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Achievements of the KOMAG Institute in the field of environmental protection over the years 1950-2020

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Abstract:

Seventy years of research-and-development activities of the KOMAG Institute of Mining Technology in the field of environmental protection are presented in this article. Special attention is paid to the projects oriented onto reducing noise emissions. Technical solutions in the field of noise control, developed at KOMAG and oriented onto passive acoustic baffles and noise silencers are discussed in the article. Some examples of research projects results and their successful implementation in the industry are described. A review of several projects relating to widely understood environmental protection, including work environment, reflect an interdisciplinary approach of KOMAG researchers to the issues of reducing hazards and increasing safety. There is also some information about innovative technical solutions, which obtained awards and were distinguished by domestic and foreign experts at fairs, exhibitions and competitions in Poland and abroad.

Streszczenie:

W artykule przedstawiono siedemdziesiąt lat działań badawczo-rozwojowych Instytutu Techniki Górniczej KOMAG na rzecz ochrony środowiska. Szczególną uwagę zwrócono na projekty dotyczące redukcji emisji hałasu. W artykule omówiono rozwiązania techniczne dotyczące zwalczania hałasu, opracowane w Instytucie, które są ukierunkowane na ekrany akustyczne oraz tłumiki hałasu. Podano przykłady wyników projektów badawczych i ich wdrożeń przemysłowych. Przegląd różnych projektów dotyczących szeroko rozumianej ochrony środowiska , łącznie ze środowiskiem pracy, odzwierciedla interdyscyplinarne podejście pracowników badawczych KOMAG-u do zagadnień ograniczenia zagrożeń i zwiększenia bezpieczeństwa. W artykule zawarto informację o innowacyjnych rozwiązaniach technicznych, które uzyskały nagrody i zostały wyróżnione przez ekspertów krajowych i zagranicznych podczas targów, wystaw i konkursów organizowanych w Polsce i za granicą.

1. Introduction

This year the KOMAG Institute of Mining Technology celebrates the seventieth anniversary of its activity. Over the years it changed its name, but has always been oriented onto designing and testing of machinery and equipment for extracting as well as processing of minerals. In the past it was a scientific, research and development organization for all the factories of mining machines such as FAMUR, FAZOS, TAGOR, RYFAMA and GEORYT, where KOMAG had its design branches. At present KOMAG elaborates and implements research results contributing to an improvement of miners` work comfort and safety as well as to widely understood environmental protection, including post-mining sites and other areas badly affected by the industry. Since 1950 more than 1100 technical documentations of machines and equipment, applied in mines of minerals in Poland and abroad, have been generated. More than 4400 patents and utility patterns, obtained so far, confirm an innovative character of these technical solutions. As far as the subject-matter of environmental protection is concerned the following activities are realized:

- development of innovative solutions reducing hazards and increasing work safety,

- environmental management of industrial and urbanized areas according to the strategy of sustainable development,
- development of technologies and methods for environmental protection of post-mining sites and other areas badly affected by the industry,
- development of technologies of using and dumping waste,
- development of techniques and technologies for a management of natural heat sources – geothermics, hydrothermics and aerothermics,
- clean coal technologies ensuring security of energy supplies.

2. KOMAG activities in the scope of reducing noise emissions to the environment

Noise emissions from industrial works or means of transport to the environment are a natural phenomenon, connected with production processes, conducted in these works and with a traffic of vehicles. Attempts of silencing production processes to create an acoustic comfort for workers do not always give required effects and they do not cause a reduction of imissions. Such a situation is described in [2], where it is shown on the example of one of hard coal mines, how the acoustic climate around this mine land is shaped. It was detected that there were higher noise levels in the environment than the permissible ones contained in the Minister's of Environment Order from 14th June 2007 [1] and revised in 2014. Thus inhabitants of houses, persons working in social or commercial-service objects are endangered to this imission which is not in accordance with the recommendation of 2002/49/EU Directive [2] which states that "no inhabitant of EU should be endangered to noise on the level hazardous to the quality and health of life". As the above actions inside the works do not give the right effects, other activities are indispensable, to be taken outside the works, to improve the existing situation. To protect the housing areas and the lands protected acousticly different kinds of methods and means as well as preventive measures are used. It should be mentioned that a reduction of the noise level by 3-5 dB gives perceptible effects for inhabitants (small changes of noise level can cause feelings of different intensity). Due to these reasons, first of all, a professional, correct identification of the acoustic climate and then a selection of proper protections, which should take into consideration both the acoustic conditions as well as others, including environmental ones, is an important element of the acoustic protection.

Technical solutions, leading to a reduction of noise emissions to the environment, include different types of passive acoustic baffles and active acoustic silencers [3, 4].

The issues from this field are in the KOMAG research activity. In the scope of the research-and-development projects, conducted within the framework of the statute activity, several methods, computer software, innovative projects and conceptions were successfully implemented in the scientific and service-and-testing activity of the Institute and contributed to a development of the scientific staff.

Among the most important and interesting projects those presented below should be highlighted:

- an elaboration of a conception of constructing an active silencing system of noise emissions of high power transformers' assembly with external cooling systems,
- an elaboration of the modelling method of acoustic field distribution in closed spaces of diffusing character of the acoustic field to reduce noise emitted to the environment by industrial objects,
- an elaboration of the method for a determination of environment acoustic climate in the area of a large surface industrial object (patent application),
- an elaboration of a technical project of a passive means for reducing noise emitted by a unit transformer,
- a determination, on the basis of industrial tests, of an impact of technical condition and load changes of a power object on shaping the acoustic climate in the surrounding environment,
- a development of a conception project of an acoustic baffle to be installed in mining areas which belong to the III category of building suitability,
- an elaboration of methods and means for a reduction of over and above the standard noise emissions from typical coal loading stations,
- an elaboration of the method for acoustic analyses of airports – conducting acoustic measures and model tests to determine acoustic field distribution; within the doctorate grant from this

scope a method for a determination of acoustic field distributions of airports and of areas endangered by air noise was developed,
- an elaboration of the author's method of reducing noise emissions in the power objects of a complex special structure,
- an elaboration of innovation conceptions of sound-insulating screens of efficiency exceeding the level achieved in implementations so far, for coal tumbling and ball mills, whose acoustic power exceeds the level of 100 dB, and low frequencies dominate,
- an elaboration, on the basis of conducted acoustic analyses with use of a numerical model of sound propagation, of two conceptions of an installation of acoustic tunnel for a reduction of over and above the standard sound emissions from A and S class roads; the final project result was a proposal of a technical solution enabling a significant protection improvement of many-story apartment buildings in relation to classical acoustic baffles used at present,
- an elaboration of a detailed method of developing roads acoustic maps of traffic intensity over 3 million vehicles a year; the developed method included the stage of data processing for a numerical model and a correlation of the data and conducted calculations; the method was subjected to a validation on the base of developed acoustic maps of selected roads,
- conducting acoustic tests for a railway section of permissible speed 160 km/h, being the basis of an analysis of problems resulting from an installation of sound-insulating screens for high speed trains and an elaboration of a sound-insulation screen to be used within the railway lines of this type,
- an elaboration and an implementation of computer software enabling a significant speeding up of the analysis of measurement results of traffic noise and of a distribution of traffic intensity, which eliminates a possibility of making mistakes in the process of developing analyses in this scope,
- an elaboration, on the basis of a multi-alternative numerical tests, of a conception of reducing over and above standard sound emissions of the mine central ventilation station consisting in an installation of two acoustic silencers effectively reducing the noise emissions generated by the diffusors of the central ventilation station,
- an elaboration of an interface of 3D data distribution system in the internet viewer and a presentation of acoustic maps in it,
- an elaboration and implementation of a visualization and 3D animations for a presentation of the results of roads' acoustic maps as 3D noise front maps, indispensable for a presentation of noise levels on individual stories of buildings,
- an elaboration of the new method guidelines for obtaining the GIS data from photogrammetric activities conducted with use of unmanned aircraft; the basis for an elaboration of guidelines included taking photographs of the land from the unmanned aircraft and making inventory of this land using the equipment of Real Time Kinematic GPS which enabled an orthorectification of photographs from the unmanned aircraft and an elaboration of the land model,
- an elaboration of assumptions for conducting tests aimed at an identification of the acoustic field in the objects of increased acoustic requirements,
- a determination of V70 acoustic diffractors' efficiency enabling an efficient reduction of traffic noise in the area of apartment buildings,
- an elaboration of RMR 2002 method for conducting numerical tests and 3D animations of the sound propagation emitted by rail vehicles; the requirements for a construction of the land numerical model and the land coverage were defined, simultaneously determining minimal conditions concerning an accuracy of mapping elements of site planning,
- an elaboration of 3D data base enabling data adolition and edition in the QGIS software environment and an interactive system for a distribution of 3D data,
- an elaboration of a conception of fixing a noise baffle to a facade which solved a problem of protecting apartment buildings against traffic noise, in particular in the case of multi-family buildings; conducted acoustic numerical tests confirmed a high efficiency of sound level reduction in the building protected by the installed baffle,

- a preparation of numerical situational - height map and of numerical models of the land and of an orthomap for mining sites together with adjacent land,
- an elaboration of a method for a generation of digital land maps for industrial areas on the base of photogrammetric data,
- an elaboration of a conception of anti-noise protections limiting the over and above standard noise emissions from the area of the water conditioning technological line; the basis of the elaboration contained measurements conducted in the area which incorporated acoustic measurements of identified sound sources, geodesic measurements and measurements of water flow, which enabled an elaboration of a numerical model of sound propagation and an implementation of noise reducing means,
- an elaboration of geometric and acoustic models consisting of architectural objects with use of ODEON models and the method of defining materials for the layers imported from the AutoCAD software,
- an elaboration of a universal geo-information system using the internet map application for which a visualization of 3D maps indispensable for analyses of sound propagation in the area was developed and started,
- an elaboration of new guidelines for modelling an acoustic field distribution for a determined category of aircrafts, in particular of military type which enabled to establish grounds for a limited use area in vicinity of airports,
- a development of the method for numerical tests of acoustic parameters in interiors of rail and wheel mounted vehicles, which enables to assess acoustic conditions of the interiors of these vehicles,
- an elaboration of a new solution of the silencing base of a roof mechanical fan, enabling a significant reduction of noise generated by the fan,
- an elaboration of a conception of an industrial sound insulating cabin, improving the acoustic comfort of the interior and protecting against mechanical vibrations at the work-place; basing on tests and analyses, including numerical ones, optimal material design features of individual barriers were selected and a transmission of mechanical vibrations by the cabin floor was reduced,
- an elaboration and an implementation of the Robot Structural Analysis Software for designing support constructions of silencers and acoustic enclosures,
- an elaboration of a conception of a light, mobile acoustic baffle for a reduction of noise generated during repairs of urban road infrastructure and of the underground one as well as during open-air events; the features of the suggested acoustic baffle were identified and standard conditions for designing solutions in the scope of environmental protection were determined,
- an elaboration of the method for assessing the hazard of inhabitants of buildings as regards mechanical vibrations generated by means of public transport; after having conducted the measurements verifying the developed method, the means of reducing this impact were suggested,
- a realization of an analysis of an impact of simplifications, used at developing numerical models of the land coverage on the acoustic field distribution around apartment buildings and in the area of the buildings protected acousticly,
- a development of the method for conducting tests of a cumulated acoustic impact of roads and railway lines,
- a determination of the conditions which should be met by the buildings in the scope of an acoustic insulation of external walls, flat roofs and windows; a numerical model of apartment buildings enabling a determination of an acoustic field distribution inside rooms, generated by the sources situated outside the building as well as assumptions of the testing method of sound penetration from the open space to the building, were formulated,
- an elaboration of a conception and a construction of a sound-insulating enclosure for an oil compressor, reducing noise emissions to the environment,
- an elaboration of the method for selecting vibration isolators of water pumps for the Warsaw University of Technology.

3. Examples of research projects oriented onto environmental protection

Besides, a three-year research project, financed by the Ministry of Science and Higher Education was realized. Within the framework of the project the method of hybrid reduction of noise level from the equipment transmitting out the power of turbine sets was developed. The basis for a development of this method was an identification of an impact of the most important equipment in the engine room in the area of the power transmission from a turbine set and an elaboration of a numerical model of the area under testing. A numerical representation of machines and equipment was conducted with use of a model of point sources, taking into consideration their characteristics, i.e. a small surface of sound emissions, versatile character of emissions and a significant acoustic power of machines and equipment under testing.

Within the framework of the COST Action a three-year project COST-EST 356 “Activities in the direction of measurable transport defining at a sustainable environmental impact”, coordinated by the INRETS Institute of Transport Safety from France, was realized. Within the project KOMAG researchers conducted environmental measurements of air-suspended dust as well as of noise generated by industrial objects and motor transport. They realized acoustic analyses and assessed an impact of harmful factors on the environment. The final result of the project included a construction of models of air pollutants’ propagation and of noise propagation in the environment [5].

The subject: “Activities in the direction of a measurable definition of transport at a sustainable environmental impact” was financed with the means of the Special Research Programme. It enabled to conduct tests of ventilation efficiency of lungs of a selected group of Gliwice inhabitants of defined places of residence. Simultaneously tests of air samples in the defined locations, analyzing a propagation of pollutants from linear sources, were conducted. Obtained results of tests of the inhabitants’ lungs ventilation efficiencies and of the levels of environmental pollution were compared.

The research project i-Protect “System of smart means of personal protection for the personnel working in complex environments of high risk” was realized within the Seventh Framework Programme of the European Union [6].

The results of the presented research as well as research-and-development projects were implemented in the industry, and the knowledge and abilities gained during their realization formed the basis for publications of the KOMAG researchers and for a realization of collaboration within scientific as well as scientific-and-industrial consortia.

One of good implementation examples of a KOMAG technical solution in the industrial practice is a sound-insulating enclosure of the WOK 1.5 centrifuge commonly used in preparation plants of mines [7]. A sound-insulating enclosure is made of sound absorbing panels of an assumed acoustic insulation R_w on the level of 40 dB for the frequencies 125-8000 Hz. The requirements of the acoustic insulation meets the mineral wool of density 150 kg/m^3 and of thickness at least 100 mm. The design project of the developed conception of the centrifuge sound-insulating enclosure is shown in Fig. 1 and a visualization of this technical solution – in Fig. 2. However, in Fig. 3 a practical realization of this solution on the real object is shown.

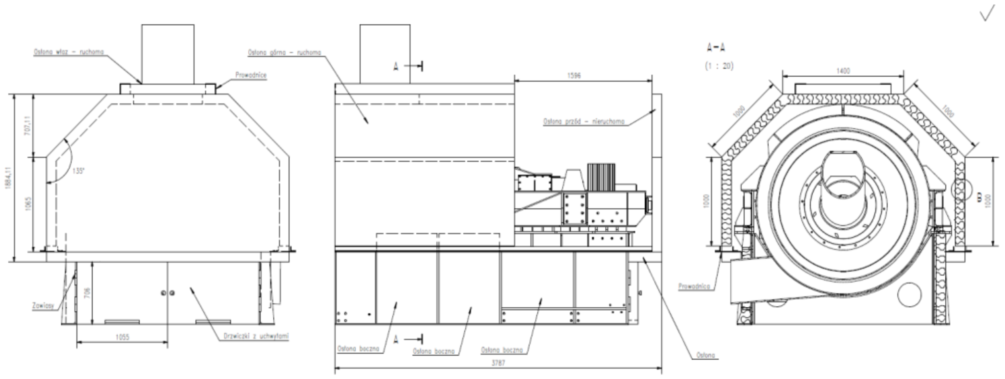

Fig. 1. Design conception project of WOK 1.5 sound-insulating enclosure [7, 8]

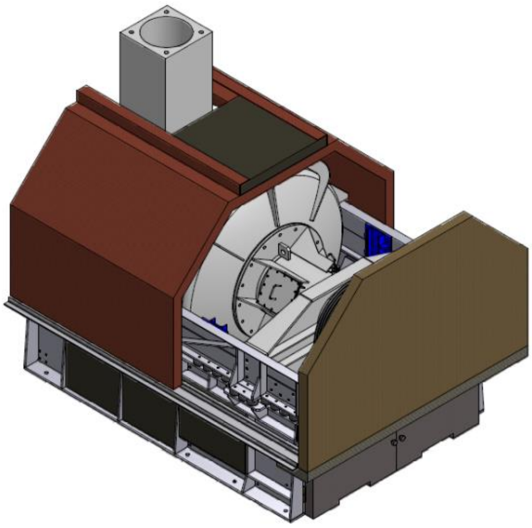

Fig. 2. Visualization of WOK 1.5 centrifuge sound-insulating enclosure [7, 8]

Fig. 3. WOK 1.5 centrifuge in sound-insulating enclosure [7]

Another example of a design solution reducing noise in the work environment, which was realized at the KOMAG Institute is a reflexive silencer of TG type, protected by the patent PL 215380 B1 [7], which is visualized in Fig. 4. An example of its application in the mine mechanical preparation plant is shown in Fig. 5 [9]. This silencer meets the requirements for this type of solutions. It reduces the energy of acoustic waves transmitted along the axes of pipes and holes, through which air or gas flows (ventilation installations, inlet and outlet systems of turbo-machines e.g. compressors, blowers, turbines, diesel engines), but it does not reduce a flow of working medium along the pipes.

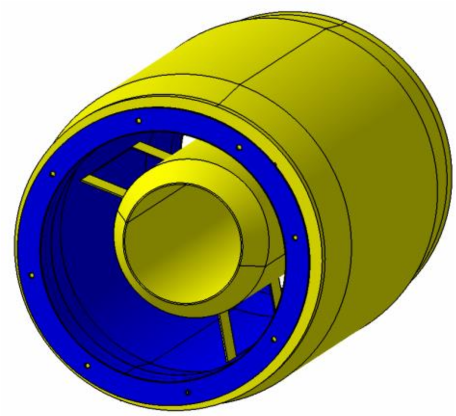

Fig. 4. Visualization of noise silencer of TG type designed at the KOMAG Institute [9, 10]

Fig. 5. View of noise silencer of TG type operated in the dust control installation at the coal mechanical preparation plant [9]

Executed research as well as research-and-development projects formed grounds for a broad service-and-testing activity of the KOMAG Institute of Mining Technology in the field of activities oriented onto acoustic climate and a reduction of noise emissions to the environment. A few examples, selected from many projects made in this scope, are given below:

- Environmental protection programmes against noise for Lubelskie and Kujawsko-Pomorskie Provinces,
- Documentation of anti-noise protections installation along the S1 express road at the section from the Brzęczkowce Junction to the Dziećkowice Junction in Mysłowice,
- Acoustic maps of areas situated in the vicinity of province roads of traffic intensity exceeding 3 million vehicles a year for the provinces: Podkarpackie, Lubelskie, Kujawsko-Pomorskie and for towns: Żory, Jelenia Góra, Gdańsk, Słupsk, Działdowo, Iława, Kętrzyn, Lidzbark Warmiński, Lubawa, Morąg, Mrągowo, Nidzica, Orneta and Pasłęk,
- Acoustic map of an impact of a military shooting-range situated in the Gliwice quarter called Wójtowa Wieś on the basis of environmental measurements of impulse noise emissions,
- Environmental impact reports and environmental protection programmes for the thermal-electric power station in Białystok, Godów Commune, technological system of beneficiating raw slurry at Knurów Mine,
- Hydro-legal assessment documents for towns: Piotrków Trybunalski, Łódź and also waste management plans,
- Projects of noise emission reduction at the area of the production plant FERROLI Poland Ltd., at the area of Shaft IV at Piast Mine, at the headframe of Shaft VII at Jankowice Mine, at the crushing node in the Czatkowice Limestone Mine, for the project offices: EKOSOUND s.c. and ATMOTERM Ltd.,
- Design project documentation for improving acoustics, dewatering and anti-humidity protection of the gym hall building in the Elementary School No. 29 in Katowice,
- Design projects of acoustic baffles E1 and E2 for WTB Konin – World Acoustic Group S.A. and of acoustic baffles for EUROMETAL Company,
- Complex project of assembly of noise eliminators of TS2 and TS4 turbocompressors for TAURON CIEPŁO S.A.,
- Conception of vibro-acoustic protections in work-places and in the rooms where the workers stay for the KGHM Polska Miedź S.A., Department of Ores' Beneficiation.

The prizes and distinctions, obtained by KOMAG and its researchers at different kinds of exhibitions and competitions, confirm an innovative character of technical solutions. One of the most interesting research work results was the silencer of noise of air draw and chute for a collaboration with high-power fans. This technical solution was announced to be the Mining Success of the year 2010. Apart from that prize the technical solution obtained:

- Gold medal with distinction at the International Warsaw Exhibition of Inventions IWIS 2009,
- Prize of I Degree at the Polish Competition of Work Conditions Improvement in 2009,
- Gold medal at the Poznań International Fair 2009,
- Silver medal at the World Exhibition of Innovations, Scientific Research and Novel Technology, Brussels Innova in 2010,
- Bronze medal at the 109. International Fair of Inventions, Concours Lepine, France, in 2010,
- Silver medal at the 62. International Exhibition "Ideas, Inventions, New Products iENA 2010", in Nürnberg, in 2010,
- Diploma and Statuette as well as Congratulations Letter from the Minister of Science and Higher Education in 2010.

Other interesting technical solutions from this field include a system of fan acoustic screens, which received a gold medal at the International Poznań Fair in 2010 and also an accousticly low-emission system of ventilating objects, which obtained a special distinction at the 110. Fair Concours Lepine – Medal of French Inventors and Producers – AIFF. In the thematic field of acoustic climate two successful doctoral procedures were conducted.

