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Increasing the wear resistance of mining machines equipment tools by FCAW with Fe-Mo-Mn-B-C hardfacing alloys

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Abstract:

In this study hardfacing by flux-cored arc welding with Fe-Mo-Mn-B-C-based alloy as an alternative technique for improving wear resistance of mining machines conical picks was investigated. The microstructure of hardfaced layer consists of the uniformly distributed faceted grains of binary $(Fe,Mn)Mo_2B_2$ boride phase with average size of 25 µm and austenite-based eutectic. The hardness measured by microindentation and microscratching techniques across the interfaces between deposited layer and base steel was within 2.2 – 18 GPa. No welding defects such as cracks, pores or non-metal inclusions in the hardfaced layer and heat affected zones were detected. Comparative studies of the developed hardfacing alloy with commercially available Capilla HR MAG hardfacing and heat treated 35HGS steel were carried out using testing machine developed at the department of machinery engineering and transport of AGH university of science and technology for semi-industrial wear tests of mining machines conical picks. Wear measurement results show that using hardfacing with proposed alloy of Fe-Mo-Mn-B-C system leads to decreasing of impact-abrasion wear rate in approximately 3 times than that for tested commercial materials. This allows to recommend hardfacing by FCAW with proposed material in form of flux-cored wire for conical picks insert holders' surfaces during mining of hard rocks.

Keywords: hardfacing, iron-molybdenum boride, impact-wear resistance, manganese austenite, mining tools

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1. Introduction

Milling heads of the mining machines in many cases are equipped with a conical cutting picks consisting of a steel holder part and cemented carbide (usually WC) insert. Due to high rates of impact-abrasion wear, occurring during underground excavation and fragmentation of hard rocks or coal, the durability of cutting picks remains very low. In some cases, conical picks need to be replaced with a new ones, even after several hours of mining operations [1]. Considering recent increasing trends in tungsten raw materials pricing, such low operational conditions of conical picks need significant additional costs. Analysis of the recent progress in WC-based cemented carbide development [2, 3] allows to conclude that the most desirable relationships between its hardness toughness and strength are almost reached, so they might be improved only within a narrow range by grain refinement, improving sintering techniques, binder alloying, etc. Besides, the pick inserts materials for different working environments only limited by WC-Co cemented carbides of B1, B2, B20, B23, G15 and similar grades are suitable [4, 5] for the pick's inserts. Moreover, in many cases cemented carbide inserts might be chipped out from the holder into the working zone due to the low abrasion resistance of the insert holder cylindrical and conical surfaces. The most widely used insert holders' materials are low alloyed mild carbon heat treated steels of GOST grades 40H, 40HN, 36HNM or 35HGS. So, the maximum surface hardness of the sample holder is about 45 HRC, cannot provide sufficient protection against abrasion wear, especially in aggressive abrasive environments with high particles microcutting ability. For these reasons, many investigations aimed at surface engineering technologies of increasing hardness and wear resistance, including laser cladding, physical vapor deposition (PVD) [3, 6, 7], hardfacing with rod electrodes and flux-cored wires (FCAW) [8, 9]. Using of hardfacing processes allows to obtain multilayered coatings with thickness up to 3-5 mm and hardness within 55 – 65 HRC. However, the most widely used commercial hardfacing electrodes are the high-chromium hypereutectic alloys with high amount of coarse-grained M_7C_3 – type carbides, characterized by very limited resistance at the impact loads due to low fracture toughness [10, 11]. Therefore, development of a new hardfacing materials with increased resistance to impact wear together with high resistance to abrasion is an important direction in improving durability of conical picks. The promising hardfacings for such purpose are the electrode materials based on Fe-Mo-B-C alloying system [9, 12], where *in situ* formation of $FeMo_2B_2$ hard phases in form of faceted uniformly distributed grains occurs, as a result of chemical reaction in electrode flux. It is expected that extension Fe-Mo-B-C system by Mn addition can provide formation of manganese austenite, exhibiting ability to deformation hardening during impact.

The present research aimed at development of a new Fe-Mo-Mn-B-C-based alloying system for FCAW hardfacing of conical picks used in mining machines as well as evaluation the impact-abrasion wear behavior of hardfacing deposits in comparison with commercially available hardfacings and materials.

2. Materials and Methods

Flux-cored wires for hardfacing were prepared by drawing the dried mixture of commercial available Mo powder of MPCh grade with average particle size of 5 μm, boron carbide (brand 2V ISO 9001:2008), ferrosillicomanganese (grade MNS17) and arc protection components into the low carbon steel sheath. The cross-section of resultant flux-cored wires was equal to 8×2.5 mm^2. Samples for investigations were prepared by arc hardfacing in two layers on the mild carbon steel (St.3) substrate in flat position at the following welding parameters: current 180 A, voltage 34-36 V and reverse polarity. The samples with dimensions of 10×20×40 mm were cut from hardfaced plate for hardness measurement, wear resistance investigation, macro- and microstructure observations. Microstructure was examined by means of scanning electron microscopy adjusted in backscattered electron diffraction mode using ZeiSS EVO 40 XVP electron microscope. Average values of grain size were measured by random intersections technique for at least 50 randomly chosen grains. Qualitative and quantitative determination of the chemical composition at the hardfaced layers was examined by energy-dispersive X-ray spectroscopy (EDS) technique. Scratch tests across the "deposition − base

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metal" interface and heat affected zones were carried out using diamond Vickers indenter (pyramid) by "edge ahead" scheme and PMT3M microhardness tester. According to GOST 21318-75 the scratch hardness (Hs) was calculated by following formula:

$$H_S = \frac{3.782 \cdot F}{b^2}, \quad (1)$$

where F is the normal force acting on the indenter (kgf); b is the track width (mm^2) after scratching. The apllied force during microindentation and microscratching tests was set to 0.1 kgf.

The typical chemical composition and hardness of the top hardfaced layer with the experimental harfacing alloy (EPM2), commercial hardfacing of the Capilla brand (Germany) and commercial heat treated mild carbon steel can be seen in Table 1.

Table 1. Characteristics of the conical picks insert holders used for comparative study

Sample	Chemical composition, wt. %								Hardness, HRC
	Fe	Mo	Cr	Mn	B	C	Si	WxCy	
EPM2	Balance	29	-	6.7	3.4	1.1	1	-	62
Commercial steel, 35HGS	Balance	0.1	1.2	1	-	0.35	1.2	-	54
Commercial hardfacing, Capilla HR MAG	Balance	-	-	0.1	-	0.05	0.3	50	55

To perform wear tests in conditions which is close to the real mining processes hardfaced conical picks as well as the serial ones were tested using semi-industrial testing machine (Fig. 1), developed at the department of machinery engineering and transport of AGH university of science and technology [8]. Four conical picks samples of each type were located at different angles with respect to the monolithic abrasive block surface providing different degrees of interaction with abrasive environment.

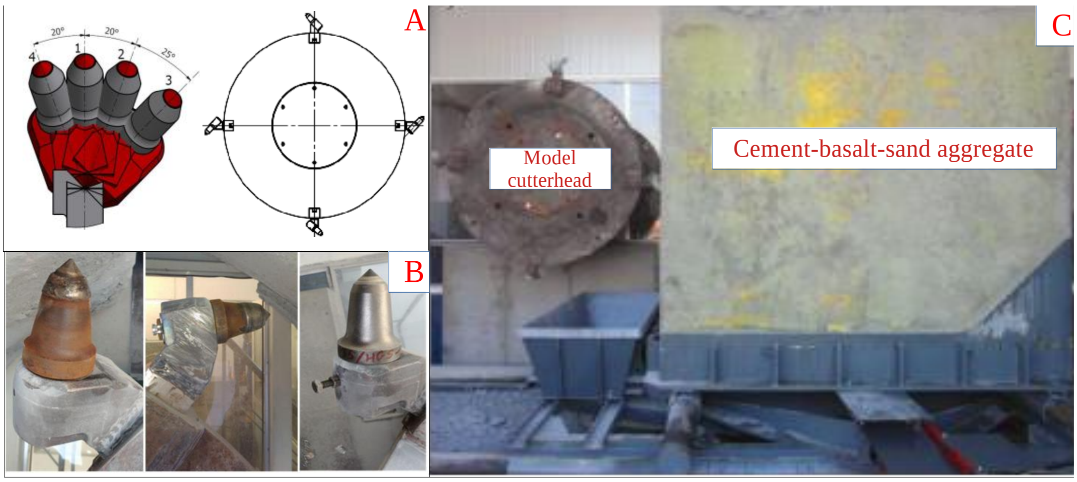

Fig. 1. Experimental conical picks testing [8]:
A – relative positioning of the conical picks samples in the model cutterhead,
B – fixed conical picks of different types, C – general view of the testing machine

Wear tests were performed at the main following parameters: cutterhead rotational speed – 42 rpm, cutting speed – 0.05 m/min, cutting distance – 50 mm, worn abrasive volume per set of picks – 0.5 m^3. The wear resistance of the samples was determined by measuring mass loss using analytical axis with measurement accuracy within 0.01 g. Hardfaced layers were deposited on the conical surfaces near the cemented carbide tips along the annular trajectories and in the form of longitudinal parallel layers (Fig. 2).

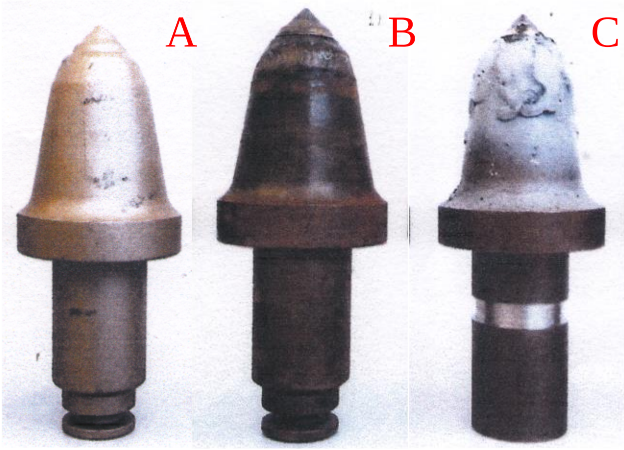

Fig. 2. The general view of tested conical picks: A – heat treated steel of 35HGS grade, B − Capilla HR MAG hardfacing, C – EPM2 hardfacing of Fe-Mo-Mn-B-C system

3. Results

Resulting microstructure of the EPM2 hardfaced top layers (Fig. 3, A) consists of faceted sharp-edged grains of refractory superhard (Fe,Mn)Mo_2B_2 phase which are uniformly distributed in matrix metal represented by fine dispersed plate-like austenite + (Fe,Mn)Mo_2B_2 eutectic. The average size of binary boride reinforcements is about 25 μm and its total amount is approximately 30% by volume. Microstructural observations of the regions at the interfaces between hardfaced coating and base steel (Fig. 3, B) show the presence of significantly finer microstructure, where (Fe,Mn)Mo_2B_2 grains with size within 1-2 μm acts as nucleation cores for eutectic formation. In the normal direction to a visible boundary between coating and base metal, there are columnar austenite grains with dendrite structure which are typical for welding joints obtained using electrodes of austenite type. No welding defects such as macropores, cracks, non-metal (slag) inclusions, delamination etc., were detected along the interface, indicating the strong metallurgical bonding between deposition and base metal. The microindentation tests show that hardness of hardfaced layer is within 11.5 – 18 GPa, while base metal remains relatively soft (tough) having hardness of 250 HV.

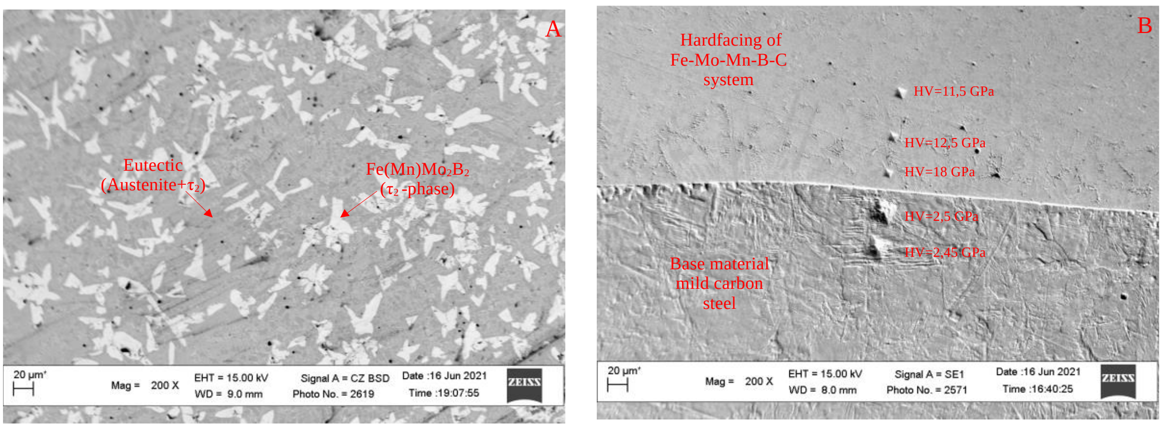

Fig. 3. Microstructures of the investigated EPM2 hardfacing alloy:
A − microstructure of the top layer, B − microstructure of the harfacing – base metal interface and related microhardness tests results

The results of microscratching tests performed in the normal direction to the coating – base metal interface (Fig. 4) show that transition zone has relatively low length (60 μm), where hardness smoothly increases from 2 to 12 GPa. The next narrow characteristic zone with length of 40 μm has the highest hardness (12 GPa), which is probably caused by significant structure refinement by high solidification speed due to significant temperature gradient. The scratch hardness in next region, corresponding to the main amout of deposited alloy remains practically unchangeable within 10-11 GPa on the rest cross-sectional area.

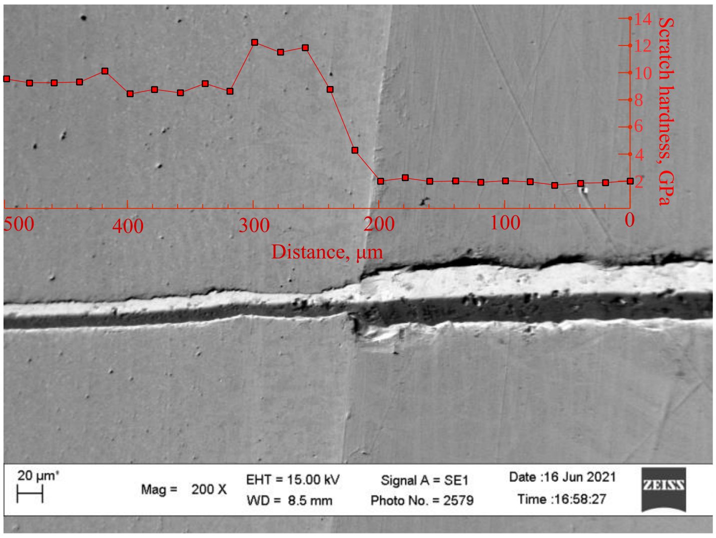

Fig. 4. Results of scratch tests of the EPM2 hardfacing

Wear resistance tests results performed using hardfaced and serial conical picks are shown in Fig. 5. As can be seen from figure the most difficult working conditions of interaction with a abrasive block is observed for conical picks placed in position № 2. These samples exhibit highest wear rate measured by mass loss for all investigated materials. However, the value of wear resistance for the experimental hardfacing EPM2 of a Fe-Mn-Mo-B-C system is almost in 2.75 and 3.75 times higher than that for Capilla HR MAG hardfacing and heat treated commercial 30HGS steel, respectively. It should be noted, that wear rate of commercial materials tested in other positions (№1, №3 and №4) are similar and lower by 10-20%, while the wear rate of EPM2 hardfacing in position № 1 is almost equal to that in position № 2. Despite this, experimental hardfacing still shows lowest wear rate among all investigated materials.

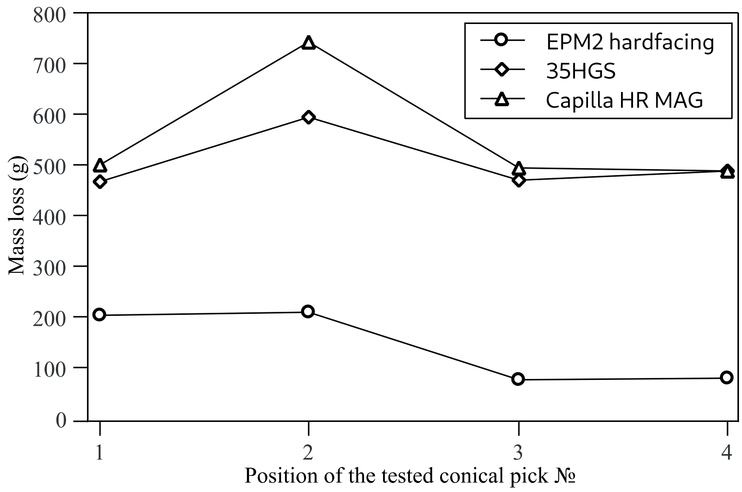

Fig. 5. Relationship between position of conical picks and its wear resistance for different tested materials

4. Discussion

The analysis of the microstructure of the experimental hardfacing of the Fe-Mo-Mn-B-C system allows to classify the type of obtained alloy as hypereutectic boride-austenitic. In contrast with the most widespread hypereutectic high-chromium hardfacing alloys the morphology of the reinforcing phase is much closer to the equiaxial form providing higher resistance to impact and cyclic loads. However, hardness of the $Fe(MoB)_2$ complex boride phase is more than 25 GPa which is in two times higher than for M_7C_3-type chromium enriched carbide and close to the mixture eutectic tungsten carbides. The further increasing of the hardness for the $Fe(MoB)_2$ might be reached by partial dissolution of the Mn in crystal lattice sites occupied by Fe. Another important role of Mn in the alloy is the promoting of stable austenite phase formation, with high deformation hardening ability. In the given case such high-manganese austenite phase allocated in form of thin layers in eutectic colonies with boride phase, providing resistance to crack propagation.

It is important to note that there is no direct relationship between hardness and wear resistance under impact-wear conditions. So, both the structure morphology features and phases mechanical properties are proved to perform the key role in resistance to impact-abrasion wear. According to this viewpoint, the *in situ* formed, during arc hardfacing, complex superhard refractory boride phases is sufficient to improve the wear resistance.

5. Conclusions

The development of new hardfacing material of a Fe-Mo-Mn-B-C system for the improving impact-wear resistance of mining machines conical picks has been studied. It was shown that componets of a given alloying system used in flux-cored wires allows to obtain coatings with high microhardness due to the *in situ* formation of complex refractory borides of $(Fe,Mn)(Mo,B)_2$ acting as reinforcements in hypereutectic austenite-boride alloys. The semi-industrial tests show that such type of alloys can be suitable for practical using, because of their impact-abrasion wear resistance, which is higher than that for tested commercial tungsten enriched hardfacing and serial heat treated steel in 2.75 and 3.75 times, respectively. The further investigations are planned to be aimed on automation of hardfacing processes within given alloying system to reach higher deposition productivity and accurate layers geometry.

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Increase in the production capacity of a hard coal mining plant

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Abstract:

During the current war in Europe and the restriction of hydrocarbon imports to the EU, there was a need to temporarily increase the production capacity of hard coal mining plants in order to ensure continuity of supply. This requires an increase in the number of longwall excavations (which is time-consuming and requires additional financial resources) or an increase in the efficiency of already operated longwall excavations. The article presents how the organization of the longwall ancestor's work would be shaped with ad hoc production work 24 hours a day, assuming a five-day working week, i.e. from Monday to Friday.

Keywords: hard coal mining plant, production, effectiveness, economic effects

1. Introduction

Socio-political changes initiated in Poland due to EU membership require ensuring profitability in the energy sector and in the entire hard coal mining industry. The sector should be adapted to the requirements of the concept of sustainable development and the so-called "Green Deal" of the EU, while maintaining competitiveness in the market of energy resources. The adaptation of the Polish hard coal mining industry to the realities of the market economy is a process that affects the entire Polish economy. This entails the necessity of radical technical and organizational changes, and consequently leads to reduction of employment in the Polish mining industry, the liquidation of unprofitable mines and mining regions, and the restructuring the unnecessary non-productive assets. Moreover, Poland is currently facing the challenge of decarbonising its economy [1-8].

