http://dx.doi.org/10.7494/miag.2018.4.536.9

ILDIKO KERTESZ BRINAS
NARCIS IONEL REBEDEA
ILIE LUCIAN OLTEAN

Bucket wheel excavator cutting tooth stress and deformation analysis during operation using Finite Elements Method (FEM)

In the case of bucket wheel excavators, the cutting process is influenced by the forces opposing the working elements and cutting tools. These forces determine the choice of machines and their parameters as well as the operating method [1, 2]. Studies conducted on the failure causes of mechanical parts show that the cutting and loading systems cause the highest rate of failure – about 32% of all recorded mechanical failures [3]. In this paper, we will use the Finite Element Method (FEM) to analyze the deformations and stresses acting on the cutting teeth mounted on the rotor of BWEs. For this, SolidWorks® software was used, both as a CAD tool to design the teeth as well as to model and simulate the phenomena.

Key words: *BWE, rotor, cutting teeth, cutting tooth support, FEM, force, strain, deformation*

1. STEPS FOR A FEM APPROACH

The starting point for any project using FEM and simulation is a model that can be a part or a set of parts. First, the characteristics of the material(s) of the parts, the tasks to which they are subjected, and the restrictions are defined [4]. Subsequently, as with any FEM-based analysis tool, the geometry of the model is divided into relatively small entities called finite elements. Creating the elements is commonly called meshing [5].

The degrees of freedom (DOF) of a node in a finite element mesh define the ability of the node to perform translation and rotation. The number of degrees of freedom that a node possesses depends on the element type. In SolidWorks® simulation, the nodes of the solid elements have three degrees of freedom, while those of the shell elements have six degrees of freedom.

Creating the mesh network often requires changes in the CAD geometry:

- cancelling – the process of removing parts of the geometry that are insignificant to the analysis, such as fillets or bevels,
- idealization – a more aggressive process of changing the geometry; for example, thin walls are replaced with surfaces or beams replaced by lines,
- cleaning – necessary for the geometry to satisfy the requirements imposed by the meshing.

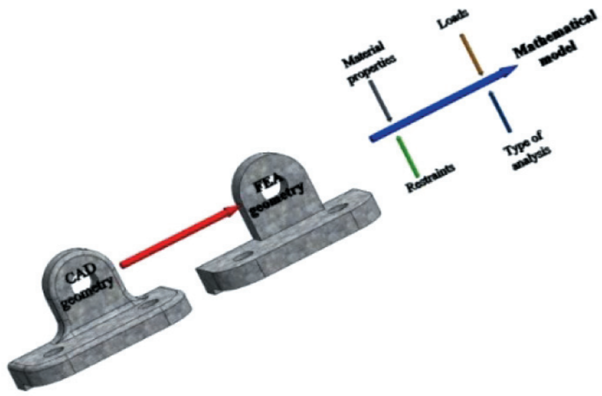

Fig. 1. Creation of mathematical model

Creating a mathematical model consists of: modifying the CAD geometry (i.e., Fig. 1 – we removed the fillets), defining the loads and strains, imposing the restrictions, defining the properties of the material, and determining the type of analysis (static, dynamic, etc.) to be carried out [6]. The properties of the material, the tasks, and the restrictions imposed on the model make up the input information for a certain type of analysis.

The mathematical model based on the FEM geometry, the information and properties of the material, the requirements to which the model is subjected, and the imposed restrictions can be divided into finite elements using the meshing process (Fig. 2).

The discreet loads and restrictions are applied to the nodes of the finite element mesh [7].

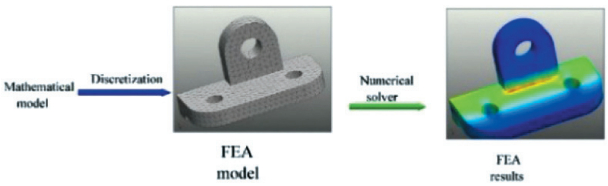

Fig. 2. Building FEM model

Often, the most difficult step of an FEM study is the analysis of the results. The correct interpretation of the results implies the understanding of all of the simplifications and errors that they induce in the first three stages: defining the mathematical model, the meshing, and coming up with the solution.

2. VON MISES YIELD CRITERION

The von Mises stress test criterion (also known as the Huber criterion) is a stress test that represents all six components of a general 3-D state (Fig. 3).

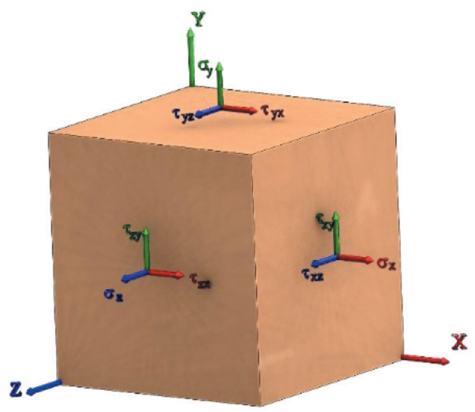

Fig. 3. General state of stresses

The general stress is represented by three normal stresses (σ_x, σ_y, σ_z) and six tangential or shear stresses. Due to the symmetry of the shear stresses, the 3D general tension state is characterized by six components: σ_x, σ_y, σ_z and $\tau_{xy} = \tau_{yx}$, $\tau_{yz} = \tau_{zy}$, $\tau_{xz} = \tau_{zx}$. Von Mises stress can be expressed by the following equation:

$$\sigma_{vm} = \sqrt{0.5 \cdot \left[\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + \left(\sigma_z - \sigma_x\right)^2 \right] + 3 \cdot \left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)} \quad (1)$$

Von Mises stress is frequently used for the structural safety analysis of materials with elasto-plastic properties (such as steel or aluminum alloys). In theory, a ductile material yields when the von Mises stress equals the permissible stress limit. In most cases, the flow limit is used as a stress limit. According to the von Mises criterion in the case of failures, the factor of safety (*FOS*) is expressed as follows:

$$FOS = \frac{\sigma_{limit}}{\sigma_{vm}} \quad (2)$$

where σ_{limit} is the flow limit.

3. GEOMETRIC PARAMETERS OF TEETH OF BWES

The geometry of the cutting teeth of BWEs is influenced by:

- the functional parameters of the excavator,
- the constructive parameters of the cups (Fig. 4) and rotor (Fig. 5),
- the shape and type of cutting teeth used,
- the type of excavated material,
- cost.

There are two types of cutting teeth: 1 – chisel-shaped cutting teeth (used on BWEs); 2 – conically shaped cutting teeth (used on both single-bucket excavators and shearer-loader machines) [10].

Fig. 4. Bucket with cutting teeth of BWE [8]

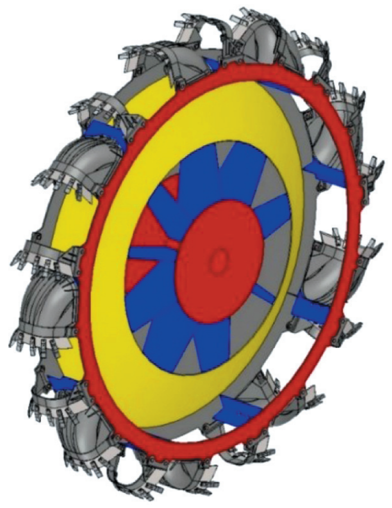

Fig. 5. Rotor assembly of BWE [9]

In Figures 6 and 7, we present a chisel-shaped cutting tooth that is mounted on an E_SR_C – 1400-type BWE used in the Oltenia Basin open-pit lignite mines [11]. From the point of view of the geometric parameters, two types of cutting teeth are needed: one for overburden excavation, and the other for lignite excavation. We analyzed the tooth used for lignite excavation; the geometric parameters of these cutting teeth are shown in Table 1 [12].