4. Other KOMAG activities in the scope of environmental protection

The activity in the scope of environmental protection, described above, were not the only ones which concerned the projects realized at the KOMAG Institute of Mining Technology. Analyzing the results of individual projects, financed from the KOMAG sources as well as service-and-research projects, the following examples should be highlighted:

- an energy and ecological analysis of aspects of hard coal combustion with waste fuels; in the project physical-and-chemical properties of mixes generated on the basis of hard coal and wastes of car tyre rubber were determined and the subject-matter was continued in the doctoral thesis, in which optimal conditions of burning hard coal and rubber wastes were presented,
- an assessment of general population hazard caused by aerosol and nitrogen dioxide from traffic, basing on routine measurements realized at monitoring stations,
- an assessment of geotechnical possibilities of dumping wastes in the LGOM rock-salt deposit (grant financed by the Ministry of Science and Higher Education),
- a conception project of an ecological building in the aspect of heat economy, in particular a preparation of heat balance of large-surface industrial objects,
- an elaboration of conception of water sterilizer with use of UVC rays which can be used for a treatment of water in private houses and in systems of urban water supply systems,
- an elaboration of technical documentation of a novel design solution of special mixers in tanks for making biogas,
- an elaboration of the method of assessing dynamic impacts of road infrastructure on selected architectural objects,
- an analysis of possibilities of using wet dust control equipment for a removal of ash from fine gas emitted from coal fired boilers in power plants and on this basis a preparation and testing of a dust controller model of a new design,
- an analysis of possibilities of modernizing useful warm water installation of the power about 1 MW for heating, using the solar installation system,
- a development of methods and testing technologies enabling a preparation of the system of recovery and conversion of heat energy into electric energy; possibilities of constructing thermoelectric cells were analyzed and a programme of rig tests of recuperation and conversion of heat energy into electric energy was developed,

- a modification of the method of assessing suitability of underground mining wastes for road construction which was directed towards hydrochemical modelling, characterizing ground-water environmental hazard as regards a migration of heavy metals,
- an elaboration of the method of shaping safe environment of children's life and development by specifying standard requirements, concerning testing the safety of products for children and an identification and analysis of hazards resulting from their use; this subject-matter was developed within a successful assistant professor's procedure,
- an elaboration of a model project of assumptions concerning the plan of the commune supply of heat, electric energy and gas fuels as grounds of the commune plan of land development, development plans of power enterprises and plans of heat, electric energy and gas fuels supplies,
- an elaboration of a multi-alternative conception of a turbine construction and a construction of the wind turbine tower of rated power 1.8-2.5 MW,
- an elaboration of the container technology for composting organic wastes consisting in conducting composting in oxygen conditions; it requires an introduction of air into the container, using a unique technical solution with its own system controlling the whole process,
- an elaboration of the thermal method of utilizing polyolefine wastes consisting in cracking in the temperature 400-500^{0}C in oxygen – free atmosphere, of the conception and preliminary design of the installation and reactor for a utilization of these materials together with the control and visualization system,
- an elaboration of a design solution of the bioreactor closure for making stabilat using a membrane made of cloth of specific properties,
- an elaboration of a technical conception of the installation for the technology of organic waste gasification, in particular plastics with a share of biomass and the factor supplying oxygen,
- an elaboration of a quick costing method of an investment from the scope of environmental protection, in particular as regards steel constructions,
- an elaboration of the conception of a station for producing ash-water emulsion of increased resistance to pressures, a transport system of thickened emulsion and portable shutters for making large-size pillars in mine workings as technologies of waste use and location,
- an elaboration of assumptions and detailed guidelines for generating solar potential maps as the basis of conducting profitability analyses of photovoltaic cells assembly; research tools used for a generation of this potential maps were analyzed and a map of a solar potential for a selected area, according to accepted assumptions, was developed,
- an elaboration of a conception of a small-size electro-filter used for purifying exhaust gases, mainly from house furnaces as an efficient tool of reducing low emissions (the solution is the subject of patent application),
- a development of a half-dry method of sulfur removal from exhaust gases in a reactor with an external circulation of the deposit,
- an elaboration of a technical documentation of a self-cleaning filter with a function of water treatment and a protection against big fractions of pollutants,
- an elaboration of a conception of hazing equipment, which effectively reduces thermal arduousnesses,
- an elaboration of the method for a dust neutralization in timber processing plants,
- an elaboration of a conception of the installation using geothermal heat from underground mines with an application of a heat pump and a co-generation system,
- an elaboration of a conception of equipment for a measurement of a geothermal potential,
- an elaboration of a conception of a network of air composition individual monitoring,
- an elaboration of a filter conception, basing on a zeolite, removing salt particles from the air supplied to diesel engines,
- an elaboration of a conception of a hydraulic system of a device for a thermoplastic processing of plastics, in particular polyethylene granulated product and from milling.

It should be mentioned that one of the above research project results, i.e. "Half-dry method of sulfur removal from exhaust gases in a reactor with an external circulation of the deposit" received a gold medal at the IV International Warsaw Exhibition of Innovations – IWIS 2010.

5. Summary

The subject-matter and scope of research-and development projects, concerning widely understood environmental protection with special attention paid to work-places and housing areas, are presented in this article. Over the period of its seventy-year lasting activity the KOMAG Institute realized many projects which enabled to commercialize the research results. Some of them are oriented onto controlling noise emissions from industrial objects, from road traffic, from aeroplanes and from railway lines. The authors of this paper undertook a task of giving a review of many different projects of innovative character, aimed at a development of novel solutions reducing hazards and increasing work safety as well as at a development of technologies and methods for environmental protection of post-mining sites and other areas badly affected by the industry. Special attention was given to the KOMAG achievements in the scope of reducing noise emissions to the environment, including acoustic baffles and active acoustic silences.

One of implementation examples of a KOMAG technical solution in the industrial practice is a sound-insulating enclosure of the WOK 1.5 centrifuge commonly used in preparation plants of mines. Other successful examples of design solutions reducing noise in the environment, which were realized at the KOMAG Institute, include a reflexive silencer of TG type which reduces the energy of acoustic waves transmitted along the axes of pipes and holes, through which air or gas flows as well as a noise silencer of air draw and chute for an operation with high power fans. The awards and distinctions, obtained by KOMAG and its researchers at different kinds of exhibitions and competitions, confirm an innovative character of these technical solutions [11].

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Capacity losses factors of fully mechanized longwall complexes

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Słowa kluczowe: wydajność ścian, straty wydajności, górnictwo, system ścianowy

Abstract:

Between longwall (LW) fully mechanized complex with shearer theoretical capacity (potential) and really achieved capacity sometimes there is a significant difference. In article sources of those differences are described. There are external and internal factors constraining real capacity below LW complex technical potential as local conditions and menaces. Mining technologies and extraction process management and organization are seriously affecting the final result. Differences between potential and achieved LW complex capacity are in fact capacity and capital asset losses. In the article main reasons of those measurable capacity losses are pointed out such as available time losses and incomplete fully mechanized LW technical potential: shearer cutting speed, cutting depth and seam thickness use ratio.

Streszczenie:

Pomiędzy teoretyczną a rzeczywistą wydajnością zmechanizowanego kompleksu ścianowego z kombajnem węglowym bardzo często występują duże różnice. W artykule podjęto próbę wskazania źródeł takich różnic. Są to czynniki zewnętrzne i wewnętrzne ograniczające możliwości wykorzystania potencjału technicznego kompleksu ścianowego w postaci warunków górniczo-geologicznych, a w tym występujących zagrożeń górniczych. Istotny wpływ wywierają także czynniki związane technologią prowadzenia robót górniczych oraz organizacją i zarządzaniem procesem wydobywczym. Jako główne przyczyny, będących w istocie stratami, mierzalnych różnic pomiędzy potencjalną a rzeczywistą wydajnością kombajnowego kompleksu ścianowego wskazano straty dostępnego czasu pracy kompleksu oraz niepełne wykorzystanie potencjału technicznego w postaci prędkości urabiania, głębokości zabioru i wykorzystania miąższości pokładu oraz niektórych przyczyn występowania takich strat.

1. Introduction

Comprehensively mechanized longwalls are potentially the most efficient technology for the implementation of the mining process in the coal extraction [1].

Among the longwall systems of hard coal mining, fully mechanized longwall complexes allow to obtain a daily production of over 50,000 tpd for mining with shearer loaders [2]. An alternative technique for mechanical mining of coal in mechanized longwall systems are coal ploughs [3], but they are much less common due to technical requirements and price (currently 17 comprehensively mechanized plough longwalls are in operation worldwide). Moreover, the plough longwall systems have a limited scope of application due to the maximum cutting height (up to about 2.2 m) and therefore, even in the most favorable conditions, they do not achieve such record results as some longwall systems with shearer loaders. For this reason, the article focuses on mechanized longwall systems with shearer loaders. Although conventional longwall systems (with blasting) and various variants of semi-mechanized longwall [4] systems are still operated in the world, the production level of longwall systems is determined by fully mechanized complexes [5].

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2. Mechanized longwall complex – idea, components and their cooperation/compatibility

Regardless of the mechanization degree, the longwall is intended to carry out the basic operations of the extraction process, i.e. [6]:

- coal mining,
- loading coal onto a haulage device (armoured face conveyor - AFC),
- hauling/transporting coal along the face.

In the extraction process implemented in the longwall heading, an additional operation is performed in the form of temporary and ultimate protection of the heading by providing a roof support (temporary and/or ultimate one). The fact that in the first longwall operations (17th century) and the modern ore mining often there wasn't a need to secure the working space of the longwall [1], the operation of temporary and ultimate protection of the heading has been recognized as of an additional/auxiliary nature. The longwall heading is secured by supporting the roof and/or covering the working space of the face. Historically, various technical and technological solutions have been applied in the longwalls:

- traditional longwalls – with hand mining. At the beginning, all operations of the extraction process were carried out manually with simple tools, gradually replaced by manual machines (the impact hammer replaced the pickaxe, the mechanical shovel replaced the manual shovel, and finally the transportation of the output material in boxes or simple cars was replaced the oscillating conveyor and then the belt conveyor).
- Conventional longwalls - with the mining of coal body with explosives (blasting). Starting from performing all operations manually through mechanical drilling of blast holes with hand drills. In order to reduce the labor consumption of blasting works, the cut/breaking in hole (i.e. an additional exposure plane) made by means of blasting works was replaced by the notch performed mechanically (using various types of cutters). Conventional longwalls are associated with the use of armoured conveyors (Upper Silesia, around 1942). Later, chain cutters were additionally used to load the output material onto the armoured conveyor.
- Fully mechanized longwalls – with mechanical mining with the use of coal ploughs and longwall shearers (initially cutting ones, being the development of chain cutters, to modern shearer loaders with ranging arms).

When considering the degree of mechanization of the extraction process in coal longwalls, three basic stages of mechanization can be distinguished:

- **Small (manual) mechanization**, where some operations are mechanized by means of hand-held mechanical tools (impact hammer, drill, mechanical shovel, etc.),
- **Partial mechanization**, where one or several operations is/are mechanized among many operations performed. The first mechanized operation to be mentioned was the transport of the excavated material in the longwall by means of oscillating or belt conveyors applied at the beginning of the 20th century (hence the replacement of Longwall Mining with the term Conveyor Mining in Great Britain at that time). Mechanical mining with cutting shearers appeared in the British mining just before the World War II, the first coal ploughs were implemented in the German mining industry during the World War II. The first mechanized (without hydraulic components) roof supports also appeared in the German coal mining in the first half of the 20th century. At similar time, the first longwall protective roof supports (without hydraulic components) appeared in the mining industry of the former USSR. The individual devices were not functionally coupled to each other at that time.
- **Complex (full) mechanization**, where all extraction process operations in the longwall are mechanized. Contemporary, comprehensively mechanized longwalls are equipped with systems of functionally combined machines and devices. In the Polish conditions, it is difficult to talk about complex mechanization of longwalls due to a large portion of manual operations performed in the area of the AFC drives in the zone of intersections of the face with the gateroads secured by the yield arch supports.

Complex (full) mechanization of the process is a necessary (fundamental) prerequisite for the automation of this process.

A modern mechanized longwall system is composed of several basic elements:

- Cutting machine (shearer or plough),
- Armoured face conveyor,
- Powered roof support,
- Beam stage loader with crusher,
- Hydraulic pump unit supplying the powered roof support,
- Set of electrical devices powering the longwall equipment.

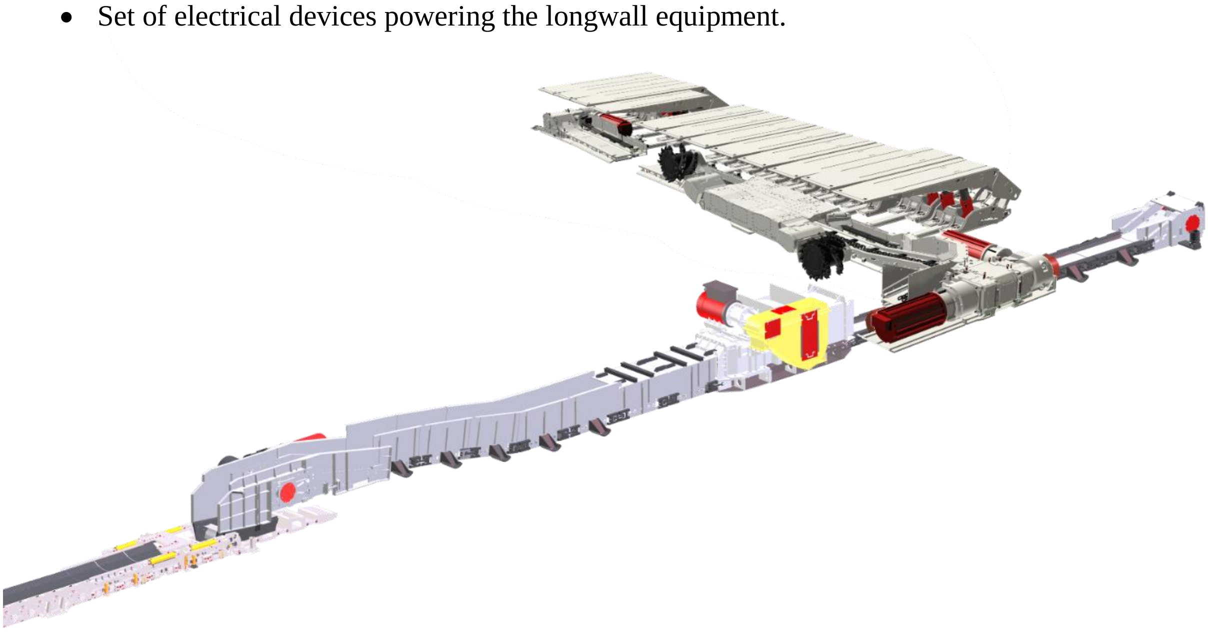

Fig. 1. Fully mechanized longwall complex with coal shearer – general view [own source]

The basic elements of the mechanized longwall complex provide various functions intended for a good operation of the aforementioned components and their mutual correct cooperation, as follows:

- The cutting machine (shearer or plough) is primarily intended to mine coal (to separate it from the unmined coal) and load it onto the armoured face conveyor. An additional function of the cutting machine is to prepare (cut) the space for the other longwall devices for their proper operation. Therefore, sometimes it is necessary to additionally trim/cut rocks in the vicinity of the coal seam (in the floor or in the roof) or to leave the coal in the floor or roof of the longwall. In the case of high longwalls, crushers sometimes are installed on the longwall shearer (from the AFC tail drive) to crush large lumps of coal, especially with the shearer cutting towards the tail drive (in the opposite direction to the AFC running direction).
- Face conveyor (so called armoured or articulated conveyor) is mainly intended to haul the coal mined by the cutting machine along the longwall. The armoured face conveyor also provides the following functions:
  - the armoured face conveyor is a specific keystone/closer (backbone) of the longwall,
  - the mining machine (plough or shearer) moves along the AFC and the powered roof support is attached to it,
  - a movable part of hoses and cables supplying the shearer is led in the cable trays (spill plates),
  - the armoured face conveyor is a mechanical connection of individual powered roof support units/shields (enabling their movement - advancing),
  - the AFC pan route also serves as a structure for leading electrical cables and hydraulic hoses through the longwall, and in the plough longwalls – for leading the pull and return chain of the plough (as in the Mikrus longwall complex),
  - the AFC structure is often also used to attach additional equipment (communication and signaling devices, and emergency stops),

  - the AFC structure enables the stream of transported material to be partially aligned during transport,
  - sometimes, especially in high longwalls, it is necessary to use an additional crusher on the main drive of the armoured face conveyor in order to crush very large lumps of excavated material that could block the transfer from the face conveyor onto the beam stage loader and cause the longwall to stop - production stoppage.
- The powered roof support - its primary function is to protect the working space of the longwall. This is obtained by supporting the roof and/or preventing the caving rocks/debris from falling into the working space of the longwall. In addition, the powered roof support provides the following functions:
  - it's a base for advancing the armoured face conveyor,
  - the advancing ram is intended to advance the armoured face conveyor,
  - the advancing ram is intended to advance the powered roof support units/shields,
  - structural elements of the powered roof support units/shields are base for installing additional yield components – rams (for correction or stabilization of the longwall equipment components),
  - it's a base for installing other longwall equipment, including:
    - hydraulic hoses
    - cables
    - components of the control system (the powered roof support control system included), communication and signalling systems.
- The beam stage loader (BSL) with a crusher (resizer) is intended to unload the output material from the armoured face conveyor, the material whose stream is uneven and containing quite large lumps. The design and construction of the beam stage loader enables to align the stream of output material, and the crusher embedded on it is intended to break large lumps of spoil before loading it onto another conveyor – a belt conveyor, which is characterized by high sensitivity to overloading and/or the presence of oversized lumps of material. Belt conveyors do not tolerate local overloads and large-size lumps, therefore the material from the armoured face conveyor is not discharged/unloaded directly onto the belt conveyor. Additionally, the beam stage loaders are equipped with boot ends enabling the BSL to be moved along the gate, sometimes together with the return station of the belt conveyor.

In the studies of the productivity or efficiency of the mechanized longwall systems, it is also necessary to indicate the elements not being part of this system, but having significant effect on its operating conditions, such as the shape and type of the gates (maingate and tailgate).

3. Factors affecting the actual productivity of the fully mechanized longwall complex.

Seemingly, productivity of the mechanized longwall system depends only on the resulting/ the lowest productivity of the devices the longwall system is composed of. However, as many years of observations show, the real average productivity of longwall complexes is lower than the theoretical technical productivity of an individual longwall complex. This is due to the fact that there are factors that limit this productivity. The main factors that decrease the actual productivity at the longwall system are as follows:

- Local conditions (geo-mining ones included) and menaces/risks,
- Applied technologies of operating the technical system of the longwall and the skills of operators and managers,
- Faulty management and organization of work (Fig.2).

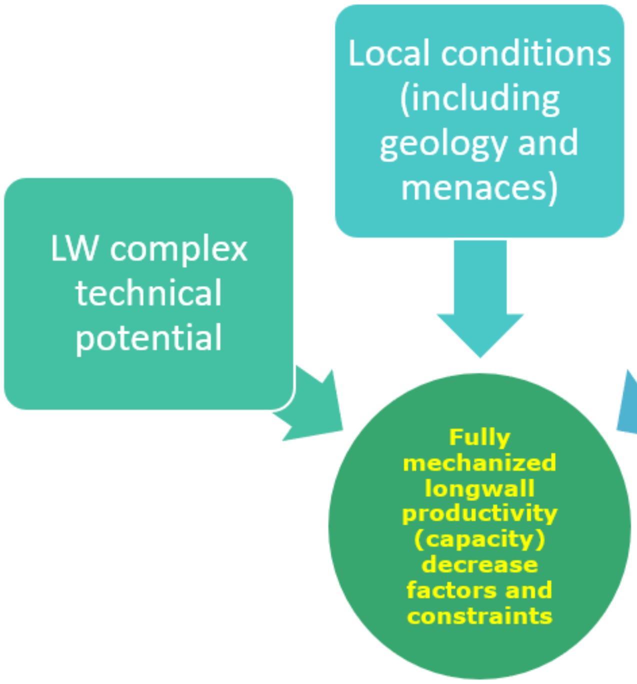

Fig. 2. Main groups of constraints – productivity decrease factor in LW extraction [own source]

As a result of the occurrence of factors (constraints) limiting the productivity/capacity of coal longwalls, their actual productivity/capacity is lower than theoretically possible (Fig.3).

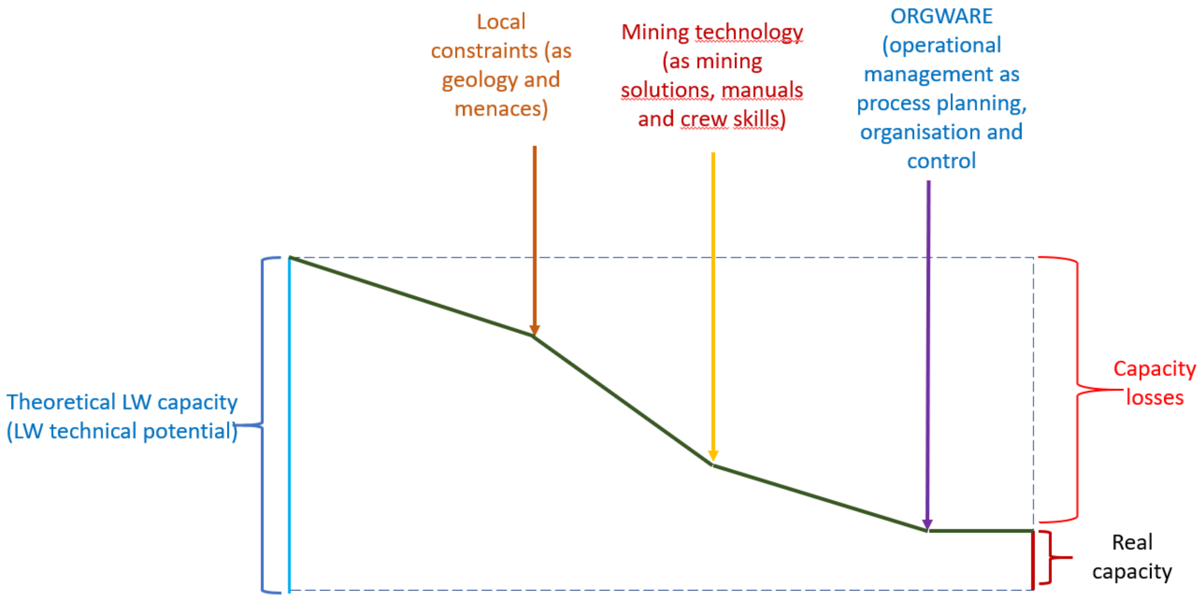

Fig. 3. Theoretical and real LW face capacity and capacity losses [own source]

In the analysis of the reasons of capacity losses, a detailed analysis of the causes of their occurrence and a possibility of eliminating or reducing them is significant.

4. Reasons for occurrence of productivity/capacity losses of longwall systems with shearer loaders.

The above-mentioned general factors decreasing the longwall systems productivity/capacity can be presented in a different way as losses of the theoretical capacity (potential) losses of this technical system (Fig. 4).