In these circumstances and legal requirements, the mining sector faces the challenge of a "state-of-the-art enterprise" characterized by: technology, economy, market and management. TECHNIQUE and technology is the modernization of technologies, introduction of new devices, adaptation to ecological requirements. ECONOMY is a comprehensive and continuous cost-effectiveness account, confrontation of economic results and expenditure, cost-effect ratio, optimization of decisions according to efficiency criteria, collection and use of broadly understood capital. MARKET is liberalism, a freely operating demand-supply market mechanism and marketing as activities adjusting the enterprise to external conditions. MANAGEMENT orientation on the effective use of resources: devices, people, financial resources. Therefore, modern tools should be used and people's behaviour should be effectively managed [9,10,11].

The issue of the effectiveness of the organization's functioning is one of the most important subjects of interest for both management theorists and practitioners [12].

Effectiveness of the enterprises functioning can be considered in organizational or economic terms. Ziębicki defines organizational effectiveness as: "*a broad category relating to the positive results and attributes of an organization*" [13]. "*Most often it is expressed in general terms as the ability of an organization to achieve its operational goals*" [13]. On the other hand, economic efficiency is a narrower concept. It is examined as the relation of results to expenditures incurred to achieve them. "*Efficiency defined in this way is widely used in research projects in the field of economic theory and business economics* (...)" [14, 15]. In the literature on the subject, attention is drawn to the need to take into account the specificity of enterprises, when measuring their operational efficiency and selecting proper indicators.

Taking into account the requirements of the so-called the EU "green deal" [16], adjusting management to the requirements of modern economic reality, the need to reduce production costs, improve operational efficiency, are today the main determinants of the activities of hard coal mining entities [5, 6, 10].

An additional impulse during the war in Europe and the blockade of hydrocarbon imports is the need for a possible immediate increase in the production capacity of hard coal mining plants to ensure the demand for energy carriers. In the case of mines or the entire hard coal mining sector, which is currently in the process of shutting down – restoring the mining capacity takes months or even years. In many places it is no longer possible due to the changed directions of mining, the commenced process of liquidation of mining regions and entire mining plants. As for the constant increase in mining capacity, it is possible with a large amount of financial investment and legal changes, but it is an investment process for many years.

2. Materials and Methods

With regard to technical restructuring the mines, the main objectives are the rules that enforce the so-called concentration of mining, consisting in extending longwall panels to about 2,000 meters and increasing the length of longwall faces to about 250-300 meters. Output from the longwall face is planned to reach 5000-8000 Mg/d. Achievement of such a goal is possible with drawing the special attention to the following issues:

- high reliability of the technical equipment of the longwall faces and run-of-mine transport,
- increasing the efficiency of the machines used, along with increasing the power of the machines,

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- ensuring an appropriate advance of preparation work, adapted to the required advance of the longwall face,
- improvement of efficiency by reducing the amount of coal fines, and thus increasing the volume of bigger size of coal in run-of-mine,
- improved quality of run-of-mine, in particular with regard to thin seams, which reduces the costs of mechanical processing of coal and transport,
- improving the methane drainage systems of the deposit to obtain the required daily output,
- deposit management achieve of the technical goal.

Thus, the effectiveness of a properly designed mechanization system depends to a large extent on the so-called concentration of mining production and cost reduction. Overall costs can be divided into two groups:

- operational costs which are only slightly changing,
- costs related to the organization of production.

Costs are a part of the company's strategy that must be constantly adapted to the rules of the market. The costs of implementing a specific project (longwall mining) consist with the following costs:

- human (e.g. longwall personnel),
- material (e.g. cost of purchase or lease of machines and equipment, costs of their operation, including the daily use of the machine),
- financial (e.g. expenditures),
- information (e.g. expert opinions, documentation).

The materials are part of the costs that have the greatest impact on the profitability of the mining plant and therefore should be minimized as much as possible. This can be achieved through a better organization of work to maximize the effective daily use of the working time of machines and equipment. This will lead to an increase in the profitability and thus will enable the company more dynamic development [1,3 6,9,10,18].

Advance of the longwall face may be limited by external conditions (natural geological constraints, e.g. CH_4, water, rock bursts), on which we have a limited impact as well as organizational conditions. Just, the organizational conditions are the biggest obstacle to increase efficiency, which we may modify. The maximum daily working time of machines and equipment will significantly improve the efficiency of the longwall face production. Organizational conditions that disturb increasing the effectiveness and efficiency of the longwall face can be divided into four basic groups: machine, electrical, ventilation and mining. By extending the daily effective working time of machines, we increase (with the same employment) the unit profit on the mined coal per one employee. This will lead to cost reduction, i.e. the theoretical possibilities of a given longwall face [1,3 6,9,10,18].

3. Assumed results

With the current technical and organizational knowledge, the longwall face can operate 24 hours a day, assuming work from Monday to Friday. The improvement of the work organization should consist in designing the longwall panel in such a way to achieve the goal. Limitations in the continuous operation of the longwall, can be eliminated by using machines and devices that meet the criterion of continuous operation. If the planned longwall face does not show significant signs of geological limitations, then the only criterion limiting continuous operation is the proper selection of machinery and equipment as well as work organization. The basic limitations of the continuous advancement of the longwall face can be conventionally divided into:

- Mining limitations – the longwall panels should be previously secured as not to affect the advance of the longwall face. On the other hand, components necessary for mining should the transported on an ongoing basis.

- Machine limitations – this is delivery of a medium necessary to supply powered roof supports, process water and compressed air (pipelines should be shortened on a day off, e.g. Saturday). Another problem is shifting of the stage loader, on an ongoing basis as the longwall face advances. However, shortening the route of the belt conveyor should take place on Saturdays.
- Electrical limitations – design the power supply to machinery and equipment to allow the advance of the longwall face for five days of the week. The power supply conversion will take place as in the previous restrictions on a day off, e.g. Saturday.
- Ventilation limitations – preparation of a proper technology for methane drainage of the longwall face as well as power supply and reinstallation of fans allowing for smooth operation of the longwall.

Maintenance should take place on Saturday. Currently, most of the maintenance operations is done on Saturday, so the operation does not disturb the mining process. The only break in the mining machine operation - the longwall shearer - should result from technological reasons (e.g. general inspection, methane measurements, replacement of cutting bits) [1,3-6,9,10,18].

Further part of the article presents averaged, real data in the mining plant production and its unused possibilities. Three longwalls of the mining plant were analysed for one month. Then, it was analysed to what extent the longwall shearers were used in longwall panels on the example of the whole plant within one year. Degree of the shearer utilization is the time of shearer activity during the day. The analysis covered 4 longwall panels mined for one year. The average degree of use over the entire analysed period is a percentage of operating time that takes into account only the shearer activity during working days, excluding Saturdays, Sundays and holidays.

For analyses, it was necessary to get information on working time, machine failure frequency, based on the ZEFIR dispatching system and daily dispatcher's reports for 1 year. The presented mining plant operated 4 longwall panels (those that ended or started their use in the analysed year were neglected), and the degree of shearers availability was from 0 to 83.33%. The daily production ranged from 0 to 7,920 Mg/d [5,17].

The mining plant output per month

Mining in longwall faces differed in number of shifts. One had 2 shifts, the other had 3 shifts, and the third one 4 shifts. All longwall faces had one maintenance shift. The longwall faces also differed in the effective working time (Table 1) [17].

Table 1. Daily output, price per Mg, economic result on sales [17]

Item	Day of month	Net output Mg per day	Coal price PLN/Mg	Profit from sale PLN
1	2	8190	247.65	2028253.5
2	3	8010	277.21	2220452.1
3	4	9210	266.33	2452899.3
4	5	10010	274.76	2750347.6
5	6	10380	264.82	2748831.6
6	9	11050	261.16	2885818
7	10	9460	245.01	2317794.6
8	12	10170	263.35	2678269.5
9	13	10500	265.49	2787645

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10	16	9720	280.58	2727237.6
11	17	9540	246.28	2349511.2
12	18	9000	266.46	2398140
13	19	9210	275.26	2535144.6
14	20	8560	276.06	2363073.6
15	23	10000	280.7	2807000
16	24	9000	239.97	2159730
17	25	10170	255.15	2594875.5
18	26	8820	268.35	2366847
19	27	10040	247.44	2484297.6
20	30	8010	233.9	1873539
Total per month		**189 050**	**5 235.93**	**49 529 707.30**
Average per day		**9 452.50**	**261.79**	**2 476 485.36**

Table 1 shows that over the one month analysis, i.e. 20 workdays, and the daily coal output varied each day, averaging 9452.5 Mg. The average coal price was 261.79 PLN/Mg, and the daily sale reached 2,476,485.36 PLN.

During analysis, the average daily breaks caused by failures and the effective operation of shearers were different depending on the failure rate and geological conditions (Table 2).

Table 2. Real breakdowns caused by failures per day, effective daily operation of the shearer as well as possible shearer operation during a day without failures [5,17]

Item	Day of a month	Breakdowns caused by failures per day		Effective daily operation of the shearer		Possible shearer operation during a day without failures	
		min.	[%]	min.	[%]	min.	[%]
1	2	1180.00	27.31	1399.68	32.40	2579.68	59.71
2	3	1140.00	26.39	1291.68	29.90	2431.68	56.29
3	4	700.00	16.20	1715.04	39.70	2415.04	55.90
4	5	340.00	7.87	2077.92	48.10	2417.92	55.97
5	6	390.00	9.03	2077.92	48.10	2467.92	57.13
6	9	210.00	4.86	2125.44	49.20	2335.44	54.06
7	10	385.00	8.91	2039.04	47.20	2424.04	56.11
8	12	195.00	4.51	2190.24	50.70	2385.24	55.21
9	13	30.00	0.69	2302.56	53.30	2332.56	53.99
10	16	145.00	3.36	2142.72	49.60	2287.72	52.96
11	17	275.00	6.37	2043.36	47.30	2318.36	53.67

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12	18	240.00	5.56	1935.36	44.80	2175.36	50.36
13	19	415.00	9.61	1995.84	46.20	2410.84	55.81
14	20	365.00	8.45	1995.84	46.20	2360.84	54.65
15	23	370.00	8.56	2125.44	49.20	2495.44	57.76
16	24	560.00	12.96	1710.72	39.60	2270.72	52.56
17	25	390.00	9.03	2095.20	48.50	2485.20	57.53
18	26	775.00	17.94	1844.64	42.70	2619.64	60.64
19	27	270.00	6.25	2013.12	46.60	2283.12	52.85
20	30	690.00	15.97	1913.76	44.30	2603.76	60.27
Total		**9 065.00**	**209.84**	**39 035.52**	**903.60**	**48 100.52**	**1 113.44**
Average		**453.25**	**10.49**	**1 951.78**	**45.18**	**2 405.03**	**55.67**

Table 2 presents average possible shearer operation during a day without failures, which is 55.67% of a day, effective operation 45.18% as well as breakdowns caused by failures, which consume 10.49% of time.

Coal production and potential output of the mining plant

The results are presented in Tables 3÷5 and Figures 1÷4.

Analysis of Table 3 and Fig. 1, shows that during the time covered by the analysis, the average breaks caused by failures, due to the additional mining shift increased by 3.50%. On the other hand, the effective working time of the shearer increased to 15.06% per day. The table also shows the possible operation of a shearer without failure, which will increase to18.56%. The effective average available working time of a mining plant due to an additional mining shift would be 74.23% of the day.

Table 3. Breakdowns during a day, effective daily operation of the shearers and possible daily operation of the shearer without breakdowns depending on the number of mining shifts [5,17]

Number of shifts	Time of breakdowns a day		Effective operation of a shearer a day		Possible time of operation of shearers without failure a day	
	hour	[%]	hour	[%]	hour	[%]
3	2.52	10.49	10.84	45.18	13.36	55.67
4	3.36	13.99	14.46	60.24	17.82	74.23
Difference	**0.84**	**3.50**	**3.62**	**15.06**	**4.46**	**18.56**

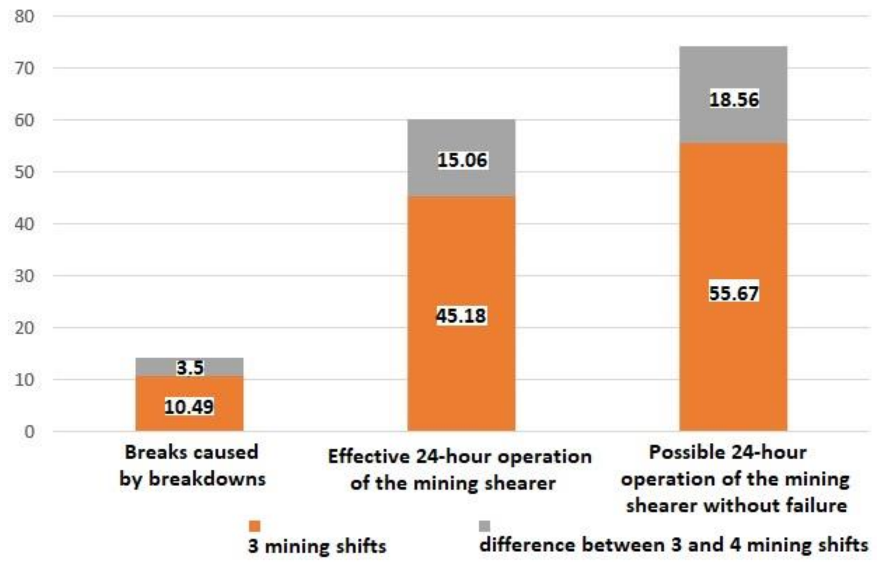

Fig. 1. Time of breakdowns during a day, effective operation of the shearers per a day and possible operation of the shearer per a day without breakdowns depending on the number of mining shifts [%] [18]

Table 4 and Fig. 2 and 3 show that comparison of the daily output for three and four shifts shows increase of the mining plant output to 3,150.8 in the case of four shifts [Mg] and difference in the economic result on sales was 822,941.2 PLN/24h.

Table 4. Daily output and economic result on sales for three and four mining shifts – additional profit of the mining plant [17]

Number of shifts	Additional output Mg/24h	Additional sale profit in PLN/24h
3	9 452.50	2 476 485.40
4	12 603.30	3 299 426.60
Potential capacity	**3 150.80**	**822 941.20**

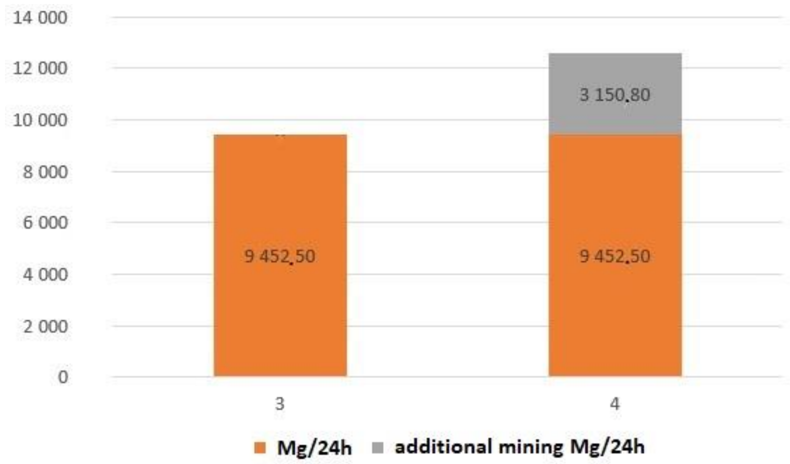

Fig. 2. Additional mining Mg/day depending on number of shifts [17]

Fig. 3. Additional profit from sale in PLN depending on number of shifts per day [18]

Analysis of Table 5 and Fig. 4, shows that during the analysis, the difference (average) in monthly output by increasing the number of shifts from three to four total output would increase to 63,016 Mg and monthly sales profit would amount to PLN 16,458,824.

Table 5. Monthly production and economic result on sales for three and four mining shifts and potential profits of the mining plant [17]

Number of shifts	Net production Mg/month	Profit from sale PLN/month
3	189 050	49 529 708
4	252 066	65 988 532
Potential profits	**63 016**	**16 458 824**

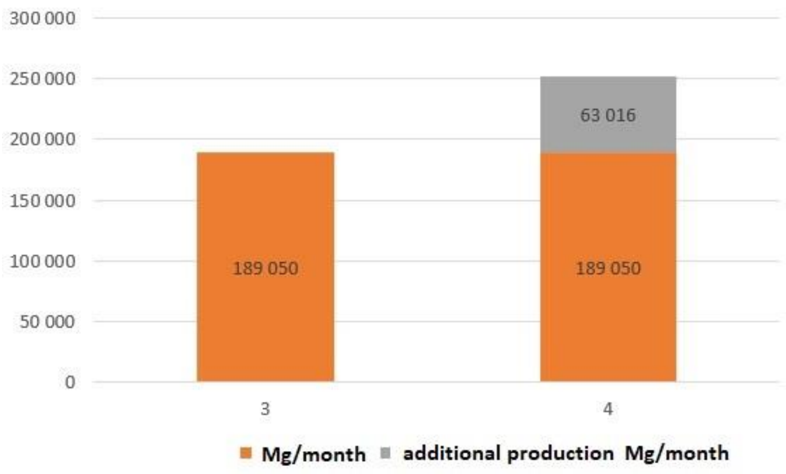

Fig. 4. Net production in Mg/month depending on the number of shifts [18]

Over the time of analysis, the average shearer availability was 43.725%, while the potential shearer operational capacity increased by 14.58% (Table 6). The average daily production during one year was 11,470 Mg/d, while the loss (potential profit) was 3,820 Mg/d. The average economic result on sales amounted to 3,002,731 PLN/day, while the potential profits of the mining plant amounted to 1,000,910 PLN/day. For the purposes of the analysis, the average unit price of coal was assumed as 261.79 PLN/Mg.

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Table 6. Actual average availability of shearers 24-h production and economic result from sales [18]

Item	Shearer type	Average availability for the entire period of longwall mining %	Average daily production for the entire longwall mining Mg/day	Average economic result on sales in PLN/24-h (unit coal price 261.79 PLN/Mg)
1	Joy 4LS20	34.5	2164	566 513.6
2	Electra 1000/A	39.4	2724	713 116
3	Electra 1000	56	4808	1 258 686
4	Eickhoff SL-300	45	1774	464 415.5
Total		**43.73**	**11470**	**3 002 731**
Potential capability		**14.58**	**3823**	**1 000 910**
Total possible		**58.3**	**15293**	**4 003 641**

The analysis based on the "Zefir" dispatcher system, gives some idea of the shearer's availability but it is not accurate enough. The data from this system show only the shearer's on/off status, not indicating whether the shearer's active operation is the result of mining, idle operation or the shearer maneuvering. A more detailed analysis is possible if the load to the shearer's driving motors is also analyzed. This would enable excluding the idle operation or the shearer maneuvering.

4. Conclusions

The article presents a comparative analysis of a mining plant output, profits from sales, possible capacity, failure breaks, shearer's effective operation time and possible shearer's operation time without failure and its dependence on the number of shifts. As a result of introduction of the fourth shift, production capacity of the mining plant will significantly increase, positively affecting the potential profits of the plant. Consequently, it will contribute to the improvement of the economic results. The four-shift work system enables extending the working time of the mining plant during the year, an increase of the annual output by about 25%, with the employment system of unchanged. The assumption of continuous operation of the mining plant from Monday to Friday will not increase the number of underground personnel and the costs of remuneration, and costs linked with remuneration, as longwall faces still work in a four-shift system. The fourth maintenance shift employs a comparable number of employees and therefore these changes were not included in the calculation.

However, to implement continuous mine operation, it is necessary to implement prediction of mining machines and equipment condition. Prediction allows to determine the future condition of objects due to continuous measurement, constant monitoring (also in real time), analysis of the current and historical states and estimation of future parameters. As a result, it is possible to plan optimal maintenance, repair, replacement and other work that minimize failures and allow to extend time between failures. Taking preventive measures at the best possible time enables more effective prevention, but also removes failures.

