Assessment of durability of load-carrying and leveling ropes in selected shafts of underground mines

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Abstract: The article presents the problem of durability of load-bearing and compensating ropes operated in selected shafts of underground mines. The basic causes of wear of hoisting ropes are described, methods for assessing the wear of wire ropes are given, and criteria for assessing the durability of hoisting ropes are presented. The authors also presented selected results from elongations of lift ropes. The article ends with conclusions resulting from the conducted research.

1. Introduction
Mining hoists are the most important link and are the basic means of transport in the Polish hard coal mining industry. With the help of the hoisting device, the transported extracted material from the underground mines is transported. Lifting equipment also performs a number of other functions, such as the departure and departure of the crew and the abandonment of various materials necessary for the exploitation of the deposit, as well as maintenance of mine infrastructure [4].

The decreasing number of coal deposits lying in favorable mining and geological conditions as well as the continuously increasing depth of exploitation affect the increase of mining costs. If we add to this low coal prices in global markets, the actual picture of hard coal mining in Poland emerges. An opportunity to improve the profitability of exploitation, and thus to maintain the profitability of Polish mines, is an increase in the concentration of extraction. This situation contributes to the need to use increasingly efficient hoisting equipment. This can be achieved by using extraction vessels of increasing capacity as well as speed of movement in the shafts. This entails an increase in the parameters of rope work, which has the effect of reducing their durability [2, 4].

Ropes used in shaft hoists undergo various wear processes. They affect the change of their mechanical parameters as a result of which they lose their operational properties. The ropes are nonlinear in the time function of wear processes. The effects of unpredictable wear are attempted to be counteracted by carrying out regular tests and inspections by various methods, from visual to non-destructive ending [4, 8].

To better understand the wear processes of ropes, it may be useful to conduct an analysis of their durability. Ropes working in shaft hoists (as well as materials) of the selected underground mine were
subjected to this analysis. The source of data were reports from tests periodically carried out by appraisers, books of periodic inspection of shaft hoists, book of shaft reports.

It should also be noted that due to the large number of test results, including tables and diagrams, the analysis of balance ropes was partially omitted in this article.

2. Causes of rope wear in mining shaft hoists

The main sources of wear of hoisting ropes include corrosion and fatigue cracking of wires. These reasons cause a reduction in the load-bearing cross-section, and hence the weakening of the rope. The phenomenon that intensifies these processes is the clash of external wires. The mechanism of this process is diverse and complex, as a result of which the intensity of this phenomenon varies depending on the type of shaft hoist [7, 8].

In the case of steel - rubber ropes, the main sources of wear include corrosion, which occurs as a result of damage to the rubber jacket. This damage is in most cases caused by falling objects falling into the shaft. Another reason for the damage of the balance ropes are rubbing the rope with elements of shaft reinforcement [8].

- Fatigue wear of steel wire ropes.

Figure 1 shows the case of loading steel wire ropes while working on the wheel drive and during multilayer rope winding on the drum.

Figure 1. Examples of load on wire ropes [8].

In the case of lifting ropes, the tensile forces are longitudinal forces that change with the lifting height or drawing depth. They appear during braking and start-up, and come from motion resistance, static loads and dynamic forces. In the case of lifting ropes of mining hoisting equipment, the phenomenon of turning the cross-section occurs. It is created as a result of the torque generated from the moment of unraveling in the strands of the rope. Many load phenomena come from bending ropes on propeller wheels. Increased bending stresses occur in the area of running up and running off of wheels and risers [6].

The impact on fatigue consumption for multi-layered winding of ropes on the drums has a high pressure load. During co-operation of ropes with running tracks of rope wheels, excessive pressure causes characteristic fatigue wear. In the first stage, plastic deformations of wires in the form of "lips" are observed. In the next stage, the wires start to crack avalanche. One wire can break in several places and its ends are not separated.

The complex state of stress is of key importance to the pace of fatigue consumption processes. The influence of stretching on rope fatigue consumption depends on the variability and average value of
loads, variability and number of cycles, degree of corrosion and rope construction. The influence of bending on fatigue wear depends on the size of longitudinal loads, length of bending, changes in the amplitude of loads, direction of bending and angle of wrap [6].

Wire breakage is a sign of fatigue wear of wire ropes. This phenomenon is possible for visual observation, however, to a limited extent (internal scrap wires).

- Corrosion of lifting ropes.
  The form of physical and chemical wear of the carbon steel from which the wires are made is called corrosion. It is the result of the formation of iron oxides, hydrated salt compounds, as well as salts of sulfuric acid. Atmosphere affects the growth of its dullness with a high content of NOX and SOX acid radicals, as well as environmental humidity. Corrosion can only occur in the presence of molecular oxygen. The hydration of iron oxides increases their volume as well as the reduction of bending and stretching strength. There are notches on the surface of the wires, surrounded by accumulation of stresses [8].