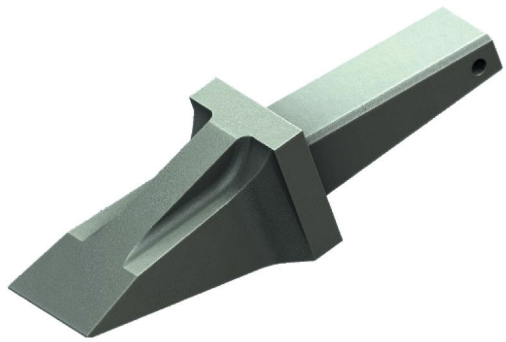

Fig. 6. Chisel-shaped cutting tooth with support bracket used in open-pit coal mines in Oltenia Basin

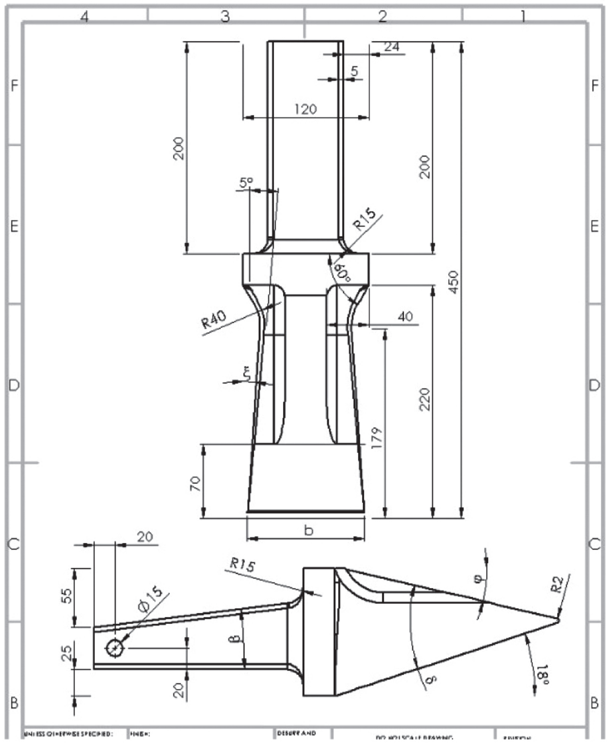

Fig. 7. Geometric dimensions of chisel-shaped cutting tooth with support bracket used in open-pit coal mines in Oltenia Basin

4. DETERMINATION OF STRAINS AND STRESSES OF CUTTING TEETH USING SOLIDWORKS®

For a realistic approach, the FEM was conducted on an assembly of a cutting tooth and its cup holder support bracket. When creating this assembly, we set up the geometrical links between the two components. Figure 8 shows the restrictions (fixation condition) imposed on the analyzed assembly.

Table 1

Geometric parameters of analyzed cutting teeth (used for lignite excavation)

No.	Geometric parameters	Symbol	Dimensions of cutting tooth [°]	Correlation
1.	angle of clearance	α	55	$\alpha + \beta + \delta = 90°$
2.	set angle	β	7	
3.	angle of sharpening	δ	28	
4.	cutting angle	γ	35	$\gamma + \alpha = 90°$
5.	longitudinal lateral angle	ξ	5	–
6.	transverse lateral angle	θ	3	–
7.	rake angle	φ	13	–
8.	cutting edge width	b	120	–

Fig. 8. Fixation conditions of cutting tooth

The maximum tangential and normal cutting forces at the tooth's trajectory were considered as well as the lateral force generated by the pivoting movement [13].

These forces have the following values:

$F_x = 60$ kN; $F_y = 18$ kN; $F_z = 10$ kN. With respect to the tooth surfaces, we will have the following component forces:

$$F_{y1} = F_x\cos\alpha - F_y\cos\gamma = 25.857 \cdot 10^3 \text{ N} \tag{3}$$

$$F_{x1} = F_x\sin\alpha - F_y\sin\gamma = 36.198 \cdot 10^3 \text{ N} \tag{4}$$

$$F_{z1} = 10 \cdot 10^3 \text{ N} \tag{5}$$

For these forces, the state of stresses for a cutting tooth with a sharpening angle of 28° (which has a leaner construction) were determined. These forces are the resultant forces of specific loads having a random distribution on the active faces of the cutting tooth, which (for our calculations) were considered as applied to the tip of the cutting tooth (Fig. 9).

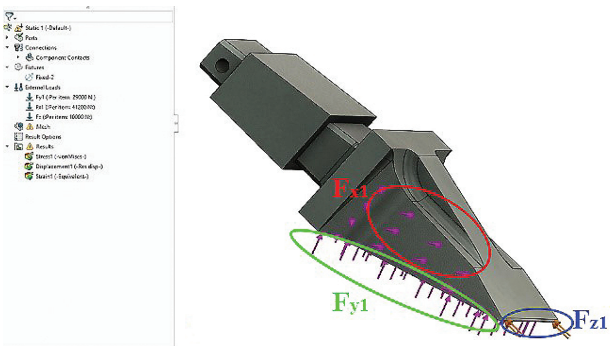

Fig. 9. Forces that act on tooth

The material used for the simulation is *41MoCr11*, or equivalent to $\sigma_{02} = 750$ N/mm^2, $\sigma_r = 950$ N/mm^2 (medium hardened alloy steel, recommended for thermal treated parts).

Figure 10 shows the cutting tooth mesh nodal network, and Figure 11 shows the deformations of the cutting tooth resulting from the FEM analysis. It can be noticed that the maximum deformation is 0.665 mm and occurs at the tip of the cutting tooth.

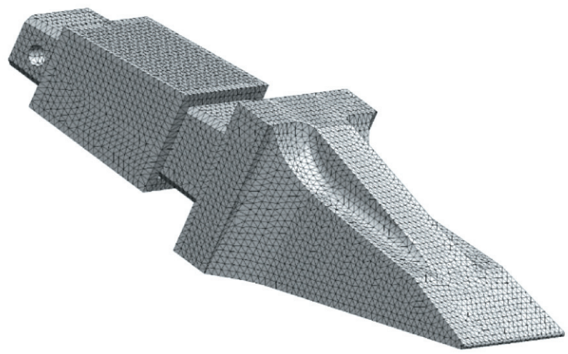

Fig. 10. Mesh nodal network

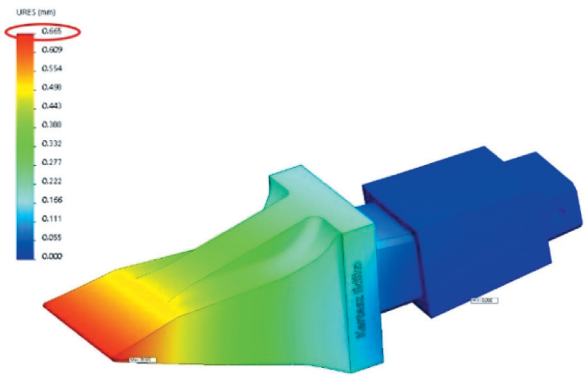

Fig. 11. Deformation of cutting tooth and its cup holder support bracket assembly

Based on Figure 12, it can be observed that the most stress occurs on the tail part of the cutting tooth (between its holder and joint). The maximum von Mises stress is 332 N/mm^2.

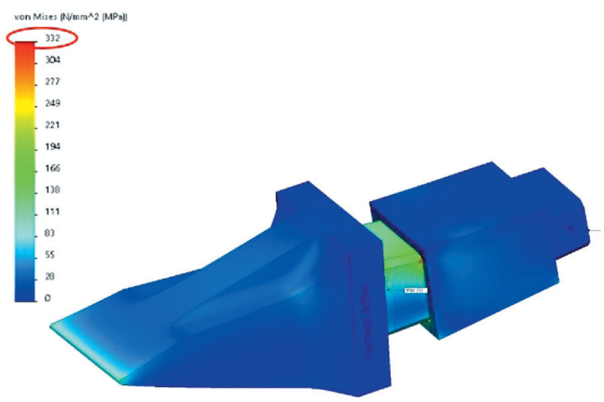

Fig. 12. Stress of the cutting tooth and its cup holder support bracket assembly

5. CONCLUSIONS

FEM is a numerical analysis method that is used to solve problems in various engineering fields. In mechanical engineering, it is widely used for solving structural, vibrational, and thermal problems; and because of its numerical versatility and efficiency, this method imposed itself on the engineering analysis software market while other methods have become niche applications.

FEM/FEA is mainly used during the product-development phase to analyze a project. The ultimate goal of using FEM as a design tool is to change the standard repetitive cycle of *design* → *prototype* → *test* into a simplified process in which the prototypes are not used as design tools but rather as a validation of the final design.

The use of FEM enables design iterations to shift from the physical space of prototypes and testing into the virtual space of computer simulation.