Thus, the financial effect for the mining plant, resulting from the introduction of the continuous work system, including the remuneration costs of the staff working in this system and costs related to remuneration, is positive. Higher concentration of production in the face, also by increasing the number of shifts reduces costs [5, 6]. However, use of continuous operation of the mining plant leads to faster exploitation of the mining front (longwall), which requires opening the subsequent operating fronts in due time.

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Innovative technology for inertization of goaf in operating longwall panel – presentation of gained experience

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Abstract:

The article presents an innovative technology of fire prevention in goaves, based on injection of nitrogen and carbon dioxide inert gases mixture from treatment of exhaust gases from a methane combusting gas engine. The developed innovative technology and the constructed prototype of the installation producing inert gases are the final result of the research project entitled "Innovative and effective technology of inerting the goaf active or dammed longwall in an underground mining plant, extracting hard coal, using mixtures of inert gases obtained from the purification of exhaust gases from a gas engine and preventing the formation of endogenous fires", co-financed by the National Center for Research and Development (NCBR). The prototype installation was demonstrated in real conditions at the "Borynia" part of "Borynia-Zofiówka" mine, where, at the end of the research project, the prototype and the developed fire prevention technology with the use of gas engine exhaust gases were optimized and validated. Until now, under normal conditions in a hard coal mine, the fumes generated as a result of methane combustion in gas engines were emitted directly to the atmosphere. Innovative inerting technology, processing and reusing the exhaust gases produced by methane-fueled gas engines, in ecological context will contribute to the reduction of pollutant emissions in the mining sector, and, with mixing at the same time the carbon dioxide and nitrogen in the proper ratio in the mixture, it will fully utilize the advantages of each of these gases, as known when used in separate form. As a result, considering the possibility of generating a much higher amount of inert gases per time unit compared to the available technologies, and combining the physicochemical properties of nitrogen and carbon dioxide in one mixture, the innovative technological solution significantly increases the effectiveness of fire prevention, thus reducing the possibility of an endogenous fire.

Keywords: endogenous fires, fire hazard prevention, intertization, diesel engine, catalyst, purification of exhaust gases

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1. Introduction

Currently, in hard coal mines, inert gases are supplied through a pipeline system to endogenous fire zones with insufficient efficiency in the result of technological and cost limitations. The issue of ventilation optimization of, goaf sealing and inertization of extinguishing technology to improve the safety of mines in longwall faces is also analysed through numerical modelling (CFD) [1,2,3]. To enable effective feeding the gases through the pipeline system, inert gases must meet certain physical and chemical parameters, and the generating equipment must function stably [4,5]. In the case of using the exhaust gases produced by gas engines, it is necessary to clean them of the excessive content of oxygen, carbon monoxide, nitrogen oxides and other harmful substances, as well as cooling them to a temperature of ≈ 20 ° C and compressing them to a pressure of ≈ 6 bar.
The developed innovative technology and the manufactured prototype of the installation producing inert gases are the final result of the research project [6]. Number of tests and optimization of the prototype, including stabilization of composition and amount of inert gases at the appropriate level, assessment of the effectiveness of fire prevention based on chromatographic measurements of the air flowing from the goaf, monitoring the technical parameters of the installation and its impact on the operation of the gas engine [7] enabled obtaining the stability of technological processes and parameters for inert gases. The refined and optimized innovative technology will enable feeding the mixture of inert gases of different specific gravity and in much larger amount to a given hazardous place, filling the space in the goaf with inert gas, ensuring effective fire prevention.

2. Materials and Methods

Analysis of the installation and product stabilization effectiveness in real conditions

After building a prototype installation, each device and system was commissioned, and then, after technical acceptance, a trial run of the installation was approved. Three series of exhaust and inert gas parameters were measured during the trial run. The results of oxygen content measurement exceeding the legal limit of 3% in the inert gas mixture forced a number of changes to the gas flow during the purification process. For this purpose, the system of nitrogen and oxygen generators was changed from serial to parallel. Work was carried out to separate the oxygen generator into two generators operating in series. By-passes were made to supply the gas mixture with a reduced oxygen content to the second oxygen generator. Discharge valves were installed in the gas columns during the oxygen desorption in the generator. Desorption gases in the nitrogen generator were discharged of to the atmosphere [8].

After the validation work on the installation, gases were into the area of the designated longwall A-32 in seam 404/1łg and chromatographic analyses of gas samples were made by the GIG (Central Mining Institute) laboratory. To assess correctness of the installation operation, safety of the personnel and the longwall mining operations, on April 14-23, 2021, daily samples were taken for laboratory analysis - two gas samples from the installation and four gas samples from the A-32 longwall area of the longwall 404/1łg [9.10].

Results from the analysis of gases composition from the installation were the basis for development of documentation at the Central Mining Institute [10] "Evaluation of the efficiency of the catalytic gas cleaning system based on precise chromatographic analysis of gases collected at the system outlet", stating that:

– not exceeding the criterion of O_2 equal to 3% in the inert gas fed through the pipeline, specified in the Regulation of the Minister of Energy of March 16, 2017 on mine rescue [11] confirms the efficiency of the catalytic gas purification system. In the analyzed period from April 14-23, 2021, the oxygen concentration at the outlet of the system was on average 2.6% and it met the condition of not exceeding 3% of the oxygen content in the gas supplied through the pipeline.

– in the above period, the average nitrogen concentration was 95.73%, while the average carbon dioxide concentration was 1.5%. The maximum concentrations of gases relevant to the fire hazard assessment point were: ethylene up to 1.78 ppm, propylene up to 0.02 ppm, acetylene 0.014 ppm, carbon monoxide 52 ppm and hydrogen 0.8 ppm.

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– based on the precise chromatographic analysis of the gases taken at the outlet of the catalytic system, its full effectiveness in gas purification was confirmed.

Results of air composition in the longwall area were the basis for the development by the Central Mining Institute of the documentation entitled "Study of the safety of the crew employed in the workings of KWK" Borynia-Zofiówka" Ruch "Borynia" mine adjacent to the inertisation [10]. Examples of test results for gas samples from the area of the A-32 longwall, seam 404/1 łg are presented in Table 1.

Table 1. Results of chromatographic analysis of gas samples [10]

Laboratorium Samozapalności Węgla

JSW S.A. KWK „Borynia-Zofiówka" Ruch "Borynia"

Lp	Nr wor-ka	Miejsce i data pobrania próbki	C2H6 Etan ppm	C2H4 Etylen ppm	C3H8 Propan ppm	C3H6 Propylen ppm	C2H2 Acetylen ppm	CO Tlenek węgla ppm	O2 Tlen %	N2 Azot %	CO2 Dwutlenek węgla %	CH4 Metan %	H2 Wodór ppm
18	1311	chodnik A-32a - na linii likwidacji - zza TO (datapobrania - 2021.04.16 -) - (woda 1337)	26,9	0,02	8,35	0,03	0,002	3	5,01	92,68	0,32	1,99	4,7
Data wykonania analizy: **2021.04.20** ***(wtorek)***													
Rejon pobrania próbek: **śc. A-32 w pokł. 404/1 łg**													
19	1444	chodnik A-32a - 10m przed przecinką A-31 (wylot) (datapobrania - 2021.04.19 -)	5,59	0,02	0,5	0,01	0,003	1	20,55	78,67	0,12	0,67	1,1
20	1379	chodnik A-32a - 10m przed przecinką A-31 (wylot) (datapobrania - 2021.04.19 -) - (woda 1338)	10,9	0,02	0,69	0,01	0,005	1	20,53	78,58	0,13	0,76	1,4
21	1295	zza ostatniej sekcji (datapobrania - 2021.04.19 -)	30,2	0,02	8,3	0,01	0,004	1	13,56	84,12	0,29	2,03	3,0
22	1336	zza ostatniej sekcji (datapobrania - 2021.04.19 -) - (woda 1326)	33,4	0,02	8,84	0,03	0,003	3	13,81	83,74	0,30	2,15	3,3
23	1182	chodnik A-32a - na linii likwidacji (datapobrania - 2021.04.19 -)	32,3	0,02	9,	0,02	0,002	3	12,87	84,80	0,29	2,04	3,0
24	1357	chodnik A-32a - na linii likwidacji - zza TO (datapobrania - 2021.04.19 -) - (woda 1324)	35,5	0,02	9,58	0,02	0,002	3	11,86	85,58	0,31	2,25	3,3
Data wykonania analizy: **2021.04.21** ***(środa)***													
Rejon pobrania próbek: **śc. A-32 w pokł. 404/1 łg**													
25	silnik 07	chodnik A-32a - 10m przed przecinką A-31 (wylot) (datapobrania - 2021.04.20 -) - (woda - silnik 08)	11,2	0,02	0,91	0,01	0,004	1	20,38	78,76	0,14	0,72	0,9
26	silnik 14	zza ostatniej sekcji (datapobrania - 2021.04.20 -) - (woda silnik 11)	31,2	0,04	7,3	0,02	0,010	3	19,41	77,99	0,29	2,31	2,8

Analysis of safety for the area of A-32 longwall, seam 404/1 łg. and workings in which the pipeline for feeding exhaust gas as inert gas is located, takes the following into account:

– safety in workings, where a pipeline for feeding the exhaust gas as inert gas is located, considering the possible unsealing the pipeline and gas outflow directly into the streamlined air stream,

– safety in the area of the longwall exit and, in the workings, discharging used air from the longwall, due to the constant outflow of goaf gases mixed with the supplied exhaust gases (treated as inert gas) in the amount of approx. 2/3 of the total amount of air stream, i.e. to Workings A-32a.

– possibility of disturbing the assessment of endogenous fire hazard, based on fire indicators (quantitative and qualitative) due to: constant outflow of goaf gases mixed with supplied exhaust gases (treated as inert gas) in the amount of approx. 2/3 of their total amount to the air flow, i.e. to Workings A-32a, which determines the amount of CO and the concentration of CO in the context of criteria, compliant with the regulations, and the increase in the amount of CO in the composition of goaf gases, due to the presence of this gas in the exhaust gases, taken into account together with oxygen and nitrogen when determining the Graham Index.

Results of the research work indicate the correctness of the installation in terms of inert gas parameters given in the mining regulations, as well as state that the amounts and concentrations of gases from goafs flowing into the workings or in the event of a complete rupture of the pipeline under the most unfavourable feeding conditions will not pose a threat to the safety of the mining personnel operating in the workings adjacent to the inerting zone [10].

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Due to geological conditions, the A-32 longwall, seam 404/1łg, which were tested and for which the gas supply was planned, was stopped and its decommissioning started.

The earlier decommissioning of the A-32 longwall in seam 404/1łg did not allow for the assessment of the effectiveness of the innovative technology of inerting the goaf of the longwall panel.

In connection with the above, the mine has designated the B-34 longwall in seam 407/1-2. Due to unpredictable geological disturbances after starting the mining operation of B-34 Longwall in seam 407/1-2, the advance of mining operations decreased to approx. 5-10 meters per month. Additionally, coal was left in the goaf of B-34 Longwall, which increased the fire risk. Therefore, the mining plant operations manager approved *The Preventive Work Plan for Longwall B-34 in seam 407/1-2 (update)*. The plan of preventive work shows that it was ordered to use - depending on the conditions - feeding inert gas, which was nitrogen produced from the atmospheric air, backfilling the goaf with a water-ash mixture, feeding inert gases such as nitrogen or purified exhaust gas, feeding water through the holes.

Beginning of the longwall panel due to difficult geological conditions limiting its progress enabled the start of inertization only from September 27, 2021. An attempt to feed inert gas into the goaf from one of the workings showed the need to increase the pumping pressure to about 6 bar to feed about 2000 m^3/h of inert gas . It was agreed with the mine representatives that it is necessary to build the second line of the supply pipeline between the DN150 mm pipeline and the pipeline branch into two single lines DN100 mm in B-33 decline and B-32a workings, seam 407/1-2. Installation of two lines of the DN100 mm pipeline on the above-mentioned section, allowed to increase the volume of inert gases supplied and to enable the feeding it into the goaf from both near-longwall roadways of B-34 longwall, seam 407/1-2.

Upon the decision of ventilation service, in the period from 27/09/2021-19/01/2022, the goaf of B-34 longwall in seam 407/1-2 was interted with the determined amount of gases. In total, during 1,733 hours and 40 minutes, 4,042,985 m^3 of inert gases, including 30,743 m^3 of carbon dioxide, were pumped into the goaf of the longwall panel. The highest obtained amount of injected gas (nitrogen and carbon dioxide mixture) was 3590 m^3/h [9].

3. Results

Assessment of the impact of gas consumption on the operation of a gas engine

The project "Comprehensive development of the duct from the exhaust gas branch of the electricity generator at KWK" Borynia-Zofiówka "Ruch" Borynia " mine" and the thermally insulated exhaust gas duct feeding the gas from the tee to the flue gas treatment installation, were designed. On the basis of the design, a branch with a flanged stub pipe was made, a throttle for the required tightness with a quick-closing electric actuator was installed as well as a 75 m long flue gas duct made of an insulated DN500 pipeline made of acid-resistant steel was installed. The flue gas duct in the area of the installation is ended with a quick-closing throttle with a pneumatic actuator.

In order to protect the installation against the emergence of explosive methane concentration in emergency states, a laser gas analyser was installed on the vertical section of the duct, connected to the control system and initiating an impulse to quick-closing throttles installed behind the tee and at the end of the duct.

When the inert gas generation installation is stopped, the exhaust gas is discharged through the existing chimney, and after the inert gas generation installation is started, the pressure controller - the fan - causes the exhaust gas to flow to the above-mentioned installation. Proper synchronization of the operation of the innovative installation with the operation of the gas engine ensures failure-free operation of the devices [8]. During the operation of the installation for generating the inert gases from exhaust gases, there were many interruptions in the engine operation, without the installation failure, but only its shutdown. There were also emergency states of the engine operation, causing the flow of methane above the set alarm threshold, and then the safety devices shut off the exhaust gas supply to the installation with throttles, shutting down the installation. The exhaust gas consumption in the amount of about 5000 m^3/h found during the operation of the installation did not cause any problems with the gas engine operation.

Validation and optimalization of the installation prototype

During the operation of the installation and supply of gases to the goaf, longwall A-32, seam 404 / 1łg, there were emergency breaks in the operation of compressors and reduced gas parameters of the generators. During the service inspection of the devices, contamination, even clogging of inlet gas filters in generators and contaminated oil in compressors were found. After the analysis of pollutants, it was decided to replace the filters and oil in the devices, dismantle the catalyst in the KAT2 reactor (low reduction efficiency, and the reduction is provided by coal and zeolite deposits in the generators), and an additional filter was installed in the reactor enclosure. Due to the very good reduction of NOx in the beds of PSA generators (nitrogen and oxygen) as well as the large corrosive effect of ammonia on the equipment in the KS-1 compression station, dosing of urea (ammonia water) for reduction of NOx compounds was abandoned. As part of the measures taken, the activated carbon deposit in the nitrogen generator was replaced, connections and drier elements in gas compression stations were replaced, the cooler in the 1st stage compressor of the oxygen generator was renovated, and the oil and filters were replaced more frequently.

After realization of the above work, the installation was started reporting its proper operation.

Content of each gas in the exhaust gases and its parameters differ significantly between the years 2016-2019 and the years 2021-2022, probably due to the intake of methane from another part of the mine, which has a higher sulphur content. During the flue gas measurements, a higher oxygen concentration was observed - up to 13% - a lower concentration of carbon dioxide, about 4%, and a significant increase in the content of sulphur as SO_2 from <3.3 to 53 mg/m^3. Such a change in exhaust gas parameters regarding the oxygen and carbon dioxide negatively affects the achievement of inert gas proper parameters, while such a large increase in sulphur content causes the formation of acids during flue gas cleaning, which destroy each component of the installation made of materials not resistant to acids.

Validation of the installation after commissioning and after design changes, such as: changing the nitrogen and oxygen generator operating system from in series to parallel, dividing of the oxygen generator into two generators with lower power operating in series allowed to obtain proper parameters of the inert gas and allowed inerting the requires area of the mine.

Comments indicated by the mine ventilation services regarding the reduction of CO concentration in the supplied inert gas forced the change of the nitrogen generator operation to the production of nitrogen from the atmospheric air. It is true that these changes resulted in a decrease in the percentage of inert gas obtained from gas engine exhaust gas cleaning in the total inert gas stream, but they decreased the concentration of carbon monoxide in the inert gas mixture to an acceptable 15-20 ppm.

The R&D work led to designing and manufacturing the prototype of an installation for producing inert gas as a mixture of nitrogen and carbon dioxide resulting from the purification of exhaust gas from a gas engine fuelled with methane from mine methane drainage to ensure the safe operation of hard coal mine [5]. Such purification of engine exhaust gases to produce inert gas allows for obtaining gas that serves not only to improve safety by using it in the inertization of goaf walls in the prevention against endogenous fire hazards, but also is an important element of environmental protection by blocking part of carbon dioxide in workings.

The inert gases can be fed to the goaf in the amount that will not cause outflow of goaf gases (e.g. carbon monoxide, methane, carbon dioxide) resulting in exceeding their permissible concentrations in the mine air. During continuous feeding the inert gases containing about 1.5-2.5% CO_2 to B-34 def. 407/1-2 goafs for several days, its concentration equal to 1% was found during the measurements in the area of the end powered roof support - which is the limit value for this gas in the circulating air. In the conditions of the longwall B-34 of the 407/1-2, for which the inertization with a mixture of gases produced in the installation and supplying CO_2 in the amount of 5, 10, or 15% in the mixture could be impossible due to its outflow into the mine air, exceeding the permissible concentrations in the mine air. In real conditions, the continuous inertization of such large volumes of carbon dioxide in inert gas to the active gobs of mining walls may be very difficult or even impossible.

Increased content of such gases such as carbon monoxide, ethylene, propylene, acetylene, hydrogen, in inert gas should be monitored each time before starting inertization by analysing the air flowing from the goaf and assessing the background concentration of such gases, to not exceed the accepted concentration are the basis for the assessment of fire hazard status.

Testing the innovative technology in real conditions in the mine confirmed its effectiveness in controlling the endogenous fires, safety of the crew employed in underground workings and effectiveness of the catalytic gas cleaning system [10].

4. Conclusions

It was confirmed that the following project objectives and tests were achieved:

- At the stage I theoretical studies for specifying the assumptions for inertization process and the assessment of its effectiveness were developed, mathematical models of gas flow in the goaf and the place of their outflow were developed made, what was confirmed during in-situ tests [12],
- at the stages II and III, the R&D project led to designing and manufacturing the prototype installation, which was tested in real conditions in the mining plant, not posing any hazard. Effective fire prevention for endogenous fires of inert gases obtained in the process of cleaning the exhaust gases from the gas engine, as a mixture of nitrogen and carbon dioxide, was proved [10].

The differences in the obtained concentration of some gases in the inert gases mixture are the result of a very high variability of the fuel supplying the engine, different engine operation, and thus the enormous variability of the composition of exhaust gases. It can be concluded with a high degree of probability that each new installation in a different mine will produce gases with different parameters, and the same installation in different periods of operation will also produce gases of different parameters.

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Economic and environmental aspects of using mining equipment and emulsion explosives for ore mining

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Abstract:

The calculation of economic efficiency during the preparatory mine operations using various mining equipment and types of explosives was performed. The general exponential regularity of determining the cost of carrying out 1 m^3 of working depending on the strength of rocks to compression when using different types of explosives and tunneling equipment was established. An environmental assessment of the use of emulsion explosives in an iron ore mine showed a decrease in concentrations of environmentally hazardous substances and a decrease in environmental hazard coefficients, which resulted in a decrease in the pollution of the atmospheric air.