- Clashes of external wires.
  It was found that there are two factors as a result of the action that occurs for clashing of external wires [7]:
  - abrasive wear as a result of mutual movement and contact with the occurrence of friction, a pair of elements cooperating with each other,
  - fretting consumption.

  The abrasive wear may occur as a result of friction between the wheel and the rope when the rope is running up or running down from the thrust or from the rope pulley. There is then slippage of the rope surface relative to the wheel surface [7].
  Fretting is called a set of phenomena occurring on the contact surface. This is a multidimensional phenomenon, which is manifested by wear on short parts of the rope. Movements and deformations as well as high stresses are necessary. For fretting to occur, relative slides between interacting elements are necessary. It is often confused with corrosion. A typical sign of fretting is the appearance of short wire thinning [7, 8].

  Variable axial force and vibrations cause uneven pressure between the rope and the propeller. At the moment when individual shear forces exceed the friction forces, they slip (Figure 2). As a result of varying pressure between the rope and the groove, both abrasive and free-standing wear may occur [7].

\[ P \]
\[ \text{Figure 2. Mechanism of freckle damage [7].} \]

In the case of shaft hoists with a machine placed on the tower, the rope has contact with only one wheel. As a result, there is no problem with wire clashes. The linings on the wheels have carefully selected material constants, which practically minimizes the clash of wires.
In the case of shaft hoists with the machine located on the framework, clashes occur mainly on the wheels. These wheels are usually without linings. However, the size of the clashes is small and it is not the dominant type of wear.

Shaft lifts with drum machines are characterized by high abrasion of external wires. At the moment of winding the ropes on the drum there is friction between the strands (Figure 3). In the case of multilayer winding on the drum, there is a strong abrasion when the layer is changed by the rope. Abrasion of the rope strands in the groove of the rim causes a rope angle of the rope and the width of the drum [7, 8].

![Figure 3](image_url)

**Figure 3.** Causes and places of abrasion of steel ropes, where [7]: a) drive wheel, b) drum and rope wheel: 1 - supporting rope, 2 - drive wheel, 3 - drum, D [mm] - diameter of the drive, d [mm] - rope diameter, S1 and S2 [N] - tension in rope branches, T [N] - friction forces, D11 and D12, [mm] - elongation of rope branch, E1 - modulus elasticity, \( \alpha \) [rad] - angle of wrap on the wheel, m - coefficient of friction, \( \varphi \) [degrees] - angle of the rope on the steering wheels, \( \omega \) [1 / min] - speed of the wheel.

As a result of abrasive wear, mass losses occur. For drum hoisting equipment there is an asymmetric abrasion of ropes, as shown in Figure 4. A similar phenomenon applies to non-rotating ropes in frictional hoist extracts. Abrasive wear of ship ropes operated in extracts with friction couplings (log and tower) occurs symmetrically.

![Figure 4](image_url)

**Figure 4.** Examples of ropes worn as a result of clashes of outer wires [7]: a) surface of the triangle-nasovian rope with worn outer wires, b) surface of the rope with strands of strands

- Wear due to the action of the torque.

As a result of the occurrence of the unscrewing moment, the ropes wear, which may result in twisting of a part of the cross-section or the whole rope. These phenomena do not occur very often, but almost always have a catastrophic character. They take place in the inner part of the rope, which makes visual observation impossible. They are very dangerous, and the only chance to detect them are periodically repeated magnetic tests [8].
3. Methods for assessing the condition of steel wire wear
In order to evaluate the condition of the rope in operation, several methods are used. Two groups can be distinguished among them [8]:

a) not apparatus - they rely on observing wear processes or on measurements of geometrical features of ropes whose condition changes along with a change in the condition of the rope,
b) apparatus - they rely on the use of specialized equipment. Magnetic tests are the most commonly used.

- Visual method.
  This method is based on visual observation of the condition, the available part of the rope. This is the most common diagnostic method for assessing the condition of ropes. It requires a lot of experience of the person conducting the observation. Due to the lack of unambiguous criteria, this method is not very objective. By performing a cyclic counting of fatigue scrap wires, this method can be used to characterize fatigue wear of ropes [8].
  Visual observations allow to reveal damage, such as [3]:
  - rupture of strands,
  - corrosion,
  - wire breaks,
  - cold rope diameter,
  - deformation,
  - waviness,
  - rope attachment points.

