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An assessment of rope durability in mining shaft hoists

The article presents the issues of the durability of lifting ropes and balance ropes operated in selected shafts of deep mines. The basic causes of hoisting ropes wear are described, the methods of steel ropes wear evaluation are given, as well as the hoisting ropes durability evaluation criteria. The authors also present selected results from the extension of hoisting ropes. The article ends with some conclusions resulting from the research. The article has also been provided with photos showing the measuring equipment used to assess the durability of steel and steel-rubber ropes. The article presents the criteria for assessing the durability of lifting ropes.

Key words: *operation, ropes, assessment, durability*

1. INTRODUCTION

Mining hoisting devices are the most important link and basic means of transport in the Polish hard coal mining industry. These devices are used to transport the excavated material from underground mines. Hoisting devices also perform a number of other functions, such as crew descent and departure, and lowering various types of materials necessary for the exploitation of the deposit, as well as the maintenance of the mine infrastructure [1].

The decreasing number of coal deposits lying in favour able mining and geological conditions and the constantly increasing depth of mining result in an increase in mining costs. If we add to this the relatively low coal prices on world markets, the true picture of hard coal mining in Poland and in the world emerges. A chance to improve the profitability of exploitation, and thus to maintain the profitability of Polish mines, is the increased concentration of extraction. This situation contributes to the need to use increasingly efficient and reliable extraction devices. This can be achieved by using extraction vessels of increasing capacity, as well as driving speeds in the extraction shafts. Such actions result in an increase in the operating parameters of the ropes, which reduces their durability [1–3].

Steel ropes used in shaft hoists are subject to various wear processes. They change their mechanical parameters, as a result of which they lose their operational properties. Ropes are subject to wear processes that are nonlinear as a function of time. Effects of foreseeable wear are counteracted by conducting regular tests and inspections using various methods, from visual to non-destructive [3–5].

In order to better understand the wear processes of ropes, it may be useful to carry out an analysis of their durability. The ropes operating in the downhill material shaft hoists in one of the selected hard coal mines were analyzed in this way. The source of the data were reports on tests periodically carried out by experts, books of periodical inspections of shaft hoists and books of shaft reports.

2. METHODS OF ASSESSING THE CONDITION OF STEEL ROPES

Several methods are used to assess the condition of a rope in service. We can distinguish two groups [4]:

- non-apparatus – based on observing wear processes or on measuring geometric features of ropes, the condition of which changes with the change of the rope condition,
- apparatus – involve the use of specialized apparatus. The most commonly used are magnetic tests [6].

2.1. Non-apparatus methods

2.1.1. Visual method

This method is based on visual observation of the condition of the available part of the rope. This is the most common diagnostic method to assess the condition of ropes. It requires a lot of experience of the person conducting the observations and due to the lack of unambiguous criteria, this method is not very objective. By performing the cyclic counting of wire fatigue scraps, this method can be used to prepare the fatigue wear characteristics of the ropes [4].

Visual observations reveal damage such as [7]:
– breaking strands,
– corrosion,
– wire fractures,
– change of rope diameter,
– deformities,
– waviness,
– rope attachment point.

2.1.2. Methods of measuring the geometrical features of the rope

The most common method of rope condition assessment in this group is the registration of changes in diameter in the determined rope cross-section. The reference is the nominal or actual dimension in the designated cross-section. The diameters are recorded after some time after putting on a new rope, when the diameter is clearly stabilized. The reduction in diameter at a given location is in most cases associated with a core damage or defect. The lateral rigidity of the rope decreases or increases, which has an impact on the acceleration of fatigue wear. The local increase of the rope's transverse stiffness and the dropping of strands onto the core are also dangerous. These phenomena in bent ropes can lead to fatigue scrap of wires [4].

Pattern example:

$$\Delta d = \frac{d - d_{nom}}{d_{nom}} \cdot 100\% \tag{1}$$

where:
d_{nom} – nominal rope diameter [mm],
d – measured rope diameter [mm].