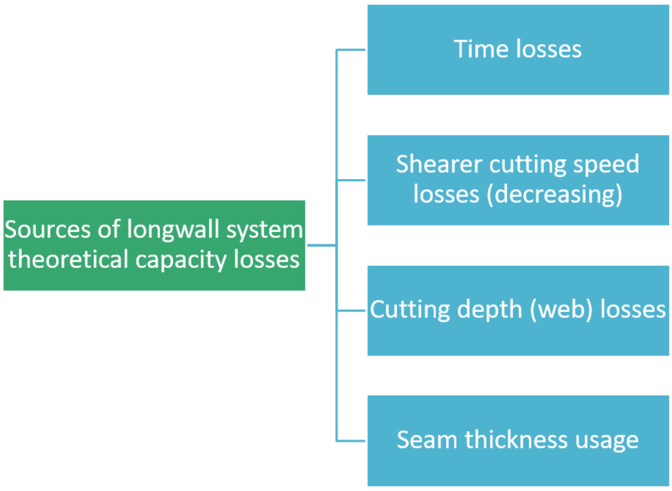

Fig. 4. Main sources/reasons of theoretical shearer longwall complex losses[own source]

All these capacity losses result from the constraints shown in Fig. 3. The research work and analyses carried out by the Author show that the greatest capacity losses of the mechanized longwall complex result from an incomplete use of the available time and the failure to use available speed of the cutting machine - the longwall shearer.

In the Polish coal mining industry, since the introduction of drum longwall shearers into operation, first in partially and then fully mechanized longwalls, studies of the degree of utilization of the technical potential of these shearers have been conducted for many years and a number of KPI - Key Performance Indicators [7] have been defined. The economic transformation in the 1990s meant that the measurements and analyses of these indicators have been gradually abandoned. Nowadays, also in the Polish coal mining industry, the analysis of the operating time of mechanized longwall systems is being restored [8].

4.1. Losses of available cutting time

The use of the available working time of mining machines is a very important element in the search for the productivity of the mining process [9].

For many years, the Polish underground coal mining has been dominated by a mechanized longwall system almost exclusively with longwall shearers, and recently only with caving. After a period of careful research on the use of longwall systems [10] in the form of a system of indicators, such analyses were gradually abandoned, mainly due to the lack of automatic measurement tools. However, advanced tools for monitoring and diagnostics of the operation and condition of longwall systems have appeared [11, 12]. For several years, the measurement the operating time use in the case of the shearer longwall systems has been applied again in the Polish companies extracting hard coal, as one of the components of the of the mining process assessment - KPI (Key Performance Indicator) [8].

Very often, in the Polish hard coal mining industry, the degree of use of longwall shearers in terms of percentage of working time of these machines in the daily time has been applied in the assessments. The low percentage of this time is treated as an assessment of the reliability of mining machines, regardless of their manufacturer. Meanwhile, similarly to the analyses used in the Polish hard coal mining industry in the past, the optimized time structure has been used in the very modern and efficient Australian coal mining, as shown in Fig. 5.

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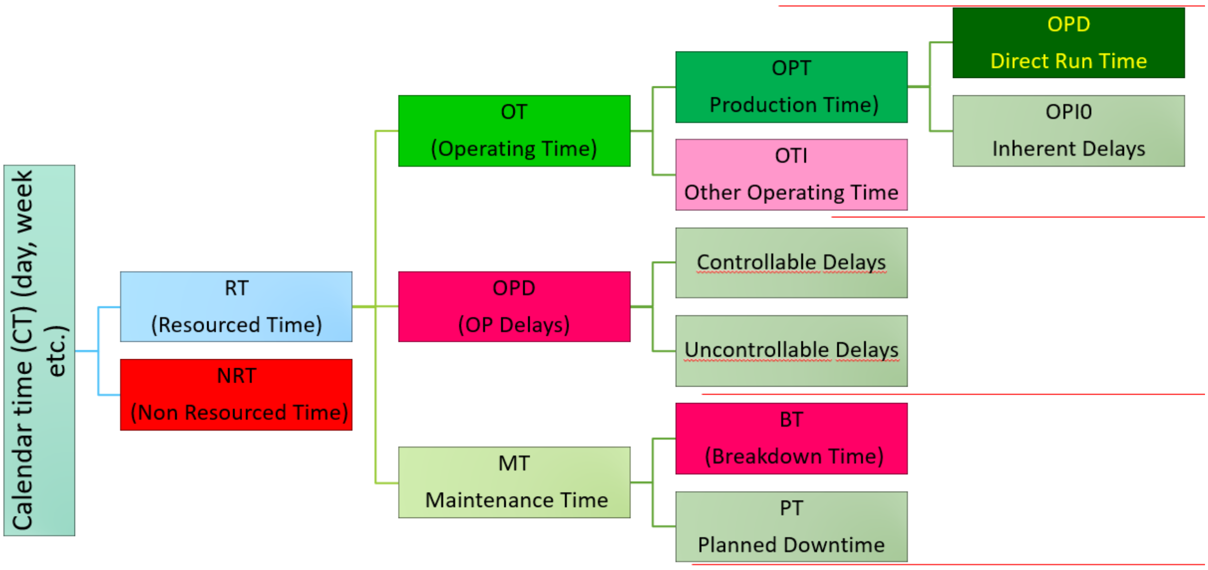

Fig. 5. Calendar time structure in longwall operations [8]

Direct Run Time is the working time of a longwall shearer while it's cutting. Theoretically, it should be aimed at 100% of this time in calendar time, but it is not feasible. It is not possible to eliminate OTI (Other Operating Time) and OPIO (Inherent Delays) completely - you can only try to shorten them. In the conditions of the Polish underground hard coal mines, operations at the longwall ends, that is at the face-gate crossings, are a significant source of time losses, which is a potential chance for a significant improvement in the time use of the longwall complex [13, 14, 15].

A question can be asked whether it is possible to eliminate breakdowns and normal technical maintenance (MT) completely by an appropriate construction and operation of the mechanized longwall system? Certainly, it is necessary to eliminate completely organizational breaks (OPD), the causes of which are outside the longwall complex itself and result from the process organization and management, mining and geological conditions and the technical condition of the technical infrastructure outside the longwall. It is unlikely to eliminate completely organizational interruptions and delays in the mining process, but any time reduction within this scope results in the OPD (Direct Run Time) increase.

4.2. Utilization of nominal speed of the shearer cutting

Observations of the actual cutting speed of shearer loaders in one group of the Polish mines show that the actual speed is lower than the nominally available one. Even an elimination of the periods at the speed "0" m/min from the analysis indicates that the average speed is significantly lower than the nominal speed (Fig. 6).

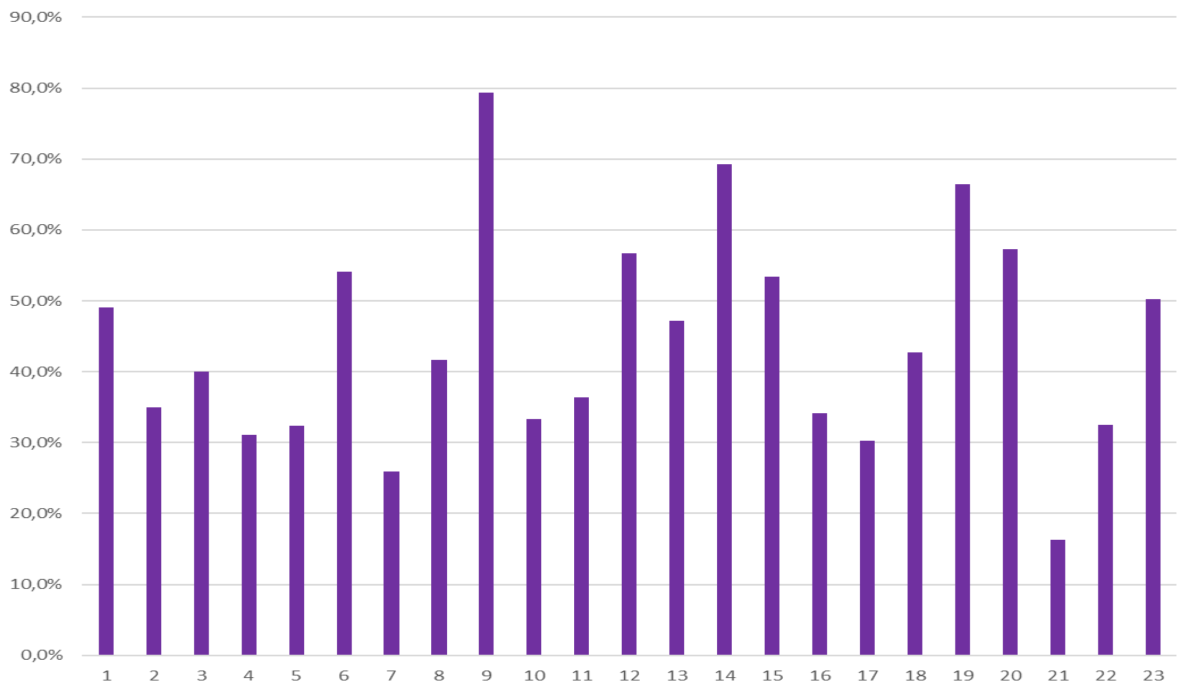

Fig. 6. Utilization of nominal speed of longwall shearers in one of the Polish mining companies in January 2019 – monthly average [own source]

The main constraints/factors limiting the average speed of longwall shearers are:

- Poor technical condition of the longwall equipment which does result in stoppages (e.g. deteriorated condition of the AFC as the runway for the shearer).
- High level of methane hazard requiring a reduction of the shearer cutting speed (for the actual longwall, the cutting speed is a factor significantly affecting the volume of methane emitted) [16].
- A large number of the shearer stops and its bringing to speed due to various reasons.

4.3. Cutting depth (web) losses

Longwall shearers have a constructionally set (nominal) cutting depth to which the stroke of the advancing systems of the powered support units/shields is adapted [17, 18]. However, there are situations when the actually obtained web of the shearer is lower than the nominal one, which is a loss of the longwall capacity. The main reasons for such situations can be as follows:

- Inaccurate loading of the output material and leaving it between the face and the armoured face conveyor, which limits the actual (performed) web of this conveyor
- In the event of errors by the operators of the powered roof support and/or the powered roof support control system, the gate support unit/shield may be positioned non-perpendicularly to the armoured face conveyor and, consequently, the actual advancing web of the longwall may be reduced. Such situations often occur in longwalls with a longitudinal slope exceeding 15°. Additional operations related to correcting the p.r.s.units/shields positioning may also reduce the shearer cutting speed, which is also a source of productivity loss (of the available longwall potential).

The Author's analyses show that the degree of utilization of the shearer nominal web in the longwalls of high productivity/capacity is 100% (and in some cases it is even slightly higher). However, there are cases when the resulting web depth (for a larger number of cycles) differs significantly from the nominal value.

4.4. Use of the seam thickness

Effective use of the seam thickness should mean cutting and loading the entire seam thickness, unfortunately sometimes with rock interlayers occurring in it. Therefore, one should strive to select the mining machine in such a way that it is able to cut the entire available seam thickness. Leaving the unmined coal layer means a waste of not only the available resources, but also of the available technical potential of the longwall system. It happens, however, that the mining machine cuts the rock in the vicinity of the seam as a result of the decrease in the seam thickness, incorrect selection of the mining machine or operator's errors. These are also potential losses resulting in the limitation of the cutting speed and loading the transported mined material with additional ballast which is also decreasing the output material quality. It should be also noted, that in many coal basins there are seams, in the mining of which there is a spontaneous collapse of the direct roof layer, but this phenomenon is independent of the selection of the mining machine or operator's errors [18, 19, 20].

5. Summary

High investment expenditures and operating costs related to an operation of comprehensively mechanized longwalls require their high productivity and an elimination of any losses of the available mining potential, as well as a full use of the available operating time of the longwall complex (understood as the cutting time of the shearer). Potential capabilities of capacity growth exist, for the real longwall complex, in the field of planning, technology and organization of the extraction process.

The observations of the majority of longwalls in operation in Poland show that, even with the existing constraints caused by geo-mining conditions and menaces (hazards), the degree of utilization of the technical potential of the longwall systems is low. The main reasons for the low utilization of the available mining capacity of the mechanized longwall systems lie in the large losses of the available/nominal time (for cutting), including the time lost at the longwall ends. Another noticeable reason is a failure to use the technical capabilities of the longwall system equipment, which may indicate errors in planning and selecting equipment adapted for in-situ conditions.

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Stand tests of a powered roof support after a long time of operation. Case study

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Keywords: mining industry, powered roof support, static strength, fatigue strength

Słowa kluczowe: górnictwo, sekcja obudowy zmechanizowanej, wytrzymałość statyczna, wytrzymałość zmęczeniowa

Abstract:

The process and results of stand tests on the powered support manufactured in 1996 are discussed. The tests were conducted at the KOMAG's accredited testing laboratory, implementing an author's testing program. After completion of the static strength, load bearing capacity and fatigue strength tests, the roof support was inspected and no mechanical damage to the basic components of the tested roof support was found. The recorded permanent deformations of the basic components of the roof support tested in 2020 were compared with the results of tests of the same roof support, conducted in 1996 (prototype tests) and 2009 (tests after modernisation), also at the KOMAG laboratory. Based on the results of tests conducted in 2020, it was shown that the current properties of the roof support meet the normative requirements. Therefore, the customer may decide to continue using them in other longwall panels.

Streszczenie:

Omówiono przebieg i wyniki badań stanowiskowych sekcji obudowy zmechanizowanej wyprodukowanej 1996r. Badania wykonano w akredytowanym laboratorium badawczym ITG KOMAG, realizując autorski program badawczy. Po zakończeniu badań wytrzymałości statycznej, podporności i wytrzymałości zmęczeniowej, przeprowadzono oględziny sekcji i nie stwierdzono uszkodzeń mechanicznych elementów podstawowych badanej sekcji. Zarejestrowane odkształcenia trwałe elementów podstawowych sekcji badanej w 2020 r. porównano z wynikami badań tej samej sekcji, wykonanych w 1996 r. (badania prototypu) oraz 2009 r. (badanie po modernizacji), również w laboratorium ITG KOMAG. Na podstawie wyników badań wykonanych w 2020 r. wykazano, że aktualne właściwości funkcjonalne sekcji spełniają wymagania normatywne. Zleceniodawca może więc podjąć decyzję o dalszym użytkowaniu w kolejnych ścianach.

1. Introduction

The safety requirements [1] applicable in the case of installation of the powered roof support that has been in use for more than 20 years in a newly opened longwall, [2], require the strength tests at an accredited testing laboratory. In the case discussed in this article, the shielding support with a 1.5 m pitch and after over 20 years of operation was tested [3, 4, 5, 6]. Due to the anticipated deterioration of the technical condition of the roof support [7], the mine ordering the tests, suggested the KOMAG Testing Laboratory to develop an additional, extended testing program, carried out in several stages until the powered roof support loses its functional features. The aim of the testing was to collect data on the basis of which the Orderer could make a rational decision to install the roof support in a new longwall panel faces or to scrap it.

The roof support strength tests were an inspiration for a broader presentation of the results of permanent deformation measurements of roof support's basic components and for comparing them with the results of previously performed tests. The analysis was possible because the authors of this article had not only information on the time and conditions of operation of tested roof supports, but also had the results of previous strength tests:

- the first tests were carried out in 1996 and concerned the roof support prototype,
- others were carried out in 2009 after the roof support was modernized.

All the aforementioned tests were conducted at the KOMAG Testing Laboratory, using the testing procedures and normative requirements in force at that time, while the purpose, scope and results of the tests conducted in 2020 are presented below.

2. Laboratory tests of used powered roof support

2.1. Scope and objectives of testing

The aim of the stand tests carried out in 2020 [8] was to determine the present technical condition of the roof support by loading it until it loses its functionality. The test program was developed on the basis of PN-EN 1804-1 + A1: 2011 Standard [9] and was submitted for approval to the Orderer. The test was divided into several stages, and after completion of the first or each subsequent stage the mine had to decide whether to continue the test or to end it. The first stage assumed static strength tests according to the program presented in Table 1 and fatigue strength tests according to the program presented in Table 2. In the following stages it was expected that the fatigue strength tests would be continued according to the program presented in Table 2, and the static strength tests according to the program presented in Table 3.

Table 1. Program of the static strength test of the roof support – stage I [own source]

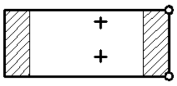
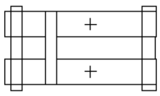
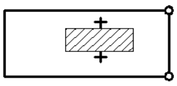
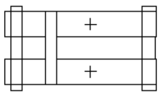
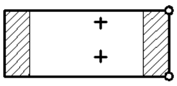
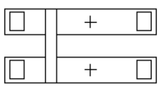
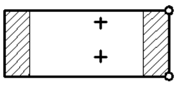
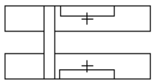
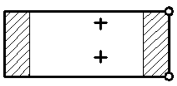
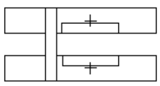
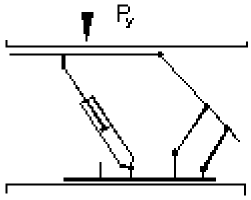
Item	Supporting diagram		Load p/p_n	Height of the roof support set to load, m
	Canopy	Base		
1.			1.2	2.0
2.			1.2	2.0
3.			1.2	2.0
4.			1.2	2.0
5.			1.2	2.0
6.			1.0	1.95÷1.81
				1.68÷1.56
				1.41÷1.29

Table 2. Program of the fatigue strength test of the roof support – stage I and the next stages [own source]

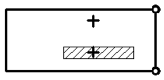
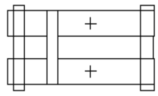
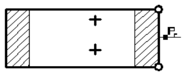
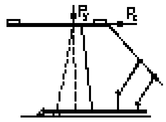
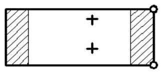
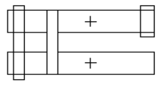
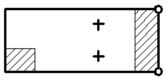
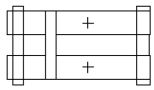
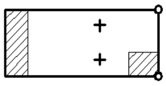
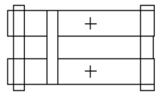
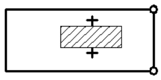
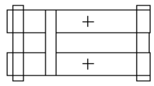
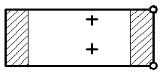
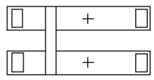
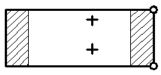
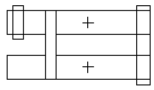
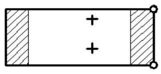
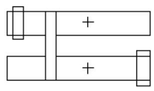
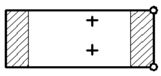
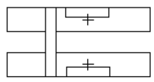
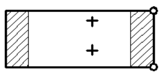
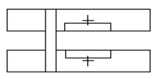
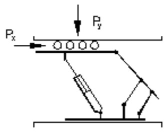
Item	Supporting diagram		Item	Load range p/p_n	Number of cycles	Max. overloads p/p_n
	Canopy	Base				
1.			1.4	0.25÷1.05	2000	1.05
2.			2.0	0.25÷1.05	10000	1.05
3.			2.0	0.25÷1.05	1000	1.05
4.			2.0	0.25÷1.05	2000	1.05
5.			2.0	0.25÷1.05	2000*	1.05
6.			2.0	0.25÷1.05	2000	1.05
7.			2.0	0.25÷1.05	2000	1.05
8.			2.0	0.25÷1.05	1000	1.05
9.			2.0	0.25÷1.05	2000	1.05
10.			2.0	0.25÷1.05	1000	1.05
11.			2.0	0.25÷1.05	1000	1.05

Table 3. Program of the static strength test of the roof support – next stages [own source]

Item	Supporting diagram	Load p/p_n	Height of the roof support set to load, m
1.		1.0	1.95÷1.81
			1.68÷1.56
			1.41÷1.29

2.2. Testing procedure and the results

After the I stage of static and fatigue strength tests, carried out in accordance with the assumed program, an inspection was made and no damage to the basic components of the tested support was found. The functionality of the roof support was maintained. Information on the results of the completed stage of the test was provided to the Orderer (the mine). After analysing the results of the I stage, taking into account the panels and geological and mining conditions of the future longwalls in which the tested roof support are to be operated, the mine decided to end the test at that stage.
Users of the powered support have considered many times the possibility of further use of more than 20-year-old roof supports. In view of the above problem, the authors, after being familiarize with the results of the stand tests from 1996 [10], 2009 [11] and 2020, as well as test programs and load parameters, which resulted from the standards and regulations in force at that time, decided to analyse the elastic and plastic (permanent deformation) deflection of the following basic components: a base, a canopy and a gob shield (Fig.1).

Arrangement of the elastic and plastic deflection measuring points on the roof support tested in 2020 is presented in Fig. 1.

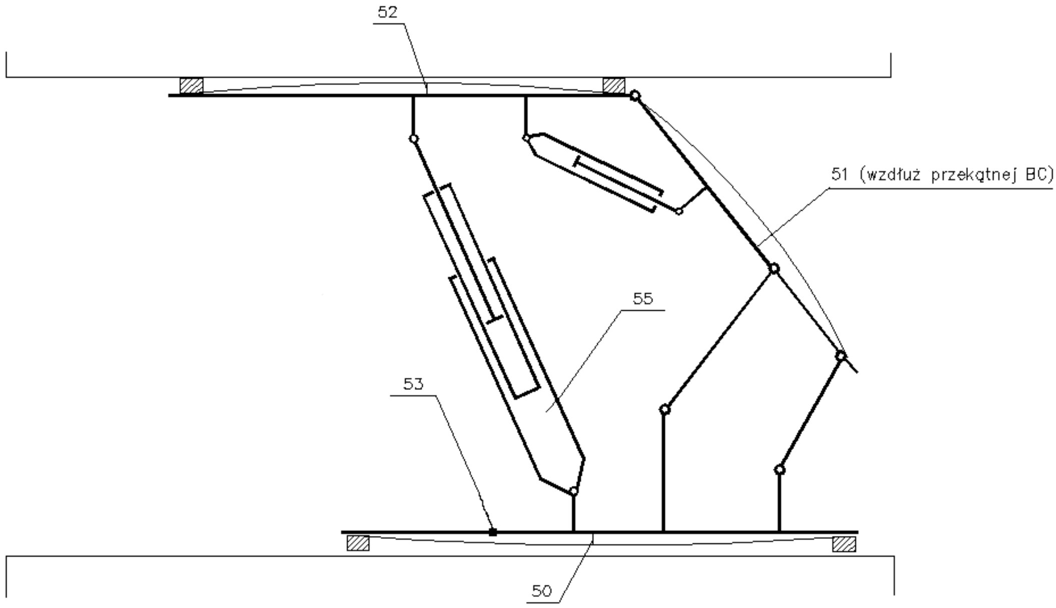


Fig. 1. Arrangement of the elastic and plastic deflection measuring points on the tested roof support [7]

Numbers of the measuring points specify the deflection measurement at the place of their location:

50 – base deflection – longitudinal measurements,
51 – gob shield deflection,
52 – canopy deflection,
53 – base deflection – transverse measurements (in a plane perpendicular to the object plane).