Keywords: iron ore, mining equipment, emulsion explosive, economic efficiency, environmental assessment

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1. Introduction

The state-of-the art stage of the mining industry development in many countries of the world includes the production concentration and improvement of extraction technologies. This is possible due to the use of the latest mining equipment, improvement and development of new methods for calculating the parameters of drilling operations (BPR), which in the system result in an improvement in the indicators of tunneling and mining operations. Known emulsion explosives (EVR) are absolutely safe to transport and store [1-4], environmentally friendly [5, 6] and cost-effective [7-9]. Therefore, nowadays one of the main objectives of mining operations is to increase the efficiency of crushing the rock mass by explosion using EVR and modern mining equipment.

The Association Agreement between Ukraine and the European Union provides for the introduction of European standards and norms in the field of environmental protection, in particular the protection of atmospheric air. In order to reduce the negative impact on the environment, especially on atmospheric air, and according to the Target Regional Program for the transition of mining and processing plants to trotless explosives (VR) in 2011 mining enterprises with an open method of development method used EVR in the amount of 99% of annual needs [10]. As for mining enterprises with an underground development method, until 2008, all iron ore mines of Ukraine used TNT-containing explosives to perform operations related to the extraction of ores. Given the high cost of these VR and their technological and environmental hazards, it is advisable to use similar products that are made directly at the sites of extraction and are safer and more environmentally friendly. On the basis of this, in order to improve environmental safety, since 2009, at the basic enterprise Private Joint Stock Company "Zaporizhzhya Iron ore Plant" (PJSC "ZZRK") the introduction of environmental EVR type "Ukrainit" and trotyl-free VR has begun.

The annual volume of consumption by the mines of PJSC "ZZRK" of trotyl-free VR and EVR of the "Ukrainit" type amounted to 16% of the annual consumption of explosives in 2009, and in 2020 it increased to 78%.

Therefore, the objective of the research is to establish the economic and environmental efficiency of using the EVR and modern mining equipment for underground extraction of ore.

To achieve this objective, the following tasks are solved:

- to determine the economic efficiency of mining while using EVR and different mining equipment;
- to establish regression models of the cost of mining and extraction processes with the use of various explosives and mining equipment;
- to conduct an environmental assessment of the use of emulsion explosives in the underground extraction of ore.

2. Methods

The methodology for establishing the economic and environmental efficiency of using the EVR and various mining equipment in underground ore extraction included the implementation of the following stages:

- a determination of economic efficiency and establishment of patterns of cost of 1 m^3 of horizontal preparatory working and crushing of the rock mass depending on the strength of ore or rock to compression, type of explosives and mining equipment;
- a calculation of surface concentration of environmentally hazardous substances and hazard indices for environmental objects when using TNT-containing VR and EVR in the conditions of mines of PJSC "ZZRK".

To compare the effectiveness of technological schemes of preparation and cutting of the rock mass, treatment operations or individual production processes when using various systems of mining equipment, the cost can be determined separately for each type of operation guided by the methodology fully presented in the papers [11]. The methodology includes the determination of the main costs associated with mining and extracting ore with the use of BPR. Cost calculation is determined by the amount of expenses for the payroll of workers and engineering staff, basic materials, energy, depreciation of equipment and the costs of its current repair and maintenance. Specific costs per 1 ton of ore are obtained by separating a specific type of costs for visible extraction by block or by a separate type of preparatory or extracting operations (excavation, extraction and cutting of chamber residues). Therefore, the most universal indicator of the cost of mining and its individual processes was the calculation of costs per 1 m^3 of ore or rock.

The calculation of the level of environmental hazard was carried out using the technique [12], which takes into account the risk to public health, which is negatively affected by pollutants released when using VR.

3. Results

3.1. Results of calculation of economic efficiency during mining operations

A determination of the cost of mining operations includes the calculation of the amount of all the costs for the implementation of basic and auxiliary processes, accounting for 1 m of the working, but the most universal indicator is the cost of 1 m^3 of the working. The following initial data have a significant impact on the workings developed with the use of BPR:

– mining and geological conditions of the working, namely the cross-sectional area and physical and mechanical properties of rocks;
– BPR parameters, which include the diameter and depth of boreholes and their number, type of BPD;
– mining equipment that is used for drilling boreholes, charging them with explosives and loading the rock mass.

An analysis of mining and geological conditions of iron ore extraction in the mines of Ukraine has shown that mine workings are carried out in rocks and ores of the strength from 30 to 200 MPa. To establish the cost of mining, depending on the change in rock strength, for calculations the strengths of rocks 60, 120 and 180 MPa are taken into consideration. Further analysis of the production activities in mines enabled to establish the most common cross-sectional area of the preparatory working, which is equal to 12 m^2.

When carrying out workings, boreholes of 0.043 m diameter at an average depth of 2.5 m became most widespread. The parameters of the BPR are calculated for the above strength of rocks using the ammunition of the Verkhovna Rada Ammonite No. 6 ZHV and EVR Ukrainit-P-SA, as well as the self-levelling EVR Ukrainit-PP-2, according to the new method of calculating the BPR parameters, taking into account the diameter of the borehole and the diameter of the VR charge itself, the detonation characteristics of the explosive and the strength of the rocks [13-16]. During an analysis of drilling rigs and loading machines used for horizontal workings in the conditions of iron ore mines of Ukraine, it was established that the mines of the Kryvyi Rih basin apply the UBSH drilling rig and the PN-3A loader, and in rare cases the Boomer system with the EST-3.5 loader. In the conditions of mines of PJSC "ZZRK", on the contrary, the systems, which include the Boomer or DD drilling rig with ST and EST or LH cargo and delivery machines are mainly used.

Based on the analysis of the production activities of iron ore mines during horizontal operations, the initial data for calculating the cost of 1 m^3 of mine working will be determined. Initial data for option No. 1: horizontal preparatory workings with an area of 12 m^2, rock strength – 60, 120 and 180 MPa, VR – ammunition Ammonite No. 6 ZHV and EVR Ukrainit-P-SA and liquid EVR Ukrainit-PP-2, borehole diameter – 0.043 m, depth of boreholes – 2.5 m, mining system – drilling rig UBSH-227 with drilling machine B106 or B140, loader PPN-3A, charging machine for liquid EVR Ukrainit-PP-2 – ZEP-10. The initial data for option No. 2 are as follows: horizontal preparatory working with an area of 12 m^2, rock strength – 60, 120 and 180 MPa, VR – ammunition Ammonite No. 6 zhV and EVR Ukrainit-P-SA and liquid EVR Ukrainit-PP-2, borehole diameter – 0.043 m, depth of boreholes – 2.5 m, mining system – drilling rig Boomer S1D with drilling machine COP MD20, truck-delivery machine EST-3.5, charging machine for liquid EVR Ukrainit-PP-2 – ZEP-10. The calculation of the complexity of operations at drilling boreholes in the working development, their charging and blasting, loading of the run-of-mine,

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as well as a determination of the consumption of energy and materials by variants were carried out according to the formulas presented in the articles [11, 17].

As an example, the impact of changing the cost of 1 m^3 of horizontal preparatory working according to option No. 1, depending on the strength of the rocks to compression when using the ammunition of Ammonite No. 6 ZHV and EVR Ukrainit-P-SA, as well as the self-levelling EVR Ukrainit-PP-2, is analyzed and presented in Fig. 1.

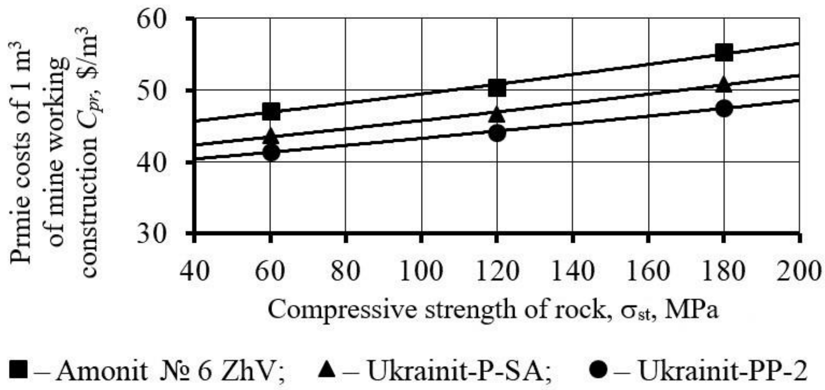

Fig. 1. Graphs of changes in the cost of developing 1 m^3 of horizontal preparatory workings according to option No. 1 depending on the strength of the rocks to compression

As it can be seen from the graph (Fig. 1), when using the cartridge EVR Ukrainit-P-SA, the cost of carrying out 1 m^3 decreases by 11 – 12%, and when using the liquid Ukrainit-PP-2 – by 17 – 19%, with respect to the use of bp-cartridge Ammonite No. 6 ZHV. When using the cartridged EVR Ukrainit-P-SA and liquid Ukrainit-PP-2, it can be seen that there is a decrease in the cost by 7 - 9% compared to the first case.

Further studies of the results enabled to develop the graphs of changes in the cost of 1 m^3 of horizontal preparatory working according to option No. 2, depending on the strength of the rocks to compression when using the Ammonite No. 6 ZHV and EVR Ukrainit-P-SA, as well as the self-levelling EVR Ukrainit-PP-2, which is presented in Fig. 2.

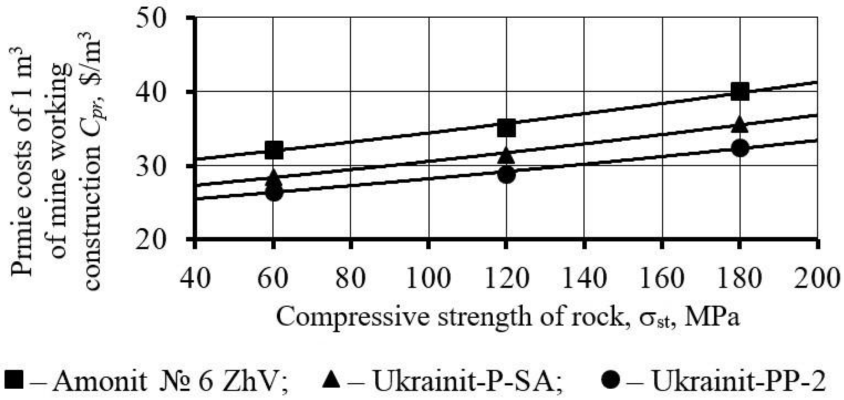

Fig. 2. Graphs of changes in the cost of developing 1 m^3 of horizontal preparatory workings according to option No. 2 depending on the strength of the rocks to compression

From the graph (Fig. 2) it can be seen that when using the cartridge EVR Ukrainit-P-SA, the cost of carrying out 1 m^3 is reduced by 10 - 12%, and when using the self-levelling EVR Ukrainit-PP-2 – by 17 - 19%, relative to the ammunition of the Verkhovna Rada Ammonite No. 6 ZHV. When using the

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cartridge EVR Ukrainit-P-SA and liquid Ukrainit-PP-2, there is a decrease in cost by 7 - 9% compared to the first case. This is due to the lower price per 1 kg of liquid EVR Ukrainit-PP-2 in relation to the cartridge EVR Ukrainit-P-SA, with sufficiently approximate detonation characteristics. Further analysis of relationships, which are presented in Fig. 1 and 2 enabled to state that the cost of developing 1 m^3 of the working when using tunnelling equipment, which includes UBSH-227 and PPN-3A, is 25 - 35% higher than when using Boomer S1D and EST-3.5.

After an approximation of the maximum values, according to the graphs shown in Fig. 1 and 2, a general empirical relationship of changing the cost of 1 m^3 of horizontal preparatory working, depending on the strength of the rocks to compression, when using various mining equipment and bp-cartridge Ammonite No. 6 ZHV and EVR Ukrainit-P-SA, as well as self-levelling EVR Ukrainit-PP-2 was obtained.

$$C_{pr} = K_{HO} \cdot K_{VR} \cdot e^{0.0015 \cdot \sigma_{st}} \ \$/\text{m}^3 \tag{1}$$

where:

K_{HO} – coefficient taking into account the composition of mining equipment, when using the system, which includes the drilling rig of UBSH type and PPN-3A K_{HO} loader = 1.0, when using the system which includes the Boomer drilling rig and the EST-3.5 K_{HO} truck and delivery machine = 0.7,

K_{VR} – coefficient taking into account the VR type of ammunition - VR Ammonite No. 6 ZHV $K_{VR} = 42$, for the cartridge EVR Ukrainit-P-SA $K_{VR} = 39$, for the liquid EVR Ukrainit-PP-2 $K_{VR} = 36$,

σ_{st} – the strength limit of rocks to compression $\geq$ 40 MPa.

Thus, the determination of economic efficiency of mining operations with the use of EVR enabled to establish that the cost of carrying out 1 m^3 is dependent not only on the type of VR and mining equipment, but also on the parameters of the BPR.

3.2. Results of economic efficiency calculations in the performance of treatment operations

Ore extraction rates in most cases are completely or almost entirely dependent on treatment operations. If the labour costs of cleaning work are assumed as 100%, then the share of direct extraction of ore accounts for 20% to 80%, which mainly depends on the accepted system of development and physical and mechanical properties of the ore. Analysis of technological schemes of treatment operations [18], shows that the extraction of iron ores in the mines of Ukraine is carried out with the use of fans. Consequently, the economic efficiency of the treatment operations, namely the crushing of rock, can be determined by the volume of the ore layer. As it is known, the cost of extracting a layer of ore includes the calculation of the amount of all the costs for drilling wells and charging them with VR, for 1 ton of ore, but the most general indicator is the cost of 1 m^3 of ore. To obtain the correct results of the cost of extracting 1 m^3 of ore, it is necessary to determine the initial data for calculation. The results of economic efficiency calculation, when extracting a layer of ore using BPR, are influenced by the following initial data:

- mining and geological conditions, namely the parameters of the ore layer, the strength and cuttability of the ore;
- BPR parameters, which include the diameter, total length and number of boreholes in the ore layer, type of VR, LNO and the distance between boreholes;
- mining equipment to be used for drilling and charging boreholes.

An analysis of mining and geological conditions of iron ore extraction in the mines of Ukraine, enabled to establish that the strength of ore ranges from 30 to 200 MPa. Therefore, to assess the nature of the change in the cost of extracted ore, depending on its strength, for calculation the strengths of ore 60, 120 and 180 MPa are taken. Further analysis of the production activities of mines enabled to establish that the extraction of ore is carried out with boreholes of the diameter 0.089 – 0.11 m in layers 15 – 30 m wide and 20 – 35 m high. BPR parameters are calculated according to the zone of intensive grinding and joint action of charges [13] for the above strength of ores using loose VR Gramonite 79/21, trotyl-free VR Ukrainit-ANFO and bulk EVR Ukrainit-PP-2, taking into account the physico-mechanical properties of the rock mass and detonation characteristics of explosives.

An analysis of the use of drilling rigs and charging machines for an extraction of ore in the conditions of iron ore mines of Ukraine, confirmed that the mines of the Kryvyi Rih basin drill boreholes with the use of drilling machines NKR-100 IPA and in rare cases Simba and DL. Charging wells with crumbly VR Gramonite 79/21 or trotyl-free VR Ukrainit-ANFO is carried out with the use of the charging machine MTZ-3, and self-levelling EVR Ukrainit-PP-2 - PZMK-500. PJSC "ZZRK" on the contrary, mainly for drilling wells used drilling machine Simba and DL, and in rare cases, NKR-100 IPA machines which are used for charging wells with crumbly VR Gramonite 79/21 or trotyl-free VR Ukrainit-ANFO, as well as the MTZ-3 charging machine, and the LPG Ukrainit-PP-2 - RTCh-23, and in some cases, the PZKK-500.

Based on the analysis of the production activity of iron ore mines in the field of treatment operations, the initial data for calculating the cost of 1 m^3 of ore will be determined. The calculation of the cost of extracting ore was performed for two options using different drilling and charging equipment using loose VR Gramonite 79/21, Ukrainit-ANFO and self-levelling EVR Ukrainit-PP-2 for the ore of the strength of 60, 120 and 180 MPa. Initial data for variant No. 1: the cross-sectional area is 12 m^2, the dimensions of the ore layer, width – 20 m and height – 25 m; ore strength – 60, 120 and 180 MPa, structural weakening coefficient of the rock mass – K_C = 0.5, borehole diameter – 0.105 m, loose VR – Gramonite 79/21 of 1000 kg/m^3 and detonation rate of 3600 m/s, trotyl-free VR Ukrainit-ANFO of 950 kg/m^3 density and detonation rate of 3800 m/s and liquid EVR Ukrainit-PP-2 of 1000 kg/m^3 density and detonation rate of 4900 m/s, drilling rig – NKR-100 MPA, charging machine – MTZ-3 and PZMK-500. Output data for variant No. 2: cross-sectional area – 12 m^2, dimensions of the ore layer, width – 20 m and height – 25 m; ore strength – 60, 120 and 180 MPa, the coefficient of structural weakening of the rock mass is K_C = 0.5, the diameter of the borehole is 0.102 m, the loose VR is 79/21 of 1000 kg/m^3 density and detonation rate of 3600 m/s, trotyl-free VR Ukrainit-ANFO of 950 kg/m^3 density and detonation rate of 3800 m/s and liquid EVR Ukrainit-PP-2 of 1000 kg/m^3 density and detonation rate of 4900 m/s, self-propelled drilling rig – Simba H1254, charging machine – MTZ-3 and RTCh-23. A calculation of the complexity of work on drilling boreholes, their charging and blasting, as well as a determination of energy and materials' consumption in variants were carried out according to the formulas presented in the work [11].

As an example, the change in the cost of extracting 1 m^3 of ore according to option No. 1, depending on the strength of the compression ore when using loose VR Gramonite 79/21, trotyl-free VR Ukrainit-ANFO and self-levelling EVR Ukrainit-PP-2, is analyzed and presented in Fig. 3.

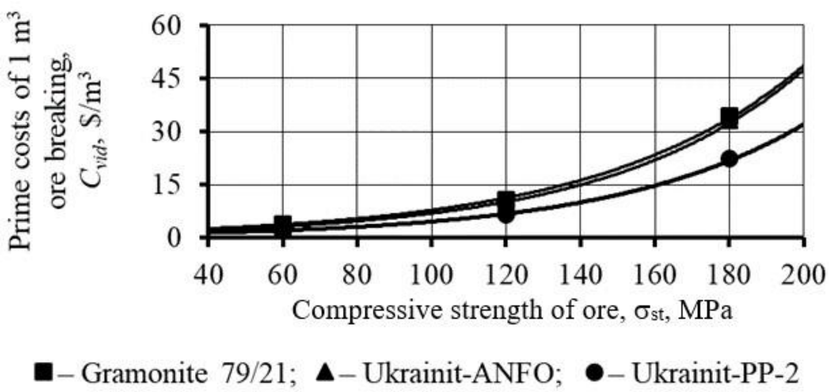

Fig. 3. Graphs of change in the cost of extracting of 1 m^3 of ore according to option No. 1, depending on the ore strength to compression

As it can be seen from the graph (Fig. 3), when using the self-levelling EVR Ukrainit-PP-2 and when using the NKR-100 IPA drilling machine and the PZMK-500 charging machine, the cost of extracting 1 m^3 of ore of the strength 60 – 180 MPa decreases by 48%, in relation to the use of loose VR Gramonite 79/21, drilling machine NKR-100 MPA and charging machine MTZ-3. Comparison with trotyl-free VR Ukrainit-ANFO, drilling rig NKR-100 MPA and charging machine MTZ-3 shows that when using the liquid EVR Ukrainit-PP-2 and when using the NKR-100 IPA drilling rig and the PZMK-500 charging machine, the cost of extracting 1 m^3 of ore of the strength 60 – 180 MPa decreases by 32%.

Having carried out the approximation of the maximum values according to the relationships given in Fig. 3, the general empirical formula of changing the value of the extraction cost of 1 m^3 of ore, depending on the strength of the ore to compression when using the drilling rig NKR-100 MPA and charging machines MTZ-3 and PZMK-500 was obtained:

$$C_{vid} = K_{VR} \cdot e^{0.019 \cdot \sigma_{st}} \text{ \$/m}^3 \quad (2)$$

where:

K_{VR} – coefficient taking into account the type of VR, when using loose VR Gramonite 79/21 K_{VR} = 1.16, for trotyl-free VR Ukrainit-ANFO K_{VR} = 1.02, and for liquid EVR Ukrainit-PP-2 K_{VR} = 0.73.

