinsically safe sensors, input/output systems and control units [22].

2.1. Structure of distributed control system

The distributed control system consists of control modules, I/O, measuring transducers, actuators and digital communication interface, connected to the CAN bus. The advantage of this solution is the possibility of power supply and data transmission in one wire harness. The block diagram of the distributed control structure with the use of a single CAN bus is shown on Figure 1.

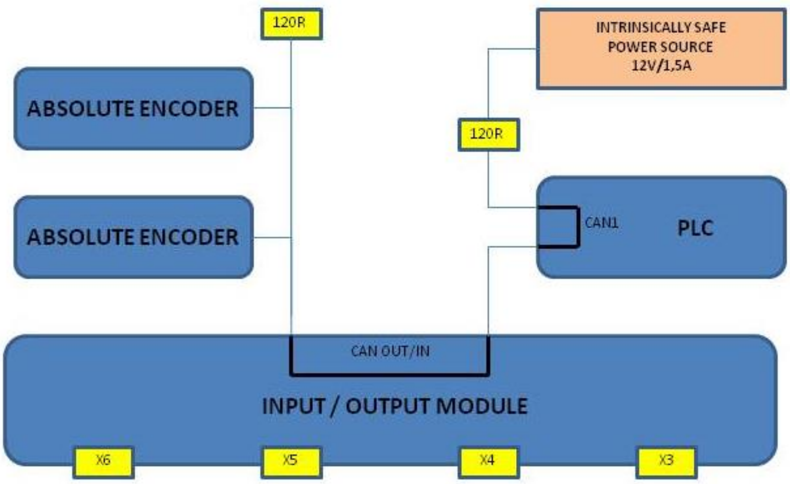

Fig. 1. Block diagram of distributed control system using a single CAN bus [23]

The CAN bus becomes reliable due to the redundancy of the cabling and the doubling of modules and transmitters. This has a negative impact on the unit cost of production, but allows to reduce costs resulting from machine failure. An example of using a redundant system is a battery-driven train equipped with two independent control panels and two drives, shown in Figure 2.

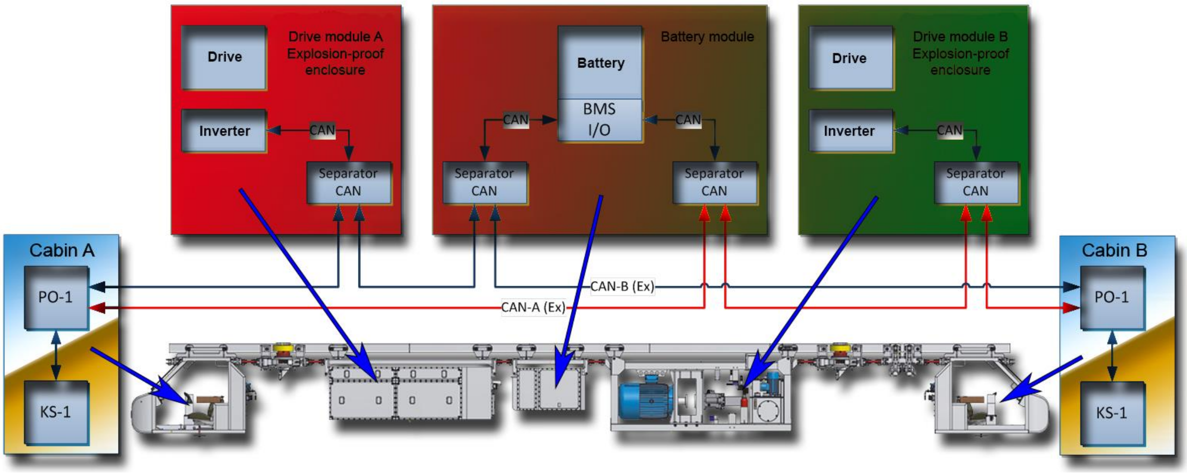

Fig. 2. Block diagram of a train control system with a redundant distributed structure [23]

3. Systems for measuring the operational parameters of roof support

Nowadays, there are systems in manufacturers offers for measuring selected parameters of powered roof support sections. The properties of these systems are strongly diversified, mainly in terms of data transfer and power supply. The analysis of solutions offered on the market indicates that mainly wired and wireless systems for measuring pressure in legs are available. The purpose of measuring the pressure in legs is to determine the load-bearing capacity of the roof support unit, as well as to verify the proper selection of the roof support section to the operating conditions prevailing in the longwall [24]. In the scope of roof support geometry measurements, wire-based systems are available.

At the present, systems of automation of longwall systems does not include monitoring of roof and preventing against danger phenomena associated with roof behaviour, such as roof falls to the longwall face or lack of roof fall behind the shield support. The KOMAG's coordinated PRASSIII project goals are focused on the Shield Support Monitoring System (SSMS), which will enable monitoring of roof condition, by monitoring the parameters of shield support, as well as on development of the Longwall Mining Conditions Prediction System (LMCPS) for a prediction of roof fall hazards and a generation of information about corrective measures [25]. Presented scope of work is realized within the PRASS III (Productivity and Safety of Shield Support) project. The project is realized by international consortium consisting of the following organization: the KOMAG, the Becker Warkop Ltd. Company, the Main Mining Institute (GIG), the Jastrzebska Coal Company Ltd. , the DMT GmbH & Co. KG, the Geocontrol and the University of Exeter.