The simulation of the behavior of cutting teeth mounted on BWEs using FEM was based on the results (obtained over the years by the Department of Mechanical, Industrial, and Transport Engineering) of research contracts aimed at improving the performance of BWEs used in open-pit mining in the Oltenia Basin.

The results obtained using this method are consistent with those determined by analytical methods in the research studies conducted within the MITE Department:

– mounting the cutting tooth into a cup holder causes the von Mises stress to be maximal in the tail area of the tooth, holder, and joint;
– the maximum deformation occurs at the tip of the cutting tooth;
– it is necessary to design a new holder that will better encase the cutting tooth and to carry out a study of the deformations and stresses in this new configuration using simulation and modeling.

References

[1] Dimirache G., Zamfir V.: *Ingineria sistemelor mecanice*, Editura Focus, Petroşani 2002.
[2] Iliaş N.: *Maşini miniere, exemple de calcul*, Editura Tehnică, Bucureşti 1993.
[3] Andraş A., Andraş I., Tomuş O.B.: *Optimization of geometric and strength parameters of teeth for bucket wheel excavator in view to increasing the cutting efficiency*, 17th International Multidisciplinary Scientific GeoConference, SGEM 2017.
[4] Akin J.E.: *Finite Element Analysis Concepts via SolidWorks*, World Scientific, 2009.
[5] Kurowski P.M.: *Engineering Analysis with SOLIDWORKS Simulation*, SDC Publications, Mission, USA 2015.
[6] Popescu F.D.: *Aplicaţii industriale ale tehnicii de calcul*, Editura AGIR, Bucureşti 2009.
[7] Pop I.A., Itu R.B., Radu S.M.: *Aplications of forces reduction in the calculation of technological mechanical loads transmited to the tower of a winding engine trough extraction pulley bearings*, 16th GeoConference on Science and Technologies in Geology, Exploration and Mining SGEM 2016.
[8] Ladányi G., Virág Z.: *Examining the Bucket Wheel Excavator's Bucket After Renewal*, "Annals of The University of Petroşani, Mechanical Engineering" 2016, 18: 93–98.
[9] Nan M.S., Kovacs J., Popescu F.D.: *Balance control by weighting and tensiometric measurements of bucket wheel excavators*, "WSEAS Transactions On Systems And Control" 2008, 11, 3: 927–936.
[10] Marian I.: *Utilaje de încărcare şi transport minier*, Editura Tehnică, Bucureşti 1991.
[11] Radu S.M., Chmielarz W., Andras A.: *Mining Technological System's Performance Analysis*, "Annals of the University of Craiova for Journalism, Communication and Management" 2016, 2: 56–64.
[12] Kovacs I., Iliaş N., Nan M.S.: *Regimul de lucru al combinelor miniere*, Editura Universitas, Petroşani, 2000.
[13] Nan M.S.: *Parametrii procesului de excavare la excavatoarele cu rotor*, Editura Universitas, Petroşani 2007.

ILDIKO KERTESZ BRINAS, M.Sc., Eng.
NARCIS IONEL REBEDEA, M.Sc., Eng.
ILIE LUCIAN OLTEAN, M.Sc., Eng.
Department of Mechanical, Industrial and Transportation Engineering
University of Petroşani
20 Universităţii str.
332006 Petroşani, HD, Romania
kerteszildiko@gmail.com

http://dx.doi.org/10.7494/miag.2018.4.536.19

TOMASZ ROKITA

Breakdown of hoisting machine in mining shaft hoist installed in southern section of R-II shaft of KGHM Polska Miedź S.A. O/ZG Rudna

This article applies to a one-of-its-kind case of the cracking of the main shaft of a hoisting machine that occurred in the southern section of the R-II shaft of KGHM Polska Miedź S.A. Oddział ZG "Rudna" in 2011. The mining shaft hoists installed in the R-II shaft are not only the basic extraction equipment in the Rudna mine but also throughout KGHM. The unscheduled standstill cases of these hoists generate huge losses for the mine. These reasons resulted in the necessity for the ad hoc repair of the damaged shaft and operational use of the hoist until a new shaft is completed and delivered.

The article describes the works related to the preparation and execution of the repair of the shaft as well as the tests that were performed. The last stage was the preparation of the operational conditions of the shaft of the machine with the repaired shaft with limited kinematic parameters and under strict supervision until the execution of the new shaft.

Key words: *mining shaft hoist, hoisting machine, main shaft, hoisting machine breakdowns*

1. INTRODUCTION

The mining shaft hoists installed in the R-II shaft are intended for extracting excavated material in skips with a capacity of 33 Mg. After thirty years of intense operational use (since 1974), their comprehensive modernization was ordered. The hoisting machine in the southern section (S) of the R-II shaft was modernized in January of 2004, and the hoisting machine in the northern section (N) of the R-II was modernized in May of 2006. The modernization consisted of replacingthe mechanical part of the machines; that is, the main shaft, hoist drum, bearings, and brake system along with the control elements.

The machine is ready for automatic control and for manual control by the hoisting operator.

The characteristic data of the hoisting machine declared in the documentation is as follows:

- hoist drum diameter 5500 mm,
- nominal diameter of hoist ropes 50–54 mm,
- number of hoist ropes 4,
- maximum static overweight 350 kN,
- maximum static force in the four hoist ropes 1200 kN,
- shearing force of the four hoist ropes 4 · 2130 kN,
- maximum speed of excavated material pulling 20 m/s.

The hoist drum of the hoisting machine is set on the main shaft supported by two rolling bearings on both sides of the hoist drum. The bearings are lubricated with oil (under pressure) in a closed system. On both of the free ends of the shaft, the rotors of the driving motors are set. The driving system of the hoisting machine consists of two separately excited PW-106 direct current motors with 3600 kW of power each and powered from DCA 600 series thyristor converters.

The break consists of four break bands with sixteen pairs of actuators (four in each band), and the control and power supply unit are composed of two hydraulic units (one of which is the reserve). The bearings of the main shaft, break bands, stators of the driving motors, and equipment for machining the rope grooves are set on the steel hoist tower structure.

This machine in the mechanical part consists of a main shaft set on two rolling bearings, a hoist drum ready for cooperation with four load-bearing hoist ropes, a break acting on two brake discs composed of four bands withfour installed pairs of hydraulically restored brake actuators controlled with a double-unit control and power supply set, two driving motors, and equipment for machining the rope grooves.

The pulse transmitters connected to the main shaft are used to supervise and control the operation of the machine; i.e.:

- a pulse generator installed on one side of the shaft,
- a tach generator with a pulse generator are set on the other side of the shaft.

The pulse generator driven from the axle of the shaft rope roller pulleys is used to control the travel of the vessels of the shaft hoist.

Both hydraulic units of the control and power supply unit of the break are located at the level of the hoisting machine. Figure 1 presents the view of the machine in the (S) section after modernization.

Fig. 1. View ofhoisting machine in section (S) of R-II shaft after modernization in 2004 [1]

On April 17, 2011, the operators of the hoist noticed damage in the shaft of the hoisting machine in the southern section in the area of the passage of the shaft in the flange used to connect with the hoist drum on the eastern side.

A crack as well as chips of the material in some places were visible along about half of the circumference of the shaft. The nature of the damage indicated fatigue crack (Figs. 2 and 3).

Due to the possibility of accessing the place of the damage only from the side of the shaft bearing (eastern), an accurate assessment of the damage was possible only after dismantling the hoist drum and completing specialized inspections with visual and magnetic particle methods. These inspections were done on April 17, 2011, by an expert from Autorytet Spółka z o.o. [2]

Fig. 2. Cracks in circumference with crushing [1]

Fig. 3. Cracks oncircumference andradial cracks [1]

On the basis of the inspections, Figure 4 was drawn up with the discovered damages marked.