Further studies of the results allowed to build graphs of changes in the cost of extraction of 1 m^3 of ore according to option No. 2, depending on the strength to compression when using loose VR Gramonite 79/21, trotyl-free VR Ukrainit-ANFO and bulk EVR Ukrainit-PP-2, which is presented in Fig. 4.

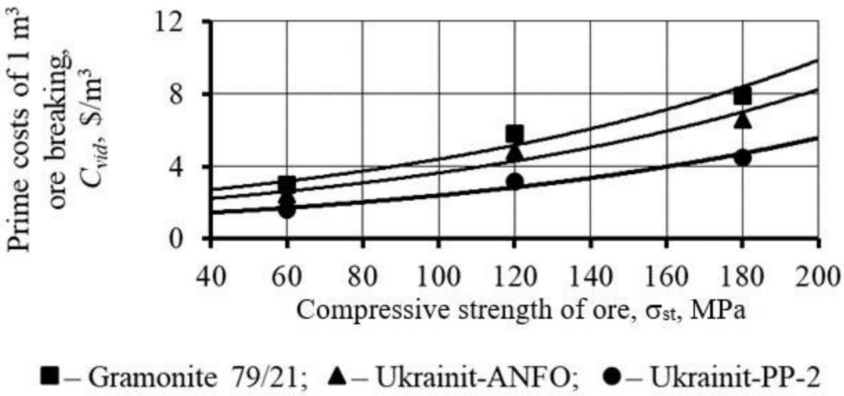

Fig. 4. Graphs of change in the cost of extracting 1 m^3 of ore according to option No. 2, depending on the ore strength to compression

As it can be seen from the graph (Fig. 4), when using the self-levelling EVR Ukrainit-PP-2 and when using the Simba drilling rig and the RTCh-23 charging machine, the cost of extracting 1 m^3 of ore of the strength from 60 to 180 MPa decreases by 46%, in relation to the use of loose VR Gramonite 79/21, Simba drilling rig and charging machine MTZ-3. Comparison with trotyl-free VR Ukrainit-ANFO, drilling rig NKR-100 IPA and charging machine MTZ-3 shows, that when using the self-levelling EVR Ukrainit-PP-2 and when using the Simba drilling rig and the RTCh-23 charging machine, the cost of extracting 1 m^3 of ore of the strength 60 – 180 MPa decreases by 32%. The strength of ore to compression, type of mining equipment and parameters of BPR have a significant impact on extraction costs.

After an approximation of the maximum values given in Fig. 4, a general empirical relationship of changes in the cost of extracting 1 m^3 of ore, depending on the ore strength to compression when using Simba drilling rigs and MTZ-3 and RTCh-23 charging machines is obtained:

$$C_{vid} = K_{VR} \cdot e^{0.008 \cdot \sigma_{st}} \text{ \$/m}^3 \quad (3)$$

where:

K_{VR}	–	coefficient taking into account the type of VR, when using loose VR Gramonite 79/21 K_{VR} = 2.0, for trotyl-free VR Ukrainit-ANFO K_{VR} = 1.6, and for liquid EVR Ukrainit-PP-2 K_{VR} = 1.1.

Thus, the determination of economic efficiency in extracting ore, using EVR, enables to state that the cost of extracting 1 m^3 of ore is influenced not only by the type of VR and mining equipment, but also by the parameters of the BPR.

3.3. Ecological assessment of using emulsion explosives in the underground extraction of ore

The current realities enforce the environmental safety of mining activities. Quite often the authors highlight the need of finding a complex solution to this problem [19]. During the years 2006 – 2010, measurements of the concentration of harmful gases in air samples around the ventilation shafts of mines of PJSC "ZZRK" were carried out and the distribution of surface concentrations was calculated. From 2009 to 2011, the toxic-mutagenic activity of atmospheric air around ejection sources, using the test "sterility of plant pollen", was investigated to determine the effect on the processes of ontogeny of winter wheat in 2011 and studies of linear values of the size and weight indicators of wheat near the ventilation shafts, as well as the analysis of the values of biological signs of germinated wheat grains [20] were carried out.

Due to the analysis of the research results, it was found that mine air entering the atmosphere from the ventilation shafts negatively affects the development of both plants and grain crops which is caused by substances released into the atmospheric air in the result of conducting BPR using EVR [21, 22]. Based on the proposed methodology in 2017 – 2018 some calculations were made and an environmental assessment of the state of atmospheric air around the mine ventilation shafts was carried out [12, 23]. This made it possible to reduce the technogenic impact on atmospheric air, reducing the environmental hazard index to 35%.

Therefore, there is a scientific and practical interest in establishing the technogenic impact and the index of environmental hazards on atmospheric air with an increase in the volume of annual consumption of EVR and trotyl-free VR to 78% of the total annual expenditure on explosives. Such questions are also in other thermochemical transformations of raw materials [24, 25]. For environmental assessment of the EVR use by the mines of PJSC "ZZRK" in the extraction of iron ore, the change in the concentration of harmful gases when using 100% TNT-containing VR in 2008, and when using 22% of TNT-containing VR and 78% of the EVR type "Ukrainit" in 2020 was analyzed which allowed to establish an environmental assessment of EVR "Ukrainit" use in the conditions of mines of PJSC "ZZRK".

An analysis of the values of surface concentrations of environmentally hazardous substances allowed to establish that the maximum concentration of environmentally hazardous substances of carbon monoxide and oxide as well as of nitrogen dioxide was found in 2008, when during the year 100% of TNT-containing VR was used in underground mining operations. When in 2020 78% of EVR type "Ukrainit" and 22% of TNT-containing VR were used the value of maximum concentrations of environmentally hazardous substances in comparison with 2008 decreased, for carbon monoxide by 5.0 – 5.5 times, and oxide and nitrogen dioxide by 1.2 – 1.3 times. This indicates that when EVR type "Ukrainit" is used, it causes a decrease in concentrations of environmentally hazardous substances and reduces the burden on atmospheric air.

A determination of the environmental hazard level was carried out using the methodology presented in the papers [12, 26]. The results of calculating the change in the hazard index in relation to the distance to source of emission were established when using 100% of TNT-containing VR in 2008. The highest values of coefficients and hazard indices for all environmentally hazardous substances were observed: carbon oxide - 5.3 times, and nitrogen oxide and nitrogen dioxide - 1.25 times compared to the use of 100% TNT-containing VR in 2008. There is also a decrease in the hazard index of 1.5 times on average when using the EVR "Ukrainit", compared with the use of TNT-containing VR, which is a decrease in the environmental hazard index to 36%. This indicates that the use of EVR type "Ukrainit" in the underground extraction of ores leads to a decrease in the concentrations of environmentally hazardous substances of carbon monoxide and oxide as well as nitrogen dioxide, formed after underground operations which reduces the burden on atmospheric air.

4. Conclusions

1. The calculation results of economic efficiency of mining operations with the use of EVR showed that the cost of developing 1 m^3 of working is affected not only by the type of VR and mining equipment, but also by the parameters of the BPR. Analysis of the cost values of carrying out 1 m^3 when using domestic and foreign mining equipment, also showed that when using the cartridge EVR Ukrainit-P-SA, the cost of developing 1 m^3 decreases to 11% on average and when using self-levelling EVR Ukrainit-PP-2 – up to 18%, in relation to the cartridge VR Ammonite No. 6 ZHV depending on the strength of the rocks when using domestic and foreign tunneling equipment using VR-cartridge Ammonite No. 6 ZHV and EVR Ukrainit-P-SA, as well as liquid EVR Ukrainit-PP-2.

2. A determination of economic efficiency in the implementation of treatment operations with the use of EVR enabled to conclude that the cost of extracting 1 m^3 of ore is affected not only by the type of VR and mining equipment, but also by the parameters of the BPR. Comparison of the cost of extracting ore when using various drilling rigs and charging machines, made it possible to establish that when using self-levelling EVR Ukrainit-PP-2 the cost of extracting 1 m^3 of ore decreases to 48% on average in relation to the loose VR Gramonite 79/21, and in relation to trotyl-free VR Ukrainit-ANFO – up to 32%. Exponential formulas of the cost determination in the case of extracting 1 m^3 of ore were obtained when using various drilling rigs, charging machines and loose VR Gramonite 79/21, trototyl-free VR Ukrainit-ANFO and self-levelling EVR Ukrainit-PP-2.

3. An environmental assessment of the EVR use of in the ore extraction in the conditions of the PJSC "ZZRK" mines over the period of 12 years showed that in 2020 78% of EVR type "Ukrainit" and 22% of TNT-containing resulted in 5.3-fold reduction of environmental hazards as regards carbon monoxide, and 1.25 times of nitrogen oxide and nitrogen dioxide compared to the use of 100% TNT-containing VR in 2008. This led to a decrease in the hazard index by of 1.5 times (up to 36%) on average when using EVR "Ukrainit", compared with the use of TNT-containing VR. The use of EVR type "Ukrainit" in underground ore extraction leads to a decrease in concentrations of environmentally hazardous substances of carbon monoxide and nitrogen oxide and dioxide, generated during underground operations and enables to reduce the pollution of atmospheric air.

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Mine dust - as a cause of respiratory diseases of miners

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Abstract:

The risk of industrial dust in the work process is one of the greatest challenges not only in Europe but also in the modern world, where over a million people die each year from pneumoconiosis and other respiratory diseases. In Poland, one of the most numerous groups of employees constantly exposed to polluted air at the workplace are miners employed in hard coal mines, who in 2021 they accounted for 89.8% of all exposed persons in Poland (34,876 employees). In order to assess the impact of industrial dust hazards on the health of miners, employees of the Department of Safety Engineering of the Silesian University of Technology, in cooperation with students of the Pomeranian Medical University in Szczecin and a pulmonology specialist, conducted a pilot assessment of the effects of long-term exposure of employees of the preparatory departments of mine X to mine dust. The scope of diagnostic tests included: interview with the patient, physical and spirometric tests. Among the surveyed miners, 18.4% had various disorders and changes in the respiratory system, including the diagnosed pneumoconiosis. The article describes the health effects of long-term exposure of miners to mine dust and the partial results of the diagnostic tests.

Keywords: mine, hazard, mine dust, preparatory departments, pneumoconiosis, respiratory diseases, preventive measures, diagnostic tests, spirometry

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1. Introduction

The report of the Central Statistical Office [1] published in 2021 shows that in Poland, among the factors related to the work environment, dust is the greatest risk right after noise to which 60.4 thousand people were exposed in 2020, i.e. 18.3% of all exposed to harmful substances in Poland (an increase by over 10,000 employees compared to 2019). For years, the greatest dust hazard has traditionally been recorded in the Silesian Voivodeship, where 74.3% of all persons exposed to dust in Poland work there. The dust hazard is mainly related to the mining process. In mining and extraction PKD section, 38,823 employees worked in dusty conditions in 2020 (an increase by 39% compared to 2019), most of which worked in the hard coal mining industry - 34,876 (89.8%), i.e. more than every second case of a person exposed to dust in Poland. The hard coal mining industry also has the highest dust hazard ratio per 1,000 employees in the plants covered by the research work, which has increased by 175.5% over the last 5 years, from 263.6 in 2016. to 462.5 in 2020. Hard coal miners are most often employed under the risk of fibrotic dusts - 20,479 people - 70.2% exposed to fibrotic dust in Poland and carcinogenic dust -14,397 people - 69.4% exposed to carcinogenic dust in Poland (Table 1). The sharp increase in the area of the risk of carcinogenic dusts appeared due the change in European regulations on the protection of workers against the risk of exposure to carcinogenic or mutagenic agents at work and the implemented Directive of the European Parliament and of the Council (EU) 2017/2398 of December 12, 2017, pursuant to which "work related to exposure to crystalline silica - the respirable fraction generated during work." [2, 3] is classified as carcinogenic.

Table 1. Number of people employed in the areas threatened by harmful dust in Poland [1]

People employed in hazardous conditions	Years				
	2020	2019	2018	2017	2016
Dust					
In Poland – total	60383	50353	50236	53381	54513
– per 10000 employees	10.1	8.3	8.4	9.0	9.5
in industry: – total	54269	43086	42108	45337	46524
– per 10000 employees	20.3	15.9	15.6	17.0	18.0
in the mining industry: – total	38823	27927	27033	28572	29228
– per 10000 employees	291.9	202.8	195.9	206.1	209.9
in the hard coal mining industry – total	34876	23764	22036	22935	23488
– per 10000 employees	462.5	302.7	281.5	290.8	263.6
Fibrotic dust					
In Poland – total	29178	34201	34291	36694	36314
– per 10000 employees	4.9	5.6	5.7	6.2	6.6
in industry: – total	25661	29400	28850	30983	31348
– per 10000 employees	9.6	10.9	10.7	11.6	12.1
in the mining industry: – total	23307	27071	26091	27415	27122
– per 10000 employees	175.2	196.6	189.1	197.8	194.8
in the hard coal mining industry – total	20479	23109	21504	22381	21605
– per 10000 employees	271.6	294.3	274.7	283.7	269.7
Cancerogenic dust					
In Poland – total	20736	2372	2567	2699	2961
– per 10000 employees	3.5	0.4	0.4	0.5	0.5
in industry: – total	19660	2086	2352	2546	2756
– per 10000 employees	7.4	0.8	0.9	1.0	1.1
in the mining industry: – total	14397	10	4	0	30
– per 10000 employees	190.9	0.1	0.1	-	0.2
in the hard coal mining industry – total	14397	10	4	0	30
– per 10000 employees	190.9	0.1	0.1	-	0.2

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Due to the change in the regulations, the employees of the Department of Safety Engineering of the Silesian University of Technology in cooperation with the "Stanisław Bielaszka" Central Laboratory for Testing the Work Environment from Jastrzębie Zdrój took measurements of airborne dust at the workstations of the preparatory departments in mine X, from which it resulted that the concentration of airborne dust and carcinogenic crystalline silica in many cases significantly exceeded the new health and safety standards, both when working with shearers and with explosives (Table 2).

To supplement the collected results of measurement at workstations, the voluntary anonymous examination of the respiratory system was conducted among 87 employees of preparatory departments (GRP-1. GRP-2. GRP-3) of the X mine related to drilling the roadways with use of roadheaders and explosives to assess the rate of respiratory disorders among the examined miners and to describe the pulmonary changes in the respiratory system of the workers resulted from long-term exposure to fibrotic and carcinogenic dust.

Table 2. Measured concentration of dust and crystalline silica at workstations of preparatory departments of X mine

Position	Range of airborne dust concertation [mg/m^3]		Average exceedance of MAC		Range crystalline silica concentration in dust [mg/m^3]	Average exceedance of MAC
	inhal.	resp.	inhal.	resp.	respirable	respirable
roadheader operator	0.71-48.68	0.35-15.12	4.6	7.3	0.046-0.621	6.0
assistant of roadheader operator	0.68-46.13	0.30-14.65	4.4	7.1	0.038-0.610	5.9
miner constructor	0.44-39.48	0.15-11.31	3.4	5.2	0.026-0.555	5.1
miner in transportation	0.25-24.14	0.07-8.30	4.2	6.4	0.009-0.214	2.0
conveyor staff	0.32-34.20	0.13-10.38	3.0	4.2	0.028-0.582	5.6
miner in a face	0.12-26.30	0.04-6.33	2.5	3.7	0.025-0.430	4.0
blasting miner	0.31-8.96	0.03-1.43	0.8	0.6	0.060-1.110	9.8
driller	0.26-7.38	0.02-1.26	0.7	0.6	0.067-1.126	10.9
MAC for inhalable dust is -10 mg/m^3, for respirable dust – 2 mg/m^3 MAC for crystalline silica – 0.1 mg/m^3						

2. Materials and Methods

MINE DUST AND ITS PROPERTIES

Mine dust is the dust with particles below 1mm, generated mainly during mining work, i.e. mining, drilling, crushing, grinding as well as during the mechanical processing and transport of hard coal and accompanying rocks. It consists of coal particles, crushed minerals, e.g. anthracite, metal particles, rock particles and substances that protect it against explosion. It also contains chemicals such as aluminosilicates, beryllium, copper, cobalt, selenium and sulfur. The dust generated during mining processes in hard coal mines can be a coal dust, or rock dust, however, it is a multicomponent airborne mixture in the mine atmosphere and is transported along with air stream along the network of mining roadways, where it may pose a threat to all people who come into contact with it [4-7].

Due to the grain size and its settling, mine dust can be classified as: inhalable, tracheal and respirable (Fig. 1).

Inhalable dust is dust visible to the naked eye, nominally less than 0.1 mm in diameter, known as PM10. In mining conditions, it enters the miner's respiratory system with each breath, but most of this dust, due to its size above 30 µm, is caught in the nose, mouth and upper respiratory tract of the worker, from where it is expelled with mucus (sputum).

Tracheal dust is a dust not exceeding 20 µm that penetrates into the middle part of the respiratory tract, including the trachea, bronchi and bronchioles.

Respirable dust is dust smaller than 0.004 mm (PM4) and therefore invisible to the human eye. This type of dust can enter the miner's lungs. In the case of fine dust fraction smaller than 0.0025 mm (PM2.5), it reaches the deepest parts of the lungs, where it can penetrate into the small alveoli where oxygen is exchanged between the inhaled air and the blood. The time of dust removal from the alveoli is long, it amounts to approx. 50% per month, however, with constant exposure in mining conditions, its total removal is practically impossible [8].

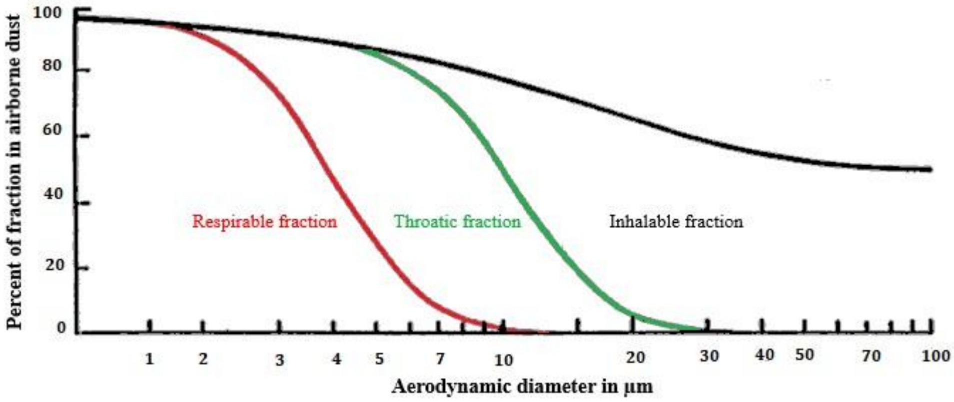

Fig. 1. Inhalable, tracheal and respirable fraction as a percentage of total airborne particles [9, 10]

Negative health effects of exposure to mine dust depend on the following:

- type of dust,
- size of dust particles (dust fraction),
- dust concentrations in inhaled mine air,
- exposure time,
- sensitivity of the exposed person,
- type technological process.

Mine dust can enter the miner's body through inhalation (inhalation exposure) or by settling on the skin, where it is absorbed by hair follicles and sebaceous glands, especially in the mine workings of high temperature and high humidity, when the harmful substances are absorbed directly through the skin.

Based on epidemiological observations, clinical studies of miners exposed to dust in the work environment and the effects that dust in hard coal mines may cause, dust can be divided into [11, 12]:

- irritating dust – these include dust of organic origin, mainly from decaying wood, dust of some plastics devoid of toxic effect, dust of coal, graphite, manganese, tin, iron oxides generated during blasting. These types of dust cause mechanical irritation to the mucosa or respiratory tract of miners.
- dust with a pneumoconiosis effect – this include dust of mineral origin, containing mainly hard coal particles.
- carcinogenic dust – this include mineral dust containing free silica. Crystalline silica particles, after penetrating the respiratory system, can cause a strong growth of connective tissue in the lungs, leading to silicosis. It develops over a few or even dozen or so years. Currently, this type of dust is classified as a carcinogenic chemical substance.