3.1. The Shield Support Monitoring System (SSMS)

The Shield Support Monitoring System (SSMS) will include geometrical parameters of shield support, hydraulic pressure parameters, tip to face distance and new wireless communication system. The SSMS will enable monitoring and recording roof support operational parameters in real time and it will be the basis for a development of the Longwall Mining Conditions Prediction System (LMCPS). For monitoring geometrical parameters of powered roof support, the SSMS will include a set of sensors enabling a determination of an absolute position of each powered roof support component. All the devices of the SSMS will meet the requirements of the ATEX Directive.

3.2. The Longwall Mining Conditions Prediction System (LMCPS)

It was concluded that by monitoring the behaviour of the both shield support (leg pressures, geometry and tip to face distance) and geotechnical conditions in longwall, warnings can be given for significant improper shield support acting and the formation of roof instabilities tens of minutes in advance. This advance warning allows miners to take preventive action (such as improvement of roof strata stability by injections or improvement the shield support) which can reduce longwall downtime and hazards.

4. Power Supply System of roadheading mining machines

Roadheading machines are commonly used in the Polish coal mining industry, for activities related to proper maintenance of the false floor in the roadway developments. They are self-running machines on a tracked electro-hydraulic drive chassis. During drilling, a hydraulic pump, driven by an electric motor, powered by a drop-down cable is connected to the mine power network. The disadvantage of this solution consist in a limited mobility and an exposure of the cable to mechanical damages, so research work was undertaken by the KOMAG.

In order to increase machine operational availability, it was planned to power the machine with electricity through the so-called electric hybrids. It is a system based on wired network power from the mine network and additionally on independent power supply from cell batteries. The machine will work on battery power. When the battery has been discharged, it will be possible to supply the machine from the mine network, thus continuing the work while simultaneously charging the battery cells. After the battery has been charged, the machine will be reenergized only from the internal source. The current regulations on the use of cells in underground explosive mines require only serial connections, and thus the possibility of increasing the voltage while maintaining the capacity of a single cell. Therefore, cells with a capacity of 100Ah in the number of 224 units connected in series were selected. The battery will consist of fourteen modules containing 16 cells in each module. Figure 3 shows an assembly of a single set of cells (modules) in the protective cassette.

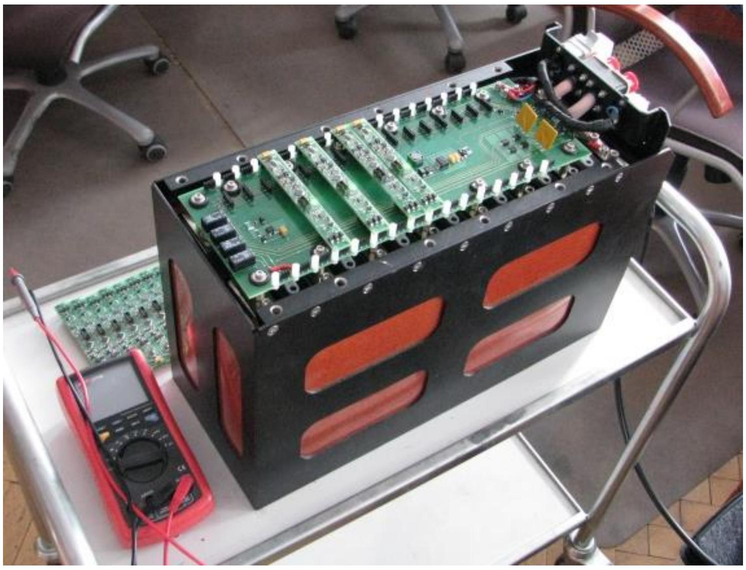

Fig. 3. A single set of cells in the protective cassette [26]

The main element of the electrical equipment of the new power supply and control system will be a fully controllable converter fulfilling the functions of the inverter and power supply for the battery. The auxiliary AC and DC auxiliary voltages necessary for operating the machine and supplying the protection are to be obtained from 500 V. Due to the higher harmonics occurring during the transformation of the battery voltage from the battery by the inverter, it will be necessary to use appropriate filters. The converter will power the dSLg250M4-EP type motor, it is a three-phase, asynchronous electric motor, adapted to work in potentially explosive atmospheres. This engine is widely used in mining, also in extant drive systems of mining tailings. The inverter and loader work on a common power line for the hydraulic pump drive motor. After discharging the battery, through the appropriate switching sequence, after connecting the power cable, the system allows battery charging and direct powering of the drive motor from the electric mining sieve. Thanks to this solution, the functionality of the machine has been increased compared to the solutions used so far. An additional functionality in which the new power supply and control system was designed is a wireless

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control and communication system. The existing solutions of mining machines of small mechanization are controlled locally by means of a manipulator located in the operator's panel. The proposed wireless control system will be based on the system developed in the KOMAG. This system is adapted to work in mining excavations where there is a danger of explosion of methane levels "a", "b" and "c" and the explosion hazards of dust class A and B. The system consists of a receiver and a pilot. The receiver, which is a part of the system, is a microprocessor device used to receive control signals sent with a wireless remote control. On the basis of sent setpoints, the receiver module generates signals controlling the machine's automation. After turning on the receiver's power supply, the microprocessor system starts, which enters the state of waiting for connection with the remote control. After starting the remote control, the receiver establishes a connection with it. Properly programmed microprocessor controls the relays according to the data sent from the remote control, which is adapted to the needs of a particular device - the number, designation and selection of the location of the buttons depend on the purpose of the system. The control signals are sent in the form of serial data, and the transmitted block of data contains information about the operating status of the keyboard's control buttons.