Another method forassessing the condition of ropes in this group is measuring the rope jump length. This is the length of the helix stroke that the individual strands draw. The pitch of ropes with steel cores is from 7 to 9 nominal diameters. In order to increase accuracy, the measurement is made at three times the stroke length. It should be performed in several marked sections. The reference is the actual or nominal size of the rope at the site. Measurement of the rope jump length is only justified after a certain time, different for each device and rope structure. This delay is to stabilize the elastic parameters of the rope (no elongation). When the jump length changes after this period, this may indicate twirling of the ropes. A significant difference in the stroke length compared to the nominal value affects the fatigue life reduction [4, 7]:

$$\Delta l = \frac{l_s - l_{nom}}{l_{nom}} \cdot 100 \tag{2}$$

where:
l_{nom} – nominal rope jump length [mm],
l_s – measured rope jump length [mm].

2.1.3. Methods of measuring the geometrical size of losses

In order to measure the size of the wire friction, three methods are used: the method of measuring the diameter of the rope, the method of measuring the dimensions of the wear of a single wire, and the method of measuring the reflection surface of the rope in print. The method of measuring the diameters is used for semi-closed and closed ropes. It is the only method of measuring this size for them. This method consists in comparing the measured diameter with the diameter of the new rope. The method of measuring the dimensions of a single wire wear (Fig. 1) consists in measuring the wear height h or the wear chord c. Measuring the wear chord is a very difficult task and burdened with a considerable degree of error. In order to measure the height of the wear, it is necessary to cut the wire. The size of the clash is calculated from the formula:

$$\Delta S_{Fe} = r^2 \cdot \arcsin\left(\frac{c}{2r}\right) - 0.5 \cdot \sqrt{r^2 - 0.25c^2} \tag{3}$$

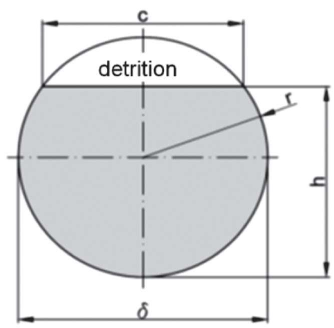

Fig. 1. Calculation of the wire wear area [8]
c – wire wear chord, h – wire wear height,
δ – wire diameter, r – radius (r = 0.5 · δ)

A more precise method of determining the wire wear chord is the "in print" method (Fig. 2). It consists in applying chalk, graphite or a paint designed for this purpose to the dirt-free surface of the rope. After making a mark on the paper, an image is obtained in which the wear surfaces are clearly visible. The bowstring can be measured very accurately, directly from a print or from a copy made to a suitable scale. In order to calculate the area of the scraped wire, the resulting chord size should be entered in formula (3). The values calculated using this method are usually lower than those calculated based on the direct measurement of the chord of clashes [1].

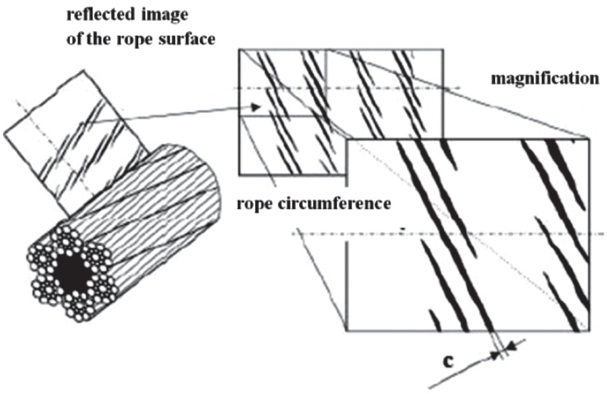

Fig. 2. Measurement of the size of the wire wear using the „in print" method of the rope surface reflection [8]

2.1.4. Apparatus methods – magnetic testing

Magnetic testing is the most common method of testing hoisting ropes in an apparatus. Poland was the first country to introduce a legal obligation in its mines to test the magnetic ropes of hoisting devices. Today's regulations also require magnetic testing of balance and guide ropes.