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In the literature [13-15] we can also find a different classification of dust in the mine environment due to the etiology of pneumoconiosis, i.e. non-collagen dust and collagen dust. Non-collagen-free dust accumulates only in the alveoli, causing changes in the body (pure coal dust). Part of this dust is eliminated by the body's lymphatic system as a result of phagocytosis. Collagen dust exhibits biological activity, causing focal fibrosis of lung tissue through toxic effects on macrophages. Silicosis is caused by the crystalline form of silica (SiO_2) [16].

TYPES OF MINERS PNEUMOCONIOSIS AND ITS CONSEQUENCES

Pneumoconiosis as an accumulation of dust in lungs and the response of lung tissue to its presence was described by the International Labour Organization at the 4th International Pneumoconiosis Conference in Bucharest in 1971 [17]. On this basis, six types of occupational pneumoconiosis, two of which are most often diagnosed among employees of Polish hard coal mines, i.e. hard coal pneumoconiosis (774 cases in 2020) and silicosis - (239 cases in 2020) - Fig. 2 were the amendment to the list of occupational diseases [18]. Increased mortality from lung cancer has been also observed among the miners exposed to airborne dust [19].

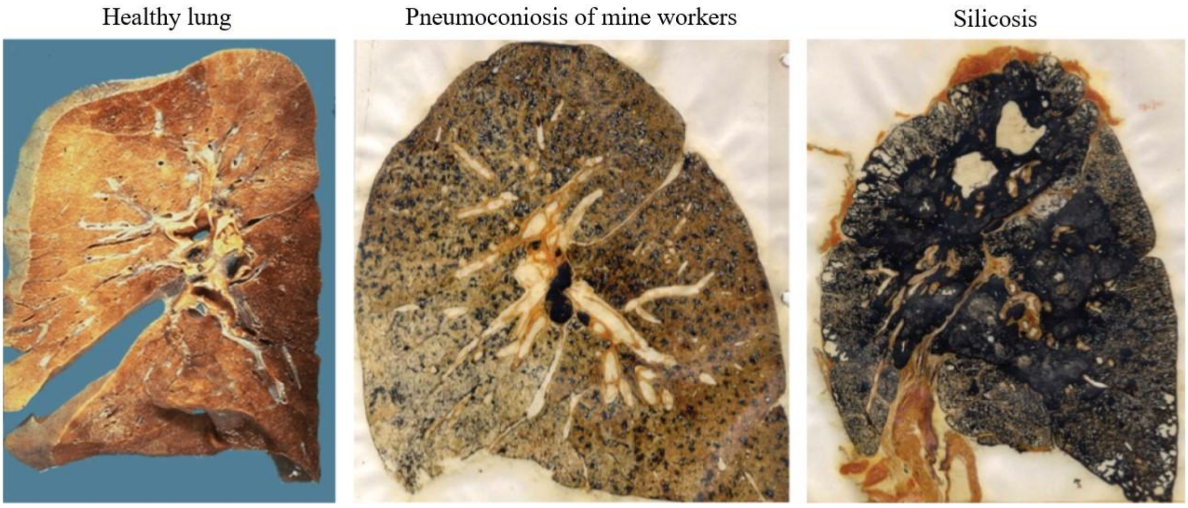

Fig. 2. Lung sections with lesions [20]

Coal mine workers pneumoconiosis is a focal fibrosis of the lung tissue caused by inhalation of mine dust after about 20 years of exposure. Numerous macrophages appear in the lungs of miners with evenly spaced, black, star-shaped deposits of coal dust, which penetrate through the walls of the alveoli, find themselves in the adventitia of the bronchioles and vessels, where they form coal nodules. The nodule is surrounded by small foci of atelectasis and emphysema. As the disease progresses, the type of tissue fibrosis changes from the initially predominant reticulin type to the collagen type (Fig. 3). Over time, mine dust accumulating in the lungs causes local expansion of alveoli and bronchioles in the lungs, i.e. focal emphysema [21, 22]. Long-term exposure to carbon dioxide dust can lead to progressive massive fibrosis (PMF).

Shortness of breath, especially dry cough, loss of appetite, weight loss, and chronic bronchitis and emphysema are the clinical symptoms of miners pneumoconiosis. However, these symptoms usually appear after 5-10 years of continuous exposure to mine dust and are closely related to its fibrotic properties. At the end of the patient's life, the so-called pulmonary heart syndrome is a consequence of chronic respiratory failure. Pulmonary tuberculosis is another fairly common complication of miners' pneumoconiosis. The changes in miners lungs are irreversible and tend to develop spontaneously into large fibrotic areas and the lung tissue scarring. Miners pneumoconiosis, however, develops more slowly than silicosis [23, 24].

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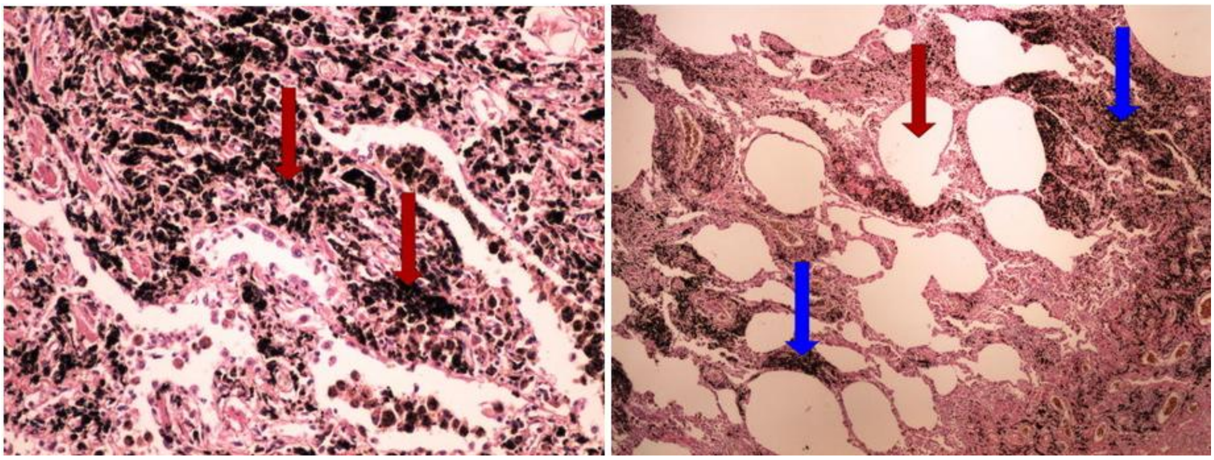

Fig. 3. Miners' pneumoconiosis seen under a microscope with characteristic macrophages and bubbles [21]

Caplan's syndrome is a special form of pneumoconiosis of coal miners [26, 27], considered a variant of spontaneous bone marrow fibrosis (BMF), and in the radiographic image it is visible in the form of oval shadows with a diameter of 0.5 cm to 5.0 cm. These changes are accompanied by symptoms of rheumatoid arthritis and the rheumatoid factor. Pathological changes are mild reticulin fibrosis of the lung tissue (Fig. 4). In addition, Caplan's syndrome is characterized by positive serological reactions for the presence of rheumatoid factor (latex and Waaler-Rose reactions) and rheumatoid arthritis.

Fig. 4. The result of the radiological examination of a patient with rheumatoid arthritis and pulmonary fibrosis in the case of silicosis [27]

Silicosis is caused by inhalation of dust containing crystalline silica (SiO_2), resulting in focal or extensive collagen-like fibrosis of the lung tissue, with a tendency to hyalinization. Usually, pathological changes in lung tissue appear after several years of exposure to silica dust, which penetrates into the interstitial tissue, where it is phagocytosed by macrophages, causing their disintegration and the release of substances responsible for lung tissue fibrosis. With high concentrations of silica in the inhaled air, lung tissue fibrosis may appear after a few or several months. At the initial stage of the disease, there are microbial changes, chronic bronchitis and emphysema.

As fibrosis progresses, the disease develops into small nodules several millimetres in diameter spread across the lungs, usually in the upper and middle parts of the lungs, but over time transforms into larger oval and kidney-shaped tumours that tend to migrate (Fig. 5).

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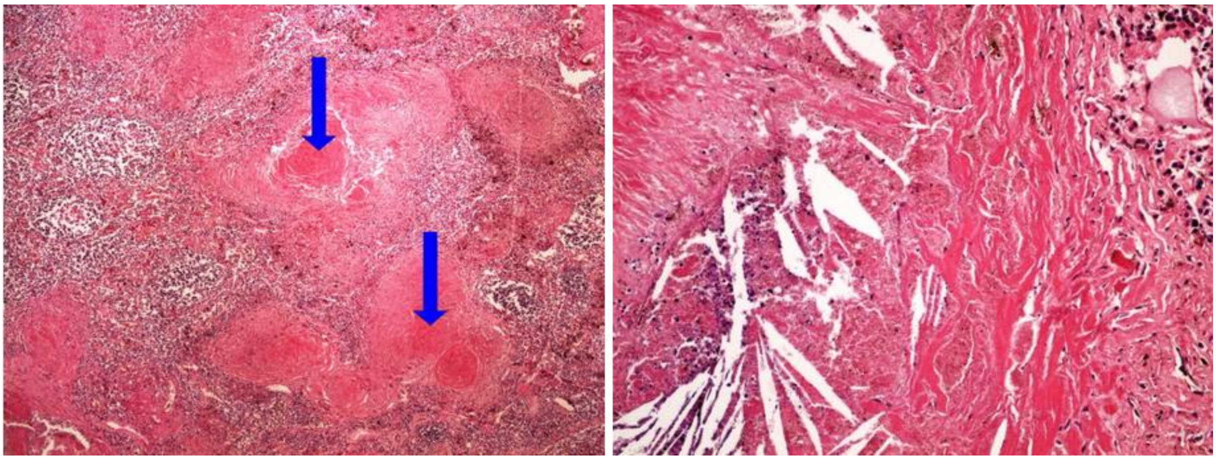

Fig. 5. Silicosis seen under a microscope with characteristic - silicon nodules [21]

There are the following symptoms of silicosis: exertional dyspnoea and cough, which is usually a symptom of chronic bronchitis. As the disease progresses, symptoms worsen and the cough changes from dry to wet. There is also a gradual, significant weight loss [28, 29]. Advanced pneumoconiosis is life-threatening as it can cause blood circulation failure by impaired function of the right ventricle (the so-called pulmonary heart). Complications of silicosis also include tuberculosis and spontaneous pneumothorax. In severe cases of silicosis, chronic obstructive pulmonary disease and lung cancer may develop [30, 31, 32].

3. Results

DIAGNOSTICS OF MINERS FROM PREPARATORY DEPARTMENTS OF X MINE

87 professionally active employees of the preparatory departments (GRP-1, GRP-2, GRP-3) of the X mine participated in a random diagnostic examination for pathological changes in the respiratory system. The departments differed in the work specificity. GRP-1 Division worked in a coal face developed with use of AM-50 roadheader. GRP-2 Division - excavated the stone surface with use of explosives. The GRP-3 division was engaged in a development of the rock and coal mine with an AM-75 shearer. The aim of the study was to assess the frequency of respiratory disorders among the examined miners. The scope of diagnostics covered an interview with an employee, which included the CAT test (Table 3), physical examinations and spirometry.

Table 3. Outcome of CAT test for employees of the mine X preparatory departments

Syndromes	Workstation / number of people per workstation							
	1*	2*	3*	4*	5*	6*	7*	8*
	6	6	12	25	12	18	4	4
	Number of examined people / (average CAT)							
cough	3 (3.3)	4 (2.5)	4 (3.0)	10 (3.8)	4 (2.8)	6 (3.5)	3 (3.2)	1 (3.5)
residual sputum	6 (3.3)	6 (4.0)	10 (3.7)	23 (2.7)	11 (4.3)	18 (3.7)	4 (4.0)	4 (2.5)
tightness in the chest	1 (3.5)	1 (3.0)	2 (2.5)	0 (0.0)	3 (3.3)	2 (3.0)	1 (4.0)	1 (4.0)
shortness of breath	1 (3.0)	1 (3.5)	2 (3.0)	0 (0.0)	3 (3.5)	2 (3.0)	1 (4.5)	1 (3.5)
tiredness	2 (3.5)	2 (3.0)	3 (4.0)	5 (3.6)	4 (4.0)	4 (3.5)	2 (3.5)	2 (3.0)
anxiety and insecurity	1 (2.0)	1 (2.0)	1 (2.5)	0 (0.0)	1 (3.0)	1 (2.5)	1 (3.0)	0 (0.0)
sleep disturbance	1 (2.0)	0 (0.0)	1 (3.0)	0 (0.0)	1 (3.5)	1 (3.0)	2 (3.5)	1 (3.0)
lack of energy	2 (3.0)	0 (0.0)	3 (4.0)	2 (4.0)	4 (3.8)	2 (3.8)	2 (4.0)	2 (3.5)

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CAT outcome	23.6	18.0	25.7	14.1	28.2	26.0	29.7	23

* The following numbers were assigned to each workstation: shearer-operator - 1, shearer-operator assistant - 2, miner-constructor - 3, miner in transport - 4, conveyor staff - 5, miner in the face - 6, blasting miner - 7, driller - 8.

Interpretation of CAT score
1. 5 points - Upper limit of normal for healthy, non-smokers.
2. < 10 points - Little impact of the disease on life. Most good days. Fatigue symptoms
3. 10-20 points - Average impact of the disease on life. Appearing shortness of breath, cough, 1-2 exacerbations a year
4. 21-30 points - Big impact on life. If you are ill, you are unable to do most activities- .
5. > 30 points - Very big impact on life. Difficult to perform basic activities.

Based on the interview and CAT test, severe respiratory system ailments were diagnosed in 12.6% of the surveyed miners, especially shearer operators and transporting staff. Less symptoms manifested by irritation of the respiratory tract and the production of excessive sputum were reported in over 63.4% of the examined people (Table 3).

The results of the interview were also confirmed by physical examinations, especially auscultation, where almost half of the respondents lungs (48.3%) showed murmurs, whistling, whirring, indicating for narrowing of the airways inside or behind the chest and the presence of secretions in the respiratory tract. Auscultation changes were found in workers of all ages and are not only the domain of miners over 40 years of age. Unfortunately, among the surveyed employees there may also be cases of atelectasis, emphysema and reduced aeration of lungs as evidenced by muffled and drum-like percussion sound (7% of respondents). Diagnostic tests also show the possibility of neoplastic changes in 4.6% of the respondents, which is manifested by pleural friction and rod-shaped fingers, which may indicate neoplastic fibrous lesions of the lung tissue (Table 4).

Table 4. Results of examination of employees in preparatory departments of mine X

Recognized symptoms	**Workstation / number of employees per station**							
	1*	2*	3*	4*	5*	6*	7*	8*
	6	6	12	25	12	18	4	4
	Number of tested people with symptoms							
skin changes	1	-	-	-	-	-	1	1
chest deformity	1	-	1	-	-	1	1	-
stick fingers	1	-	1	-	1	-	1	-
shortness of breath, apnea	2	1	2	1	3	2	1	1
prolonged exhalation	1	-	1	-	-	1	1	-
one-sided weakening of the movements of the klp	2	-	1	-	1	1	2	1
decrease in the number of breaths	2	-	1	-	1	1	2	1
breathing disorders	2	1	2	1	2	2	2	1
lowering the lungs	-	1	1	-	1	1	1	-
a muffled percussion noise	1	-	1	-	1	0	1	-
an eardrum tapping sound	1	-	-	-	-	1	-	1
voice tremor	-	-	-	-	1	1	2	2
bronchial or pulmonary murmurs	2	1	4	7	8	6	2	2
wheezing	-	2	-	3	2	2	0	2
whirring	2	4	2	8	7	3	2	2
pleural friction	-	1	-	1	-	-	1	-

* The following numbers were assigned to each workstation: shearer operator - 1, assistant of the shearer operator - 2, miner-constructor - 3, miner in transport - 4, conveyor staff - 5, miner in the face - 6, blast miner - 7, driller - 8.

This observation was also confirmed by spirometry tests, which in 3.5% of respondents showed a severe degree of respiratory obstruction below 35%. In total, the features of respiratory obstruction were diagnosed in 16 people, i.e. 18.4% of the respondents, which is a high number, especially in a situation where among 87 surveyed employees of the X mine preparation departments only two employees were under the supervision of a pulmonologist, and the rest were unaware of their ailments. Their preventive examinations in the diagnosis of respiratory diseases were mostly limited to a chest X-ray every few years and irregular spirometry tests. All persons with diagnosed respiratory obstruction were sent for further diagnostic tests as part of the examinations conducted by the Department of Safety Engineering at the Silesian University of Technology, students of the Pomeranian Medical University in Szczecin and a pulmonology specialist at mine X.

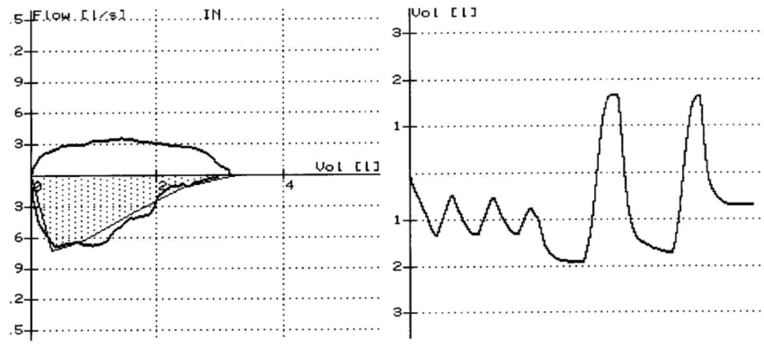
Examples of the results of diagnostic tests and diagnosis of employees who have decided to undergo additional tests are as follows:

Case 1.

Interview: Work position: - shearer miner. Employed in GRP department - 1. Age: - 42 years. Work in mine: - 23 years. Work in GRP department: - 18 years. Weight - 84 kg. Height - 175cm. Stimulants – non-smoker. CAT test result: - 22.0 points, main ailments: dry cough, sputum retention in the respiratory tract, sleep disturbances caused by apnea, symptoms of dyspnea after prolonged exertion. The patient has not been pulmonologically consulted so far.

Examination result: marked symmetrical bronchial whirring caused by residual secretion, muffled percussion sound, respiratory distress at greater exertion.

Spirometry: Spirometry showed no impairment of lung function (Fig. 6).