Maximum elastic deflection of the powered roof support components is presented in Table 4.

Table 4. Maximum elastic deflection of the powered roof support components in mm [own source]

Point No.	Ratio p/p_n	Supporting method according to Table 1				
		1	2	3	4	5
		Roof support height, m				
		2.00	2.00	2.00	2.00	2.00
50	1.00	-3.3	-2.7	-2.3	---	---
	1.05	-3.4	-2.9	-2.3	---	---
	1.20	-3.3	-3.2	-2.8	---	---
51	1.00	0.5	0.7	1.3	0.0	0.5
	1.05	0.7	0.9	1.3	0.6	0.5
	1.20	0.9	1.0	2.0	0.8	0.8
52	1.00	-14.7	-1.7	-15.1	-12.1	-13.0
	1.05	-15.3	-1.8	-15.5	-12.8	-13.3
	1.20	-17.9	-2.0	-18.0	-15.4	-15.9
53	1.00	---	---	---	-0.8	0.7
	1.05	---	---	---	-0.8	0.7
	1.20	---	---	---	-1.0	0.9

The measurements results of permanent deformations of the canopy (Fig. 2) and the gob shield (Fig. 3) are presented in Table 5 and Table 6, respectively. Measurement of permanent deformation was taken by the method developed at KOMAG Testing Laboratory using the instruments for flatness measurements being at KOMAG disposal [12]. Measurements uncertainty was estimated for the confidence level of 95% and is U = 0.4 mm. Measurements of flatness were made just after the roof support delivery and after the tests were completed. Points A and B are the supporting points of the measuring bar. The measuring points are 500 mm apart from each other, starting from the reference point A which is 100 mm from the edge of the tested part. The permanent deformation of the tested part is a difference between the measurements before and after the strength tests, at subsequent measuring points. The sign "+" means that the part is bent upwards, the sign "-" means that the part is bent downwards in relation to the measuring bar.

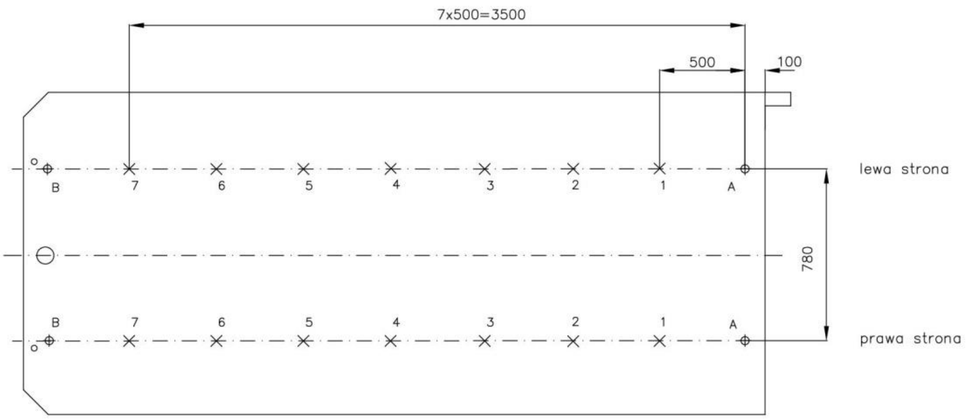


Fig. 2. Arrangement of the measuring points on the canopy: A and B – points of supporting the measuring bar; 1 ÷ 7 measuring point located at left and right side of the canopy [7]

Table 5. The results of measurements of the canopy permanent deformations [own source]

Distance from the edge of the part, mm	Point No.	Measurements results, mm				Permanent deformations, mm	
		Left side of the canopy		Right side of the canopy		Left side of the canopy	Right side of the canopy
		Before testing	After testing	Before testing	After testing		
600	1	+1.6	+1.6	-0.1	+0.1	0	+0.2
1100	2	+1.0	+1.2	-1.0	-0.7	+0.2	+0.3
1600	3	-0.7	-0.3	-2.1	-1.7	+0.4	+0.4
2100	4	-5.1	-4.8	-2.4	-2.0	+0.3	+0.4
2600	5	-9.9	-9.1	-7.6	-7.3	+0.8	+0.3
3100	6	-1.5	-1.0	+1.1	+1.4	+0.5	+0.3
3600	7	+5.1	+5.8	+4.7	+4.9	+0.7	+0.2

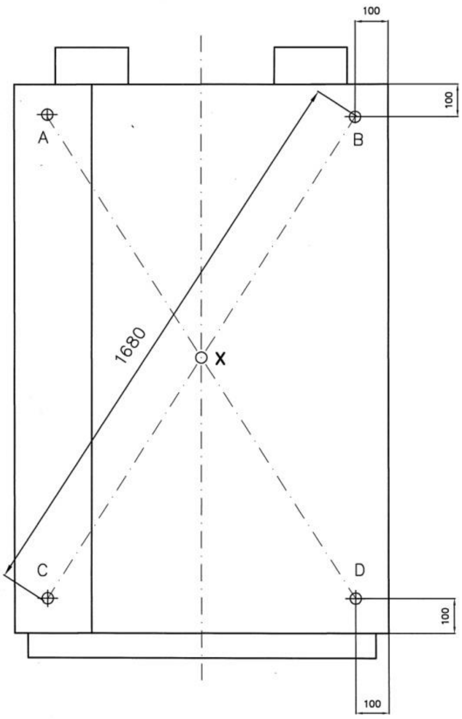


Fig. 3. Arrangement of the measuring points on the gob shield:
A, B, C, D - supporting points of the measuring bar; x - measuring point on the shield [7]

Table 6. Results of measurements of permanent deformation of the gob shield [own source]

Point No.	Measurement results, mm		Permanent deformations, mm
	Before testing	After testing	
X_{AD}	+9.6	+9.8	+0.2
X_{BC}	+1.0	+10.5	+9.5

Publisher: KOMAG Institute of Mining Technology, Poland

3. Laboratory tests of the powered roof support prototype in 1996

The stand tests were conducted according to the requirements of the Ministry of Industry and Trade Guidelines, being in force then, to verify the design assumptions [13] in the field of kinematics, fatigue and static strength requirements of the PN-G-50041 1994 standard [14]. The prototype tests were necessary to get approval for the powered roof support from the State Mining Authority to be used in mine underground.

The elastic deflection of the powered roof support tested in 1996 is presented in Table 7.

Table 7. Maximum elastic deflection of the powered roof support components in mm [own source]

Point No.	Ratio p/p_n	Supporting method according to Table 1	
		1	2
		Left side	Right side
		Roof support height, m	
		2.10	2.10
50	1.00	-2.9	-3.0
	1.25	-3.7	---
51	1.00	0.8	0.3
	1.25	1.3	---
52	1.00	-15.9	-16.2
	1.25	-20.2	---
53	Not measured		

Arrangement of the measuring points from Table 7 is shown in Fig.1.

The results of measurements of permanent deformations of the canopy (Fig. 2) and the gob shield (Fig. 3) are presented in Table 8 and Table 9, respectively.

Table 8. Permanent deformations of the canopy [own source]

Distance from the edge of the part, mm	Point No.	Measurements results, mm				Permanent deformations, mm	
		Left side of the canopy		Right side of the canopy		Left side of the canopy	Right side of the canopy
		Before testing	After testing	Before testing	After testing		
600	1	+3.5	+4.2	+2.8	+4.5	0.7	+1.7
1100	2	+7.2	+9.1	+4.9	+8.2	+1.9	+3.3
1600	3	+10.0	+12.5	+8.3	+11.8	+2.5	+3.5
2100	4	+13.2	+16.0	+11.9	+15.5	+2.8	+3.6
2600	5	+12.9	+15.7	+11.7	+14.8	+2.8	+3.1
3100	6	+9.5	+9.6	+96	+11.5	+2.3	+1.9
3600	7	+3.5	+3.2	+3.2	+3.8	+1.0	+0.6

Table 9. Permanent deformations of the gob shield [own source]

Point No.	Measurements results, mm		Permanent deformations, mm
	Before testing	After testing	
X_{AD}	+11.5	+11.4	-0.1
X_{BC}	+12.4	+12.6	+0.2

4. Laboratory tests of the modernised powered roof support

The powered roof support tested and approved for operation in 1996, had been used for 13 years. After this period of operation, the user decided to have it modernized. The stand tests on the modernised powered roof support, conducted in 2009, was to verify the design assumptions of the roof support after the modernisation (the canopy was modernised by extending it by 300 mm). The tests were conducted in accordance with the requirements of the PN-EN 1804-1:2004 standard, which was introduced after Poland joined the European Union in 2004 [15, 16].

Elastic deflection of the powered roof support tested in 2009 is shown in Table 10.

Table 10. Maximum elastic deflection of the roof support components in mm [own source]

Point No.	Ratio p/p_n	Supporting method according to Table1				
		1	2	3	4	5
		Roof support height, m				
		2.00	2.00	2.00	2.00	2.00
50	1.00	-2.1	-2.1	-2.0	---	---
	1.05	-2.2	-2.1	-2.1	---	---
	1.20	-2.5	-2,5	-2.4	---	---
51	1.00	0.6	0.7	0,6	0.9	0.6
	1.05	0.6	0.6	0,7	1.0	0.5
	1.20	0.8	0.8	0,8	1.2	0.6
52	1.00	-16.7	---	-17.0	-16.2	-15.9
	1.05	-17.7	----	-18.1	-16.7	-16.8
	1.20	-20.4	----	-20.9	-19.8	-19.3
53	1.00	---	---	---	-1.1	1.2
	1.05	---	---	---	-1.1	1.6
	1.20	---	---	---	-1.2	1.4

Arrangement of the measuring points from Table 10 is shown in Fig.1.

The results of measurements of permanent deformations of the canopy (Fig. 2) and the gob shield (Fig. 3) are presented in Table 11 and Table 12, respectively.

Publisher: KOMAG Institute of Mining Technology, Poland

Table 11. The results of measurements of the canopy permanent deformations [own source]

Distance from the edge of the part, mm	Point No.	Measurement results, mm				Permanent deformations, mm	
		Left side of the canopy		Right side of the canopy		Left side of the canopy	Right side of the canopy
		Before testing	After testing	Before testing	After testing		
600	1	+5.1	+5.1	+3.2	+3.6	0.0	+0.4
1100	2	+11.5	+11.8	+7.9	+9.0	+0.3	+1.1
1600	3	+17.6	+18.6	+16.2	+17.4	+1.0	+1.2
2100	4	+22.7	+23.9	+23.0	+23.9	+1.2	+0.9
2600	5	+24.6	+26.0	+22.9	+23.8	+1.4	+0.9
3100	6	+19.7	+21.4	+18.1	+18.7	+1.7	+0.6
3600	7	+12.8	+14.3	+12.2	+12.5	+1.5	+0.3

Table 12. The results of measurements of the gob shield permanent deformations [own source]

Point No.	Measurement results, mm		Permanent deformations, mm
	Before testing	After testing	
X_{AD}	+10.0	+10.0	0.0
X_{BC}	+9.9	+9.9	0.0

5. Comparison of permanent deformations

In order to analyse elastic and plastic deflection (permanent deformations), the results, included in tables 5, 6, 8, 9, 11 and 12, were presented as graphs of the permanent deformations in a function of distance from the edge of the tested canopy part (Fig.4, and 5), as well as the permanent deformation of the gob shield (Fig. 6 and 7).

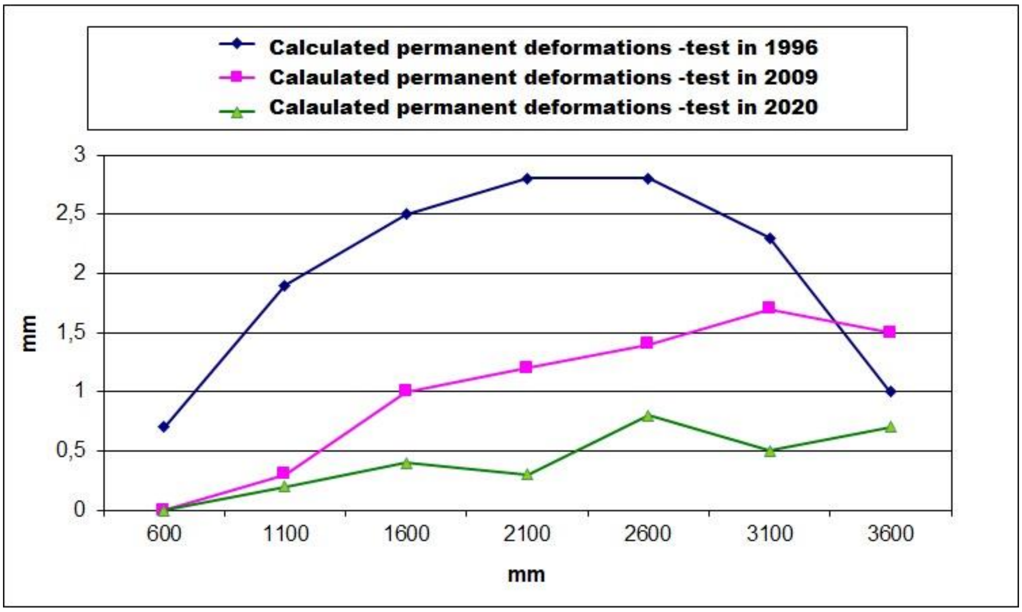


Fig. 4. Graph of the maximum permanent deformation of the left side of canopy (own source)

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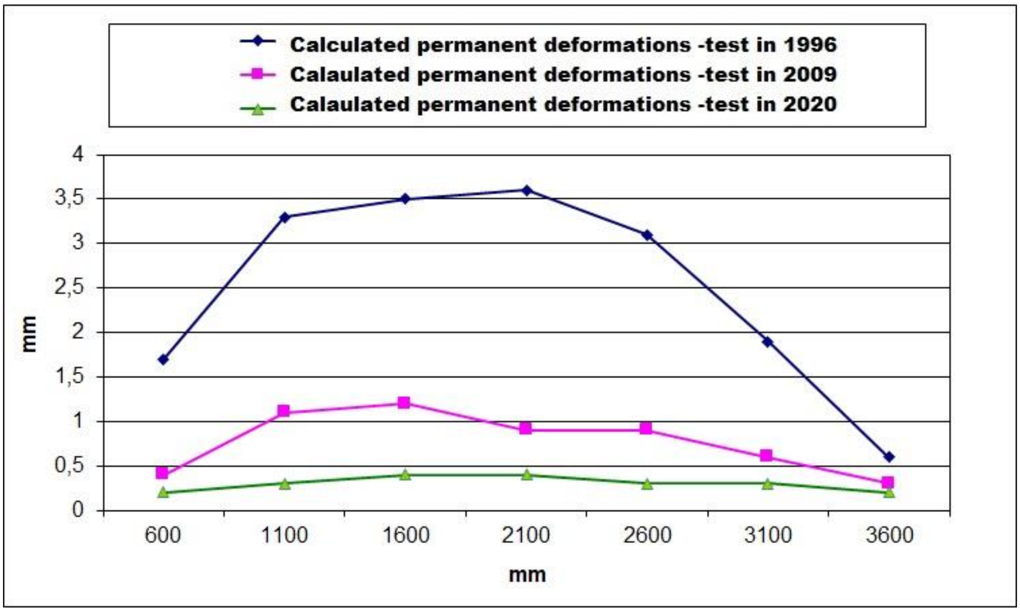

Fig. 5. Maximum permanent deformation of the right side of the canopy (own source)

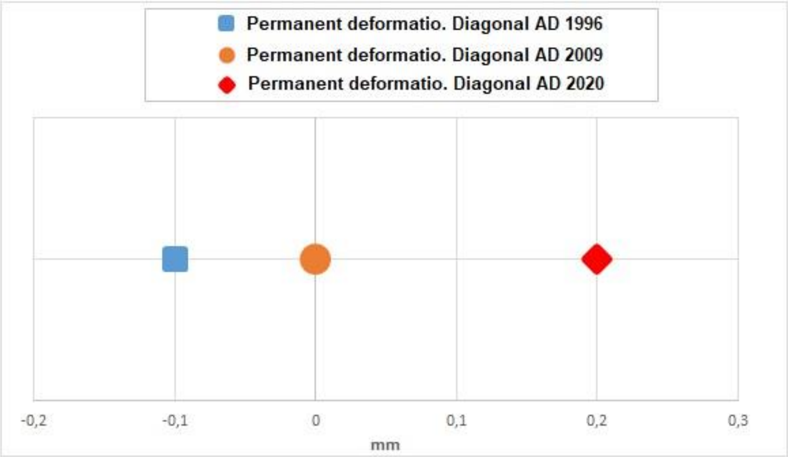

Fig. 6. Maximum permanent deformation of the gob shield – roof support diagonal AD (own source)

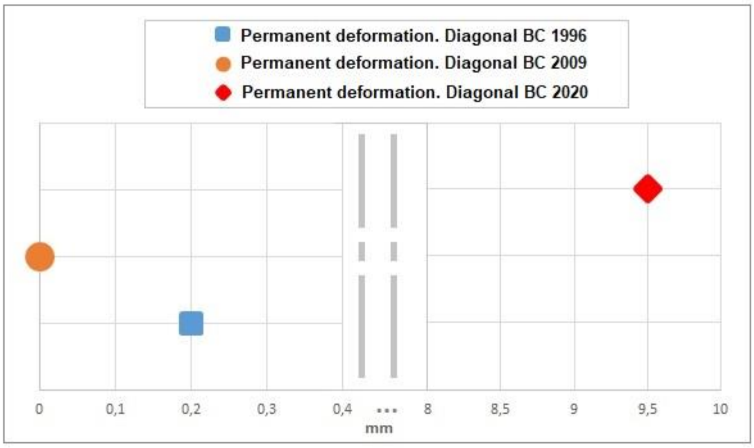

Fig. 7. Maximum permanent deformation of the gob shield – roof support diagonal BC (own source)

Comparing the deformations presented in Fig. 4 and 5, it has been found that the highest permanent deformation was in the canopy tested in 1996, and the lowest in the canopy tested in 2020. These may,, result from the fact that in 1996 laboratory tests were conducted with greater overload required by the regulations (standards) being in force at that time.

On the other hand, when comparing the deformations presented in Fig. 6 and 7, it is noted that the highest permanent deformation of the gob shield, both in the diagonal AD and BC, was recorded during the tests in 2020. Larger permanent deformations of the gob shield can be explained by a significant number of fatigue load cycles (approximately 36,000 cycles) applied to the powered roof support over the entire 24-year of service life.

6. Summary

After completion of the stand tests of an over 20 years old powered roof support, no loss of functionality was found after 26,000 cycles of fatigue load and static strength tests according to the programs presented in Tables 1 and 2. The results of the tests conducted in 2020 may be the basis for the user's decision on the installation of the remaining powered roof supports of the same type as the tested roof supports in the next longwall panels. It was proved that long-term operation did not significantly weakened the structure of the powered roof support. This roof support meets all the requirements included in the PN-EN 1804-1+A1:2011 standard in terms of static and fatigue strength put for new designs.

Comparing the recorded permanent deformations of the roof support's basic components tested in 2020, with the test results of the same roof support from 1996 (prototype testing) and 2009 (testing after modernization), larger deformations of the roof support tested in 2020 are found. Despite the larger deformations, the roof support has not lost its functionality, proved by tests and visual inspections on the test stand.

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Pressure pulsations in power hydraulics systems

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Keywords: pressure pulsations, power hydraulics, water hammer, fatigue strength

Słowa kluczowe: pulsacje ciśnienia, hydraulika siłowa, uderzenie hydrauliczne, wytrzymałość zmęczeniowa

Abstract:

The paper discusses the problem of pressure pulsation in hydraulic systems. The most important causes of pressure disturbances were discussed, such as: instability of the pump performance, variability of the system load and transient states related to the control of the system. The next part presents the threats caused by pressure fluctuations. On the one hand, the effects of the occurrence of a water hammer are presented, as a temporary exceeding of the maximum operating pressure of the system. On the other hand, the problem of fatigue strength of the system was presented, which was illustrated on the example of tests and calculations of hydraulic cylinders and hydraulic hoses. In the last part, the author indicated further directions of literature, simulation and experimental research.

Streszczenie:

W pracy został omówiony problem występowania pulsacji ciśnienia w układach hydraulicznych. Poruszono najważniejsze przyczyny powstawania zaburzeń ciśnienia takie jak: niestabilność wydajności pompy, zmienność obciążenia układu oraz stany przejściowe związane z sterowaniem układem. W kolejnej części przedstawiono zagrożenia wywoływane przez fluktuacje ciśnienia. Z jednej strony zostały przedstawione skutki wystąpienia uderzenia hydraulicznego, jako doraźne przekroczenie maksymalnego ciśnienia roboczego układu. Z drugiej strony przytoczono problem wytrzymałości zmęczeniowej układu, który został zobrazowany na przykładzie badań i obliczeń siłowników hydraulicznych oraz węży hydraulicznych. W ostatniej części autor wskazał dalsze kierunki badań literaturowych, symulacyjnych i eksperymentalnych.

1. Introduction

The first hydraulic installations and devices were used to meliorate of farmland and provide drinking water to cities. Besides to using canals, pipelines and aqueducts to transport water from sources above the point of need, the ancients developed a series of water pumps that allowed water to be transported from lower levels to places above. In addition to simple structures for lifting water, e.g. the Archimedes screw, around 270 BCE a much more advanced piston pump design was developed by the Ctesibius of Alexandria (Fig. 1) [1].

A big leap towards modern power hydraulics took place in the period from the mid-17th century to the end of the 18th century. It began with the formulation of Pascal's law in 1648. The first hydraulic cylinder was patented by Joseph Bramah in 1795 [2]. Further development of power hydraulics was related to the use of hydraulic oils as working fluids, and the use of new structures and materials in hydraulic systems [3].