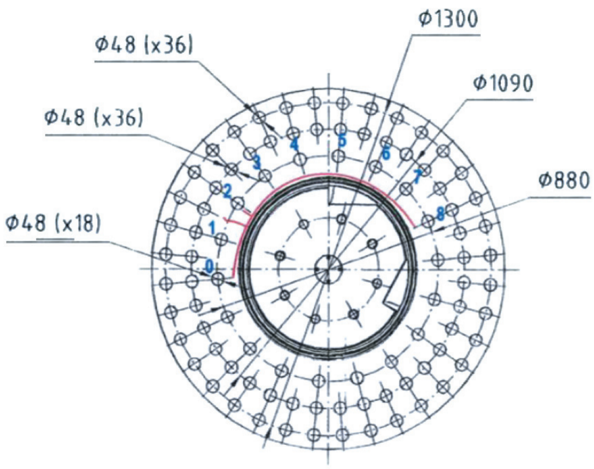

Fig. 4. Side disc of hoist drum of hoisting machine in southern section (eastern side) with cracks marked (red) [2]

The inspection resulted in the following conclusions:

- a crack on the circumference ~ 1000 mm long in the axial direction (in parallel to the axle of the shaft) through the material,
- a crack with some crushing of the material ~ 460 mm long in the axial direction through the material,
- two radial cracks (perpendicular to the axle of the shaft) from the circumference ~ 100 mm long and ~ 60 mm between the Bolts 1 and 2.

The found damages did not allow for the further operational use of the hoisting machine. The consequence of the above inspections was the decision of the Director of the Mining Office to the Power and Mechanical Equipment Test Inspections to stop the operation of the mining plant in the part related to the mining shaft hoist installed in the southern section of the R-II shaft O/ZG Rudna [3].

2. CONCEPT OF REPAIR OF SHAFT

The decision was made to repair the cracked shaft by welding in accordance with the technology developed by the Institute of Welding in Gliwice and agreed with by ZG Rudna [4]. Due to the vast loss of the material of the flange, the preparation of a weld groove was necessary; that is, the execution of the appropriate undercuts (geometry) of the connected elements (Fig. 5). After the appropriate preparation of the edges of the weld groove, penetration tests were conducted (to detect any cracks).

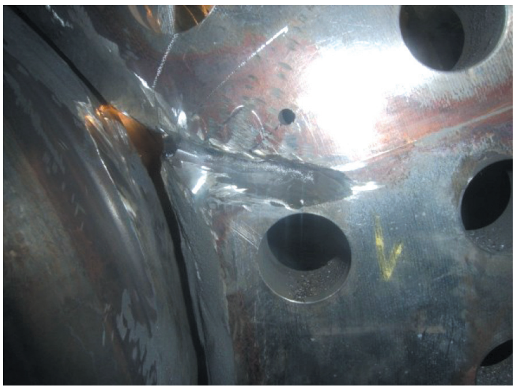

Fig. 5. The repair. Preparation of weld groove with view on depth of flange and size of crack [1]

The area around the site of the repair was isolated and then heated up to a temperature of ca. 100°C with an electric heating unit and heating mats ata rate of about 25°C/h. After stabilizing the temperature on the shaft and the flange, the welding work was started while at the same time continuously recording the temperature of the elements neighboring the site of the welding (Fig. 6). Special attention was paid to maintaining the difference of the temperatures of the elements of the bearing supporting the shaft within the proper range [5–7].

Fig. 6. Area around place of welding was isolated and then heated up with electric heating unit and heating mats. Heating speed was about 25°C/h [1]

To protect the rolling bearing against possible damage as a result of thermal expansion, the bearing case was heated up so that the temperature difference between the internal and external races would not exceed 15°C.

Due to the fact that the material of the shaft is made of steel with highly difficult weldability (as well as considering the scope of the damage), the welding process was done in two stages. First, the buffer layer was done on the side of the shaft and of the flange. Then, the surface of the buffer layer was properly smoothened by grinding, and the weld groove was started in accordance with the prepared instruction (Fig. 7). Figure 8 presents a view of the part of the shaft in the area of the crack after applying the buffer layer.

The next stage was connecting the flange to the shaft (closing the weld). An ENiCrFe-3 wire was used as a binder according to AWS A 5.11. After connecting the flange with the shaft, the whole weld groove was filled in along with the machining allowance (Fig. 9).

In each stage of the welding work, penetration tests were executed. If cracks were detected, the material was ground to remove them, with the welding work being continued only afterwards. The additional materials used for the welding were selected so as to enable the execution of the weld of the difficult--for-welding shaft material and obtain the properties of the weld deposit as close to the properties of the native material of the shaft as possible. The welding work related to the repair of the shaft was executed uninterruptedly (day and night) for about a week.

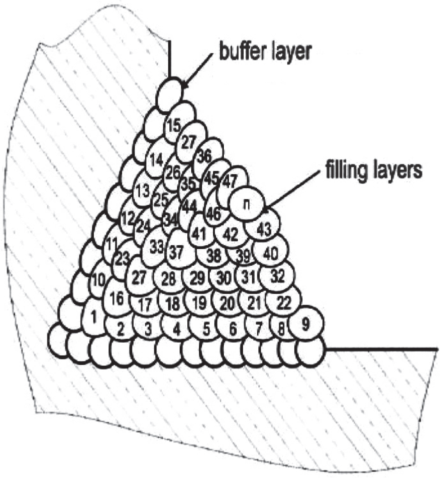

Fig. 7. Order of execution of welding work: buffer layer and filler layer [4]

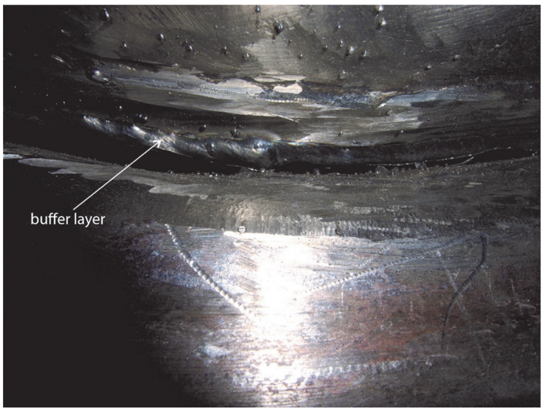

Fig. 8. View of shaft after applying buffer layer [1]

Fig. 9. Machining of shaft after welding to render proper curvature radius for part of shaft [1]

3. INSPECTION OF MACHINE SHAFT AFTER REPAIR

After the repair, an inspection of the machine shaft was conducted in order to confirm the readiness of the repaired shaft for further operational use. The inspection was executed by experts from Autorytet Spółka z o.o. [8, 9] (a non-destructive inspection of the shaft) and by employees of the Rope Transport Department (Katedra Transportu Linowego) of AGH University of Science and Technology in Krakow (the stress tests), among others. The extensometric tests of the stresses executed by KTL-AGH University of Science and Technology in the cylindrical part of the shaft and in the flange connecting it to the hoist drum as well as the thermovision tests of the repaired part of the shaft were to confirm the lack of stress accumulation in the part of the shaft where the repair was done.

The purpose of the performed measurements of temperature distribution in the machine shaft in the area of the passage to the flange used to connect the shaft to the hoist drum [10] was to determine any changes in the temperature in this spot. An FLIR P660 thermovision camera with a tripod was used for the inspection. The recorded results of the inspection were compared with the results recorded for the same machine on October 23, 2010; that is, before the breakdown [11]. Figure 10 shows the sample thermogram of the part of the drive shaft and of the disk of the drive wheel.

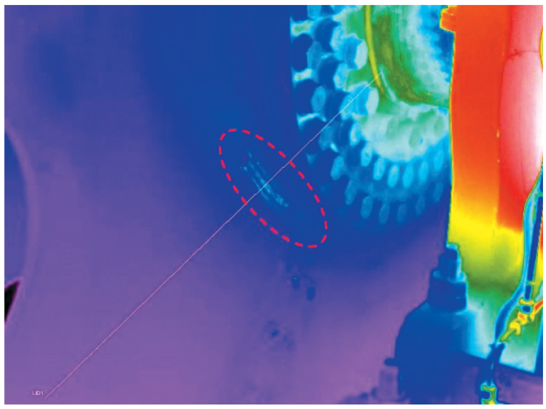

Fig. 10. Thermogram of part of drive shaft and of disk of drive wheel from southeastern side ("rain" pallet) [10]

The thermovision measurements showed a lack of significant temperature differences of the analyzed driving structure (the shaft – the hoist drum). No major differences were recorded against the measurements before the breakdown. The average temperatures of the shaft in both measurements differed due to the differences in the ambient temperature during the measurements. For this reason, the differences in the temperatures were more important at the passage from the cylinder part of the shaft to the flange to the connection with the hoist drum. The temperature difference was about 5.3°C. One should remember that the measurements could be burdened with measurement uncertainty resulting from the different emissivity factors for the different examined structures, flow of warm and cold masses of air forced by the fans of the motors, vibrations of the tower that may have negatively affected the thermovision camera, effect of the reflection of radiation from other sources of heat, etc.