During the tests, a correct operation of the battery charging and discharging module as well as the control and safety system was checked. In the result of these tests, no irregularities were found. The current intensity when charging cell batteries was about 30A, this allows to charge the battery in about 3 hours, which is the fulfilment of the technical and technological assumptions. The combined control and safety system guarantees that every irregularity, created in the power module, is detected and blocked by the developed security system. When the power module did not confirm a connection of the mobile machine's electrical motor during testing, only the output voltage and communication of the power electronic converter were verified during the tests.

5. Intelligent algorithms for routing sensory networks

Sensory networks must ensure a reliable transmission of measurement data in order to detect fault conditions that pose a direct threat to the progress of the mining operation and often also to the health and safety of employees.

Working conditions in mines make it difficult to service machinery and equipment. The installation of a new measuring system, a replacement of a sensor, and maintenance actions should be simplified by the type of machine sensors used. The following elements become important for operational reasons:

- an easy assembly and replacement of the sensor (no need to use wires makes it easier to install and adapt to the structure of the machine or the environment in which it works); the sensors should be powered by batteries or by energy recovery, with the sensory data transmitted via radio signal,
- sensors should be replaced without the need to reconfigure the network in which they are located,
- sensors should transmit information among themselves so that, due to interference from metal elements, it is not necessary to transmit information directly to the access point.

In order to meet these requirements, it is necessary to implement appropriate routing algorithms in sensory networks:

- Proactive algorithms - store routes between individual network nodes in the so-called routing tables; these routes are cyclically refreshed so that the stored data are consistent with the current state of the network (the so-called maintenance of paths takes place regardless of whether there is traffic to individual nodes of the network),
- Reactive Algorithms - these algorithms search for a route when necessary, at the time of sending a packet,
- Hybrid algorithms - in these algorithms, the network is divided into smaller parts. Only separated parts of the network are saved.

5.1. Routing algorithm for conveyer sensory network

For eight years KOMAG has been developing the concept of a self-organized communication structure protocol called SSKIR [21], which is based on the implementation of hive intelligence [10].

Based on the behavior of individuals in animal swarms, a number of principles were developed [21, 27] and proposed to create a system of communication in the sensory network (Fig. 4). Each data frame transmitted by the Measure Transmission Unit (MTU) is marked with the transmission quality factor Wp defining the transmission priority related to the efficiency of data transmission to main transmitting stations. This factor may take a value according to one of the connections or route metrics.

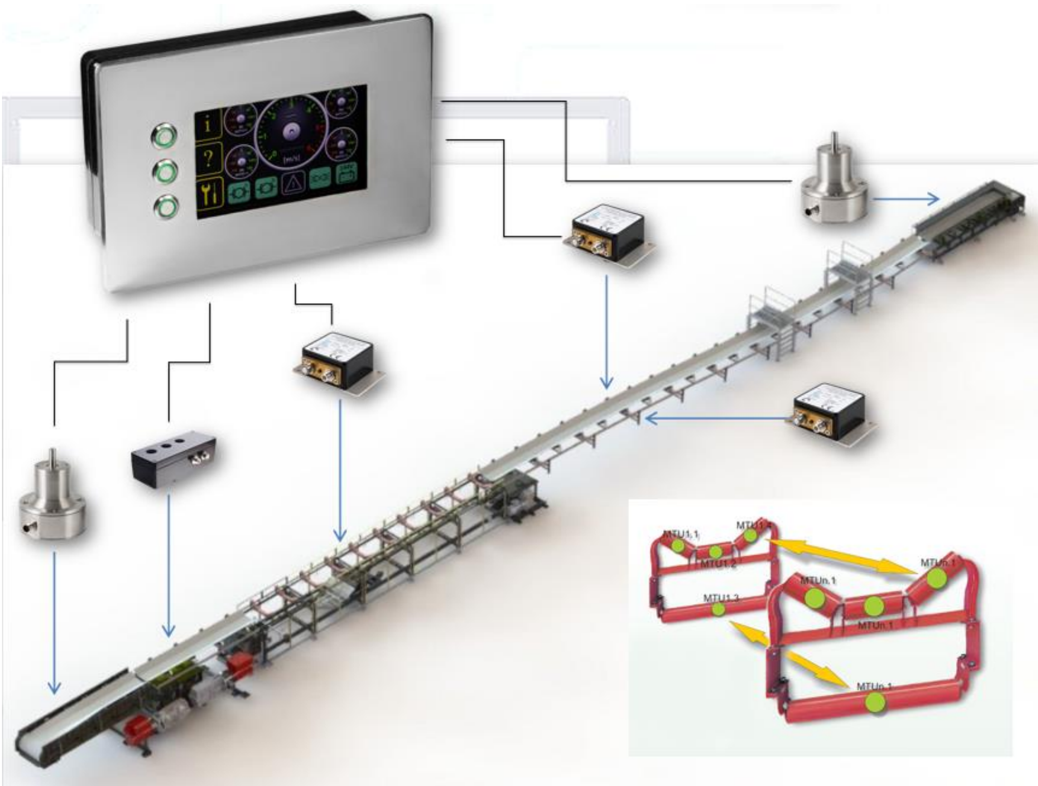

Fig. 4. Sensory network of belt manipulator rollers [27].