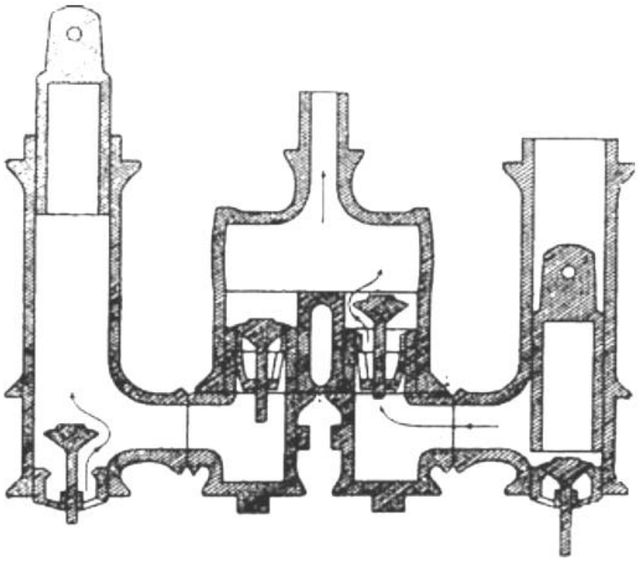

Fig. 1. Reconstruction of force pumps found at Bolsena, Italy [4]

Thanks to all these modifications, today's hydraulic systems generate tons of times greater forces from a unit of volume than electric or pneumatic systems. Unfortunately, such technological advancement has led to the occurrence of such phenomena as cavitation, water hammer and pressure pulsation in these systems. These lead to faster wear and failure of hydraulic systems. Mentioned harmful phenomena will be discussed in the following chapters.

2. Sources of pressure fluctuations

There are several terms in the literature relating to the types of non-stationary pressure. The most frequently used, and at the same time those that should be indisputably distinguished are: pulsating pressure and oscillating pressure. Pulsating pressure is a state in which the fluid pressure is the sum of two components (equation 1): the average pressure and the variable component of the pressure. Oscillating pressure is a special case of pulsating flow in which the average pressure of the medium is equal to zero [5].

$$P_{tot} = P_{avg} + P_f \tag{1}$$

where:

P_{tot} – Total pressure, Pa,
P_{avg} – Average pressure, Pa,
P_f – Variable component of the pressure, Pa.

An example of the transient pressure changes shown below (Fig. 2):

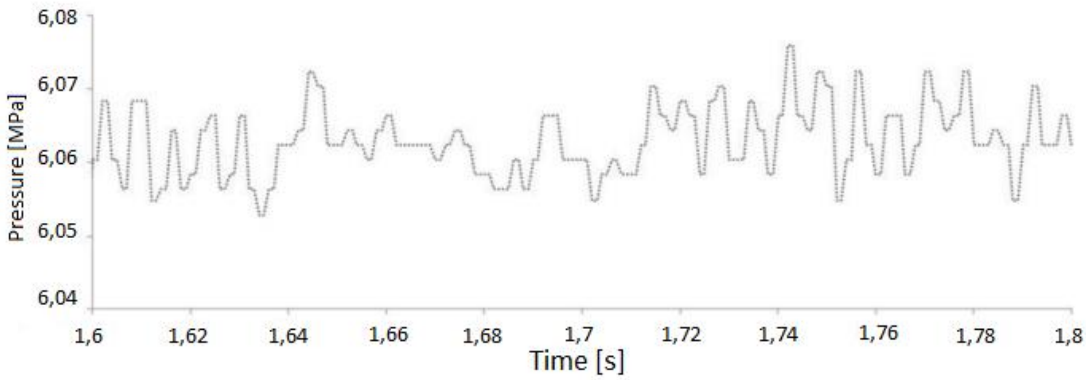

Fig. 2. Experimental pressure measurement results [6]

Fluid pressure fluctuations can have several causes, the most important of which are:

- periodic operation of hydraulic system components such as pumps and control valves,
- variability of the load on the executive elements of the hydraulic system, such as the hydraulic cylinder and hydraulic motors,
- unsteady states from shifting, starting and breaking the system,
- moving of the frame to which the system is attached,
- turbulent flow of the medium.

The following parts of the article discuss pressure changes caused by: uneven performance of the pumping device, variation of the system load and changes in the operating state.

2.1. Instabilities arising from pump operation

Unevenness of the displacement pumps operation results from the cyclic operation of a finite number of working elements. In the literature [7] to describe the temporary work variability of positive displacement pump, delivery fluctuation coefficient described by the equation (equation 2) is used.

$$\delta_p = \frac{Q_{max} - Q_{min}}{Q_{avg}} \tag{2}$$

where:

δ_p – delivery fluctuation coefficient,-,
Q_{max} – Maximum pump flow, m^3/s,
Q_{min} – Minimum pump flow, m^3/s,
Q_{avg} – Average pump flow, m^3/s.

The dependence of the delivery fluctuation coefficient on the number of working elements for selected types of pumps is presented in the diagram (Fig. 3).

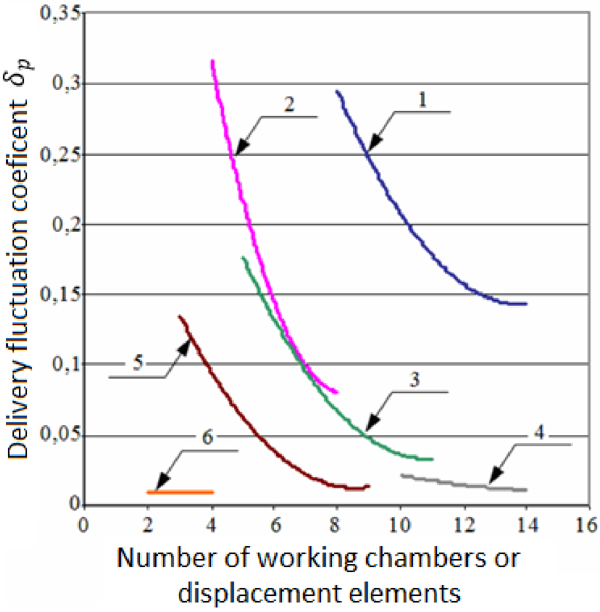

Fig. 3. Comparing the delivery fluctuation coefficient of positive displacement pumps: 1 - external gear, 2 - piston with an even number of pistons, 3 - single action vane, 4 - internal gear, 5 - piston with an odd number of pistons, 6 - screw [8]

On the basis of the graphs it can be seen that the coefficient takes the highest values for pumps with a small number of working elements. An exemplary pump, outside the range presented in the chart, of the Duplex type, working at 70 rpm and a nominal flow of 0,0057 m^3/s (340 l/min), generates the actual flow in the range from 0,007 m^3/s (420 l/min) to 0,0042 m^3/s (250 l/min) [9], which gives the delivery fluctuation coefficient equal to 0,5.

2.2. Pressure fluctuations related to working load of the device

Another factor that can generate pressure pulsation in the hydraulic system is the change in working load. As an example, a screw-type cutting head can be cited (Fig. 4). Machine load variations can be caused by the following factors:

- periodicity plugging knives in mined material.
- uneven breakout of the brittle raw material
- stochastic course of the friction forces between the tool and the material being cut.

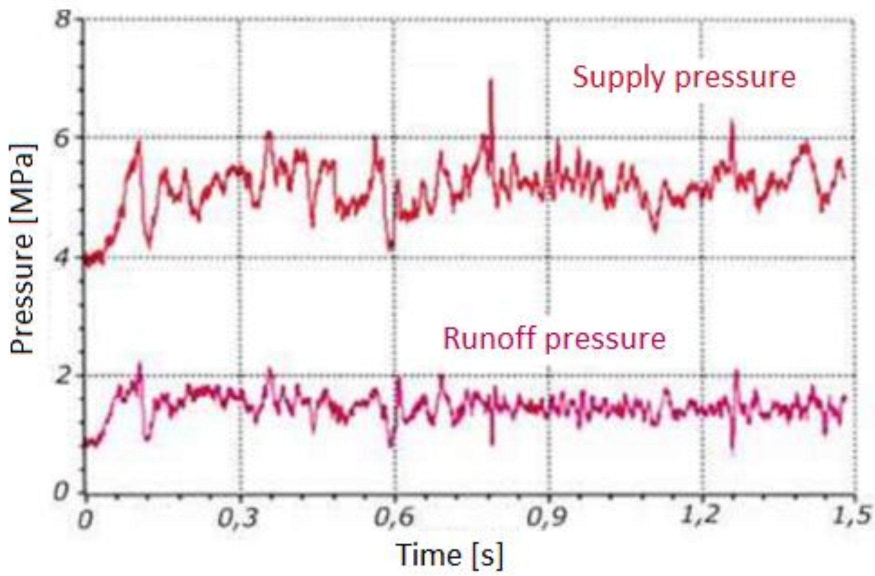

Fig. 4. Measurement signals during coal cutting [10]

2.3. Adjusting the hydraulic system as a source of pressure instability

Hydraulic fluid pressure changes in the system may also be caused by sudden system adjustment, e.g. starting / stopping the pump (Fig. 5), closing / opening the valve [11]. This phenomenon in the literature is called water hammer, and its prevention is the subject of many scientific studies. These changes are mainly caused by the inertia of the fluid in the operating system. These effects are more noticeable the longer the hydraulic line is, and the faster the changes to the system shifting.

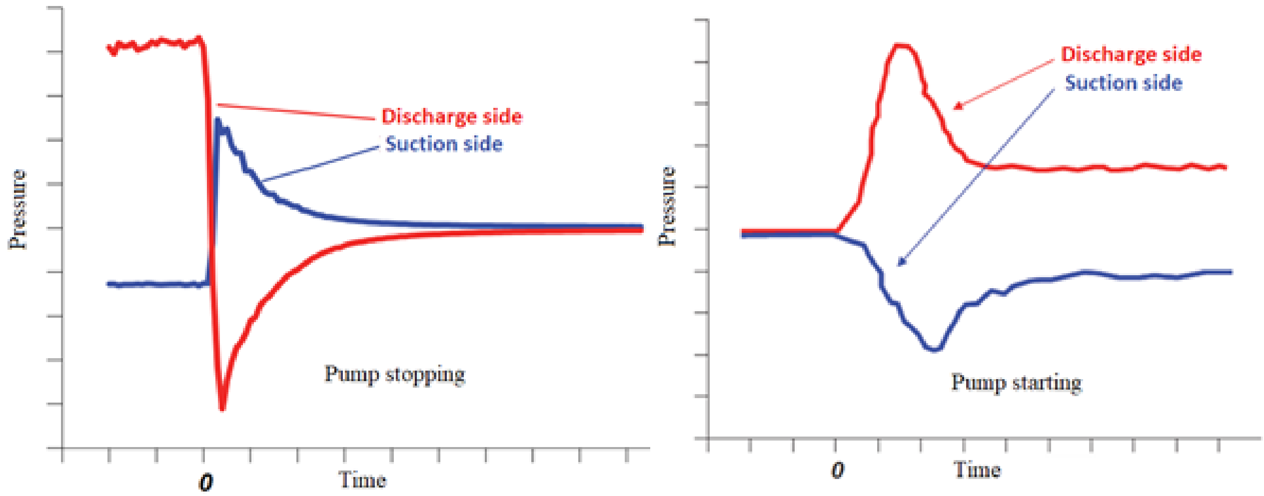

Fig. 5. An example of the pressure changes on the suction and discharge side after the rotor stop (left) and start (right) of the centrifugal pump. 0 – time of the rotor stop/start moment [11]

For example, if in a pipeline 300m long, with an internal diameter of 2.5" and an output of 680l/min, at a pressure of 1.7MPa, the water flow is stopped by a valve closed for 0.3 seconds, the dynamic pressure of water will increase to 6.7MPa [12]. Which gives almost 4 times increase in fluid pressure.

3. Propagation and amplification of the pressure disorders

Correct determination of the pressure wave propagation velocity in the hydraulic line is very important because of its influence on the accuracy of analytical and numerical calculations, both in terms of amplitude and frequency of their changes. This parameter is determined from the formula described in the literature (equation 3) [7, 13].

$$c_o = \sqrt{\frac{\beta_c}{\rho_o(1 + \frac{\beta_c D}{E g_p} c_1)}} \tag{3}$$

where:

- c_o – Pressure wave propagation speed, m/s,
- β_c – Liquid bulk modulus, Pa,
- ρ_o – Liquid density, kg/m^3,
- D – Internal pipe diameter, m,
- E – Young's modulus of the material the pipe, Pa,
- g_p – Wall thickness of the pipe, m,
- c_1 – Constant depends on the mounting of the pipe, -,

The constant c_1 is conditioned by the method of mounting the pipe and can be determined by one of the following equations (equations 4, 5, 6) [13]:

- for monolithic pipe with one-side fasten

$$c_1 = 1 - 0{,}5\nu_p \tag{4}$$

- for a pipe fixed on both sides (no axial displacement)

$$c_1 = 1 - {\nu_p}^2 \tag{5}$$

- for a pipe with longitudinal compensation (expansion joints)

$$c_1 = 1 \tag{6}$$

where:

- c_1 – Constant depends on the mounting of the hydraulic line, -,
- ν_p – Poison's modulus of the material the hydraulic line,-.

3.1. Construction of hydraulic hoses

Hydraulic hoses used today are most often of a layered structure. They differ in the number of layers of cord, their arrangement and the material from which the reinforcement is made. For this reason, it is very difficult to unequivocally determine their Young's modulus and Poison's coefficient, which are necessary to determine the velocity of the pressure wave in the medium. The problem is described in the literature [8] where the dependencies of the wave propagation velocity depending on the structure of the pipeline and the pressure in the system have been developed (Fig. 6).

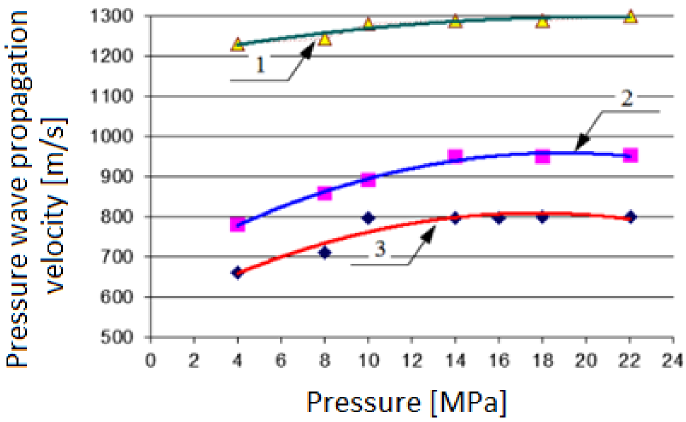

Fig. 6. The dependence of the velocity of propagation of the pressure wave on the mean pressure along the length of the pipeline for different pipe materials: 1 - rigid pipe, 2 - hose with two layers of steel cord, 3 - hose with one layer of steel cord [8]

We can see here that the speed of wave propagation depends not only on the design of the hose, which determines the coefficients needed for calculations (equation 3), but also on the pressure in the system.

3.2. Length of the hydraulic line

When testing pulsating flows, particular attention should be paid to the case where we are dealing with a long hydraulic line, i.e. when the length of the hose is on the order of the length of the pressure wave propagated in it or is greater than it [8]. Then it should be taken into account that the changes in pressure and flow rate propagate along the axis of the pipes with a finite speed in the form of current and reflected waves [14, 15, 16].

In the literature, two fundamentally different methods of describing transient (quasi-steady) waveforms in systems with a long hydraulic line are commonly used: the frequency waveform study method and the method of studying transient processes as a function of time. A hydraulic line is treated as a two-way element of a system with two inputs and two outputs: pressure p and flow rate q. Fluctuations in the efficiency of positive displacement pumps in systems with a long hydraulic line can be described using the so-called a hydraulic four terminal network (Fig. 7) [8].

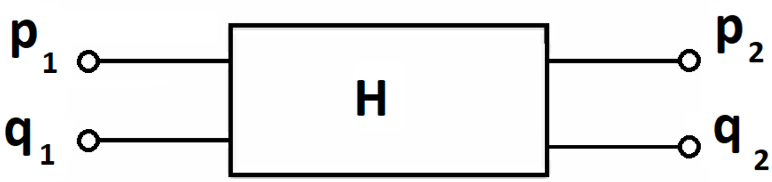

Fig. 7. Hydraulic four-terminal network

The results of sample calculations using the frequency waveform study method are presented below (Fig. 8). We can observe that for a flexible hose, the vibration amplitude gain is much higher than for rigid line.

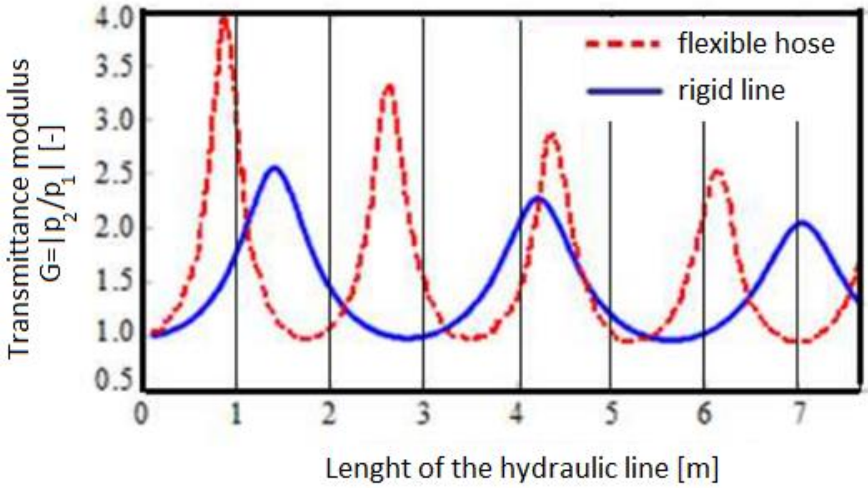

Fig. 8. Transmittance modulus as a function of the hydraulic line length [17]

4. The effects of the occurrence of pressure pulsations

The effects of pressure pulsation may be visible immediately or appear over time. The most immediate effects are water hammer or a combination of corrosion and pressure peaks. The latter issue is dealt with in detail by Tribo-Fatigue - a sub-discipline of mechanics that combines elements of tribology and fatigue wear. The types of wear that develop over time include fatigue wear on hydraulic components, especially joints. In addition, under the influence of pressure pulsation, displacement of hydraulic lines may occur, which, if insufficiently fastened, may be damaged or slowly abraded.

4.1. Exceeding allowable system operating pressures

During sudden pressure fluctuations caused by e.g. water hammer, the system components may burst, fail and blow out of the seals or implode some components (Fig. 9). An additional factor increasing the risk of sudden exceeding of the pressure resistance of the elements may be corrosive wear resulting from the flow of the medium through the system, e.g. corrosion or cavitation.

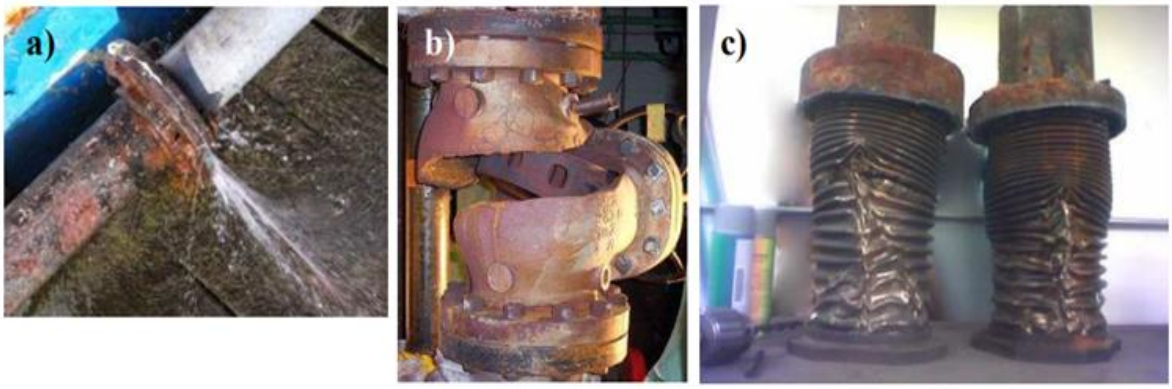

Fig. 9. Effects of a water hammer: a) failure of a seal, b) destruction of the valve casing, c) collapsing of expansion joints [18]

4.2. Fatigue wear of system elements

In the literature [2] we can find studies dealing with the fatigue strength of the hydraulic cylinder body. Out of the entire structure, the weakest elements were the welded joints of the structure (Fig. 10). The comparison of the results of analytical calculations and experimental tests is presented in the table (Table 1).

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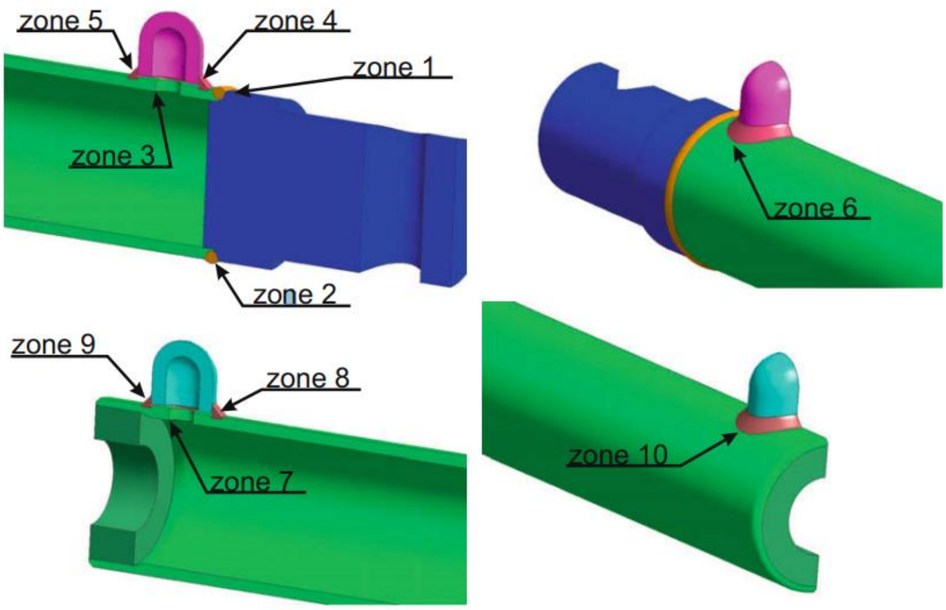

Fig. 10. Critical zones of the hydraulic cylinder: 1 and 2 correspond to the weld between cylinder tube and the end cap, 3–6 correspond to oil port (near end cap), 7–10 correspond to rod oil port [19]

Table 1. Comparison of calculated and real fatigue resistance of hydraulic cylinder [19]

Critical zone	Stress value [MPa]	Fatigue resistance, calculation [number of cycles]	Fatigue resistance, experiment [number of cycles] [20]
1	387,2	309 719	384 000
2	321,2	1 774 879	352 249 / 350 395
3	366,9	520 395	436 887
4	243,5	> 5 000 000	598 798
5	221,4	> 5 000 000	347 427
6	372,3	452 944	358 947
7	357,0	672 740	675 891
8	208,5	> 5 000 000	581 900
9	248,3	> 5 000 000	740 698
10	245,5	911 011	763 187

Another element of the system that is exposed to fatigue wear is the hydraulic hoses. The fatigue strength of a hydraulic hose can be checked by a hydraulic test with pulsating pressure without bending or with simultaneous bending (test methods are defined in ISO 6803, ISO 6802 and ISO 8032). The required resistance to pulsating pressure is the number of pressure pulsation cycles (pulses) that the hose should withstand (it is specified in the standard for a given type of hose). Pressure pulsations are characterized by a high frequency of changes, the test pressure is from 100% to 133% of the maximum working pressure, and the test temperature is increased (100 °C) [21].