- Instrumental methods - magnetic testing.
  Magnetic testing is the most common, apparatus-based method for testing hoisting ropes. The first country that introduced in its mines the legal obligation to test the magnetic lifting ropes of lifting devices was Poland. Today’s regulations require magnetic testing of both balance ropes and guide [1, 4, 5].
  During the test the rope is magnetized with a permanent magnetic field. The magnetic flux flowing through the rope is generated by permanent magnets. On the fragment of the rope, which undergoes magnetization, an inductive sensor (measuring coil) is located between the pole pieces. The instantaneous value of the magnetic flux associated with the measuring coil changes when the line section on which the damage is located is moved. As a result of this phenomenon, an electromotive force is induced, the value of which is directly proportional to the change of the ferromagnetic cross-section of the tested rope. The influence of this force is also influenced by many factors depending on the measuring head and rope damage parameters. Part of the magnetic flux induced by permanent magnets flows through the space surrounding the rope. This part of the stream is called the stream of distraction. The lines of the scattering flux are parallel to one another, provided that there is no change in the ferromagnetic cross-section of the tested rope on the magnetized section (Figure 5) [6].

![Figure 5](image_url)

**Figure 5.** Distribution of the magnetic field lines in the undamaged line, where [3]:
1 - rope, 2 - permanent magnets, 3 - polepieces, 4 - jumper, 5 - stream of dispersion.
If there is a step change in the rope cross-section (corrosion pits, cracks, etc.) or there is a change in the uniform structure of the rope, the force lines of the magnetic field will be deformed. The value of the magnetizing flux does not change.

For magnetic testing of hoisting ropes, the same method is used - magnetizing the rope with permanent magnets. However, different manufacturers use different types of sensors. Depending on the number and type of detector elements, the design of magnetic concentrators, magnetization susceptibility, sensor operation principles, they provide different signals. Inductive sensors and hallotrons are the most commonly used detection elements. The basic task of the inductive sensor is detection and measurement of step defects. If it is used, the damage should move relative to the sensor. Hall-effect sensors are also used, which give the possibility of measuring the so-called continuous damage such as wire clashes and corrosion. They are also used to increase detection of damages such as corrosion pits, wire breaks [6].

They can be used as external or internal sensors. Data on the components derived from the radial magnetic field force lines are collected by an external sensor. It should be located at a suitable distance from the tested rope immediately next to the armature. Using information from external and internal sensors, it is possible to obtain data on the depth of occurrence of the defect in the tested line. If the defect is deep in the line, the values from both sensors have a similar value. In case when the value of the signal from the external sensor is lower than the value of the signal coming from the internal sensor, the defect is located on the outer layer of the rope. These solutions are considered to be the best for detecting a significant part of typical rope damage [6].

Apparatus for performing magnetic defectoscopy consists of two elements: a measuring head and an output signal recorder. The result of the test is a defectogram on which the test results are registered. The apparatus is equipped with an additional system whose task is to balance the speed changes. The stroke of the tape on which the results are recorded is adapted to the speed of movement of the rope. 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, according to standards, every 3 years.

4. Criteria for assessing durability of load-bearing ropes

The selected criterion for assessing rope durability is the rope time indicator "A" expressed in [MNm/kg]. Ropes with a similar structure, but working in different conditions have a different lifespan. This coefficient is used to compare their "work intensity". For exhaust devices, it is referred to as a formula R. Meebold [1]:

\[
A = \frac{N \times Q}{100 \times q_i \times i_n} \quad [\text{MNm/kg}]
\]

where:
\(N\) – number of work cycles of the statement,
\(q_i\) – the weight of the meter of the current carrying rope [kg/m],
\(i_n\) – the number of carrying ropes,
\(Q\) – maximum permissible load [MN].

The maximum permissible loads come from: the weight of the load rope section from the axis of the rope wheels to the suspension in the upper position of the vessel, the weight of the suspension of the lifting rope, the weight of the suspension rope suspension, the weight of the rolling guides, the weight of the skip or cage, the useful weight of the spoil, the own weight of the trolleys cage), the weight of the balance rope section, measured from the discharge level at the shaft head to the point where the rope returns in the sump [1].
Sample calculation of the working time indicator for cables operating in the selected mine shaft - eastern range (Figure 6).

Table 1 presents the number of cycles and the value of the work indicator for subsequent sets of ropes working in the eastern range of the selected mine shaft. The following data was used for the calculations [6]:
- maximum static load on the carrier rope: \( Q = 501 \text{ [kN]} \).
- the weight of the meter of the current carrying rope: \( q_i = 6.9 \text{ [kg/m]} \).

| The number of the next set of ropes | Number of lifts cycles | Rope time indicator „A” [MNm/kg] |
|------------------------------------|------------------------|----------------------------------|
| 1                                  | 90848                  | 1649                             |
| 2                                  | 92595                  | 1680                             |
| 3                                  | 76159                  | 1382                             |
| 4                                  | 96820                  | 1757                             |

Figure 6. Indicators of working time A for individual sets of ropes, selected production shaft - eastern compartment [6].