During the test, the rope becomes magnetized with a permanent field. The magnetic flux flowing through the rope is generated by permanent magnets. An inductive sensor (measuring coil) is located between the pole pieces on the part of the rope that is magnetized. The instantaneous value of the magnetic flux associated with the measuring coil changes when the section of rope on which the damage is moved. As a result of this phenomenon, an electromotive force is induced, the value of which is directly proportional to the change in the ferromagnetic cross-section of the tested rope. The value of this force is also influenced by many factors depending on the measuring head and the parameters of rope damage. Part of the magnetic flux induced by permanent magnets flows through the area surrounding the rope. This part of the stream is called the leakage stream. The lines of the scattering flux are parallel to each other, provided that there is no change in the ferromagnetic cross-section of the tested rope on the magnetized section (Fig. 3) [8].

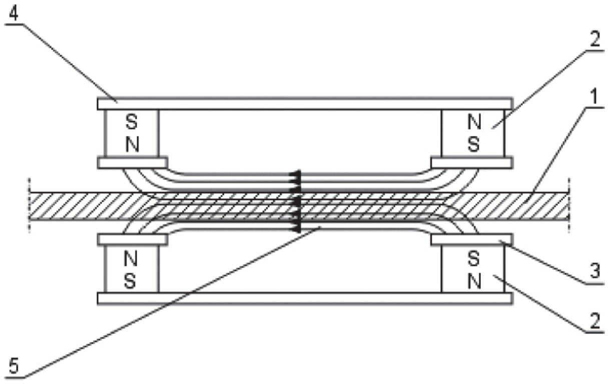

Fig. 3. Distribution of the magnetic field lines in an undamaged line [6]
1 – rope, 2 – permanent magnets, 3 – pole pieces, 4 – jumper, 5 – scattering flux

If there is a step change in the rope cross-section (corrosion pits, cracks etc.) or a change in the homogeneous structure of the line occurs, the magnetic field force lines are deformed. However, the value of the magnetizing flux does not change (Fig. 4).

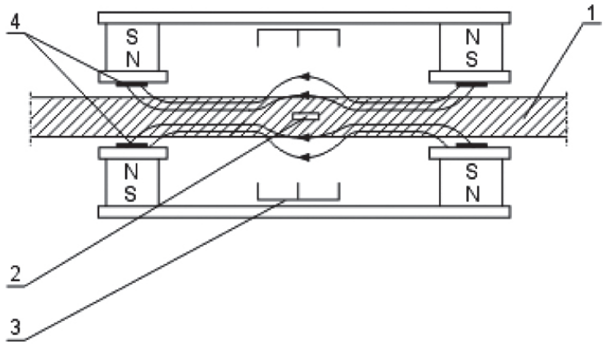

Fig. 4. Distribution of the magnetic field in the damaged line [6]
1 – rope, 2 – rope damage, 3 – inductive sensor for step changes in cross-section, 4 – hall sensor for cross-section changes

The most important parameters affecting the nature and value of the impulse induced in the measuring coil include: the distance between the ends of the broken wire, the damage distance from the rope axis, and the loss of the ferromagnetic cross-section of the tested rope.

The same method is used for magnetic testing of hoisting ropes – rope magnetization with permanent magnets. However, different manufacturers use different types of sensors. Depending on the number and type of detection sensors, the design of magnetic concentrators, susceptibility to magnetization, and the principle of operation of the sensor, they provide different signals. Inductive sensors and Hall sensors are the most commonly used detection elements. The main task of an inductive sensor is to detect and measure spike failures. If it is used, the damage should move in relation to the sensor. Hall sensors are also used, which enable the measurement of the so-called continuous damage such as wire abrasion or corrosion. They are also used to increase the detection of damages such as corrosion pits or wire breaks [6].