As mentioned above, the W_P coefficient can take a value that conforms to one of connections or path metrics; therefore, transmission speed and the number of hops of transmitted frames containing the following measurement data is based on data propagation times:

- Expected Transmission Count (ETX) is a metric that is widely used in mesh networks; ETX is the metric specifying the number of expected transmissions, which is indispensable when sending data to the next node without errors; the number varies from 1 to infinity.
- Expected Transmission Time (ETT) is an extension of ETX metrics, since it takes into consideration the difference in the speed of data transmission. The relationship between ETT and ETX metrics can be expressed as follows:

$$ETT_l = ETX_l \frac{s}{b_1} \tag{1}$$

where:

b_l - a speed of transmission of information in connection l,

s - a size of transmitted package.

- Hop count is the most often used routing metric in the existing routing protocols, such as DSR (Dynamic Source Routing), AODV (Ad Hoc On-Demand Distance Vector), or DSDV (Destination-Sequenced Distance Vector).

– Weighted Cumulative ETT (WCETT) is a metric that includes both the quality of a connection (losses, throughput) and the number of hops; thus, we can reach a compromise between delay and throughput.

$$WCETT(p) = 1 - \beta \cdot \sum_{l \in p} ETT_l + \beta \cdot \max_{1 \le j \le k} X_j \tag{2}$$

where:

β - a set parameter from the range $0 \le \beta \le 1$ (higher values of β give priority to paths using many channels and its lower values give priority to shorter paths),

$\max_{1 \le j \le k} X_j$ - counts the maximal time of appearance of the same channel in a given path.

– MIC is metric that improves the operation of WCETT by solving its isotonicity and inability of detecting the collisions; MIC metrics of p path can be defined as follows:

$$MIC(p) = \frac{1}{N \cdot \min(ETT)} \sum_{linkij \in p} IRU_{ij} \sum_{nodei \in p} CSC_i \tag{3}$$

where:

N - a number of all nodes in the network,

min(ETT) - the lowest *ETT* in the network and it can be determined on the basis of the lowest speed of data transmission in radio charts.

The transmission factors are calculated and stored in the network nodes. There is no need to create a master routing map describing the structure of the entire network. Application of specified rules causes that a group of MTU units creating a transmission path automatically creates a structure of reliable transmission routes, omitting units which have failed. Data frame in SSKIR protocol is defined by four additional values:

– its own unique MTU identification number,
– *X* and *Y* coordinates defining the occupied position in the solution space of the communication path structure,
– the priority factor in the communication path of which the frame is an element,
– the baud rate for the *X* and *Y* dimensions, i.e. *vX* and *vY*.

The neighbours of frames with the number of a given MTU are called other frames that are in the MTU transmission range, i.e. those that are in a sufficiently short distance d and simultaneously in the field of view, defined by the value of virtual angle *r*. In order to check whether a given frame *e* of coordinates *e.X* and *e.Y* respectively, is a neighbour of MTU *b* of coordinates *b.X* and *b.Y*, it is necessary to check first whether the element is in a sufficiently short distance. If the condition is not met, then the next rules are not checked, because a given frame from the MTU *e* is certainly not a neighbour of frames from the MTU *b*. If the condition is met, it is checked if the frame is in the virtual viewing angle *r* by determining the angle r_1 under which the frame moves virtually:

$$r_1 = \arctan\left(\frac{b.vY}{b.vX}\right) \tag{4}$$

and the virtual angle r_2 of the segment connecting the MTU *b* frame with the MTU *e* frame assuming that $b.vX \neq 0$ and $e.X\text{-}b.X \neq 0$. Then the absolute value of the angle difference is calculated and the inequality checked. If the condition is met, then the frames come from neighbouring MTU. Next, the first rule is applied, and each frame adjusts its path to frames from neighbouring MTU. One must calculate the average speed v_{avg} of all frames from the neighbouring MTU (separately for the *vX* and *vY* components) and then modify the frame transmission speed, taking into account the path priority factor, the current speed, and the calculated average.

To apply the second rule, the average number of frame jumps in the d_{avg} transmission path should be calculated in relation to frames from neighbouring MTU, and then the frame transmission speed should be modified in relation to neighbouring MTU.

The third rule shows that, when a frame in a path with a lower priority coefficient tries to carry out the transmission, competing with a frame with a higher priority, it should avoid it by modifying its speed. Formula (5) also use the triangular similarity claim. Let *b* be a lower priority frame competing with a frame from the neighbouring MTU, with a higher priority *e*. In regard to the above rule, the following formula should be applied:

$$
\begin{aligned}
& d = \sqrt{(e.X - b.X)^2 + (e.Y - b.Y)} \\
& b.vX = b.vX + \left(\frac{(e.X - b.X) \cdot d_{\min}}{d} - (e.X - b.X) \right) \\
& b.vY = b.vY + \left(\frac{(e.Y - b.Y) \cdot d_{\min}}{d} - (e.Y - b.Y) \right)
\end{aligned} \tag{5}
$$

where:

d_{min} - a preset minimum number of jumps in the transmission path, which should not be exceeded by the transmitted frame.