Both extensometric and thermovision inspections showed the lack of a clear increase in the concentration of local stresses (the notch effect) in the examined area of the shaft after its repair.

4. PARAMETERS OF OPERATION OF MACHINE WITH REPAIRED SHAFT

After finding that the shaft after the repair did not show clear defects, documentation of the parameters of operation of the machine with the repaired shaft was started until the time of execution of the new shaft.

The shaft was made of E335 steel with the following values of strength properties:

- yield point R_{el} = 280 N/mm^2,
- temporary tensile strength R_m = 590 N/mm^2,
- limit substitute allowed stress taking into consideration permanent fatigue strength R_{limit} = 50 N/mm^2.

The damage of the cross section was found in the place of the base of the eastern flange of the shaft, with the two halves of the side disk of the hoist drum fixed with three rows of bolts. In the strength calculations of the shaft [12], it is the cross section with the diameter of ϕ685 mm with the following coefficients: bending strength W_g = 31,555,249 mm^3; torsion strength W_s = 63,110,498 mm^3. The maximum calculated accident stresses for the given case of load are as follows (respectively):

- normal load σ_e = 30.87 /mm^2,
- exceptional load σ_e = 179.96 /mm^2.

It was assumed, however, that the completed repair of the damaged cross section of the shaft cancause a decrease in the general load capacity of the shaft of an estimated value of ca. 30%. Therefore, the reduction of the technical parameters of the operation of the hoisting machine after the repair was proposed up to the following values:

- actual usable mass 25,000 kg,
- extraction speed 12 m/s,
- travel acceleration and delay 0.5 m/s^2.

For such assumed parameters, the strength calculations of the shaft were done, achieving the following maximum calculated accident stresses for normal load σ_e = 21.20 N/mm^2. Exceptional load causes stress of an unchanged value against the condition before the repair. The reduction of the values of the operational parameters of the machine will cause the reduction of stress in the repaired cross section by 9.67 N/mm^2; i.e., by 31.32%. The limitations of the travel parameters of the hoisting machine (in particular, acceleration and delay to a value of 0.5 m/s^2) will cause a major limitation in the value of the dynamic moment, which is decisive for the fatigue process of the structural elements of the machine.

The strength analysis of the shaft submitted by the producer of the shaft, drafted up with the finite element method (FEM) with the assumed operational parameters of the hoisting machine after the repair of the shaft also showed the acceptable level of stresses, confirming the results of the traditional strength calculations. The reduced values of the proposed operational parameters after the repair of the shaft resulted in ca. 40% reduction in the maximum value of the moment from the overweight in the condition of acceleration of the travel of the machine; i.e., from 1766 kNm to 1046 kNm. It was the significant reduction of the load with the moment of the flange of the shaft in the situation when the load-bearing cross section of the base of the flange of the shaft was damaged. The consequence of the reduction of the operational parameters of the hoisting machine also came in the form of an increase in the strength excess of the connection of the flange of the shaft with the side disk of the hoist drum from a value of 5.62 to 9.49.

It was found that the repair had not caused the material notch that may develop in the case of a significant difference in the hardness in a small area of the element. It is another premise proving that, after the repair and limitation of the load, the further operational use of the shaft is possible.

Considering:

- the assessment of correctness of the technology and execution of the repair of the shaft;
- the estimated assessment of load-bearing capacity of the executed connection;
- the results of the classic strength calculations of the shaft;
- the strength analysis of the shaft provided with the FEM method.

In reference to the above considerations, the decision was made on allowing for the time-limited (up to six months after the time of repair) operational use of the hoisting machine with limited travel parameters until the execution of the new shaft. The internal cross section of the base of the flange of the shaft (where the crack probably started) was invisible from the inside of the hoist drum, as it was covered by the (eastern) side disc of the hoist drum. For this reason, after arrangement with the designer of the shaft, for the inspection of this cross section, three openings were executed in each half of the side disk of the hoist drum to enable a visual or technical inspection of this cross section. The visual inspection of the cross section of the base of the flange of the shaft from the eastern bearing side was fully possible all the time. Due to the accessibility, this cross section could be inspected with the available technical methods.

Control arrangements:

- continuous visual inspection of a properly prepared employee of the area of the shaft of the hoisting machine between the case of the eastern bearing and the flange of the shaft was recommended; this inspection was important due to the fact that the operators do not have visual contact with the machines in the tower of the R-II shaft;
- after each shift, visual inspection of the repaired cross section should be done by entering the interior of the hoist drum through the openings and providing good lighting; the inspection should also cover the western flange of the shaft;
- in the first three weeks of the operation of the machine after the repair, inspections should be done as often as possible, minimum after each shift, as well as during the technological stopping of the hoisting machine;
- after three weeks of operation of the machine, the inspections of the repaired cross section should be conducted once per shift;
- the revisions of the area of the repaired shaft should be conducted following the effective regulations of safety of work.

5. SUMMARY AND CONCLUSIONS

As a result of the breakdown, the R-II mining shaft hoist in the southern section was out of operation for 27 days (April 17, 2011, through May 13, 2011). The hoisting machine was operated during the next 118 days (until September 8, 2011) with limited travel parameters (ca. 54% of the nominal capacity). From September 8, 2011, until September 16, 2011, the shaft was replaced with a new one with a different design.

The breakdown related to the crack of the flange of the shaft caused the total losses in the extraction of copper ore estimated (according to the ZG Rudna data) at 43, 240 skips (1,362,060 Mg). Additionally, due to the emergency stopping of the R-II S mining shaft hoist, changes were necessary in the logistics of deliveries of ore to O/ZWR Rejon Polkowice i Rudna. One should remember that the losses would be significantly higher had the repair of the shaft of the hoisting machine in the southern section of the R-II shaft not been successfully provided.

References

[1] Opinion on inspections and assessment of the emergency repair of the shaft along with statement of the technical parameters of further operational use of the hoisting machine 4L-5500/2×3600 in the R-II shaft in the southern section KGHM Polska Miedź S.A. Oddział ZG "Rudna" Drawn up by the team headed by dr hab. inż. Marian Wójcik, prof. AGH, Krakow, 11 May 2011.

[2] Inspection results no. 114/11/N/Ł of 17.04.2011. Zespół Rzeczoznawców Urządzeń Technicznych "Autorytet" Sp. z o.o., Polkowice, ul. Kopalniana 1.

[3] Decision of Urząd Górniczy do Badań Kontrolnych Urządzeń Energomechanicznych, ref. UGB/0232/0001/11/01520/Sz. 2011.

[4] Welding repair guidelines for the crack in the flange of the main shaft of the hoisting machine in the R-II shaft in the southern section in O/ZG "Rudna" KGHM Polska Miedź S.A. Instytut Spawalnictwa, Gliwice 2011.

[5] Description of the technology of heating up for welding of the machine shaft. Firma LMS s.c. T. Macioła i K. Scheithauer, Chorzów, ul. Wieniawskiego 18, 2011.

[6] Report from the repair by welding of the crack at the flange of the main shaft of the hoisting machine in the R-II shaft in the southern section in O/ZG "Rudna" KGHM Polska Miedź S.A. along with the Welding Guide W/P/Z/11 and Material Attestations. Warexim Przedsiębiorstwo Wielobranżowe Aleksander Warsz, 44-114 Gliwice, ul. Czajki 11/38, 2011.

[7] Shaft heating up technology. Firma LMS s.c. T. Macioła i K. Scheithauer, Chorzów, ul. Wieniawskiego 18, 2011.

[8] Inspection results no. 138/11/N/Ł. Ultrasonic tests of the shaft of the hoisting machine 4L-5500/2×3600 in the R-II shaft in the southern section. "Autorytet", Polkowice, 10.05.2011.

[9] Inspection results no. 139/11/N/Ł – Non-destructive inspections of the shaft of the hoisting machine 4L-5500/2×3600 in the R-II shaft in the southern section. "Autorytet", Polkowice, 10.05.2011.

[10] Extensometric measurements of stresses in the design of the drive wheels along with the analysis of results in the hoisting machines of mining hoist units in the R-II shaft KGHM Polska Miedź S.A. O/ZG "Rudna". Katedra Transportu Linowego AGH, Krakow, June 2010.