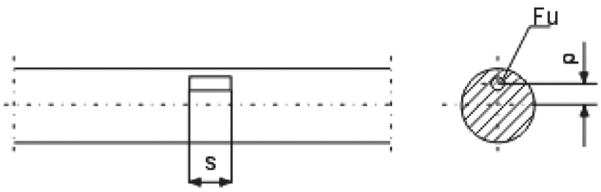

Fig. 5. Parameters influencing the pulse induced in the coil [3]
S – length of the gap between the ends of the broken wire, Fu – ferromagnetic section loss, α – radial distance from the rope axis

They can be used as external or internal sensors. The data on the components of the radial force lines of the magnetic field are collected by an external sensor. It should be located at an appropriate distance from the tested rope by the armature. Using information from sensors: external and internal, it is possible to obtain data on the depth of the defect occurrence in the tested line (Fig. 5). If the defect is deep in the line, the values from both sensors have a similar value. If the value of the signal from the external sensor is lower than the value of the signal from the internal sensor, the defect is located in the outer layer of the rope. These solutions are considered to be the best detection of a significant part of typical rope failures [1, 9].

The apparatus for performing magnetic flaw detection consists of two elements: the measuring head and the signal output recorder (Fig. 6). The result of the test is a defectogram on which the test results are recorded. The apparatus is equipped with an additional system whose task is to balance the speed changes. The ejection of the tape on which the results are recorded is adjusted to the rope speed. As a result, the signal coming from the sensors and recorded on the tape does not depend on this speed. The measuring head should be calibrated by an independent person, in accordance with the standards, every 3 years [9].

The rope speed has no effect on the accuracy of the measurement, if a compensation system for this value is used.

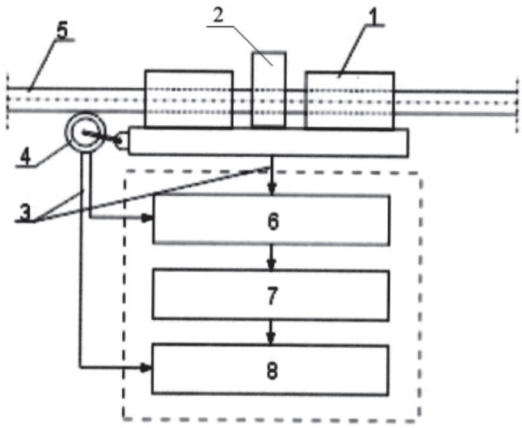

Fig. 6. Diagram of the measuring apparatus mounted on the rope [3]
1 – measuring head, 2 – recording part, 3 – connecting wires, 4 – rope movement and displacement sensor roll, 5 – tested rope, 6 – compensation pulley, 7 – signal amplifier, 8 – recorder

Due to its metrological parameters, the MD-120 defectograph shown in Figures 7 and 8 has become very popular.

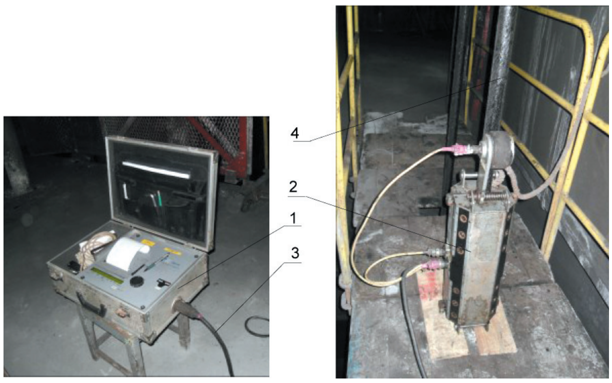

Fig. 7. A set of apparatus for testing round steel ropes
1 – MD-120 recorder, 2 – GP-2 head, 3 – cable connecting the head with the recorder, 4 – tested rope

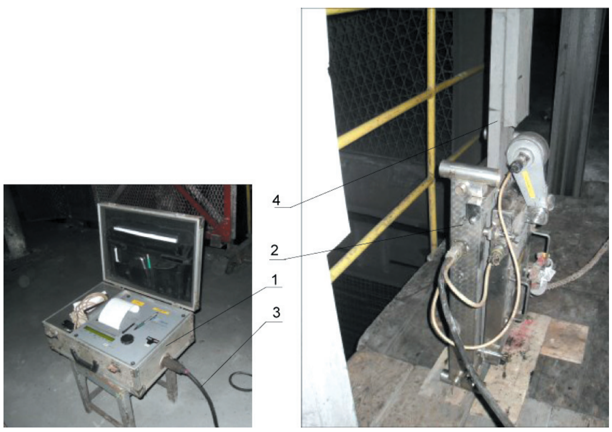

Fig. 8. Set of apparatus for testing steel-rubber ropes
1 – MD-120 recorder, 2 – SAG / LRM head, 3 – cable connecting the head with the recorder, 4 – tested rope