The last two rules are introduced to the system by modifying the fourth rule based on the dependencies [21]. It should be noted that each frame can move with a certain maximum speed imposed by the physical system. In simulations, this speed should be limited and the following entered:

- limitations resulting from the presence of MTU in the emergency or start-up state (elements that frames should avoid creating transmission paths),
- attractors in the form of main receiving and transmitting stations.

6. Summary

Adaptive control systems are used more and more widely in industrial practice. Industrial Internet of Things (IIoT) and direct communication of machines (M2M, Machine to Machine) significantly impact technical and management structures in companies implementing Industry 4.0 solutions. KOMAG develops these solutions by designing adaptive, self-organizing communication systems based on mesh topology. The method of system self-organization is based on a swarm algorithm. It enables implementation of state-of-the-art and effective routing technology in networks with mesh topology, especially in diagnostic systems. Networks equipped with MTU nodes can be treated as components of measurement swarms. This is particularly important for the safety of underground mine operations due to the reliability of transmission in mesh networks.

The practical use of low-power waste energy recovery has become possible thanks to the use of low energy consumption sensory and communication systems, which enable the management of energy coming from vibrations, heat, light and supply it to entire sensory and communication networks.

KOMAG has strongly marked its position in the area of distributed explosion-proof control systems. The KOGASTER control system based on the CAN bus and CANopen protocol has been designed mainly for the control of mobile machines, and the use of intrinsically safe components in the KOGASTER system enables its implementation in the control of machines and equipment operating in areas with methane and coal dust explosion hazard.

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Seventy-year activity of the KOMAG Institute in support of environmental protection

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Aleksander Lutyński [1a], Małgorzata Malec [1], Dariusz Prostański [1]

[1] KOMAG Institute of Mining Technology, Pszczyńska 37, 44-101 Gliwice, Poland

[a] e-mail: alutynski@komag.eu

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Abstract:

Seventy years of interdisciplinary activities of the KOMAG Institute of Mining Technology in support of widely understood environmental protection are presented in the article. The research and development projects oriented onto subject-matter of environmental protection and realized within the framework of the statute, research, research-and–development, ordered, thematic as well as testing-and-servicing activities are described. The article also contains some information about a dissemination of knowledge on environmental protection during the KOMEKO scientific and technical conferences which have been organized by KOMAG since the year 2000.

Streszczenie:

W artykule przedstawiono siedemdziesiąt lat interdyscyplinarnych działań Instytutu Techniki Górniczej KOMAG w zakresie szeroko rozumianej ochrony środowiska. Opisano projekty badawczo-rozwojowe, ukierunkowane na tematykę ochrony środowiska, zrealizowane w ramach działalności statutowej, projektów badawczo-rozwojowych, zamawianych, celowych oraz działalności badawczo-usługowej. Artykuł zawiera również informację na temat dzielenia się wiedzą, dotyczącą ochrony środowiska, podczas konferencji naukowo-technicznych z cyklu KOMEKO, organizowanych przez KOMAG od 2000 roku.

1. KOMAG Institute of Mining Technology – a short history of a seventy-year activity

The KOMAG Institute of Mining Technology was established on 1st January 2009 [1], but its history dates back to 1950. An establishment of the Institute was preceded by organizational activities changing both the name of the organization as well as the scope of its activity. In 1950 Centralne Biuro Projektów (Central Bureau of Projects) was transformed into Biuro Konstrukcji Maszyn Górniczych (Design Bureau of Mining Machines). In 1953 the name was changed for Centralne Biuro Konstrukcji Maszyn Górniczych (Central Design Bureau of Mining Machines) with its seat in Gliwice. In 1957 Centralne Biuro Konstrukcji Maszyn Górniczych and Instytut Mechanizacji Górnictwa (Mining Mechanization Institute) established in 1951, were combined. In the result of such a combination Instytut Doświadczalno-Konstrukcyjny Przemysłu Węglowego (Experimental-and-Design Institute of Mining Industry) was established. In 1958 its name was changed into Zakłady Konstrukcyjno-Mechanizacyjne Przemysłu Węglowego (Design-and-Mechanization Works of Mining Industry). An increasing demand from the mining industry caused a dynamic development of ZKMPW. Within a few years new organizational branches were added such as: Zakład Elektroniki Górniczej (Plant of Mining Electronics) in Tychy, Elektrometal in Cieszyn, Zakład Budowy Maszyn Doświadczalnych (Construction Plant of Experimental Machines) and Zakład Cybernetycznych Kompleksów Górniczych (Plant of Cybernetic Mining Systems) in Biskupice. The M300 Experimental Mine and the Jan Experimental, Automated Mine in Katowice were included in the ZKMPW structure. Then Ośrodek Szkolenia Maszynowego (Centre for Machine Training), functioning within this organizational structure was transformed into Zakład Doskonalenia Kadr (Plant of Personnel Improvement). The next reorganization was implemented in 1975. The Construction Plant of Experimental Machines, the M300 Experimental Mine and the Plant of Personnel Improvement were separated from the Design-and-Mechanization Works of Mining Industry, establishing Centralny Ośrodek Projektowo-Konstrukcyjny Maszyn Górniczych KOMAG (KOMAG Central Design-and-Construction Organization of Mining Machines) in Gliwice. This organization obtained the status of a research-and-development centre, subordinated to the POLMAG Association of Mining Machinery Industry. Then KOMAG became the design, research and development base for all the factories in the POLMAG Association. They were: FAMUR, FAZOS, TAGOR, RYFAMA and GEORYT. In all those factories KOMAG had its local design branches [2].