[11] Inspections and assessment of the drive wheel in the hoisting machines of the mining hoisting units in the R-II shaft KGHM Polska Miedź S.A. O/ZG "Rudna". Katedra Transportu Linowego AGH, Kraków, October 2010.

[12] Documentation with the application for approval of operational use of the hoisting machine 4L-5500/2×3600 by ABB, the R-II shaft, the southern and northern sections, KGHM Polska Miedź S.A. Oddział ZG "Rudna", no. 3BPC001189D0144, vol. 1 and 2.

TOMASZ ROKITA, Ph.D., Eng.
Department of Rope Transport
Faculty of Mechanical Engineering and Robotics
AGH University of Science and Technology
al. Mickiewicza 30,
30-059 Krakow, Poland
rokitom@agh.edu.pl

http://dx.doi.org/10.7494/miag.2018.4.536.33

JAN GIL
MICHAŁ KOŁODZIEJ
DAWID SZURGACZ
KAZIMIERZ STOIŃSKI

Introduction of standardization of powered roof supports to increase production efficiency of Polska Grupa Górnicza S.A.

Text The introduction of the standardization of a powered roof support is a key point in increasing production efficiency in the mines of Polska Grupa Górnicza S.A. The introduced changes will increase the safety of the miners and affect the economic result associated with the exploitation of coal. The purpose of introducing this standardization is to systematize the construction solutions of roof supports in terms of power and control hydraulics, focusing on all technical conditions that powered roof supports operating in underground mining facilities must meet (including mining tremors). This article presents the method of standardizing the powered roof supports that are produced, modernized, and renovated by Zakład Remontowo-Produkcyjny within Polska Grupa Górnicza S.A.

Key words: *standardization, powered roof support, increased production efficiency*

1. INTRODUCTION

Polska Grupa Górnicza S.A. (PGG) currently conducts mining work in about 50 longwalls in 8 mines. The average working depth reaches 710 meters. The natural hazards mainly include tremors, methane, and water. The operation is carried out only by longwall systems based on caving, using a combine harvester as a mining machine [1, 2]. The thickness of the longwalls reaches about 2.6 m. The annual production of PGG is about 30 million tons (82 thousand tons a day on average). Supporting and shielding systems equipped with supporting legs are mainly used. Over 60% of the exploitation of longwalls are carried out under conditions of tremor hazards. The degree of the threat of rock mass impact assessed on the basis of the n_{tz} coefficient ranges from 1.1 to 1.4 [1–3], whereas the g indicator must stay within a range of 0.7 to over 1.2 to ensure the adequate maintenance of the roof described, which indicates that there is no optimized load-bearing capacity of the roof supports to the actual needs. Between two and five types of roof supports are used in one longwall, with the basic supply pressure reaching 25 MPa. The majority of the control systems are based on RB, with pilot control being applied much less often. The electro-control has not been applied yet. In some cases, electronic pressure monitoring systems are used. There are about 200 types of roof supports registered. They are mainly supporting and shielding structures with various leg parameters (cylinder diameters, lengths). An exemplary list of the used supports of the selected PGG mines is presented in Table 1.

A considerable number of longwalls are equipped with several types of sections that often differ in their geometry and load-bearing capacity. There are cases when the original elements are replaced with *substitutes of dubious quality* for different reasons. (financial, organizational, no availability of original spare parts). This makes it difficult to exploit and maintain the support to a significant extent and to determine the real causes of a malfunction. It is worth noting that the majority of powered roof supports operating in PGG's mines have been used for twenty years on average, and there are still supports that were introduced almost thirty years ago. Table 2 presents the number of sections operating in PGG, depending on the year of production.

Table 1

Exemplary list of used supports of selected PGG mines

Type of powered roof support	Range of working height of section [m]
Fazos 08/22 2x2690	1.0–2.1
Fazos 08/22 2x2690-1	1.0–2.1
KW 09/26 POz/ZRP w. III	1.5–2.5
KW 09/26 POz/ZRP/BSN w. III	1.5–2.5
Fazos 16/37 POz	1.7–3.7
Fazos 16/37 POz/BSN	1.7–3.7
KW 16/37 POz/ZRP	1.8–3.6
KW 16/37 POz/ZRP/BSN	1.8–3.6
Tagor 18/36 POz	2.0–3.5
Tagor 18/36 POz/S	2.0–3.5
Fazos 19/35 OzM5	1.9–3.4
KW 20/36 POz/ZRP	2.2–3.5
KW 20/36 POz/ZRP/BSN	2.2–3.5
KW 20/36 POzW1/ZRP	2.2–3.5
KW 14/28 POz/ZRP	1.5–2.7
KW 14/28 POz/ZRP/BSN	1.5–2.7
Fazos 15/31 OzM5	1.7–3.0
BW 20/36 OzMR2	2.5–3.5
BW 17/43POz	2.0–3.6

Table 2

List of number of power roof supports in PGG with breakdown per year of production

Year of production	Number of supports [pcs.]
By 1980	434
1981–2000	6620
2001–2016	8056

The variety of the types and technical solutions complicates the maintenance and the possibility of using working roof supports in other longwalls.

Regardless of the way they are placed on the market, all roof supports are subject to additional assessments of the load-bearing capacity often conducted by a scientific research unit in the case of usage under conditions of rock mass impact. Table 3 shows the number of support sections in PGG, depending on the method of placing on the market.

Table 3

Number of supports in PGG depending on method of placing on market

Year of production	Number of supports [pcs.]	Legal basis for market introduction
By 2004	7443	admission issued by the President of the Higher Mining Office
Since 2004	7667	EC type examination certificate

Currently, roof supports are introduced on the market in compliance with the security requirements set out in the European Parliament's Machinery Directive [4] and harmonized Polish standards PN-EN 1804 series [5–7]. Due to the fact that the standards of the PN-EN 1804 series include a record excluding their validity in the case of rock mass hazard, the support should be adapted by "allowing" it to take over dynamic loads under the Regulation of the Minister of Energy of November 23, 2016, [8] on the detailed requirements for running underground mining facilities (effective July 1, 2017).

In contrast to the previous regulation of the Minister of Economy of June 28, 2002, on the Occupational Health and Safety, Traffic, and Specialized Fire Protection in Underground Mines (valid until July 1, 2017), The new regulation of the Minister of Energy does not recognize the requirement assessment of the possibility of the cooperation between different types of supports in one longwall. This means that, in light of the currently binding legal acts, the assessment of the possibility of the cooperation of several roof supports in one longwall is optional and rests solely on the manager of the mining department, who may support the opinion of appointed teams of consultants. The use of several types of powered roof supports in one longwall leads to a number of issues. Analysis [9] shows that an important stage in the process of adapting the support to the prevailing geological and mining conditions in a given excavation is the selection of its support system [10, 11], strictly resulting from the assessment of roof maintenance index *g*. Therefore, for the safe and effective operation of a longwall complex, further cooperation with the Central Mining Institute is recommended. Roof index *g* should be included in the process of selecting the support for the actual operating conditions. This paper presents the standardization process of powered roof supports (both renovated and produced) as a part of PGG S.A.

2. RULES FOR OPERATION OF ROOF SUPPORTS

The prospect of meeting the requirements of the market enforces the decisive rationalization of the costs of coal mining through the improvement of the organization, employment, and degree of use of the machinery, which should lead to an increase in daily output from the wall. Such a tendency should be maintained with deteriorating mining conditions and strong external competition. The benefits of the above process include ensuring the operation of the longwall system as well as the functionality while minimizing the purchase and operation costs.

The standardization was initiated at Zakład Remontowo-Produkcyjny, which has been a branch of Polska Grupa Górnicza for ten years. Cooperation with scientific and research units (including the Main Mining Institute and the KOMAG Institute of Mining Technology) was indispensable. The increasingly difficult mining and geological conditions contribute to the increase in the risk of rock mass shocks, precisely imposing the technical conditions that the powered roof support must meet and indicating the need to standardize the support structure.

Based on an analysis of this state and the anticipated needs for the coming years, the most important directions of action in the field of standardization of the construction of powered roof supports were set out [12]. Determining the basic directions of the standardization of roof support construction has allowed us to optimize roof support management, taking full advantage of the existing powered roof supports and the production potential of Zakład Remontowo-Produkcyjny.