3. ANALYSIS OF ROPE WORK IN A SELECTED SHAFT

Chase characteristics:

- shaft type: exhaust, one-compartment,
- purpose of the shaft: people driving, stone mining,
- extraction levels: framework, level 840 m, level 1000 m,
- shaft diameter: 7.5 m,
- dhaft depth: 1050 m,
- tower height: 27 m (single-shot turret),
- spine depth: 28 m,
- vessel routing: rigid, double-sided, frontal.

Characteristics of the hoist device:

- Dishes: two years old.
- Useful capacity:
  - people rides: 4.5 Mg,
  - driving with material: 12.0 Mg,
  - stone mining: 7.5 + 2.6 Mg.
- Diameter of rope pulleys: 5000 mm.
- Type of drive wheel lining: ModarR3.
- Driving speed:
  - human travel: 10 m/s,
  - material ride: 10 m/s,
  - stone extraction: 10 m/s.
- Driving distance: 992.8 m.

Extractor machine:

- Location: felling.
- Type: 2L-5000/2000.
- Year built: 1990.
- Manufacturer: ZUT ZGODA-DOLMEL.
- Motor urine: 2300 Tw.

Carrying ropes [1]:

- Number of supporting bales: 2 pieces.
- Marking: 48.0-6×36 WS+FE–S/z-n-1-g 1570.
- Construction: 6 (14 × 2.72 + 7 × 1.7 / 7 × 2.15 + 7 × 2.24 + 1 × 3.00) + FE.
- Ropes work intensity: 180 hauls/day.
- The ropes worked in wet conditions.

Rope wear analysis [1, 10].

The supporting ropes in this shaft hoist operated from 27 to 32 months. In all cases, the reason for replacing the ropes was a deterioration of the safety factor due to corrosion. In such cases, magnetic tests are the dominant diagnostic method.

As a result of the survey carried out on May 21, 2015, charts from the defectograph were obtained, which are shown in Figure 9. It was a reason for the decision to replace the ropes. Oxidation of the zinc coating and corrosion raid turning into point pitting corrosion on the entire length of the ropes were found. Moreover, clashes and single factory wire breaks were observed.

The diagnostic methods based on which the decision to replace the ropes was made are:

a) A – visual method, corrosion tarnish and pitting corrosion along the entire length.
b) B! – magnetic method, corrosion raid and progressive pitting corrosion, abrasions and factory shortages of wires.

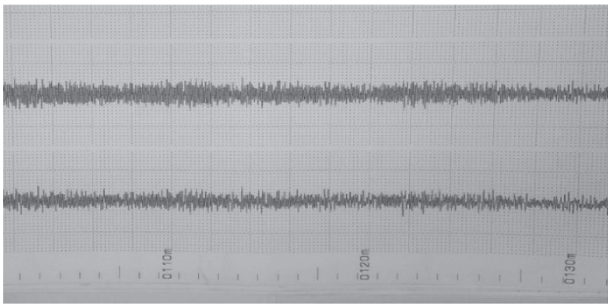

Fig. 9. Fragment of a defectograph from the last test of the rope put aside on February 21, 2015

Table 1

List of lifting ropes in the analyzed shaft [1]