The Ośrodek Projektowo-Technologiczny Maszyn Górniczych ORTEM (ORTEM Design-and-Technical Centre for Mining Machines), with its seat in Mikołów, was incorporated into KOMAG in 1979. This change caused that the KOMAG scope of activity was broadened by the subject-matter of a production technology of mining machines and equipment as well as by the subject-matter of production organization and management. The name was changed into the Centrum Konstrukcyjno-Technologiczne Maszyn Górniczych KOMAG (KOMAG Design-and-Technological Centre of Mining Machines). In the result of the next rearrangement, conducted in March 1990, the Centrum Mechanizacji Górnictwa KOMAG (KOMAG Mining Mechanization Centre), a research-and-development organization was set up.

In the consolidation process of research-and-development organizations, supervised by the Minister of Economy, the Ośrodek Badawczo-Rozwojowy Reduktorów i Motoreduktorów REDOR (REDOR Research-and Development Centre for Reducers and Motoreducers), with its seat in Bielsko-Biała, was included into KOMAG in 2005 and in 2006 the Ośrodek Badawczo-Rozowojowy Budownictwa Górniczego BUDOKOP (BUDOKOP Research-and-Development Centre for Mining Construction), located in Mysłowice, was incorporated by KOMAG.

Due to significant broadening of the KOMAG scope of activity, the name of the organization, did not reflect a broad spectrum of the scientific, research and technical activity, conducted by KOMAG, within innovative solutions for the economy. Taking this fact into consideration, a letter of application was sent to the Ministry of Economy with a request of approving the change of the name, i.e. Centrum Mechanizacji Górnictwa KOMAG (KOMAG Mining Mechanization Centre) into Instytut Techniki Górniczej KOMAG (KOMAG Institute of Mining Technology).

In the first years of its seventy-year lasting history the research-and-design projects were mainly oriented onto machines and equipment for mining coal seams. The subject-matter and scope of these projects were developed within years. At present scientific, research and technical projects, realized at KOMAG are oriented onto mechanical and mechatronic systems such as: machines and equipment for underground exploitation of mineral resources, mechanical preparation of minerals as well as supply, control, diagnostic and monitoring systems. The developed conceptions, projects and technical documentations of machines and equipment, are adapted for an execution of required functions and tasks in the in-situ mining and geological conditions. Model, laboratory and industrial tests are conducted to increase life, reliability, operational safety and ergonomics of mining machines. Several projects deal with, widely understood, environmental protection, in particular as regards mining sites and also other areas badly affected by the industry. Since 1950 more than 1100 technical documentations of machines and equipment, applied in mines of minerals in Poland and abroad, have been generated. More than 4400 patents and utility patterns, obtained so far, confirm an innovative character of KOMAG technical solutions.

The scope and the subject-matter of the research-and-development projects have been modified and up-dated since the beginning of the KOMAG activity which resulted from a current demand of the developing and restructuring industry. In general, the thematic scope of the projects can be presented as follows:

- a development of innovative mechanical solutions for longwall and road-heading systems of minerals' mining,
- shaping of smart work environment in the mining industry,
- a development of innovative systems for horizontal and vertical transportation and for men-riding in mines of minerals,

- an improvement of technologies and technical systems for a beneficiation and classification of minerals,
- a development of innovative mechatronic solutions supporting production processes of minerals,
- a development of innovative solutions reducing hazards and increasing work safety,
- an environmental management of industrial and urbanized areas according to the strategy of sustainable development,
- a development of technologies and methods for environmental protection,
- a development of technologies of using and dumping waste,
- a development of techniques and technologies for a management of natural heat sources- geothermics, hydrothermics and aerothermics,
- “clean” technologies ensuring safety of energy supplies,
- a creation of smart solutions according to Industry 4.0,
- a use of smart solutions in supply, control, diagnostic and monitoring systems of machines and equipment,
- a use of innovative hydraulic and pneumatic systems for machines and equipment,
- a development of innovative drive systems,
- an improvement of the management system and a development of methods and procedures of products’ conformity assessment,
- an expansion and modernization of the Institute testing infrastructure,
- a generation and a development of testing methods and procedures,
- an application of new construction materials and new manufacturing technologies.

In the mentioned thematic fields the Institute realized:

- the statute activity within research tasks, “Young Scientist” grants, initial grants, doctoral and post-doctoral grants,
- research-and-development projects, targeted and ordered projects financed from different external sources,
- European projects with different foreign and domestic partners,
- service, expert and specialist activity,
- training activity.

The KOMAG Institute of Mining Technology has three specialist accredited testing laboratories equipped with the state-of-the-art apparatus:

- Laboratory of Applied Tests,
- Laboratory of Tests,
- Laboratory of Material Engineering and Environment,

and the Division of Attestation Tests, Certifying Body.

The Institute collaborates with foreign partners from Spain, the Netherlands, Germany, Portugal, Romania, Slovenia, Hungary, Great Britain, Finland, Latvia, Ukraine, Czech Republic, Greece, Bulgaria, Slovakia and France. It is a member of three clusters: Cluster of Mining Machines, Silesian Cluster of Design and Cluster of Culture and Industrial Tourism. It participates in the activities of three technological platforms, in particular in the Polish Technological Platform “Environment”.