The standardization included three main components of a roof support:
- construction of the section,
- power hydraulics,
- control hydraulics.

For this concept, actions have been taken in the following areas:

1) construction of section:
   - adjusting the working height of the powered roof support to the current needs;
   - increasing the load-bearing capacity of the roof support while strengthening the structures of the roof supports owned by PGG;
   - introduction of proprietary procedures – Zakład Remontowo-Produkcyjny has tightened the safety coefficients imposed by standards on the load on stand seats (introduction of Coefficient 2 instead of the required 1.5) [13];
   - introduction of facilities to the roof support at the request of representatives of the mines that facilitate operation and repair;
   - introduction and application of the same auxiliary cylinders for different types of roof supports (longwall face shield actuator, transition cover, side shield correction actuator).
2) power hydraulics:
   - legs were limited to one type, with a two-telescopic structure with a bottom valve, with first-stage diameters:
     - 0.21 m – KW-08/22-POz/ZRP, KW-09/26-POz/ZRP,
     - 0.25 m – KW-14/28-POz/ZRP, KW-18/34-POz/ZRP, KW-20/36-POz/ZRP, KW-17/43-POz/ZRP,
     - 0.32 m – KW-16/37-POz/ZRP;
   - hydraulic legs are equipped with ZRP connections:
     - size I: DN12/DN12 – min. flows for 60 MPa 450 l/min at 15% flow losses for a 0.21 m diameter,
     - size II: DN19 / DN12 – min. flows for 60 MPa 650 l/min with flow losses of 15% for a leg with a diameter of 0.25 m and 0.32 m.
3) control hydraulics – introduction of a procedure to select the protection of the powered roof support sections against dynamic overloads based on the method of determining the resultant flow of the system: connection-valve (Fig. 1). For this purpose, Zakład Remontowo-Produkcyjny has developed detailed requirements for the purchase of pressure/relief valves.

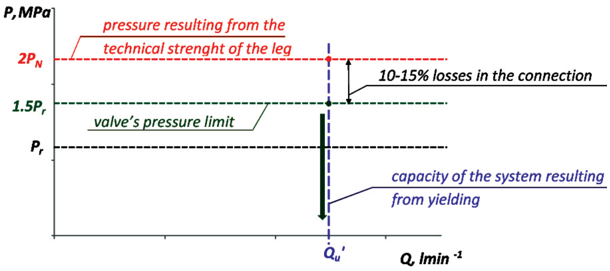

Fig. 1. Method of determining resultant flow of connection-valve system

3. DIRECTION OF STANDARDIZATION

The section of the powered roof support in accordance with machinery directive [2] is a machine consisting of a structure as well as power and control hydraulics and, as a whole, should be placed on the market and used unchanged throughout the life of the machine. This is extremely important for safety, technical, and cost reasons; any deviation from the above-mentioned principles results in a radical increase in the risk of failure, which translates into a deterioration in work safety. A derivative issue that is also beneficial is the unification of the demand for purchasing elements, the simplification of maintenance works, and all kinds of repairs.

To meet these requirements, PGG S.A. has decided to secure its immediate needs in the field of longwall development and powered roof supports acquired based on its own documentation, taking into account the standardization and aggregation of the purchase system. An analysis was based on the scope of work of the roof support sections through 2020 (Tab. 4) carried out in order to assess these needs.

Table 4

List of needs in area of powered supports sections for 2018–2020

Scope of work	Number of sections
1.0–2.5	178
1.8–3.3	425
2.0–4.0	318
2.6–4.6	121

Having regard to the above needs and optimizing the working ranges for newly designed powered roof supports in Zakład Remontowo-Produkcyjny, design work was undertaken to develop new types of roof supports. Three basic types of support and shielding systems based on a pitch of 1.5 m were determined (Fig. 2):

- I: geometric 1.2–2.4 m; working 1.4–2.3 m,
- II: geometric 1.5–3.5 m; working 1.7–3.4 m,
- III: geometric 1.9–4.1 m; working 2.1–4.0 m,
- IV: geometric above 4.1 m, working above 4.0 m, where a pitch of 1.75 m is recommended to ensure the stability of the support.

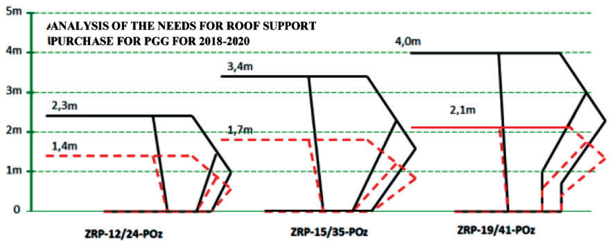

Fig. 2. Operating scope chart, supply for 2018–2020

The simplification of the components of a powered roof support and their unification is the next step in the standardization process. After completion of the already-started process, Polska Grupa Górnicza will be able to obtain a whole range of measurable benefits, such as:

1) increased work safety for miners:
   - the structures will become repetitive, known to miners,
   - equipment training will be easier and faster,
   - good knowledge of a given structure directly reduces the risk of an accident resulting from poor knowledge about a given structure;
2) simplification of the structure – standardization:
   - fewer technical solutions,
   - optimal selection of component construction,
   - interchangeability of basic elements, such as canopies and floor bases, auxiliary cylinders for all three types of newly designed roof supports;
3) improvement of purchase procedures of construction elements, power and control hydraulics;
4) significantly increase the possibility of using roof supports in other mines/longwalls;
5) basic reduction of costs related to renovation, modernization, and production of new support;
6) increased production capacity.

In Zakład Remontowo-Produkcyjny, Polska Grupa Górnicza, an algorithm of actions was developed to improve the investment process in the scope of servicing mines with the required types of powered roof supports (Fig. 3). The improvement of the efficiency of the repairs, modernization, and production of the new roof supports is based primarily on the process of aggregation of the components. Figure 4 presents examples of the possibilities of using standardized components to adapt the roof supports to the individual needs of the mines on the example of a prototype type ZRP-15/35-POz roof support. On the basis of the attached example, the principle of aggregation is clarified in which a given roof support can be configured depending on the requirements of the mine and the specific conditions of the extraction longwall.