Set number	Creationdate	Exchange date	Producer/Wearsymptoms	Workingtime [months]	Diagnostic method: A – visual method, B! – magnetic method
1	28.07.2002	23.04.2005	Polskie Liny Sp. z o.o. w Katowicach/Corrosion	32	B! A
2	24.04.2005	26.10.2007	Polskie Liny Sp. z o.o. w Katowicach/Corrosion	30	B! A
3	27.10.2007	16.05.2010	ŽDB a.s. Bohumin – Czech Republic/Corrosion	31	B! A
4	17.05.2010	8.12.2012	ŽDB a.s. Bohumin – Czech Republic/Corrosion	31	B! A
5	9.12.2012	14.03.2015	ŽDB a.s. Bohumin – Czech Republi/Corrosion	27	B! A
6	15.03.2015	15.11.2017	ŽDB a.s. Bohumin – Czech Republic/Corrosion	32	B! A

4. ASSESSMENT CRITERIA OF LOADING ROPES

The considered criterion for assessing the durability of ropes is the rope service life index "T", expressed in [MNm/kg]. Ropes of similar construction, but operating in different conditions, have a different service life. This coefficient is used to compare their "workload". For hoisting devices, it is given by Meebold's formula [2, 9]:

$$T = \frac{N \cdot Q}{100 \cdot q_i \cdot i_n} \tag{4}$$

where:
- N – number of work cycles of the extract,
- q_i – mass of one running meter of the lifting rope [kg/m],
- i_n – number of lifting ropes,
- Q – maximum allowable rope load [MN].

The maximum load on the rope comes from: the weight of the vessel with its suspension on the lifting rope or ropes, the guides, the suspension of the rope or balance ropes, the maximum weight of the transported load, the weight of the rope overhang or the lifting and balance ropes.

5. CALCULATION OF THE WORKING TIME INDEX OF ROPES WORKING IN A SELECTED SHAFT

Table 2 presents the number of cycles and the value of the work index for successive sets of ropes working in shaft VI. The following data was adopted for the calculations:
- maximum static load on the lifting rope: Q = 429 kN,
- weight of one meter of the lifting rope: q_i = 8.7 kg/m.

6. EXTENSION OF SERVICE ROPES

In order to observe the elongation of the lifting ropes during operation, their elongation as a function of the number of cycles worked is examined. The relative elongation of the rope is expressed by the relationship (Tab. 2) whereas Figure 10 shows the indicators of working time T for individual sets of ropes in the VI shaft [4]:

$$\varepsilon = \frac{\Delta L}{l} \cdot 100\% \tag{5}$$

where:
- ε – rope relative elongation [%],
- ΔL – absolute rope elongation [m],
- l – length of the working rope [m].

Table 2

The number of cycles and the value of the working time index for successive sets of ropes in operation in the western section of the selected mining shaft [1]

Number of the next set of ropes	Number of lift cycles	Rope operating time indicator T [MNm/kg]
1	123 573	3 046.7
2	100 853	2 486.5
3	88 621	2 185.0
4	94 156	2 321.4
5	95 019	2 342.7

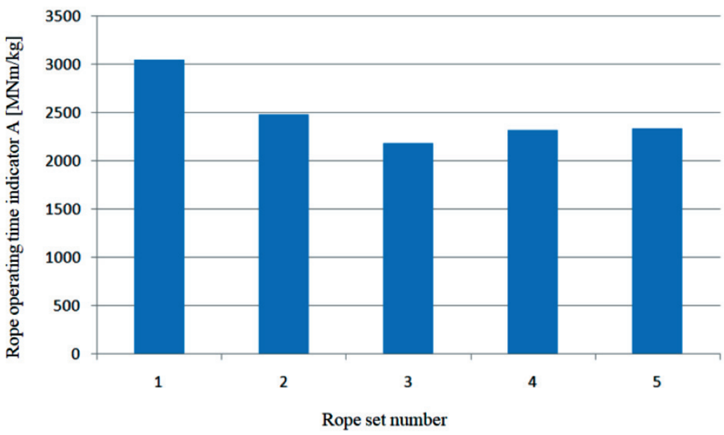

Fig. 10. Indicators of working time T for individual sets of ropes, shafts VI

6.1. Service life of ropes operating in the analyzed hoist of the selected shaft

6.1.1. A set of ropes operating in the period from May 17, 2010 to December 8, 2012

Eastern rope ∅ 48.0 mm, marked 48.0-6×36 WS+FE–S/z-n-l-g 1570, during operation it was extended by a total of 3.95 m. The course of rope operation as a function of the number of hoisting cycles and time index the work is summarized in Table 3.