1000hPa, 60%, 20°C, Ke=1.00, Ki=1.00

F(V)	Akt.	Nal.	%Nal
FEV1 [l]	2.65	2.56	103.50
FVCEX [l]	3.03	3.28	92.30
PEF [l/s]	6.96	7.28	95.60
MEF75 [l/s]	6.55	6.46	101.30
MEF50 [l/s]	4.67	3.74	124.80
MEF25 [l/s]	1.14	1.17	97.40
MEF25/75 [l/s]	3.84	3.01	127.50
MEF50%FVCEX [%]	154.10	114.02	135.10
FEV1%FVCEX [%]	87.40	75.33	116.00
FVCIN [l]	3.19	3.39	94.10
PIF [l/s]	3.71		
MIF50 [l/s]	3.63		

Spirometria	Akt.	Nal.	%Nal
FEV1%VC [%]	77.03	75.33	102.20
VC [l]	3.44	3.39	101.40
IC [l]	3.10	2.08	149.00
ERV [l]	0.34	1.31	25.90
TV [l]	0.75		
BF [1/min]	14.70		

Ocena badania: Badanie wykonane zgodnie z zaleceniami ERS

Fig. 6. Shearer miner's spirometry result

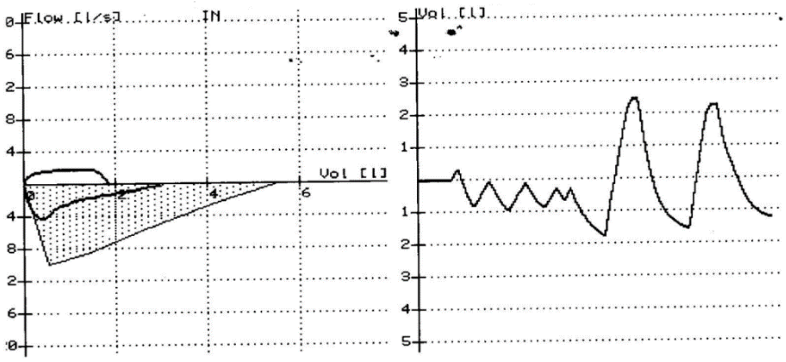
Additional examinations: X-ray. The patience's full-size chest X-ray showed the focal densities corresponding to the effects of fibrotic dust in the form of organic small nodular pneumoconiosis. **HRTC.** Spiral technique with the reconstruction of 0.625 mm layers in transverse planes without contrast enhancement was used during examination. In segment 4 of the right lung, there is an irregular nodular lesion with dimensions of 22 x 24 x 10mm with finger-like protrusions that connect to the pleura with the oblique interlobular fissure. The change causes a narrowing of the end part of bronchus of segment 4. It is necessary to extend the diagnostics by a CT scan of the chest with contrast. Moreover, the trachea and main bronchi are open. In the segment 3 of the right lung, calcification 5mm was found. Minor focal lung parenchyma in segment 5 of the right lung and in the left lung, in segment ½ in segment 5 and in segments 8 and 9. Focal pleural thickening at the apexes of both lungs with a predominance on the right side. Further diagnostics and treatment are recommended.

Case 2.

Interview: Work position: - blasting miner. Employed in GRP department - 3. Age: - 44 years. Work in mine: - 24 years. 8 months before retirement. Work in GRP department: - 20 years. Weight - 60 kg. Height – 180 cm. CAT test result: - 26.0 points. Stimulants: - Non-smoker for 20 years. Main ailments: difficulty breathing, shortness of breath, dry persistent cough, anxiety and respiratory problems, especially at night. The patient has not been pulmonologically consulted so far. He uses an inhaler - recommendation of his family practitioner.

Examination result: wheezing, cyanosis, auscultation changes over the pulmonary fields, poor exercise tolerance associated with frequent shortness of breath, marked weight loss, scoliosis.

Spirometry: Spirometry indicates a severe degree of lung function impairment (Fig. 7).



1000hPa, 60%, 20°C, Ke=1.02, Ki=1.01

F(V)		Akt.	Nal.	%Nal
FEV1	[l]	2.00	4.52	44.20
FVCEX	[l]	3.07	5.56	55.20
PEF	[l/s]	4.27	10.11	42.20
MEF75	[l/s]	2.90	8.74	33.10
MEF50	[l/s]	1.72	5.61	30.60
MEF25	[l/s]	0.96	2.57	37.30
MEF25/75	[l/s]	1.93	4.66	41.40
MEF50%FVCEX	[%]	56.00	100.89	55.50
FEV1%FVCEX	[%]	65.10	80.01	81.30
FVCIN	[l]	1.90	5.82	32.60
PIF	[l/s]	1.95		
MIF50	[l/s]	1.87		

Spirometria		Akt.	Nal.	%Nal
FEV1%VC	[%]	44.54	80.01	55.60
VC	[l]	4.49	5.82	77.10
IC	[l]	3.65	4.18	87.30
ERV	[l]	0.84	1.64	51.20
TV	[l]	0.67		
BF	[1/min]	24.24		

Ocena badania: Badanie wykonane zgodnie z zaleceniami ERS

Fig. 7. Blasting miner's spirometry result

Additional examinations: X-ray. Nodular-fibrous lesions in the upper and partially medial fields, confluent in places in the left lung, with the appearance of post-Tbc lesions. The silhouette of the heart is similar to the pulmonary one. Spine scoliosis. **TK.** The chest was CT scanned using the spiral technique, with 3.75- and 2.5 mm thick layers in the transverse planes, before and after the intravenous administration of the contrast agent. Numerous disseminated nodular changes in both lungs with a tendency to consolidate mainly in the upper lobes were found during examination. In the vicinity of consolidation changes, visible changes covering the pleura and distorting the lungs. The lesion image is consistent with silicosis. Mediastinal lymph nodes without visible calcifications, diameter up to 11 mm, numerous. Subostral lymph node bundle 12 x 40mm. The changes may also correspond to changes in pneumoconiosis. Apart from that, the lungs had no visible pathological changes. Heart, large vessels within normal limits. Spine scoliosis. Patient referred for further examination.

4. Conclusions

Increasing number of employees exposed to industrial dust is a problem not only in Poland, but for the whole world various types of respiratory disorders are the most common effect of long-term exposure to industrial dust as shown in research work cited above. this phenomenon is mostly observed in the rock mining industry, mainly in hard coal mines, where the highest rate of pneumoconiosis has been observed for years. Mine dust is the main cause of morbidity. Dust composition and its particles size is not homogeneous, as it is a mixture of multiple particles, travelling with the mine air current through most of the mine workings. Preparatory departments of mines and mining plants, due to the specificity of work in blind workings, are the place where harmful mine dust is most abundant. Its differentiation also depends on the type of the mined rock and technological process used. Results of measurements of the dust and crystalline silica concentration show that the introduction of new legal regulations on MAC increased the area of hazardous dust zones in mines and the accidences of exceeding the MAC increased. The introduced new regulations impose additional obligations on employers and physicians who watch after the preventive measures for health of employees exposed to harmful dust. These measures consist not only in increasing the dust concentration measurements in the mine air, but also in extending medical prophylaxis.

Students of the Pomeranian Medical University and the pulmonology specialists examined employees of preparatory departments of mine X showed that the problem of hidden occupational morbidity in mine employees exists and will continue to exist despite the prevention widely implemented in mines because people are afraid of losing their jobs and a reduction in earnings due to occupational disease and the need to change job or being transferred to a sickness pension. As long as the law on greater protection of people with symptoms of occupational diseases, who risk their life and health for the future mining retirement pension and protection of their families is not changed, the detection of pneumoconiosis among professionally active employees will be difficult, as shown by the statistics of the Institute of Occupational Medicine in Łódź.

Therefore, it is worth perceiving the change in NDS regulations in Poland and Europe neither as a "witch hunt", which today are the sick miners, nor as a tool against employers, but as an attempt to extend medical prophylaxis to facilitate early detection of pneumoconiosis symptoms and to develop pro-safe behaviour among the miners, who today are diagnosed with pneumoconiosis only after retirement already at a significant degree of its advancement.

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Use of the MBS method in mining industry R&D projects

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Abstract:

Virtual prototyping methods are an important aspect both in the designing process and in research processes aimed at the modification and optimization of machines and devices. It allows one to analyse the way of operation, the flow of forces, the cooperation between components, as well as finding the weakest points of the structure. This article presents the possibilities of using the MBS method, which is one of the tools used in virtual prototyping, on the basis of the results of R&D projects realized at the KOMAG Institute of Mining Technology. The main objective of the MBS method is to simulate the kinematics and dynamics of multi-body systems, the results of which will enable a series of analyses related to the operation of machines and devices.

Keywords: numerical simulations, kinematics and dynamics, MBS (MultiBody System), mining industry

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1. Introduction

Development in the field of computers, state-of-the-art software as well as staff, enabled implementation, application and continuous improvement of virtual prototyping techniques, which are used in R&D projects at the KOMAG Institute of Mining Technology. Virtual prototyping allows learning and analyse many aspects related to the design, manufacture and operation of machines and devices. Ability to check and then modify innovative solutions and new ideas without the need to build a physical prototype is the most important advantage of the research work in developing the virtual prototyping. Use of virtual prototyping techniques, apart from economic benefits (no need to build a prototype), is in line with the current trends in taking care for the natural environment and reducing greenhouse gas emissions during the manufacture of physical prototypes. In addition, attention should be paid to the unquestionable advantage of virtual prototyping methods over traditional bench tests, consisting in the possibility of analysing the flow of forces, distribution of stresses and deformations in any structure node, which is often unattainable for technical reasons at traditional test stands. Virtual prototyping is therefore a perfect complement to traditional testing even before the production of each components of machines or devices.

Virtual prototyping is used in the following tasks in the research projects of KOMAG Institute: creation of geometric models of the selected machines and devices for strength calculations using the FEM (Finite Element Method) method for the selected machine components, simulating kinematics and dynamics (simulations such as MBS - MultiBody System) of the selected kinematic systems and entire machines and devices, for CFD (Computational Fluid Dynamics) simulations related to fluid mechanics and heat flow simulations. The above-mentioned virtual prototyping tools are complemented by the work related to visualization of both the obtained results and ready-made solutions developed at the Institute. Photogrammetry, the use of which allows one to easily and simply visualize the space in which a given device is to work is one of the methods used for this purpose. Using this method, you can also make inventories of large post-industrial areas. This article presents the possibilities of using MBS simulations. This method is used in research projects and in scientific work related to the development of innovative machines and devices.

2. MBS method

MBS method consists in numerical simulations aimed at kinematic or dynamic analysis of a mechanical system. For this purpose, the real object is represented by a geometric model consisting of many bodies (solids). In the process of building a computational model, geometric constraints are superimposed on the geometric model of a mechanical system, thus creating the kinematic pairs with a certain number of degrees of freedom. Moreover, the computational model can define excitations in the form of various vectors of forces and moments acting in selected nodes of the mechanical system.
Kinematic or dynamic analyses of the selected mechanical system are the purpose of the MBS simulation. In the case of kinematic analysis, the movements of each body of the mechanical system is searched for, assuming that at least movement of one member, being for example a driving body, is known. In this type of simulation, the number of degrees of freedom is the same as the number of factors determining motion defined in the so-called directional constraints. The solution of the kinematics problem consists in solving the system of N algebraic equations with N variables collected in a vector **q (1),** as well as constraints in relation to speed (2) and generalized accelerations (3) [1]:

$$\boldsymbol{\Phi}(\mathbf{q},\mathrm{t}) = \begin{bmatrix} \boldsymbol{\Phi}^{K}(\boldsymbol{q}) \\ \boldsymbol{\Phi}^{D}(\boldsymbol{q},t) \end{bmatrix} = 0_{Nx1} \qquad (1)$$

where:
- q - vector of generalized coordinates,
- K - number of kinematic pairs in the system,
- D - number of driving constraints,
- Φ^{K} - vector of constraints of kinematic pairs,
- Φ^{D} - vector of driving constraints,
- Φ - system of N nonlinear algebraic equations.

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$$\mathbf{\Phi}_q \dot{q} = -\mathbf{\Phi}_t \quad (2)$$

$$\mathbf{\Phi}_q \ddot{q} = -(\mathbf{\Phi}_q \dot{q})_q \dot{q} - 2\mathbf{\Phi}_{qt} \dot{q} - \mathbf{\Phi}_{tt} = \Gamma \quad (3)$$

where:

- Φ_q - Jacobian matrix,
- t – time,
- Γ - constraint equations for accelerations.

Using the above equations, the components $\mathbf{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}$ of the position, velocity and general acceleration vectors are determined in given time t_0, t_1, ..,t_M.

In the case of dynamic analyses, the defined geometric constraints do not receive all the degrees of freedom of the analysed mechanical system. In dynamic analyses, initial conditions are defined in the form of position and velocity of all bodies of the mechanical system, as well as time curves of all forces acting on each bod of this system. During dynamic analyses, it is important to correctly define the masses and moments of inertia of each member of the system. During the dynamics task, the movement of the mechanical system is determined as a result of forces acting on it. In order to solve the dynamics problem, it is necessary to integrate the system of differential algebraic equations. The Euler-Lagrange equation can be written in the form of (4) [1, 2, 3, 4]:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\boldsymbol{q}}}\right) - \frac{\partial L}{\partial \boldsymbol{q}} + \mathbf{\Phi}_q^T \boldsymbol{\lambda} = \boldsymbol{Q} \quad (4)$$

where:

- *L* – Lagrange function (5) i.e. difference of kinetic energy *T* and potential energy *V* of the system:

$$L = T - V \quad (5)$$

- **λ** – vector of Lagrange multipliers,
- Q – vector of generalized forces acting on a multi-body system (6):

$$\boldsymbol{Q} = \boldsymbol{Q}(\boldsymbol{q}, \dot{\boldsymbol{q}}, t) \quad (6)$$

Generally the Newton-Raphson iteration method, most often is used to solve the nonlinear Differential-Algebraic Equations of motion. Apart from the geometrical constraints between the selected bodies of the mechanical system, it is possible to define the method of mutual interaction in the case, when the bodies colliding with each other. The nature of the collision behaviour is defined by the contact parameters between these solids. The characteristic parameters of the contacts include contact stiffness, damping coefficient, penetration depth of one body into another, coefficient of friction, etc.

3. Application examples - results

Analysis of correct operation of a new type of planetary gear is an example of applying the MBS method for kinematic analyzes. At the first stage of the analysis, a simulation has to verify geometrical form of the gear wheels to avoid a situation of wedging each gear stage (Fig. 1).

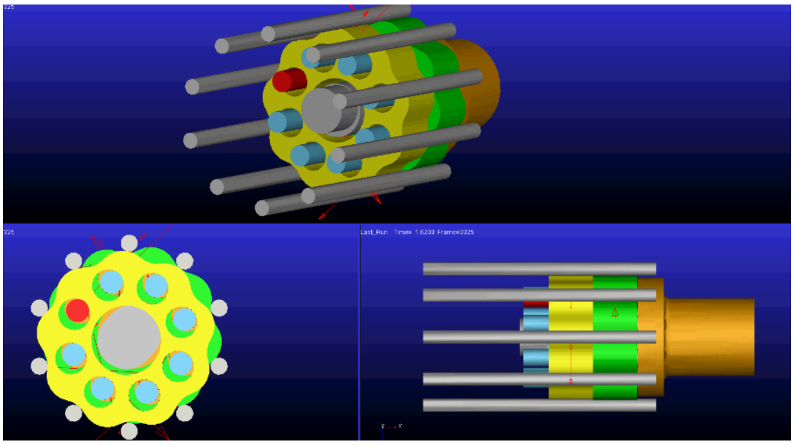

Fig. 1. Simulation of planetary gear operation [5]

After the stage of geometry verification which excluded the possibility of wedging the gears, dynamic analyzes were made to analyze the flow of forces in the gear and to optimize the new solution.

Dynamic analyzes are the majority of analyzes as a part of R&D work. Distribution of forces in the powered roof support was an example of dynamic analysis in various variants of testing the roof support on test stand (Fig. 2).

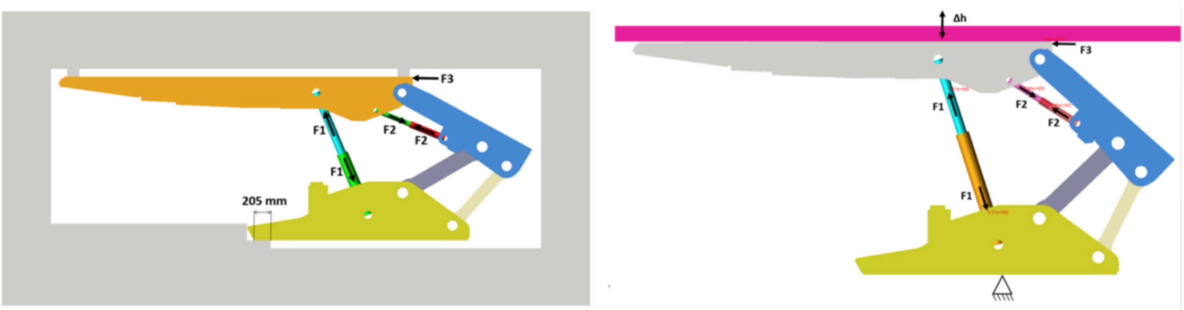

Fig. 2. Analysis of the flow of forces in powered roof support

Based on the simulations, it was possible to accurately determine the forces in each node of the roof support in each type of stand tests, allowing the specialists to select the proper test variant. Moreover, the forces determined during such simulations may constitute the boundary conditions, such as the forces acting on particular places of the structure, for the FEM strength analyzes.

Simulation of emergency situations, e.g. braking of the suspension during the transport of powered roof support using the suspended monorail was another example of dynamic analyzes with the use of the MBS method (Fig. 3).

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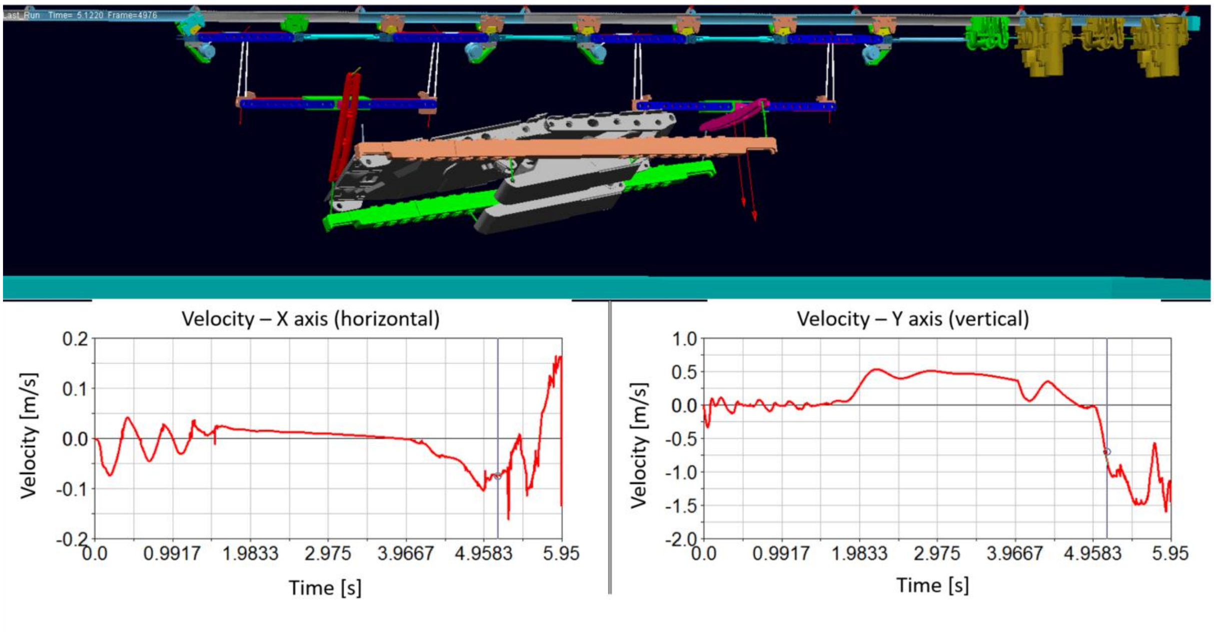

Fig. 3. Simulation of emergency situations, breaking the suspension during transportation of a powered roof support [6]

Analysis of forces in the chains that did not break, as well as in the joints and suspensions of the rails of the suspended monorail route was possible in simulation. The results of the simulations also include the speed and acceleration of the roof support, as well as the predicted trajectory of its motion during the fall. Extensive analyzes of such simulations may result in development of guidelines aimed at increasing the safety of both the personnel and the mine infrastructure.

Ensuring the proper load-bearing capacity of the rail joint during the development of a new type of 4 m long rails was one of the tasks related to the safety of the suspended monorail route (Fig. 4).