5. Summary

The effects of damage to hydraulic systems presented in the previous chapter confirm the validity of research on methods of securing hydraulic systems against both cyclic pressure changes and sudden peaks of its value. In the near future, the author intends to conduct literature research on current methods of securing hydraulic systems against pressure pulsations. The next steps will be to develop a new structure, perform numerical calculations of its effectiveness, and validate model studies through experimental studies.

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Impact of additive manufacturing temperature on strength of 3D printouts made of PLA and ABS

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Keywords: 3D printing, FMD, strength tests, pull test

Słowa kluczowe: druk 3D, FMD, badanie wytrzymałości, próba zrywania

Abstract:

The 3D printing technology is an example of innovative approach to the manufacturing technology. It finds further application fields, due to the rapid development of printers and the materials to be used. The article presents and describes the currently used additive manufacturing technologies called 3D printing, the materials used and the results of tensile strength tests of PLA and ABS prints. The process of preparing objects for 3D printing is presented and the testing methodology is described. Conclusions are formulated regarding the impact of printing nozzle temperature on the objects tensile strength. Standardized samples printed from ABS and PLA were tested. The summary also presents the possibilities of using objects made by 3D printing in practice.

Streszczenie:

Technika druku 3D jest przykładem innowacyjnego podejścia do zagadnień technologii wytwarzania. Znajduje ona kolejne obszary zastosowań, co jest możliwe dzięki szybkiemu rozwojowi drukarek oraz stosowanych materiałów. W artykule przedstawiono i opisano obecnie stosowane technologie druku przestrzennego potocznie określanego jako druk 3D, wykorzystywane materiały oraz wyniki badań wytrzymałości wydruków z PLA i ABS na rozciąganie. Zaprezentowano proces przygotowania elementów w technologii druku 3D oraz opisano sposób przeprowadzenia badania. Sformułowano wnioski odnośnie wpływu temperatury dyszy drukującej na wytrzymałość elementów na rozciąganie. Badania przeprowadzono na znormalizowanych próbkach wydrukowanych z ABS oraz PLA. W podsumowaniu przedstawiono również możliwości zastosowania obiektów wykonanych metodą druku przestrzennego w praktyce.

1. Introduction

Additive manufacturing technology, called 3D printing, is the process of creation of 3D objects, where 3D printers can be used. Their principle of operation is similar to operation of commonly used numerically controlled machine tools as their kinematic chains are of similar design. Additive manufacturing technology, in large simplification, consists in application of subsequent material layers into which the virtual model of the required part was previously divided [1, 2].

The beginnings of 3D printing back to the 1980s, but the dynamic development of this technology, caused by increased availability and reduced costs of materials and devices, is being observed now. 3D printing was first used by Charles Hull, who introduced the 3D printer developed in 1984, while in 1986 he obtained a patent. The 3Dprinter developed by Charles Hull used SLA technology for printing. SLA is the colloquial name of stereolithography, one of the technologies of 3D printing that uses a laser beam to locally harden the material (usually in the form of a special resin).

Development by Scott Crump a device for printing the objects in Fused Deposition Modelling (FDM) technology in 1988 was another breakthrough in 3D printing. FDM is recommended for melting thermoplastics, which are then applied to the 3D printer platform layer by layer. FDM technology is the most popular nowadays, mainly due to the fact that low-cost devices can be used.

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Today, 3D printing is a technology for manufacturing not only plastic object. This process is realized by precise application and subsequent sintering or hardening of various materials. At present, it is possible to print not only using inorganic materials such as polymers, metals, wood-like materials, ceramics, concrete and resin, but also applying live tissues, i.e. stem cells, have been developed. It will allow, for example, to print the ear, and in the future, perhaps even entire human organs. Unfortunately, due to the complex structure of human organs, the vision of their printing remains distant [4, 5, 6, 7, 8].

Manufacturing of objects from inorganic materials is the basis of 3D printing. 3D printing is a very universal technology used in many industries. It is possible to make objects such as engine components, casting moulds, parts for airplanes and cars, but also the objects used in everyday life, e.g. decorative elements, gadgets, game figurines or even a functional coffee mug. This is due to the continuous development of this technology and the increasing number of types of materials used in this process [2, 3, 5, 6].

However, this technology is not suitable for mass production, because compared to injection moulds it is more time-consuming and therefore the cost of producing a single object is higher. 3D printing is used in applications, where there is a need to make individual unique component. Currently, the industry uses 3D printers to make prototypes, mock-ups, prostheses. With the development of 3D printing technology, it is possible to apply this technology in the mining industry. Due to the individual character of each machine used in underground mines, the 3D printing technology is ideal for making, for example, enclosures for intrinsically safe electronic equipment. At the KOMAG Institute, the 3D printing technology has been implemented comprehensively for manufacturing prototypes of mining machines and equipment which are tested then. Selection and purchase of components for 3D printers took place in parallel with the development of knowledge resources enabling the training of all participants in the 3D printing process. Training materials describing the possibilities of available 3D printers, guidelines describing the requirements for the preparation of 3D models for the printing process, potential problems and examples of applications from various fields are compiled in the form of an e-learning course prepared by experts from KOMAG [9, 10, 11, 12].

2. 3D printing technologies [2, 3]

These devices are used within the following technologies:

- FDM (FFF) – based on application of layer by layer of molten material.
- DLP – using the DLP projector for light-curing of resins.
- SLA – involving a laser beam to harden the photopolymer.
- SLM (DMLS) – a method consisting in printing metal components by local action of a laser beam on a metal powder.
- CJP - technology that uses gypsum powder to print objects, the method enables multi-colour printing.
- SLS – technology in which the objects are produced by sintering polymer powder using the laser beam.

2.1. Fused Deposition Modelling

FDM (Fused Deposition Modelling) or FFF (Fused Filament Fabrication) are the most commonly used 3D printing technologies. They consists in printing the objects by applying a molten thermoplastic, e.g. ABS, PET, PLA, HIPS layer by layer (Fig. 1). In this method, it is possible to use elastomers, e.g. TPU or TPE, to make not only hard objects but also flexible ones. The material is fed in the form of a filament, i.e. a line wound on an extruder spool. Then the material is heated and pressed through a nozzle of a diameter 0.3 mm to 0.8 mm. The melted filament in the form of a path of a thickness 0.05 to 0.4 mm is applied to the 3D printer table path by path and layer by layer until the entire object is printed (Fig. 2) [2, 9, 13].

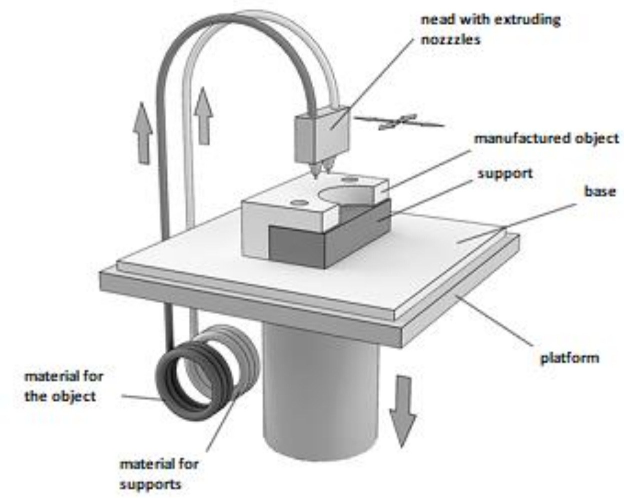

Fig. 1. Schematic diagram of FDM technology [2]

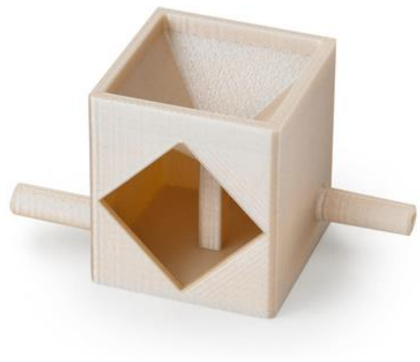

Fig. 2. Object manufacture in FDM technology [2]

3. Materials used in 3D printing technology

In different 3D printing technologies, different printing materials are used. A list of the most popular materials with a short description is presented in Table 1.

Table 1. Materials used in 3D printing [3, 5, 14]

Technology	Material	Description
FDM/FFF	PLA (Polylactide)	Used for large-size prints, it is characterized by low shrinkage after printing, it is possible to contact the objects with food.
	ABS (thermoplastic polymer acrylonitrile butadiene styrene)	Used in manufacturing the majority of prototypes
	Elastomers	Rubber-like materials used to print imitations of rubber objects, characterized by high flexibility.
	Nylon (Polyamide)	The material is popularly used in industry. It is characterized by high temperature and mechanical resistance. It also shows resistance to most chemicals.
	PET-G	Used for the production of, among others, bottles in the food industry. A material with high mechanical strength and resistance to grease and oils.
	SKU GRPHN-175	Conductive graphene filament for printing electrically conductive components. The filament can be used for EMI/RF shielding, capacitive sensors and enclosures for intrinsically safe equipment in the mining industry.
DLP	MakerJuice SF	Intended for manufacture of large-size objects
	MakerJuice G+	Material of higher mechanical strength.
	B9R-1	Resign for manufacturing precise components enabling melting after printing
SLS	DuraForm ProX	Strong and durable plastic, used for engineering applications, characterized by high mechanical strength. Powder made on the basis of PA12.

	PA 12 (polyamide PA12)	The material was created by pulverizing PA12 polyamide, used to make structural components and tools. Used in the automotive and aviation industries. Allows tinting in any colour.
SLM	Stainless steel	EU 1.4542 X5CrNiCuNb16-4 steel – Used for manufacture of machines components
	Martensitic steel	EU 1.2709 X3NiCoMoTi 18-9-5 steel – Often used in the aviation industry. Enables printing the components such as gears, pressure moulds and components of pressing machines.

ABS and PLA are the most popular materials used in FDM printing. ABS is a plastic material of a density 1.05 g / cm^3. Printouts made of ABS are characterized by high hardness, which makes them scratch-resistant. The material has good insulating properties and has a satisfactory resistance to fats, oils, greases and diluted acids. The disadvantage of ABS is its low resistance to acids and UV radiation. ABS objects are printed by melting the material at a temperature of 230°C-270°C at the temperature of the 3D printer table in the range of 40°C - 80°C [3, 5].

PLA (polylactic acid) is a thermoplastic and biodegradable polyester, made from renewable raw materials. Sugar beet or corn is most commonly used for the production of PLA. Production of 1 kg of PLA uses approx. 2.5 kg of corn kernels of a moisture content approx. 15%. Time of PLA decomposition, ranging from several months to several years is its advantage. For this reason, it is possible to use the components made of PLA in medicine for example. The material has very good organoleptic properties and objects made of PLA may come into contact with food. PLA requires a lower temperature of the printing head in the range of 190°C-220°C. Slight and almost imperceptible shrinkage is the PLA advantage. PLA is a material much easier for 3D printing than ABS [3, 5].

4. Testing the strength of samples made of PLA and ABS

Number of profiles (samples) were made to analyse the strength of 3D printout. The shape and individual dimensions comply with the EN ISO 527-1:2012- Plastics - Determination of tensile properties - Part 1: General principles [15]. The graphic model of the sample was made in accordance with the above-mentioned standard in the Autodesk Inventor program. Then the 3D model was exported to the .stl format, which is necessary to create a file with instructions for the 3D printer. In the next step, the printing instructions were entered to the Anet A8 device. During one printout, 3 samples were made, and each printout was done with a different printing head temperature. PLA samples were printed with head temperatures of 190°C, 195°C, 200°C, 205°C and 210°C at the printing table temperature of 55°C, while ABS samples with temperatures of 230°C, 235°C, 240°C, 245°C and 250°C at a table temperature of 110°C. The main parameters are presented in the Table 2.

Table 2. Basic parameters of 3D printing [15]

Layer height	Wall thickness	Thickness of bottom/top	Infill	Printing rate	Filament diameter
0.2 mm	1 mm	1 mm	50%	60 mm/s	1.75

Where:

- Layer height - parameter specifying the height of a single layer applied by the device,
- Wall thickness - parameter defining the thickness of printout walls that are exposed outside the model,
- Thickness of bottom/top - parameter specifying the thickness of the walls printed directly on the heatbed (bottom) and thickness of the parts that are exposed to the outside of the model, facing up towards the nozzle (top),
- Infill - parameter defining the degree of filling the internal structure of the 3d print,
- Printing rate - parameter defining the speed of movement of heatbed and the printing nozzle-parameter defining speed of movement of the heatbed and printing nozzle,

- Filament diameter - parameter describing the diameter of material used in the form of a filament.

The 60% filling value was selected because during the strength tests of 3D printed samples with different filling, it was shown that there was no significant difference in the strength of samples with 30% -70% filling [4].

Fig. 3 shows a 3D printing station consisting of a 3D printer and a PC. The Anet A8 printer does not require a direct connection to the computer during printing. The use of a PC makes it much easier to supervise the correctness and parameters of 3d prints. Fig. 4 shows ready-made 3D prints. Black samples were made of ABS, while pink ones were made of PLA. In order to identify the samples, they were individually described and sorted according to the material and printing temperature

Fig. 3. Stand for 3D printing [3]

Fig. 4. The printed objects [3]

The tensile strength of the materials was tested in the static tensile test. This test is based on the axial stretching of a standard sample with a constant rate until it breaks. The test should take place at room temperature, i.e. about 25^{o}C. The tested sample (profile), was made in accordance with the relevant standards. The test was carried out on a tensile testing machine called a ripper which during the test recorded the correlation between the tensile force and increase in the sample length. The ripper used for the static tensile test is constructed on the basis of a modified hydraulic system with a double-acting cylinder (Fig.5).

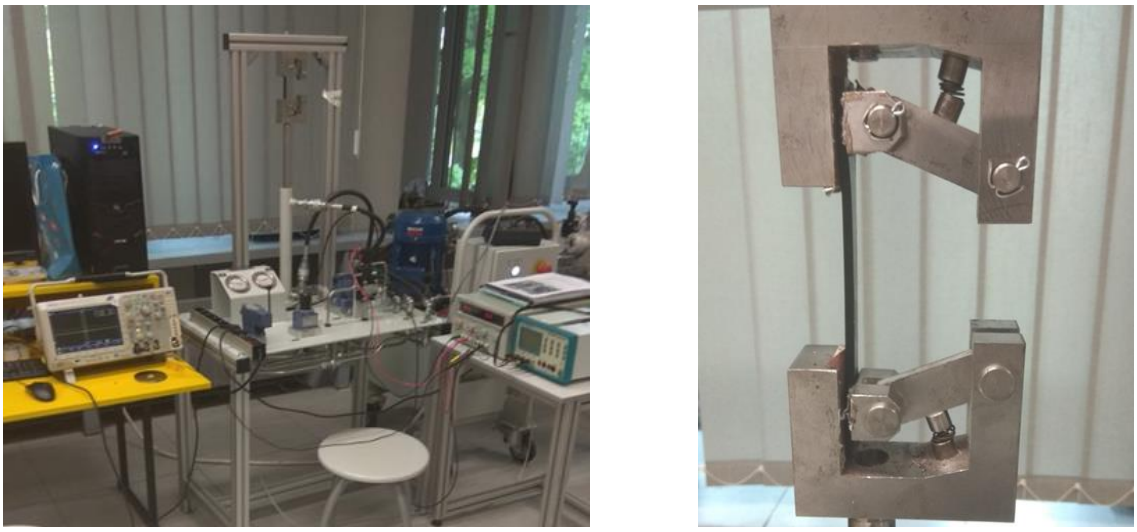

Fig. 5. Laboratory test stand of the ripper [3]

The method consists in indirect pressure measurement in the chamber using PT5402 sensor.

The hydro-electric transducer converts the pressure in the range 0-100 bar into the current in the range 4-20 mA. A 330 Ω resistor was plugged into the measuring circuit, so it was possible to measure the voltage drop across this element by an oscilloscope. Then, each of the printed object underwent the static tensile test. The direction of the tensile force during the static tensile test was parallel to the layers of the printed objects.

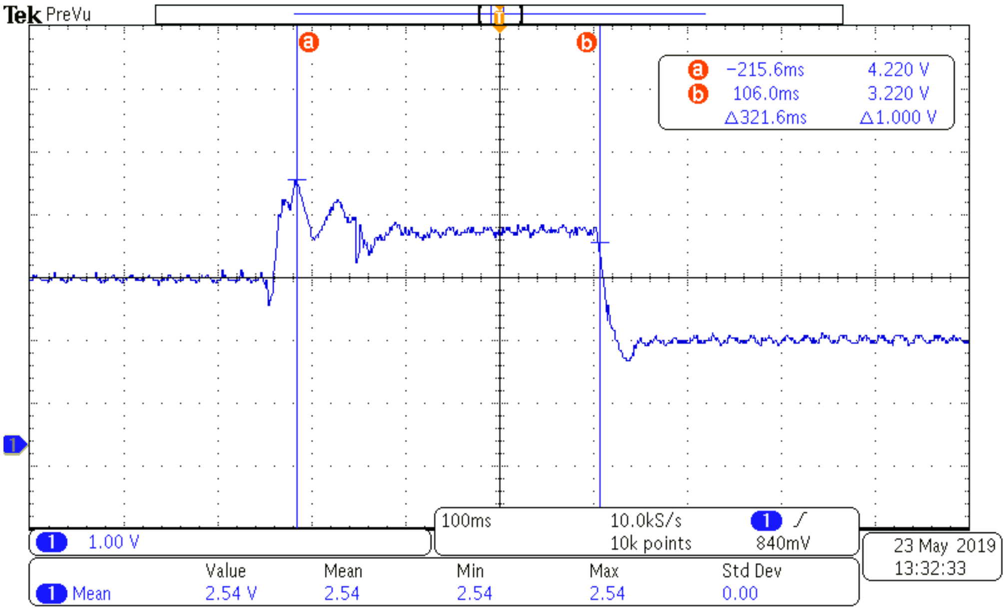

Fig. 6. Oscilloscope displays during testing sample no.2 made with ABS printed with the nozzle temperature 200°C [3]

Then the recorded electrical parameters were converted into force values. The transformations were made using the formula (1).

$$F = \frac{(U - 1{,}32) \cdot 10^5}{0{,}0528} \cdot S \tag{1}$$

where:

F – force during the tensile static test, N

U – voltage drop across the resistor, V

S – surface area of the piston (424,1mm2 $=0{,}4241 \cdot 10^{-3} m^2$)

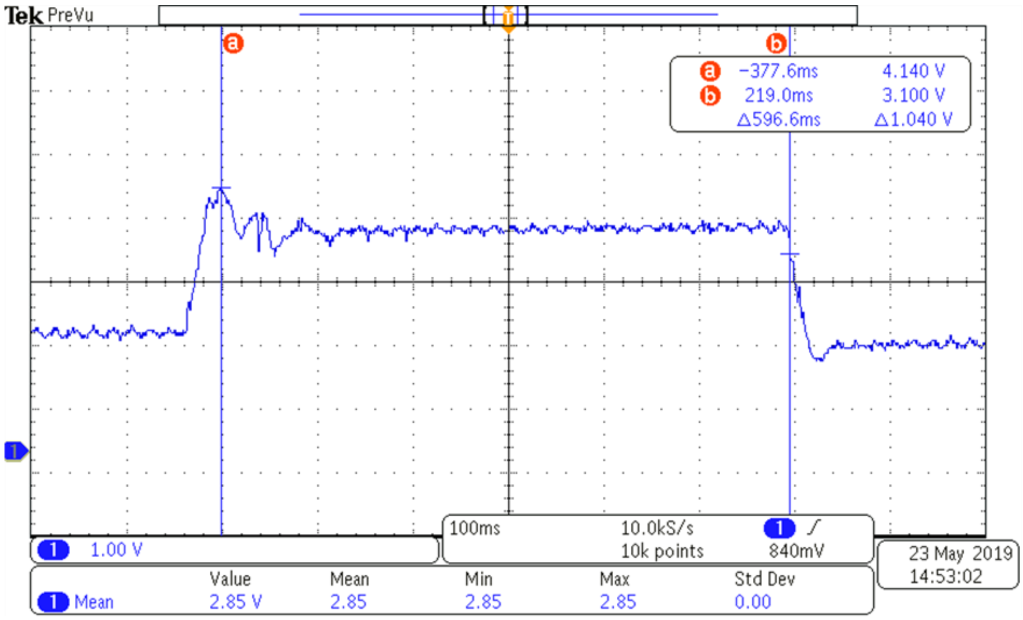

Fig. 7. Oscilloscope displays during testing sample no.2 made with ABS printed with the nozzle temperature 240°C [3]

During the static tensile test, the following waveforms were obtained, shown in the oscillograms Fig.6 and Fig.7. The waveforms shown are typical for hard and durable plastics. On the basis of the obtained results, individual force values were calculated using the formula (1). The values of the forces are presented in Table 3.