Western rope ∅ 48.0 mm, marked 48.0-6×36 WS+FE–Z/s-n-l-g 1570, during operation it was extended by a total of 3.95 m. The course of rope operation as a function of the number of hoisting cycles and time index the work is summarized in Table 4.

Table 3

The course of rope operation as a function of the number of hoisting cycles, eastern rope, set 4 [1]

Rope working time [months]	Number of lift cycles	Indicator T [MNm/kg]	Length of the cut rope ΔL [m]	ε [%]
1	2 851	70	2.05	0.18
6	16 995	419	3.45	0.31
12	34 587	852	3.65	0.32
18	50 756	1 251	3.85	0.34
24	68 845	1 897	3.95	0.35
30	83 965	2 070	3.95	0.35

Table 4

Course of rope operation as a function of the number of rope hoists' cycles, west rope, set 4 [1]

Rope working time [months]	Number of lift cycles	Indicator T [MNm/kg]	Length of the cut rope ΔL [m]	ε [%]
1	2 851	70	2.05	0.18
6	16 995	419	3.25	0.29
12	34 587	852	3.55	0.31
18	50 756	1 251	3.85	0.34
24	68 845	1 897	3.85	0.34
30	83 965	2 070	3.95	0.35

6.1.2. A set of ropes for operation in the period from 12/09/2012 to 03/14/2014 (set 5)

East rope ∅ 48.0 mm, marked 48.0-6×36 WS+FE –S/z-n-l-g 1570, during operation it was elongated by a total of 4.1 m. The course of operation of the eastern and western ropes as a function of the number of extract cycles and the working time index are summarized in Table 6.

Figures 11–14 show the characteristics of the dependence of the rope elongation ε as a function of the number of hoisting cycles worked.

Table 5

The course of rope operation as a function of the number of hoisting cycles, eastern rope, set 5 [1]

Rope working time [months]	Number of lift cycles	Indicator T [MNm/kg]	Length of the cut rope ΔL [m]	ε [%]
1	3 658	90	2.0	0.18
8	30 102	742	3.5	0.31
12	46 011	1 135	3.8	0.34
18	66 780	1 648	3.8	0.34
27	92 582	2 285	4.0	0.35

Table 6

The course of rope operation as a function of the number of rope hoists cycles, west rope, set 5 [1]

Rope working time [months]	Number of lift cycles	Indicator T [MNm/kg]	Length of the cut rope ΔL [m]	ε [%]
1	3 658	90	2.1	0.19
8	30 102	742	3.6	0.32
12	46 011	1 135	3.9	0.35
18	66 780	1 648	3.9	0.35
27	92 582	2 285	4.1	0.36

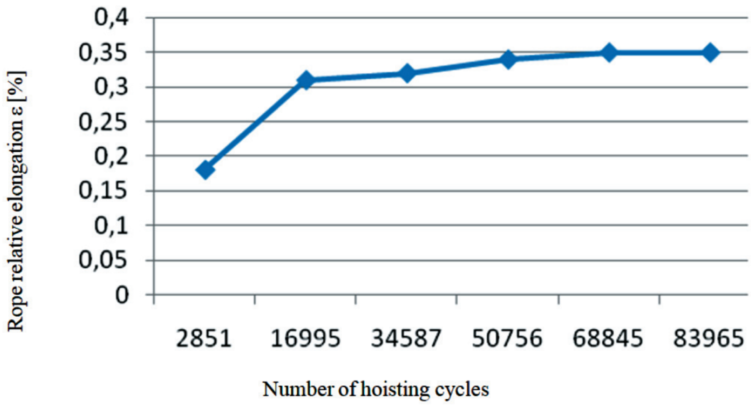

Fig. 11. Graph of the relative elongation of the rope ε as a function of the number of hoisting cycles, eastern rope set 4