2. KOMAG activities in the scope of clean coal technologies

One of the most important activities in environmental protection includes clean coal technologies (CCT). These technologies aim at an improvement of coal extraction, preparation, processing and utilization and at an increase of acceptance of these processes from the point of view of their impact on the natural environment. This classical definition comes from the publications of the International Power Organization and the World Coal Institute (since 2010 it has been the World Coal Association) [3, 4]. The term “clean coal technologies” relates to the “whole coal chain” starting from the coal extraction to a utilization of the waste after its use. Four main subdomains of the CCT are distinguished:

- coal extraction taking into consideration sustainable management of resources together with coal preparation understood as a process of preparing coal for being used, most often it is so called coal mechanical preparation,
- coal transport and depositing,
- use of coal (in power engineering and in coal processing), together with all the activities reducing a negative impact of coal usage on the environment (apart from the issues of wastes and “semi-products”),
- management of “residues” from coal usage, i.e. different type of wastes, and also semi-products, suitable for a further economic use.

As far as this scope is concerned, the role of the KOMAG Institute of Mining Technology is crucial, because since its very beginning mechanical preparation of hard coal and other minerals has been an essential field of its activity. In this scope the segment of machines and equipment for a beneficiation of the run-of-mine in heavy medium (DISA separators) and in pulsating water environment (jigs) belongs to the most important ones. Over the years 1955-2019 technical documentations of more than three hundred twenty separators (new and modernized ones), including over two hundred separators in water pulsating environment [5], were elaborated. At present the jigs of KOMAG type for a beneficiation of different grain classes are under construction. They include OM fines jigs for grain class 20-0(0.5) mm, OS medium-size grain jigs for grain class 80(50)-0(0.5) mm and OZ grain jigs for grain class 120-20 mm. The jigs have different modifications resulting from the users’ requirements and installation conditions. Jigs are operated in Polish and foreign hard coal mines – in Brazil, China, India, Romania and Vietnam and their modified constructions – in production plants of aggregates. A modification of jigs’ design enabled to use them for processing of extraction waste deposited on dumps. Due to an improved design of jigs, it is possible to regain coal which is contained in the waste and also aggregates which can be used in the construction industry or road construction technologies. An example of such a classifier is shown in Fig. 1. It is operated in the Plant of Aggregates in Przezchlebie [7]. A list of jigs, designed in the years 1955-2019 and implemented in the Polish hard coal mines, production plants of aggregates and with a destination for export, is presented in Table 1 [6].

A development of pulsatory jigs’ design over years consists in an improvement of technical solutions, aiming at changing technical parameters, which have an essential impact on operational advantages, including quality of obtained coal, production capacity and exploitational costs of a beneficiation process. The conducted research-and-development projects concerned a wide scope of activities, which resulted in innovative technical and technological solutions. Over the years a design of jigs’ working compartments, of pulsatory valves, of sieve decks, of control systems of pneumatic rams and of the systems collecting beneficiation process products was developed. A unique, authors’ System of Pulsatory Jig Control of the KOMAG type (KOGA) together with a bucket conveyor in a jig beneficiation node [6, 8] was implemented. Many innovative solutions are protected by patents.

A design modernization results from many projects realized within the framework of research tasks of the statute activity “Young Scientist” grants, initial and doctoral grants. Some research-and-development, targeted and ordered projects, financed from different external sources, and also European projects with a participation of different foreign and domestic partners, were conducted. An active role of the KOMAG specialists, dealing with a preparation of minerals in the scope of service expert and specialist activities, should be highlighted. As far as the subject-matter of minerals’ preparation is concerned four doctoral procedures were successful. It is worth mentioning that an innovative design solution of a pulsatory classifier obtained the prize at the Fair of Power and Metallurgical Industry in Katowice, in 2007.

The changes of selected parameters in the result of a design development, which can be seen over the period of several dozen years of designing jigs of KOMAG type, are presented in Table 2.

Fig. 1. K-102 No.2 pulsatory classifier built in the installation for a reclamation of extractive waste dump [7]

Table 1. List of jigs of KOMAG type designed over the years 1955-2019 [6]

Period of production	Type of jig	Place of installation
1955-1970	OBM12, OBM15, OBSZ15, OBZ10, OBZ12	Hard coal mines: Anna, Dębieńsko, Knurów, 1-Maja, Nowy Wirek, Mysłowice, Rydułtowy, export to China, India and Vietnam.
1971-1985	ODM10, ODM18, ODZ15, OM12, OM12-2, OM12-3, OM12-3S, OM12G3, OM12P3, OM12L3, OM18P3, OM18L3, OM24-3, OM24D, OM24B3, OM24D3, OZ18L, OZ12, OZ12L, OZ12P3, OS36D3, OZ36D3, OC8, OC10	Hard coal mines: Bogdanka, Borynia, Dębieńsko, Gliwice, Halemba, Knurów, Krupiński, Jankowice, Makoszowy, Marcel, Pniówek, Dymitrow, Rydułtowy, Sośnica, Staszic, Wujek, Szczygłowice, Wawel, Zabrze, Zofiówka, Moszczenica, export to Brazil, India and Romania.
1986-2014	OM8L2e, OM8L2E, OM10L2E, OM15P3E, OM12P3E, OMPE-3x6,5, OM18L3E, OM18P3E, OM20P3E, OM20L3E, OM24P4E, OM24L4E,OM24D3E, OS24D3E, OM30-3E, OM18 3x8, OM30D3E, OS30D3E, OM30, OZ18, OZ18L3E, KOD Jig	Hard coal mines: Andaluzja, Anna, Barbara-Chorzów, Bogdanka, Borynia, Budryk, Dębieńsko, Halemba, Jastrzębie, Jas-Mos, Knurów, Krupiński, Marcel, Pniówek, Rozbark, Rymer, Rydułtowy-Anna, Sośnica, Staszic, Szczygłowice, Wawel, Wujek, Zofiówka, export to Czech Republic and India. Budryk for stone removal.
2003-2018	Pulsatory classifiers: K-100, K-150, K-50, K-80, K-101, K-102, K-151	KSM Ltd in Borzęcin, PPMD KRUSZBET, J.S.C. in Suwałki, PRInż. Surowce Ltd. in Januszkowice, PUHM „M +" Ltd. in Kędzierzyn Koźle, Gravel Mine Bierawa, PRESTO Emil Potręć, Rokitno, Rent-Pol – Przezchlebie
2014-2019	OM30, OS18L, OS18P, OM15L, OM15P, OS4, OM20, OS18L OS18P, OM24, OM15L i OM15P	Hard coal mines: Sośnica, Krupiński, Pniówek, Budryk, Zofiówka, ZG Eko-Plus, ZG Sobieski.