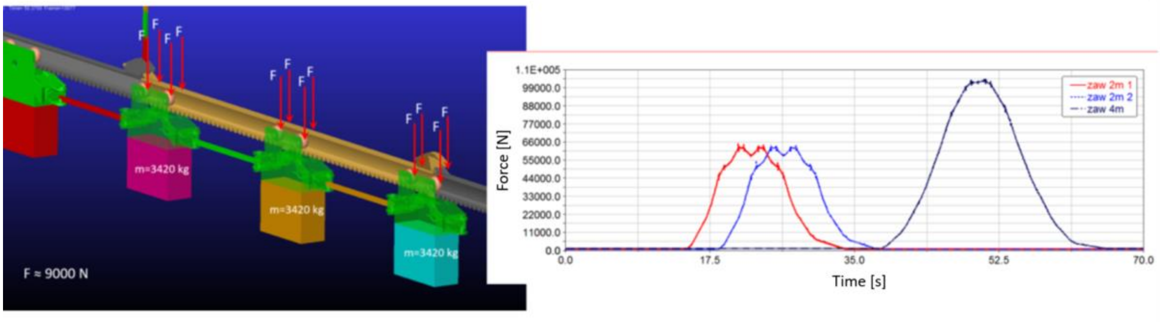

Fig. 4. Simulation of the load on the rail joints of a suspended monorail regarding the length modification [7]

For this purpose, a series of simulations were made. Forces in each direction acting on the rail joints during the monorail travel were the simulations result. These data were boundary data for FEM strength analyzes.

Simulations of emergency braking of a suspended monorail at various speeds, including driving at a speed of 5 m/s (driving at this speed is impossible in real conditions due to legal restrictions) were another example of analyzes affecting safety. The forces in the route suspensions, the forces in the rail joints, the forces acting on the transported load, as well as the forces acting on the arches of the roadway support were simulated (Fig. 5) [7, 8, 9, 10].

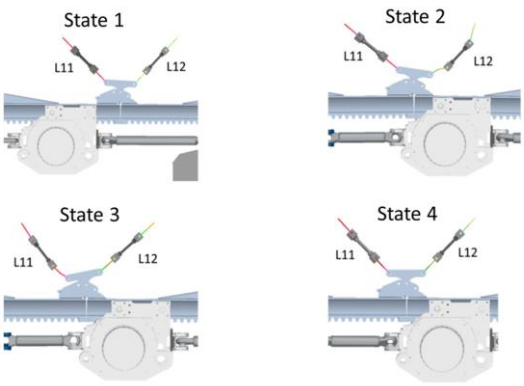

Fig. 5. Different states of the suspension tension depending on the emergency braking phase of the set [8]

Acceleration and vibrations acting on the monorail operator in the operator's cabin and on the moved personnel in the passenger cabin were also recorded, during the simulation of emergency braking and monorail travel at higher speed (5 m/s) Fig. 6 [8, 11, 12].

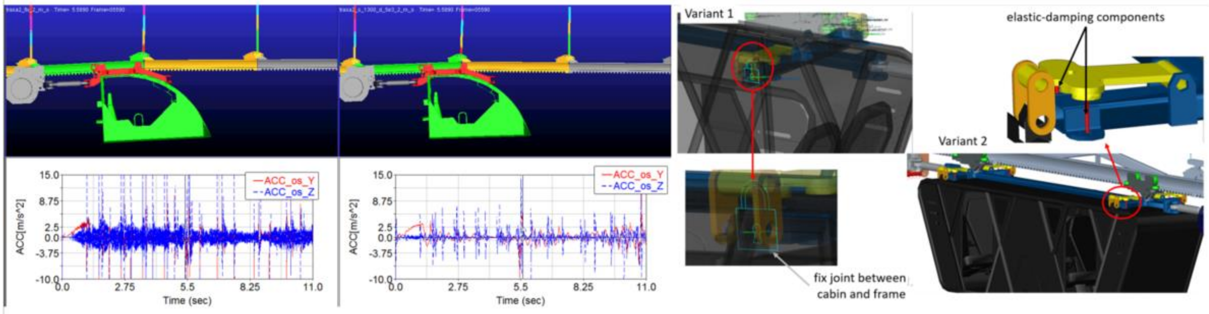

Fig. 6. Simulations of vibrations affecting operator and personnel in suspended monorail [7]

The simulation series for acceleration and vibration analysis was aimed at optimizing the design of the operator's cabin by selecting the optimal stiffness of the vibration damping inserts, installed as a component of the operator's cabin suspension (Fig. 7) [7, 12].

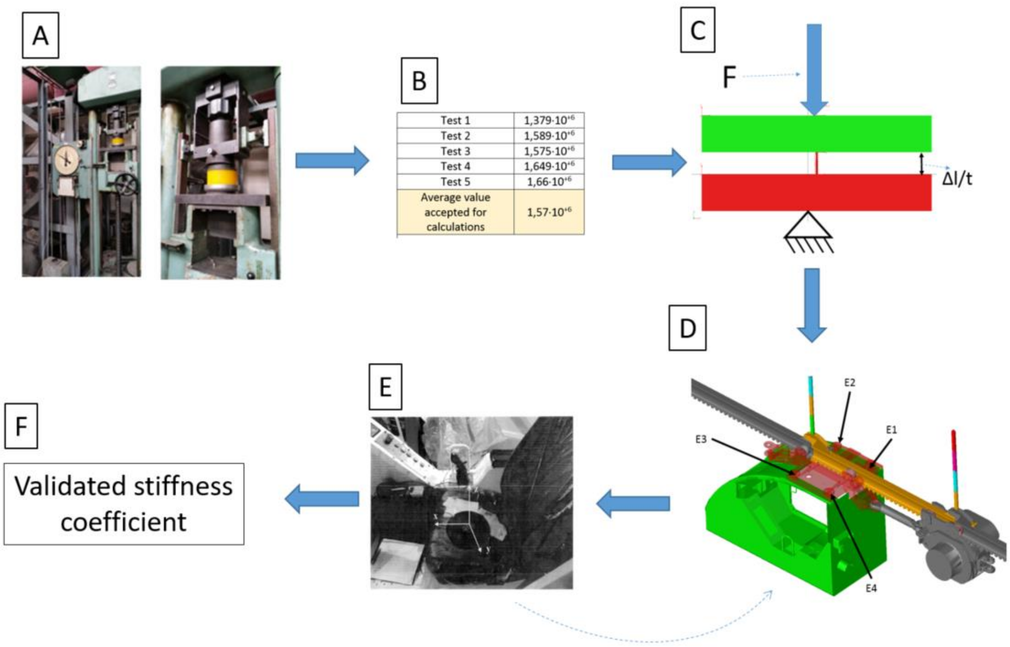

Fig. 7. Process of selecting the rigidity of flexible components in the operator's cab suspension and their verification [12]

In simulation of a multi-bucket excavator operation in open pit mines, vibrations were also analyzed. Capability to build a computational model with flexible solids (flex type) was used in this simulation. This allowed for the analysis of vibrations resulting from the excavator's operation and in emergency situations, such as hitting the bucket on a boulder in the excavated deposit. The vibrations recorded at selected points on the excavator structure were presented both in the time domain and in the frequency domain (Fig. 8). Selecting the optimal place for installing the additional measuring equipment and assessment of the vibration impact on of these devices operation of and on the accuracy of measurements was the tests objective [13, 14].

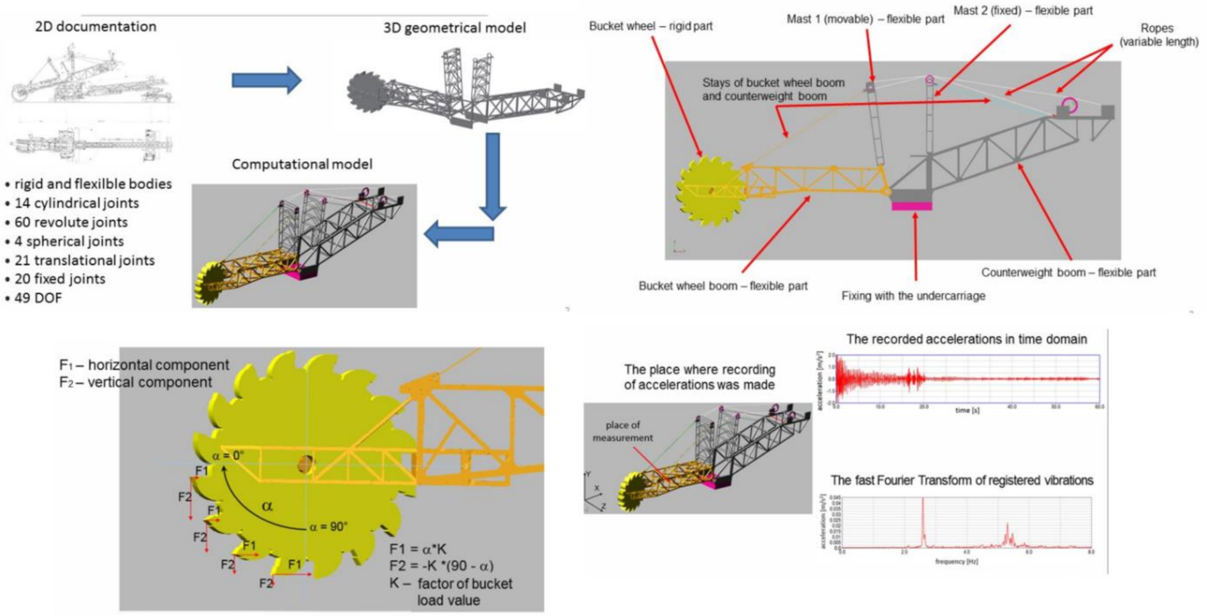

Fig. 8. simulation of a bucket excavator operation [14]

Moreover, due to the use of flexible solids, deformation of the structure resulting from the load on the excavator was taken into account in the model. The natural vibrations of selected components of the excavator, e.g. rope masts, were also analyzed (Fig. 9).

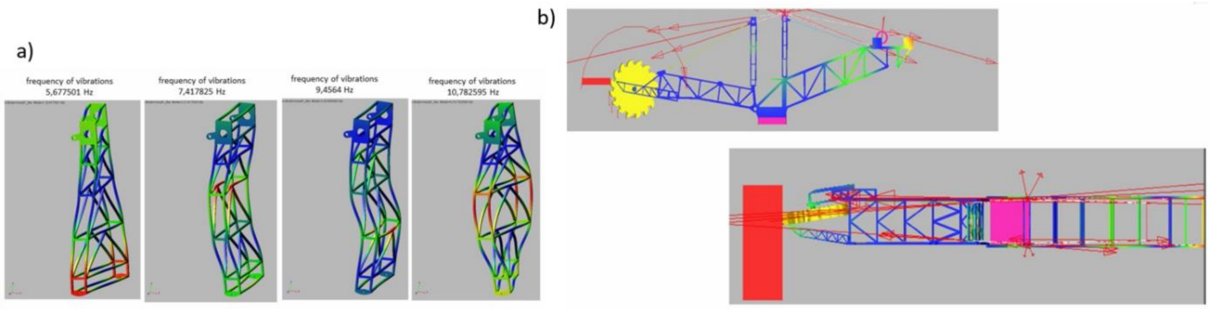

Fig. 9. Simulation with the use of flexible solids:
a) modal analysis of the rope mast, b) deformation of the excavator structure [13]

The ability to perform co-simulations in conjunction with e.g. MATLAB/Simulink software is a very useful and valuable functionality of MBS analyzes. Building a virtual controller that controls the model in the environment for the analysis of kinematics and dynamics is possible due to such integration. Another module that can be integrated with the calculation model in a similar way is the model of additional electrical equipment, including own models of electric motors, models of sensors, controllers, etc. (Fig. 10).

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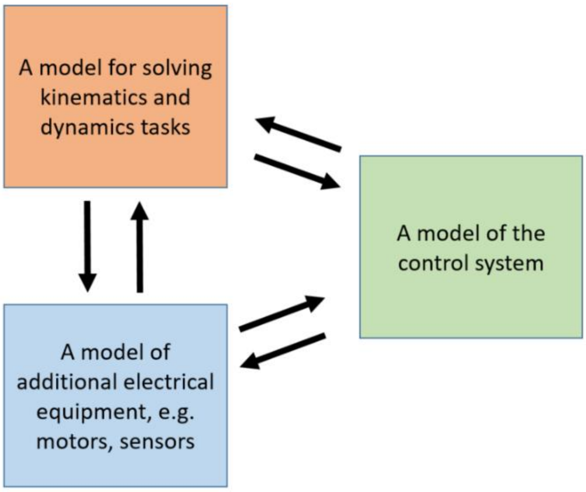

Fig. 10. Co-simulation principle**.**

This approach can be used when simulating a monorail run at a given speed or in other simulation cases where there is a need to use a PID controller, or other methods of controlling or maintaining the set values of selected parameters depending on external factors, e.g. machine load (Fig. 11).

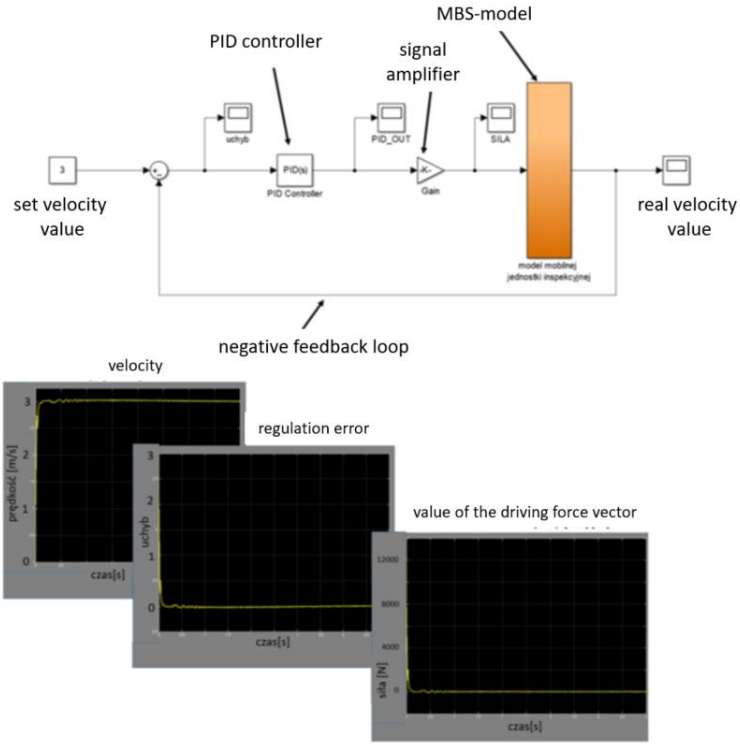

Fig. 11. Possibility of using the PID controller in MBS simulations

Another example of the application of the MBS simulation coupled with the model of the control system and additional electrical equipment were simulations of the operation of the scraper conveyor (Fig. 12) [15, 16].

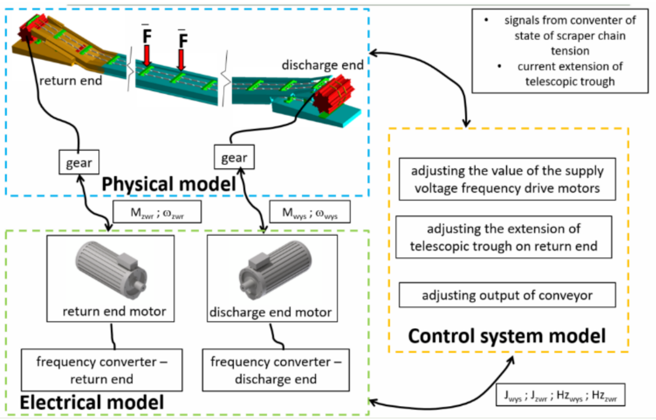

Fig. 12. An example of applying the simulation to analyze the scraper conveyor operation [16]

The simulations enabled identifying the conveyor's operating condition by detecting the condition of excessive tension on the scraper chain or its excessive loosening at the discharge or end station. Then, on the basis of the relationships implemented in the model of the control system, the power frequency of the drive motors was corrected or the extension of the telescopic chute on the return drive was corrected (Fig. 13).

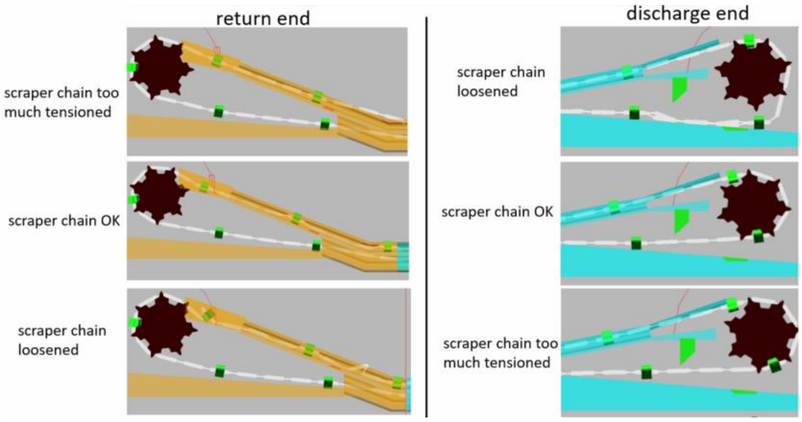

Fig. 13. Selected conditions of the scraper chain tension on the return and discharge drive [15]

Application of the presented co-simulation approach allowed for the development, testing and improvement of the control algorithm aimed at optimizing the operation of the conveyor by maintaining the optimal tension of the scraper chain, regardless of the load condition of the conveyor.

4. Conclusions

Use of the MBS method in virtual prototyping allows for many analyses to support the optimization and development of new innovative machines and devices. As presented, such simulations are used in simple analyses aimed at checking the possibility of a collision, but also in simulations aimed at analysing the flow of forces and determining the boundary conditions for FEM strength analyses. The MBS method is an important tool in analyses aimed at improving the safety and minimizing the impact of vibrations on the operator and the simulations taking into account the machine control depending on their load. Use of virtual prototyping techniques accelerates development of the product and contributes to the care of the environment by not having to build a physical prototype until its correct operation is proved. In addition, numerical simulations enable the analysis of forces, dynamic overloads, even in cases, where bench tests are impossible. Such a situation took place, for example, during the tests of impact of changes in the speed of a suspended monorail. Tests on movement at higher speed required

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constructing the special dedicated test track. It is not possible to test the behaviour of the railway in emergency situation outside this track.

Creating the computational model and its validation on the basis of the above-mentioned test stand enables simulations at any driving speed with emergency braking at different braking forces. In this way, it is possible to analyse the sequential braking method with any distribution of the braking force among a defined number of braking stages. Due to technical limitations consisting in the lack of the possibility of smooth and cheap control of the braking force, such bench tests were not possible. Incorrectly selected parameters in the computational model may result in large errors in the obtained simulation results that is why it is very important to properly validate the computational model. The computational model should be verified and validated whenever it is possible. Such verification may consist in comparing the time process of the forces recorded on the real object with the values calculated in numerical calculations. Fig. 14 shows an example of verification of the validated model of the suspended monorail during in-situ measurements.

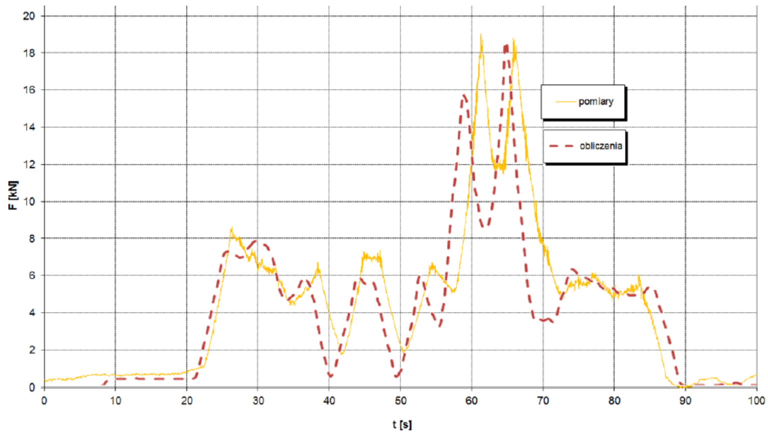

Fig. 14. Comparison of the forces in the suspension recorded in real conditions and obtained in numerical calculations [17]

Sometimes, however, it is not possible to compare the results of numerical analyses with real values, because the analysed device or machine is at the design stage and it is not possible to test it. In such cases, experience simulation is very important, as well as a thorough analysis of the obtained simulation results. Use of MBS methods supports conceptual and modernization work in designing new and innovative machines and devices, the use of which increases their capabilities and at the same time improves the comfort and safety of employees.

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