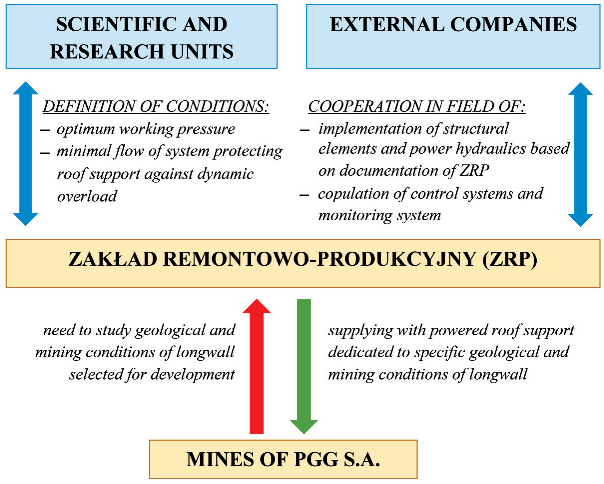

Fig. 3. Algorithm developed by Zakład Remontowo-Produkcyjny

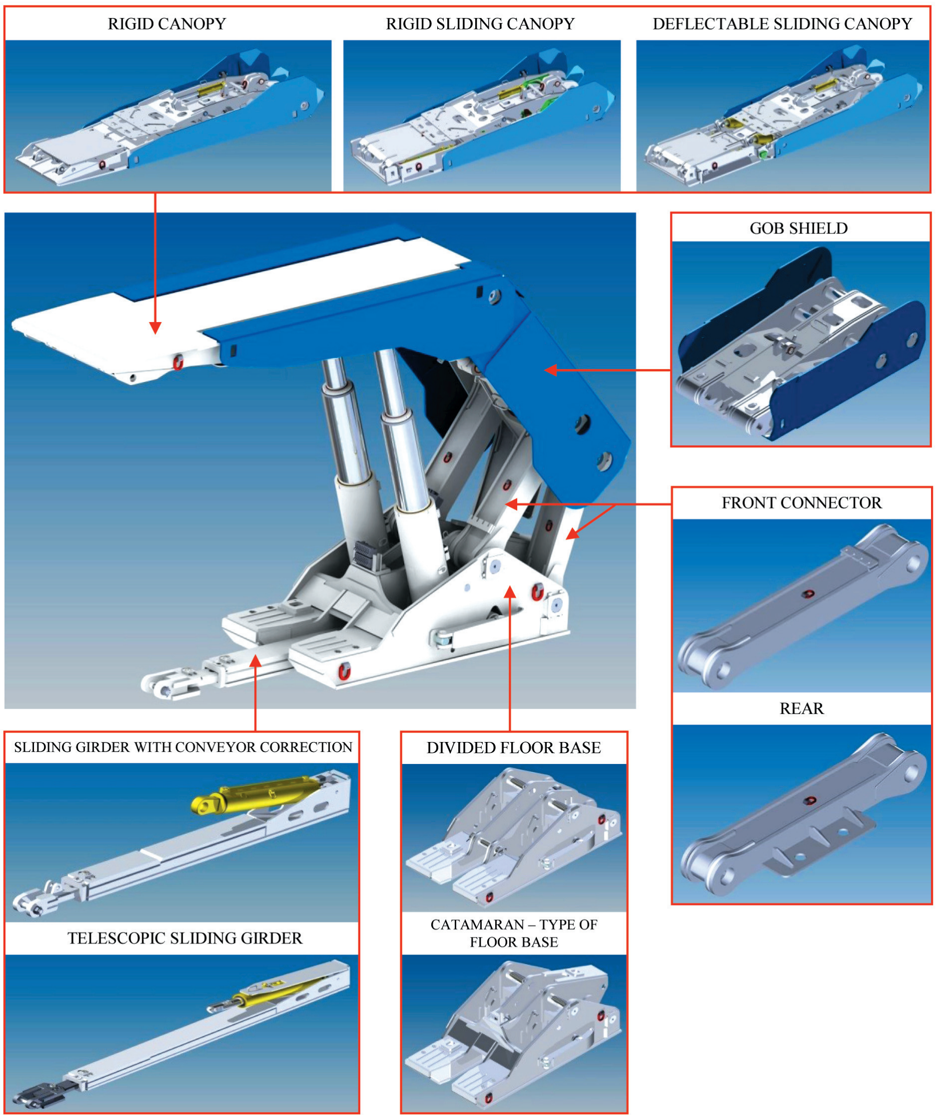

Fig. 4. Principle of aggregation – configuration of powered roof supports components

The roof support can be configured from standardized elements (which are repeatable and fully meet safety and technical requirements and, to a significant extent, reduce production costs). The introduction of aggregation allows for the use of the same canopy or floor base for both the medium and high roof support produced, for example. It is also possible to use a canopy in various construction variants (rigid, rigid sliding, or deflectable sliding) in one support. Aggregation of the power hydraulic elements (standardization of actuators: wall face shields, transitions shields, correction of side shields of canopy and shield support, section shifters) as well as the control gear will enable the unification of the whole range of solutions and increase the production and purchase capacities and reduce costs.

4. CONCLUSION

Polska Grupa Górnicza implements the standardization process for powered roof supports. It is a difficult and demanding plan that will help bring tangible benefits. The risk of mining tremors is a significant natural threat to which the produced and modernized roof support should be adapted. For this purpose, activities were undertaken by Zakład Remontowo-Produkcyjny to obtain a high degree of safety of powered roof supports by means of technical and organizational measures as well as the method of production. Changes in Polish mining and the constantly deteriorating conditions for selecting coal deposits require the consistent implementation of rational solutions. The aggregation of the components of powered roof supports is constantly being developed and improved by Zakład Remontowo-Produkcyjny in close cooperation with scientific institutions; i.e., the Central Mining Institute and research laboratories. The purpose of the activities undertaken by Zakład Remontowo-Produkcyjny, PGG, is primarily to improve the safety of the work in underground longwall excavations while at the same time streamlining costs.

References

[1] Doległo L., Gil J., Kubiesa R., Stoiński K.: *Układ sterowania stojakiem hydraulicznym typu ZRP dla potrzeb zmechanizowanych obudów ścianowych Kompanii Węglowej SA*, XX Międzynarodowa Konferencja "Trwałość elementów i węzłów konstrukcyjnych maszyn górniczych" – TEMAG 2012, Politechnika Śląska, Gliwice.

[2] Gil J., Stoiński K.: *Bezpieczeństwo zmechanizowanych obudów w systemach ścianowych*, VI Międzynarodowa Konferencja Techniki Urabiania TUR 2013, Akademia Górniczo-Hutnicza, Kraków.

[3] Stoiński K.: *Obudowy górnicze w warunkach zagrożenia wstrząsami górotworu*, Główny Instytut Górnictwa, Katowice 2000.

[4] *Dyrektywa 2006/42/WE Parlamentu Europejskie i Rady z dnia 17 maja 2006 r. w sprawie maszyn, zmieniająca dyrektywę 95/16/WE*, Dziennik Urzędowy Unii Europejskiej L157/24.

[5] PN-EN 1804-1+A1:2011: *Maszyny dla górnictwa podziemnego – Wymagania bezpieczeństwa dla obudowy zmechanizowanej – część 1: Sekcje obudowy i wymagania ogólne.*

[6] PN-EN 1804-2+A1:2012: *Maszyny dla górnictwa podziemnego – Wymagania bezpieczeństwa dla obudowy zmechanizowanej – Część 2: Stojaki i pozostałe siłowniki*.

[7] PN-EN 1804-3+A1:2012: *Maszyny dla górnictwa podziemnego – Wymagania bezpieczeństwa dla obudowy zmechanizowanej – Część 3: Hydrauliczne układy sterowania.*

[8] *Rozporządzenie Ministra Energii z dnia 23 listopada 2016 r. w sprawie szczegółowych wymagań dotyczących prowadzenia ruchu podziemnych zakładów górniczych*, Dz.U. 2017, poz. 1118.

[9] Stoiński K., Gil J., Żak A., Karczewski T.: *Zmechanizowane obudowy ścianowe – doświadczenia projektowe i produkcyjne PGG Sp. z o.o. oddział Zakład Remontowo-Produkcyjny w Bieruniu*, IV Polski Kongres Górniczy, Akademia Górniczo-Hutnicza, Kraków 2017.

[10] Gil J., Kubiesa R., Stoiński K.: *Identyfikacja uszkodzeń hydrauliki sterowniczej zmechanizowanej obudowy ścianowej*, XX Ogólnopolska Konferencja Nauk.-Tech. CYLINDER 2010 nt. Badanie, konstrukcja, wytwarzanie i eksploatacja układów hydraulicznych, Gliwice, KOMAG.

[11] Szurgacz D.: *Sposób dostosowania obudowy ścianowej do warunków obciążeń dynamicznych*, Przegląd Górniczy 2016, 7: 57–62.

[12] Stoiński K., Gil J.: *Procedura optymalizacji upodatnienia zmechanizowanej obudowy ścianowej na przykładzie KW-12/25-ZRP*, in: *Mechanizacja, automatyzacja i robotyzacja w górnictwie*, t. 1: *Wybrane problemy górnictwa podziemnego*, red. K. Kotwica, Lędziny – Kraków, Centrum Badań i Dozoru – Akademia Górniczo-Hutnicza, s. 76–83.

[13] Gil J., Łabuzek M., Wencel H.: *Innowacyjne rozwiązania eliminujące połączenia spawane i gwintowane w siłownikach hydraulicznych stosowanych w obudowach zmechanizowanych*, XX Ogólnopolska Konferencja Nauk.-Tech. CYLINDER 2010 nt. Badanie, konstrukcja, wytwarzanie i eksploatacja układów hydraulicznych, Gliwice, KOMAG.

JAN GIL, Ph.D., Eng.
MICHAŁ KOŁODZIEJ, M.Sc., Eng.
Polska Grupa Górnicza S.A.
Oddział Zakład Remontowo-Produkcyjny
ul. Granitowa 132,
43-155 Bieruń, Poland
zrp@pgg.pl

DAWID SZURGACZ, Ph.D., Eng.
Polska Grupa Górnicza S.A.
KWK ROW Ruch Chwałowice
ul. Przewozowa 4,
44-206 Rybnik, Poland

KAZIMIERZ STOIŃSKI, prof.
Główny Instytut Górnictwa
pl. Gwarków 1,
40-166 Katowice, Poland