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Table 2. Changes of selected technical parameters of KOMAG type jigs designed over the years 1960-2018

Parameter characterizing the jig	Years of production			
	1960	1970	1975	2018
	Type of jig			
	OBM12	ODM18	OM24	OM24
Nominal capacity, t/h	125	250	500	640
Unit capacity (for 1m^3 of sieve),t/h	10.5	14.0	20.8	26.7
Jig weight, t	120	70	40	41
Consumption of compressed air, m^3 /min	200	140	100	90
Consumption of water, m^3/h	1800	1200	1000	900
Total installed power of equipment, kW	250	200	130	110
Imperfection coefficient	0.20	0.16	0.15	0.15

In the scope of the coal mechanical preparation KOMAG design-and-research projects also concerned hydrocyclones, for example a type-sites of hydrocyclones “water only” of diameters: 300, 225 and 150 mm, screens and crushers. They are essential elements of technological preparation systems. Design projects from this scope, based on technical documentations, were implemented into industrial practice successively.

Thus the activity of the KOMAG Institute of Mining Technology, in the scope of clean coal technologies, consists in improving machines and equipment for use in mechanical preparation plants in mines which enables to obtain beneficiated coal of high quality parameters and when used in plants of aggregates – to liquidate the mining waste dumps as well as to gain valuable sources for an industrial use.

3. Dissemination of knowledge on environmental protection

Presenting KOMAG achievements in the scope of environmental protection, it is worth giving some information about the KOMEKO scientific and technical conferences which have been organized by the Institute since the year 2000 (since 2019 it has been named KOMEKO-IMTech). KOMEKO-IMTech is oriented onto innovative and environment friendly techniques and technologies for processing of minerals. The thematic scope of this conference is broad and it incorporates:

- rational management of minerals in preparation and processing systems,
- latest technologies of minerals’ preparation,
- new materials and technologies for a production of preparation machines,
- new design solutions of preparation machines,
- smart mechatronic systems supporting preparation processes,
- automation of preparation processes,
- systems of control, diagnostics and visualization of processes,
- harmful factors in preparation processes – control of hazards,
- ecological aspects in preparation processes,
- modernization trends of preparation plants,
- problems of safety and health protection in preparation plants,
- recovery and processing of industrial wastes,
- innovative technologies of extractive waste management,
- coal gasification technologies,
- methods of production and use of alternative fuels,
- recultivation, revitalization and remediation of degraded post-mining sites,

- beneficiation and gaining rare earth elements,
- systems of supervision, visualization and inventory control of post-mining and revitalized sites,
- closed-loop economy,
- water management.

Organized every year, cyclic conference meetings of Polish and foreign scientists, researchers, representatives of machinery producers and of end-users of minerals' preparation machines and equipment as well as specialists from widely understood environmental protection field, enable to exchange experience and present scientific, technical and implementation achievements realized by scientific and industrial organizations. In total about two thousand participants have taken part in twenty KOMEKO conferences organized so far. Four hundred ninety five papers were presented and published. Descriptions of the achievements, presented during these conferences, were published in a form of conference proceedings, monographs and they were also published in the KOMAG Quaterly "Maszyny Górnicze" (Mining Machines). In 2019 some of the presented papers (nineteen) were published in English in the conference proceedings IMTech – Innovative Mining Technologies, in a form of Open Access in the IOP Conference Series: Materials Science and Engineering, Volume 545.

4. Summary

The activities of the KOMAG Institute of Mining Technology, conducted during nearly all the period of its functionning, respond to needs and development trends of science and technology in the scope of environmental protection. These activities give extremely valuable research results which are beneficial for the national economy and also for each citizen of our country, who lives in this environment.

The undertaken activities effectively reduce, and in many cases eliminate, hazards generated by an industry development. A multi-year experience of the KOMAG researchers, a significant role of the Institute, which is highly appreciated both in Poland and abroad, confirm its high scientific, technological and technical position in the European Research Area.

All the achievements of the past contribute to a further development of the KOMAG Institute of Mining Technology, strengthening its position in all the spheres of activities described in this article.

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