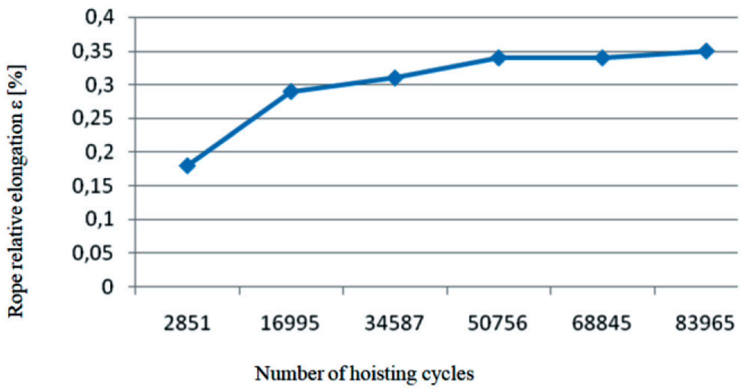

Fig. 12. Graph of the relative elongation of the rope ε as a function of the number of hoisting cycles, west rope set 4

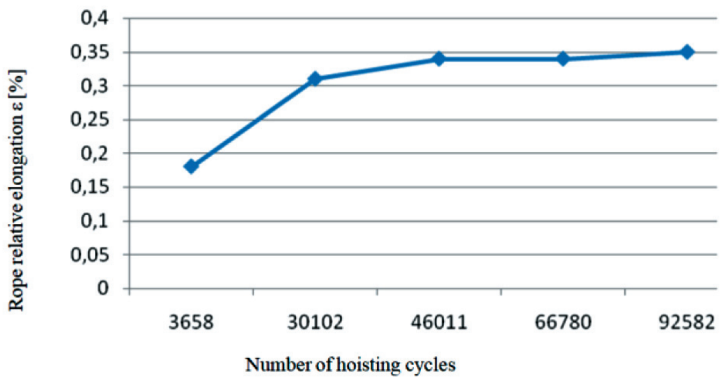

Fig. 13. Graph of the relative elongation of the rope ε as a function of the number of hoisting cycles, eastern rope set 5

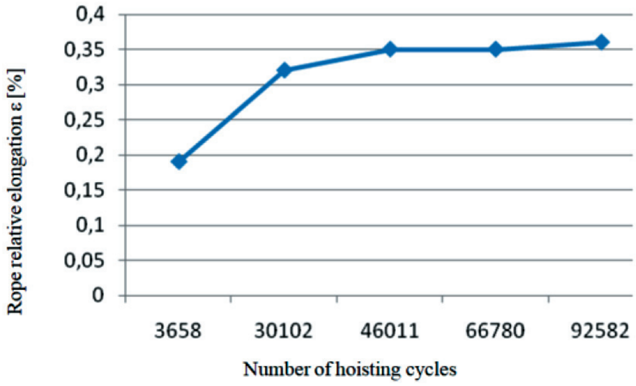

Fig. 14. Diagram of the relative elongation of the rope ε as a function of the number of hoisting cycles, west rope set 5

7. SUMMARY

Based on the analysis carried out in this article, the following conclusions can be drawn [5, 7, 10]:

- The load-bearing ropes used in one of the analyzed mines in shaft hoists mainly wear due to corrosion. In order to extend their service life, the frequency of the relubrication of the ropes should be increased.
- Bearing ropes working in hoisting devices with the machine located on the framework not only wear as a result of corrosion, but also as a result of the abrasions of the outer layer wires. This is due to the design of the hoisting device where the rope runs over the steering wheel at an angle.
- In each of the analyzed shaft hoists, the ropes were the most elongated in the first 6 months of operation. This elongationis between 62% and 90% of the total elongation.
- Ropes of the same construction, working in the same shaft hoist, but with a higher work index, are subject to greater elongation.
- Following further research, the results of which were not presented in this article, it was also found that steel-rubber compensating ropes operating in shaft hoists in one of the mines under consideration wear mainly as a result of corrosion. It especially occurs as a result of damage to the rubber coating. In order to extend their service life, the period between the detection of damage to the rubber coating and the vulcanization should be shortened.

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