Table 3. Results from testing the ABS and PLA samples [3]

Material	**Temp.** [°C]	**$F_{0.2}$ [N]**	**F_M [N]**	**Material**	**Temp** [°C]	**$F_{0.2}$ [N]**	**F_M [N]**
PLA	190	2318.08	1622.12	ABS	230	2350.20	1611.41
	195	2478.69	1536.46		235	2243.13	1643.54
	200	2339.49	1461.52		240	2275.25	1482.93
	205	2393.03	1525.76		245	2221.72	1568.59
	210	2285.96	1632.83		250	2296.67	1670.30

$F_{0.2}$ – the force generating permanent deformation equal to 0.2% of initial length of a profile
F_M – the highest force recorded in the sample after exceeding the yielding point. [16]

Then, based on the obtained results, the tensile strength of the objects was calculated according to the formula (2).

$$R_M = \frac{F_M}{S_0} \tag{2}$$

where:
R_M – tensile strength, MPa
F_M – maximum force during the tensile static test, N
S_0 – the sample cross-section surface area before test, mm^2 [9,17]

The results are presented in Table 4.

Table 4. Results of tensile strength for ABS and PLA [3]

Material	Temp. [^{o}C]	R_M [MPa]	Material	Temp [^{o}C]	R_M [MPa]
PLA	190	39.37	ABS	230	41.21
	195	36.49		235	41.37
	200	37.82		240	37.09
	205	38.48		245	39.79
	210	41.45		250	41.77

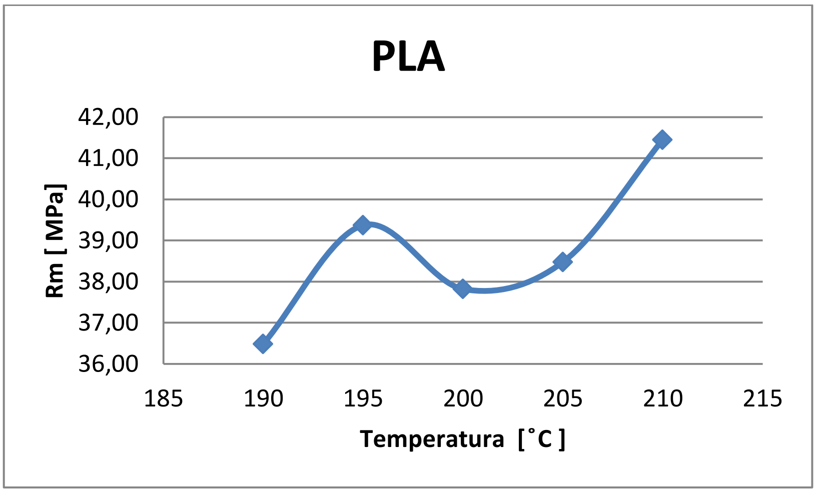

Fig. 8. Relationship between tensile strength and temperature of 3D printing for PLA samples [3]

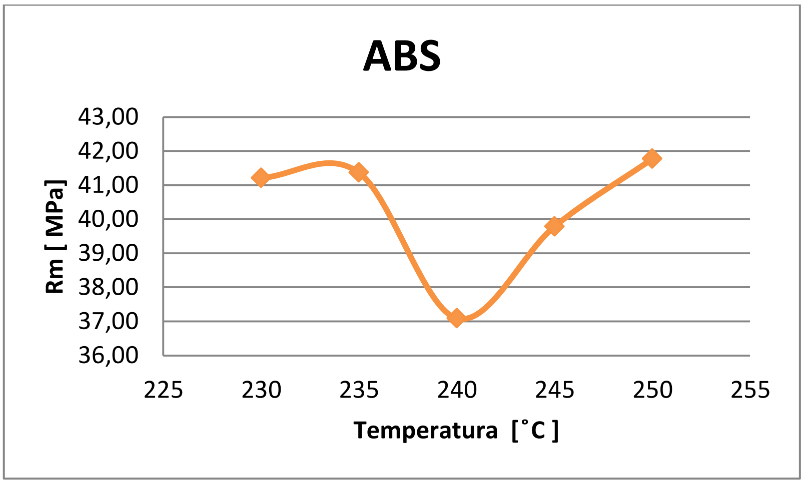

Fig. 9. Relationship between tensile strength and temperature of 3D printing for ABS samples [3]

The highest tensile strength in the case of PLA elements was 41.45 MPa, obtained for the printing temperature of 210^{o}C (Fig. 8), while in the case of ABS samples it was 41.77 MPa printed at 250^{o}C (Fig. 9). Tests have confirmed that ABS is the more durable material. The highest value of stresses in both cases was measured for samples printed with the highest temperatures in the tested compartments.

5. Conclusions

The 3D printing technology enables the production of elements from many types of materials. Due to the rapid development of this method, it is possible to obtain better and better results of quality and durability. Another advantage of 3D printing is the ability to make the objects that cannot be made with other technologies. The disadvantage of this technology is the speed of making 3D printouts, so this method is not suitable for the production of a large number of components. 3D printing is used mainly in the production of prototypes and low number of components. The increasing popularity of this technology is related to the availability of low-cost 3D printers, thanks to which 3D printing is available to a large number of users. [5, 18, 19]

Static tensile test of the manufactured objects enabled determining their tensile strength and the yield point. The objects made of ABS had much better tensile strength than objects made of PLA. The highest tensile strength was obtained for ABS equal to 41.77 MPa for samples printed at 250oC, while for PLA fittings it was 41.45 MPa for samples printed at a temperature of 210oC. The lowest strength was obtained for PLA samples printed at 195oC - 36.49 MPa, while for ABS samples printed at 235oC it was 37.09 MPa.

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Research on balancing BMS systems in a climatic chamber

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Keywords: mining industry, cell balancing, battery drive, electronics, battery, underground railways

Słowa kluczowe: górnictwo, balansowanie ogniw, napęd akumulatorowy, elektronika, akumulator, koleje podziemne

Abstract:

Assumptions for testing the selected lithium cells in the climatic chamber are presented. Two different active balancing methods and one passive will be used. Three batteries consisting of eight cells each will be build for this purpose. The tests were aimed at determining the impact of cells temperature on their balancing process. They have many advantages over the traditional lead-acid batteries. The most important advantages include fast charging, high energy density and power as well as a wider range of operating temperatures. However, they require the use of battery surveillance and management systems (BMS) to increase work safety. One of the most important functions of such a system is the method of balancing, i.e. charge equalization of each cell.

Streszczenie:

W artykule przedstawiono założenia do badań wybranych metod balansowania ogniw litowych w komorze klimatycznej. Zostały zastosowane dwie różne aktywne metody balansowania oraz jedna pasywna. W tym celu zbudowane zostały trzy akumulatory składające się z ośmiu ogniw każdy. Badania mają na celu sprawdzenie, jaki wpływ na balansowanie ogniw ma temperatura pracy ogniw litowych. Ogniwa litowe posiadają wiele zalet w porównaniu z tradycyjnymi akumulatorami kwasowo-ołowiowymi. Do najważniejszych zalet można zaliczyć możliwość szybkiego ładowania, wysoką gęstość energetyczną i moc oraz szerszy zakres temperatur pracy. Jednak wymagają one zastosowania systemów nadzorujących i zarządzających baterią akumulatorów (BMS Battery Management System) w celu zwiększenia bezpieczeństwa pracy. Jedną z ważniejszych funkcji BMS jest zastosowana metoda balansowania, czyli wyrównywania poziomu naładowania poszczególnych ogniw.

1. Introduction

Batteries made of lithium cells appeared in a commercial application in the early 90's and quickly began to spread. Today, various lithium batteries are available, and their popularity is growing rapidly. They are widely used in mobile phones, tablets, laptops, cameras, power tools, in electric and hybrid cars, in aviation, as well as in the mining industry, where they start to replace the acid-lead batteries used so far.

Lithium batteries offer the highest energy density from all the batteries available on the market. However, they require quite a special attention because both overloading and over-discharge can lead to permanent damage. In order to eliminate such cases, it is necessary to use appropriate safeguards, mainly electronic ones, as well as a special casing protecting them against overheating, moisture, vibrations and mechanical damages.

Effective protection of cells can be obtained by using special electronic circuits referred to as BMS (Battery Management System), which are used for a specific battery solution adapted to the number, type and method of connecting cells [1, 2, 3, 4].

The BMS system has several functions, such as: measuring the cell voltage, current and temperature, cell charge level, cell protection, temperature management, charging / discharging

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control, data acquisition, communication with internal and external modules, monitoring and storage of previous data, and voltage equalization on battery cells.

The discrepancies on the cells in the battery system are very important for the battery life, because without the equalizing system, the voltage on each cell may, after some time, appeared to be different. The capacity of the entire pack can also quickly decrease during its operation, what can be a reason of loss in the battery system ability for further operation.

2. Balancing Cells

Balancing cells methods can be passive or active. Balancing of battery cells consists in equalizing the charge level of all cells, which is realized by the system specially designed for this purpose. This is necessary because each cell, even this supplied by the same manufacturer, can differ in their levels of maximum discharging, capacity and internal resistance. These differences can increase during operation. Operation of cells in different temperatures may be an additional unfavourable factor [5, 6, 7].

This results in a final different level of charge, which in turn affects the total battery capacity (some cells in an imbalanced battery can discharge or charge faster than others). Balancing the cells is recommended for the batteries consisting of three cells, and in the cases of a larger number, it becomes necessary [3].

Effective battery pack diagnostics is required to be a reliable and stable sources of electricity for as long time as possible, having high energy efficiency and a high level of safety.

The cell balancing methods can be divided into three main groups (Figure 1):

- battery selection (setting the battery pack by selecting the cells of similar properties),
- passive methods (no active control is used to balance),
- active methods (external circuit with active control is used to balance).

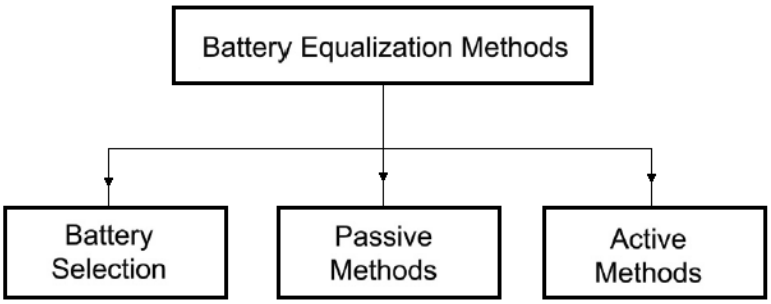

Fig. 1. Classification of the battery equalization methods [3]

Battery Cells Balancing by the Cell Selection Method

The battery pack consists of the selected cells. They are selected in terms of uniformity of electrochemical properties. This type of cell selection does not require cell balancing, because the voltage and current differences are neglectable [8, 9].

This method is not sufficient to keep the battery cells connected in series in balance throughout their lifetime. Significant differences associated with their self-discharge and different levels of charge associated with aging of the cells may occur over time. This method can only be used for the selected cells [10].

Passive Cell Balancing

Passive balancing consists in dissipation of excessive energy to resistors. In this case, the voltage of each cell is monitored in the microcontroller through an analogue-to-digital converter, on whose input terminal the cells are switched on through the multiplexer. If the voltage of one of the cells significantly exceeds the voltage of the other cells, it is closed by a switch. As a result the cell is discharged through a part of the passive balancing circuit – a resistor, connected in parallel with each cell and lasts until the voltage of the overcharged cell equals the voltage of the other cells. Then charging of the pack continues. At the same time the voltage of all other cells is monitored [8, 11, 12].

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However, the passive balancing has some disadvantages. One of them is low efficiency, resulting from the fact, that the excess energy accumulated in unbalanced cells is lost in the resistor and converted into heat. In addition, the total capacity of the battery pack is limited by the need to adjust the charge level of the cells to the capacity of the "weakest" cells [13, 14].

Therefore, passive balancing can only be realized during the cell charging process. However, in this way it is impossible to prevent the imbalance of cells that occurs during their use and which is usually a consequence of self-discharge [15, 16].

However, overcharge equalization is only effective for a small number of cells connected in series, because the difficulty of equalization increases exponentially relative to the number of cells connected in the series. In general, these methods are cost-effective solutions for low-voltage lead-acid batteries and those based on nickel compounds.

Active Cell Balancing

Active cell balancing is am alternative methods to the passive method. The main idea is to use an external system designed for active energy transfer between cells. The method of active cell balancing can be used in most innovative lithium cells, due to the temperature of this type of cells, which must be strictly controlled for safe operation [17, 18, 19, 20, 21].

There are many methods of active cell balancing and the methods are divided in different ways. Due to the flow of energy, the methods are grouped into five basic subcategories (Figure 2): cell bypass, cell to cell, cell to battery pack, pack to cell and cell(s) to pack and to cell(s) [3].

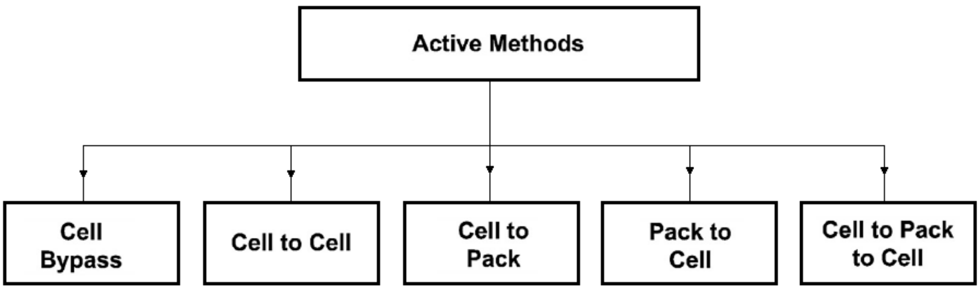

Fig. 2. Classification of the different active balancing methods [3]

3. Lithium cells

The purchased Headway LFP38120(S) lithium cells (Fig.3) were used to build three battery packs consisting of eight cells each (Fig. 4).

Fig. 3. Headway LFP38120(S) 10000 mAh cell

Technical data:

- voltage: 3.2 V
- capacity: 10 Ah
- internal resistance: < 6 mOhm
- charging voltage: 3.65 V±0.05 V
- energy density: 105 Wh/kg
- technology: lithium-iron-phosphate ($LiFePO_4$)
- maximum discharge voltage: 2.5 V-2.0 V

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standard charging current: 0.5 C (5 A)
standard charging time: 2 h
maximum direct charging current: 2 C (20 A)
standard discharging current: 1 C (10 A)
maximum direct discharging current: 3C (30 A)
impulse discharging current: 10 C (100 A)

Range of operational temperatures:
- charging: 0 ÷ 45ºC
- discharging: -20 ÷ 65ºC

life: over 2000 cycles (80% of capacity when loading with 1C current).

Fig. 4. Battery pack made of eight lithium cells

4. BMS systems used for testing

Three BMS systems were used for testing. Two active ones were designed and manufacture in KOMAG, the third passive one BMS ORION was purchased.

BMS system with the passive balancing

The system works by dissipating the excess energy into heat using resistors (Fig. 5). In this case, the voltage of each cell is monitored in the microcontroller through an analogue-to-digital converter, the input of which, through a multiplexer, is connected to individual cells. If the voltage of one of the cells significantly exceeds the voltage of the others, it is closed by a proper switch. This results in the discharge of the cell through the passive balancing circuit component - a resistor, connected in parallel with each cell and lasts until the voltage of the overcharged cell equals the voltage of the other cells. Then loading of the packet continues. At the same time, the voltage of all other cells are monitored.

Fig. 5. System BMS ORION

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Technical data:

- Number of cells – 16
- Maximum current – 350 mA
- Maximum switch on voltage – 3.8 V
- Minimum switch off voltage – 2.0 V

BMS system with active balancing by the cell to battery method

The cell to battery method consists in transferring the energy from the mostly charged cell to the entire battery.

BMS system consists of the following:

- BMS-S modules (Fig. 6) – assigned to each cell, used to measure its parameters and realization of the balancing process, i.e. energy transfer to other cells,

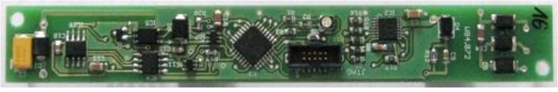

Fig. 6. BMS-S module

- Assembly board (Fig. 7) – installed on each pack, the board integrating the BMS-S modules, have no programable logics, have the circuits associated with communication and energy exchange among the packs,

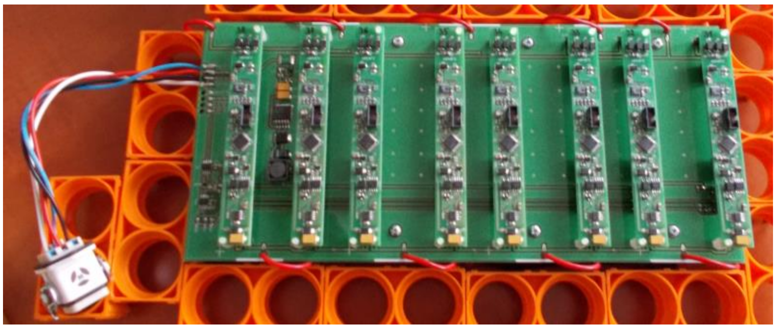

Fig. 7. BMS-S modules installed on the assembly board

- BMS-M module (Fig. 8) – master control system, used to control operation of all modules making the BMS system as well as for supervising the battery operation.

Fig. 8. BMS-M module

Data between modules is exchanged using the RS485 series interface and the MODBUS RTU protocol.

The BMS-M master module is equipped with a CAN communication bus. Measurement data will be read and recorded by the CAN Studio program.

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Configuration active balancing by the cell to battery method

Active balancing realized by the BMS system, balances the charges on each battery cell. Modules built on cell packs are used to transfer charges (Fig. 9).

Fig. 9. BMS installed on the cells pack

Energy is collected from single, overcharged cells, and then transferred to be used in the case of battery operation in discharge mode, or returned to packs, in the case of battery operation in charging mode.

BMS system with active balancing by the battery to cell method

The battery to cell method consists in transferring the energy from the mostly charged cell to the entire battery.

BMS system consists of the following:

– measuring and controlling module (Fig. 10) – controlling system used to measure cells voltage and for control of BMS operation as well as for supervision over the battery operation,

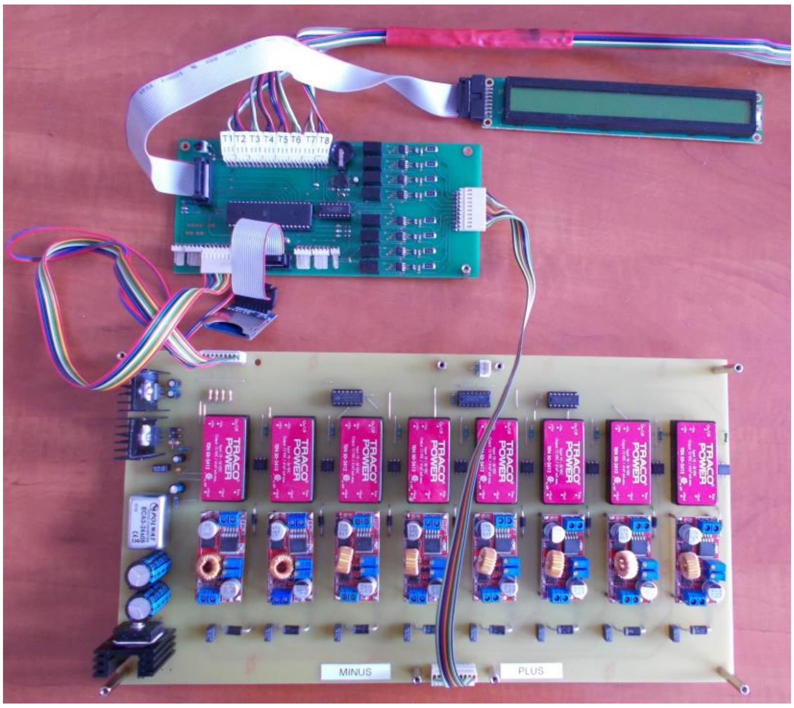

Fig. 10. Measurement and control module

– balancing system module (Fig. 10) - assigned to each cell, used to measure its parameters and realization of the balancing process, i.e. energy transfer to other cells.

The measurement data are read out and recorded on SD card.

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Configuration active balancing by the battery to cell method

The active balancing method uses a galvanically separated converter as the cell charging system. Its primary winding is connected to the pack of cells, and the secondary winding is connected to the cell through a rectifier and relays. The energy transferred to the cell has the form of short pulses selected by the electronic controller.

5. Test stand

Test stand with a climatic chamber was built at KOMAG for testing the BMS systems and lithium cell batteries. It is shown in Fig. 11 and Fig. 12.

Fig. 11. Arrangement of battery packs in the climatic chamber

Battery pack 1 connected to the BMS with passive balancing.
Battery pack 2 connected to the BMS with active balancing using the cell-to-battery method.
Battery pack 3 connected to the BMS with active balancing using the battery-to-cell method.

Fig. 12. Arrangement of battery packs in the climatic chamber

The stand consists of the following components:
- climatic chamber,
- battery packs made of Headway LFP38120 (S) LiFePO4 10Ah lithium cells,
- *DT8873-24* ***VOLTpoint*** measuring system,
- temperature measuring system,
- laboratory power supply units,
- computer with a special software.

6. Scope of tests

The scope of tests included the measurement of the surface temperature of the lithium cell during discharge and balancing, and the cell voltage at the same load. During cells discharging and balancing, the maximum and minimum voltage was within the limits provided by the manufacturer.

The tests consisted in discharging a single cell to the minimum limit specified by the manufacturer and balancing all cells in the batteries.

The tests were performed in a climatic chamber for the temperature of + 5°C and humidity of 75%. During the tests, cell voltages and temperature distribution on the cells enclosure in the batteries were recorded.

AD22100 temperature sensor

The AD22100 sensors from Analog Devices were used to measure temperature. Temperature sensors were installed on the cell's enclosure in the middle of its length.

Technical data:

Temperature sensor type	digital
Temperature measuring range	-50...150°C
Accuracy of temperature measurement	±0.5°C
Sensor characteristics	temperature coefficient of 22.5 mV/°C

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Configuration of the BMS systems

Technical parameters were configured in the same way to compare the operation of two BMS active balancing methods. In both systems, balancing begins when a cell voltage lower than 3.05 V is detected, while balancing break occurs when the voltage on all cells is lower than 2.55 V or when the voltage on any of the cells is lower than 2.5 V or greater than 3.65 V. The balancing current is set at 2 A.

In the case of the purchased BMS system with passive balancing, the balancing current was set by the manufacturer to 350 mA, while the technical parameters were set using the software. In a result of the configuration, the balancing of the cells was set and it activates when a voltage above 3.2 V is detected on the cell and is turned off when the voltage on any cell is lower than 2.5 V or greater than 3.65 V. The balancing process is activated when the cell voltage ranges between 3.2 V and 3.6 V.

7. Test results

The presented diagram show that depending on the type of BMS system, the service life of the lithium battery changes. The most advantageous system seems to be the BMS system with active balancing by the battery-to-cell method, because it maintained the voltage above the minimum for the longest time on the discharged cell (Fig. 13). This situation is beneficial for the user, as it extends the battery life without having to stop operation while charging.

In the second battery with a connected BMS system with active cell-to-battery balancing, the voltage on the discharged cell also remained long above the minimum compared to a battery with a passive BMS system, but shorter than with a BMS system with active battery-to-cell balancing. On the other hand, in a battery with a connected BMS system with passive balancing, the loaded cell was discharged the fastest, which causes shorter battery life and more frequent breaks due to charging.

During the test, temperatures were measured on all cells of the tested batteries. The temperature difference between the beginning and the end of the test did not exceed 2°C and amounted to 4°C to 6°C, what means that the load to the cells did not have a large impact on the warming-up of the cells. Such a situation will not be dangerous if the battery consists of hundreds of cells and their cooling is limited and unequal. Then the risk of exceeding the permissible temperature of the cells inside the package will be unlikely.

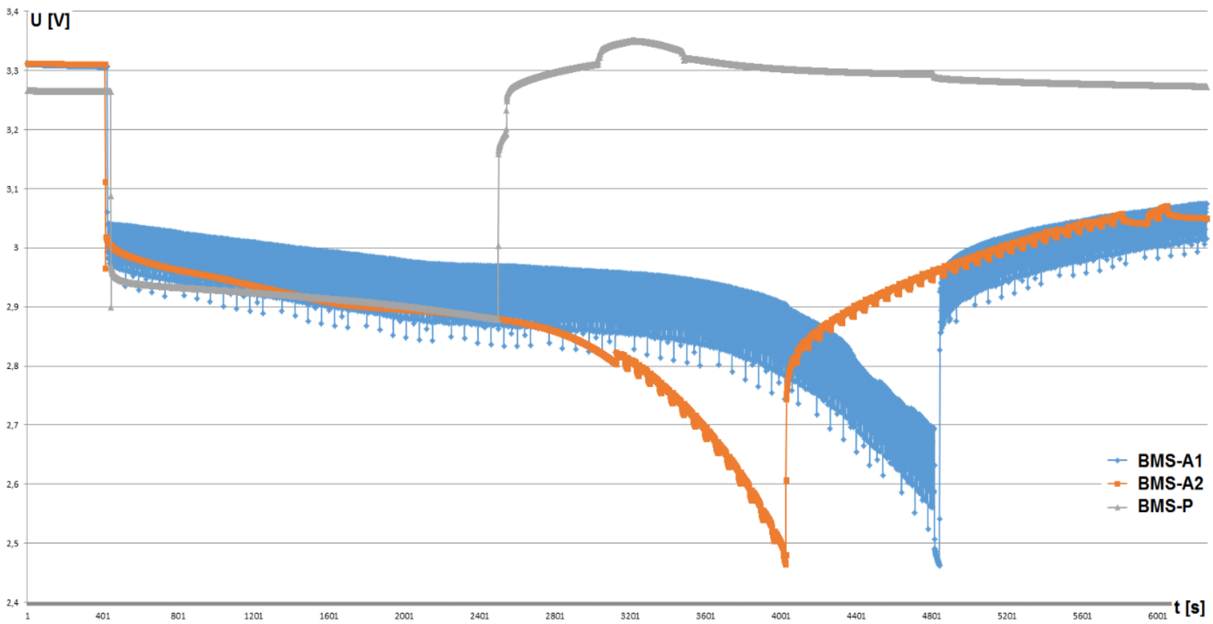

Fig. 13. Diagram of the voltage changes on a loaded cell for all tested BMS systems
BMS-A1 – BMS with active balancing, the battery-to-cell method
BMS-A2 – BMS with active balancing, the cell-to-battery method
BMS-P – BMS with passive balancing

8. Conclusions

The test shows that the battery pack containing the LiFePO4 cells should be controlled by a BMS system with active balancing to fully use up all the stored energy. Various factors can contribute to faster wear of the lithium cell. This is mainly due to the gradual change in the properties of the active materials.

There are variety of cell balancing systems that can work with batteries used in the mining equipment and machines. The selection of such a system should be customised to the specific application, regarding the maximum and minimum voltage, operating temperature and the capacity of the cell used, given by the manufacturer. Additionally, when using active balancing, the charging current of the cells should be selected depending on the cell's capacity. However, in the case of using passive balancing, depending on the cell's capacity and the charging current, the appropriate power of a shunt resistor connected in parallel with each cell should be selected, which shunts the charged cell, losing the excess energy to heat.

Passive cell balancing methods are the cheapest but also the least effective. They are used in batteries with a small number of cells connected in series because the difficulty of equalization increases with the number of cells in a row. The main disadvantage is the low efficiency, due to the fact that the excess energy accumulated in unbalanced cells is lost to heat in the resistor.

However, the methods of active balancing of cells can be used in majority of state-of-the-art cells from the lithium group. This method allows energy to be transferred between the cells while charging, discharging or not used. This is its big advantage compared to the passive balancing method, because some of the energy losses occur mainly in the systems that convert and transfer some of the energy to the remaining battery cells.

Comparing both passive and active methods, it should be stated that the methods of active cell balancing are more efficient.

As it was the first initial test, it was decided that in order to draw conclusions from the operation of BMS systems, further tests should be performed for the remaining temperatures. After obtaining all the test results, it will be possible to compare the characteristics and draw conclusions as to the impact of the temperature of the working environment of lithium cells on the effect of cell balancing.

Preparations are currently underway for further testing of lithium cells in a climate chamber. It is planned to perform the following series of comparative tests on cells at different temperatures, i.e. +5°C, +20°C, +45°C, +60°C:

- single cell discharge and balancing,
- two cells discharge and balancing.

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Strategy and Objectives in the Management System. Implementation of the Balanced Scorecard in a Research Institute

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Keywords: strategy; mission**,** objective related to strategy, objective related to quality, Balanced Scorecard (BSC)

Słowa kluczowe: strategia, misja, cele strategiczne, cele dotyczące jakości, Balanced Scorecard (Zrównoważona Karta Wyników)

Abstract:

The article presents a general aspect of development strategies, created by organizations together with dedicated strategic objectives indicating the basic activity directions. Long-term strategic objectives are connected to operational objectives in the aspect of determining the objectives related to quality, resulting from the quality system functioning in the organization. One of the article objectives is a presentation of the possibility of using the Balanced Scorecard for shaping the institute management system, in particular as regards planning of research institute development strategy. A conception of the Balanced Scorecard and a general methodology of its elaboration is described. A configuration of card, analyzed from four perspectives: financial, customer`s, internal processes, learning and growth is discussed. The objectives and general assumptions of this tool are presented and the mechanism of decomposing the BSC is discussed. The advantages and hazards related to using the Balanced Scorecard are described.

Streszczenie:

W artykule przedstawiono ogólne spojrzenie na sposób tworzenia strategii rozwoju wraz z przypisanymi celami strategicznymi nakreślającymi podstawowe kierunki działania. Powiązano długoterminowe cele strategiczne z celami operacyjnymi w aspekcie wyznaczania celów dotyczących jakości wynikających z funkcjonującego w organizacji systemu jakości. Jednym z celów artykułu jest przedstawienie możliwości wykorzystania Balanced Scorecard (Zrównoważonej Karty Wyników) w kształtowaniu zarządzania instytutu, a szczególnie w procesie planowania strategii Instytutu badawczego. Przedstawiono koncepcję karty oraz zaprezentowano ogólną metodologię jej opracowania. Omówiono układ karty, rozpatrywany w czterech perspektywach: finansowej, klienta, procesów wewnętrznych, wiedzy i rozwoju. Przedstawiono cele i ogólne założenia tego narzędzia oraz omówiono mechanizm dekompozycji karty BSC. Zaprezentowano korzyści i zagrożenia wiążące się z wykorzystywaniem Balanced Scorecard.

1. Introduction

Each organization, which wants to maintain a leading position on the market, must be well organized, i.e. it should apply state-of-the-art management methods.

The basic management element in each organisation is a determination of its activity direction against the background of changes taking place in the surrounding environment, thus defining a vision and a mission.

The main reason of organization existence is determined in the mission, however the vision should indicate objectives in the time perspective. A strategy is an element merging a mission and a vision. It guarantees a realization of basic objectives and presents the most important development directions together with the ways of their realization.

A strategy identifies basic challenges of the organization and it is a plan, which determines a set of objectives, related both to resources as well as to time perspectives. It enables to assess if the organization should continue its activity in the existing shape or to develop or change the scope of activity.

The strategy indicates which path the enterprise should follow to achieve planned objectives.

The conceptions, mentioned before, have been introduced in the management philosophy and to the quality terminology. A new edition of the ISO 9000 International Standard defines as follows [1]:

- a mission: "organization's purpose for existing as expressed by top management",
- a vision: "aspiration of what an organization would like to become as expressed by top management".

According to the quality philosophy it is recommended that each organization should establish and use the following principles for an implementation of the strategy which enable [2]:

- a transformation of the strategy and of policies into measurable objectives for all the organization levels,
- an establishment of the time –schedule for each objective,
- a determination of responsibilities for achieving an objective,
- a risk assessment and a definition of means minimizing this risk,
- an assurance of resources indispensable for a realization of activities.

A development strategy of each organization includes a set of objectives.

Tactical and development objectives, which determine activity methods and short-term operational objectives concerning current activities (Fig.1) [3, 4, 5], come from the long-term strategic objectives.

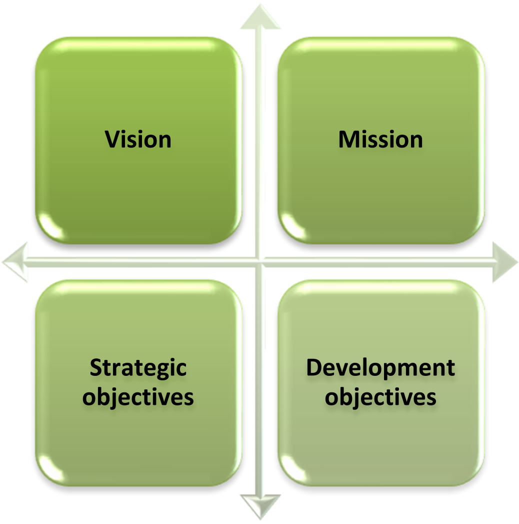

Fig. 1. Strategy stages and elements

The objectives should incorporate all the management levels and they should concern all the essential areas of activity both in a short as well as long time horizon. They should be tightly connected to a vision and a strategy of activity and to a realization of the organization operational objectives as it is shown in Fig 2.

Fig. 2. Objectives related to quality and organization strategy

Strategic objectives, formulated insufficiently or not synonymously, may cause that the organization does not achieve its intentions and does not have a stable market position.

Then a lack of defined operational objectives and a lack of their monitoring result in a lack of supervision of current activities. Analyzing the role of strategy and of strategic objectives, an aspect of determining the objectives related to quality appears in the background. According to the standards, concerning widely understood subject-matter of quality systems and management systems, the management system of each organization should establish objectives related to quality periodically.

These objectives should be defined both in relation to the strategy as well as to the mission and address the most essential processes taking place in the organization [6].

The organization, planning its quality related objectives, should determine [6]:

- what is to be done,
- what resources will be required,
- who will be responsible,
- when the task will be done,
- how the results will be evaluated.

The objectives related to quality should be: cohesive with the quality policy, measurable, related to made products and rendered services. When a need arises, they should also be monitored and up-dated. In other words the objectives, related to quality, are to some extent an obligation for a continual improvement of the organization.

2. Balanced Scorecard – an idea and used indicators

A determination of both strategic and operational objectives, in the case of small organizations causes a problem as regards a definition of a long-term vision.

In the case of big organizations, when their scope of activity covers a series of differentiated aspects, a definition of primary objectives may be an issue.

A determination of objectives, related to quality, also causes difficulties, in particular as regards their formulation and documentation. These objectives are often generated without any relation to a general strategy of the company.

As quality related objectives, in a logical way, inscribe in strategic and operational objectives of each organization, one can attempt to use one of the management tools such as a Balanced Scorecard (BSC) for defining them.

The suggested method was elaborated in the nineties by R. Kaplan and D. Horton [15].

A Card enabling to transform a vision and a strategy of the organization into measurable objectives, using a system of financial and non-financial indicators [3, 7, 8, 9,10], is an instrument of this method.

The BSC is commonly used in nearly all the branches of industry, irrespective of the company size and it transforms the strategy into a system of indicators.

The objectives and measures, contained in the Balanced Scorecard, resulting from the organization vision and strategy, are analyzed according to four perspectives [9, 3, 12]:

- financial,
- customer,
- internal processes,
- learning and growth.

Within the framework of each perspective the following items are determined (Fig 3):

- strategic objectives,
- detailed objectives which the organization wants to achieve,
- measures/measurements of these objectives,
- activities enabling to achieve the assumed objective.

Fig. 3. Four perspectives in Balanced Scorecard (BSC)

Financial aspects are determined in the financial perspective as financial measures define the objectives perfectly, they are easy to be measured and they indicate if a realization of the strategy contributes to an improvement of economic results.

Customer and market segments are determined in the customer`s perspective. The customer`s perspective can contain such measures as: a satisfaction, a maintenance, an acquisition of customers and a quantitative and valuable share of the in-coming market. It can also contain other measures which condition a realization of strategic objectives and have a decisive meaning for a customer`s decision as regards a change or a further collaboration.

Key internal processes, which are to enable a correct functioning of the organization itself, are determined in the perspective of internal processes.

In the perspective of internal processes the measures concentrate on internal processes, which will have the biggest impact on a customer.

Innovation processes which enable to broaden the organization activity directions are determined in the perspective of learning and growth.

The Balanced Scorecard (BSC) determines an equilibrium between:

- short-term and long term objectives,
- financial and non-financial indicators,
- evaluation and growth indicators,
- perspectives of internal and external activity.

Mutual interconnections between perspectives as well as interconnections of processes taking place in the organization, characterize the Card structure. Each objective should be a part of reason-results chain describing the organization strategy.

The ISO 9001 International Standard, concerning quality systems, in Item 5.1.1 introduces relationships among the quality policy and quality objectives and the organization strategic direction.

The objectives related to quality complete other organization objectives such as: a development, financing, a remunerativeness, an environment etc.[6].

Analyzing the structure of the Balanced Scorecard, it is not possible to help feeling an impression that the quality objectives, set forth by the organization, can be included perfectly in four perspectives mentioned above.

It is expected that the Balanced Scorecard should be a precise tool, so used measures must enable an explicit interpretation of the result obtained with use of a given measure.

That is why in construction of a BSC it is possible to apply the S.M.A.R.T. principle characterizing the objectives which are formulated correctly [13].

According to it, each objective formulated correctly should be:

– *Specific* – defining planned effects accurately,
– *Measurable* – enabling an evaluation of the realization on the base of defined indicators,
– *Attractive* – having sense as regards a realization,
– *Realistic* – possible to be realized in the aspect of possessed resources,
– *Timed* – exactly determined as regards time.

A selection of objectives, transferring the organization strategy to a system of indicators in four perspectives as well as a selection of the indicators as such, is an individual matter, however the mentioned perspectives should always answer the question: what resources should an organization have at its disposal and how should they be located to realize the indicated objectives ?

Most typical examples of indicators, presenting the objectives for individual perspectives are shown in Table 1 [9, 19 ,14].

Table 1. Exemplary indicators in relations to four perspectives

Financial perspective	- an increase of company value - a sales remunerativeness - a profit rate - a reduction of costs and an increase of production rate - a management of operational costs
Customer`s perspective	- ranking of customers (new, lost) - a market share - a level of customer`s satisfaction - an improvement of company image
Perspective of internal processes	- a number of new products/services - a duration of a product realization - an efficiency of a production process - a product defectiveness
Perspective of learning and growth	- a personnel potential (level of education) - trainings of employees - evaluations of employees - an access to new technologies

Analyzing the data, presented in Table 1, reason-result relationships between objectives and measures for individual perspectives can be found.

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For example an increase of employees` competences can improve an efficiency of internal processes, then have an impact on a product quality and as a consequence cause an increase of the customer`s satisfaction.

Thus Balanced Scorecard (BSC) is a method, which enables a realization of strategic assumptions, transforming strategic objectives into specific activities. The Card is transferred to lower organizational levels. The following BSCs can be generated for individual organizational divisions or operational objectives, belonging to strategic objectives, can be situated on one comprehensive Card.

This process is often determined as *cascading.* It can be conducted as dependent one on the area size, strategic significance of the organizational unit, its independence and a kind of interconnections occurring in an organization.

The most popular cascading methods include [16]:

– an independent formulation of the strategy and objectives – strategic objectives are formulated on individual levels of the organizational structure,
– an exact transmission of objectives - objectives are transferred from the primary BSC,
– an adaptation of objectives values and /or strategic activities - the objectives in the Card are obligatory for all the organization divisions,
– a combination of standards objectives with individual objectives of the organization - objectives from the primary BSC are taken over only in the case when a division can participate in their realization,
– a direct transfer of strategic activities – this method is used when an organizational division does not participate directly in the process of generating values.

It is worth highlighting here that a continual supervision of the measures, which indicate a degree of the Balanced Scorecard realization, plays an extremely essential role.

3. Use of a Balanced Scorecard in research institute - a case study

The Balanced Scorecard (BSC) is an efficient tool ensuring a cohesion between the determined strategic objectives and undertakings under realization.

An introduction of the Card into the Institute management system enabled to transform the strategy into concrete tasks and measures of their realization for individual organizational divisions.

A case study of its use in a research institute, i.e. at the KOMAG Institute of Mining Technology, is presented below.

The Institute mission includes: “Innovative solutions for economy”, which is transformed into a concrete vision: “Research and development centre of organizational and proprietary structure adapted to the market activity in the European Research Area and of the organizational culture creating a friendly climate for generating new ideas and realizing innovative activities, i.e. transforming new ideas into new products. [18].

Basing on the analysis, conducted in the Institute, strategic areas which were identified. They include among others [17]:

– an innovativeness,
– a commercialization,
– a work safety and product safety,
– an environmental protection,
– an international collaboration,
– a staff development,
– sharing knowledge.

Strategic Institute objectives were defined for the mentioned areas which were grouped according to four perspectives of the Balanced Scorecard (BSC).

A description of selected strategic objectives, which are combined with planned activities and measures, are presented in Table 2.

They aim at a quantitative verification of realization degree of accepted objectives (due to the data confidentiality real values of measures are omitted).

Table 2. Selected strategic objectives in relations to the Institute strategy

***Balanced Scorecard (BSC)* Perspective**	**Strategic objective**
Financial perspective	- a sales remunerativeness - a change of income structure - obtaining budget financial means for a realization of determined tasks - an efficiency increase of collaboration with the economic environment and of a commercialization of research results - an increase of income from the research activity
Customer`s perspective	- an increase of customer`s number from a new area - a new scope of services, new branches - tightening collaborative links with other organizations in the region - an increase of promotional activity - an improvement of relationships with customers
Perspective of internal processes	- an improvement of the Institute management system - an efficiency increase of information flow within the Institute - an elaboration of system tools of rewarding employees for their scientific achievements - an increase of interdisciplinarity of conducted research projects - an increase of testing infrastructure use - an optimization of the Institute organizational structure
Perspective of learning and growth	- an improvement of the staff scientific development system - a modernization and development of testing infrastructure - a development of editorial and publishing activites

The following stage included cascading of the Card through an independent formulation of objectives and an exact transfer of objectives in relations to individual processes and organizational divisions. For example in the case of the Customer`s perspective the strategic objective “ *Increase of customers` number from a new area“* was established. Through cascading, the strategic objective from the Balanced Scorecard (BSC) is presented below as an example of the transfer concrete of activities for one of the testing laboratories according to Table 3.

Table 3. Cascading of a strategic objective

***Balanced Scorecard (BSC)* for testing laboratory**			
Financial perspective	Customer`s perspective	Perspective of internal processes	Perspective of learning and growth
- an increase of income from testing activity	- an increase of customers` number from the determined area - an increase of participation in local market	- an implementation of new testing methods - an increase of use of measurement infrastructure - ensuring a high quality of tests	- a purchase of new measurement equipment - trainings of the personnel in the scope of new techniques

	- an increase of promotional activity in a new testing offer - an increase of customer`s satisfaction level	confirmed by the accreditation	- scientific and publishing activity

4. Summary

As both the environment and the organization are subject to continual changes, establishing of strategic objectives is one of the key abilities in the management process. An ability of their determination and realization is one of the elements which decide about a state-of-the-art organization.

A Balanced Scorecard (BSC) becomes more and more popular due to the fact that it guarantees a possibility of transforming an organization vision and strategy into a set of unit objectives and measures as well as monitoring the realization stages of the strategy, described in this way . It is an instrument, used for a strategic management, which enables to measure a subject efficiency in many planes of its activity.

The Card is one of several methods, which can be used for connecting different elements of the organization management system into an integrated whole.

A realization of strategic objectives has an impact both on the processes which take place inside as well as on the environment. However, it is a prerequisite that the Card should be something more than a set of a dozen or so measures included in four perspectives.

It must have a close relation with the organization strategy, aid a realization of objectives and be implemented on all the organization levels.

A correct use of the Card is required not only at the stage of generating the strategy, during its implementation, but it is tightly connected to a continual monitoring of the laid out objectives realization [18].

The most frequent mistakes, made during an implementation of the Balanced Scorecard, include:

– a lack or incorrect definition of reason-result relationships between objectives and indicators,
– a too big number of objectives/ indicators,
– a lack of real relationships between objectives and the organization strategy,
– a lack of monitoring of realization degree.

The Card elaborated correctly can be the basis of the management system as it integrates and supports the most important processes such as:

– polishing up or up-dating the strategy,
– a presentation of the strategy in the whole organization,
– a combination of objectives of organization individual divisions with the strategy,
– a combination of the strategy with annual and long-term objectives,
– obtaining information in return to improve the strategy.

A Balanced Scorecard is a management tool developed by managers. It is to motivate people to realize the organization vision and concentrate efforts of the whole organization on achieving strategic objectives. This Card is to deliver information in return about the current situation and indicate a system of measures enabling to achieve a future effectiveness of people.

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