Calculation of the working time indicator for ropes working in the selected mine shaft - west compartment (Figure 7).

Table 2 presents the number of cycles and the value of the work index for subsequent sets of ropes operating in the western range of the selected mine shaft. The following data was used for the calculations [6]:
- maximum static load on the carrier rope: \( Q = 564 \text{ [kN]} \).
- the weight of the meter of the current carrying rope: \( q_i = 6.9 \text{ [kg/m]} \).
Table 2. Number of cycles and the value of the working time indicator for subsequent sets of ropes working in the western range of the selected mine shaft [6].

| The number of the next set of ropes | Number of lifts cycles | Rope time indicator „A” [MNm/kg] |
|------------------------------------|------------------------|----------------------------------|
| 1                                  | 105483                 | 2155                             |
| 2                                  | 95896                  | 1959                             |
| 4                                  | 101819                 | 2080                             |
| 5                                  | 91386                  | 1867                             |
| 6                                  | 165864                 | 3389                             |

Figure 7. Indicators of working time A for individual sets of ropes, selected mine shaft – compartment western [6].

5. Service life extension of lifting ropes

In order to observe the extension of load-bearing ropes during operation, their elongation is tested as a function of the number of cycles worked. The relative elongation of the rope is expressed by the dependence [8]:

\[
\varepsilon = \frac{\Delta L}{l} \times 100\%
\]  

where:
\( \varepsilon \) – the relative elongation of the rope [%],
\( \Delta L \) – elongation of the rope [m],
\( l \) – the length of the working rope [m].

The tables below present examples of elongations of selected sets of supporting ropes installed in the eastern and western ranges of the analyzed mine shaft.
Extending the service life of ropes operating in the shaft hoist of the selected mine shaft - eastern compartment (set 3).

Rope number 1 Ø42,0 mm, marked 6x36 WS + FE -Z / z and S / z-n-l-g-1570 during operation was shortened by 3,1 m in total. The rope work as a function of the number of extraction cycles and the working time indicator is presented in Table 3.

**Table 3.** The course of rope work as a function of the number of lifts cycles, rope 1 set 3 [6].

| Rope work time [months] | Number of lifts cycles | Indicator "A" [MNm/kg] | The length of the cut rope ΔL [m] | ε [%] |
|------------------------|------------------------|------------------------|----------------------------------|-------|
| 2                      | 5241                   | 95                     | 1,6                              | 0,18  |
| 6                      | 16587                  | 301                    | 1,9                              | 0,21  |
| 12                     | 30661                  | 556                    | 2,5                              | 0,28  |
| 18                     | 47230                  | 857                    | 2,75                             | 0,30  |
| 24                     | 62330                  | 1132                   | 2,95                             | 0,32  |
| 27                     | 70457                  | 1271                   | 3,1                              | 0,34  |

Extending the service life of ropes operating in the shaft shaft of the shaft III west compartment.

Rope number 1 Ø42,0 mm, designated WS6x36 Ap- S / z and Z / s-n-l-g during operation was shortened by a total of 3,3 m. The rope operation as a function of the number of extraction cycles and the operating time indicator is shown in Table 4.

**Table 4.** The course of rope work as a function of the number of lifts cycles, rope 1 set 4 [6]

| Rope work time [months] | Number of lifts cycles | Indicator "A" [MNm/kg] | The length of the cut rope ΔL [m] | ε [%] |
|------------------------|------------------------|------------------------|----------------------------------|-------|
| 1                      | 3902                   | 80                     | 1,8                              | 0,16  |
| 6                      | 23718                  | 484                    | 3,00                             | 0,27  |
| 12                     | 47440                  | 966                    | 3,05                             | 0,27  |
| 18                     | 67654                  | 1378                   | 3,2                              | 0,29  |
| 26                     | 94547                  | 1926                   | 3,3                              | 0,30  |

Figures 8 and 9 show the characteristics of the relative elongation coefficient ε as a function of the number of lifts.
• Shaft III - eastern compartment.

![Graph](image1.png)

**Figure 8.** Graph of elongation of the rope $\varepsilon$ as a function of the number of exhaust cycles, rope 1 set 3 [6].

• Shaft III - west compartment.

![Graph](image2.png)

**Figure 9.** Graph of elongation of the rope $\varepsilon$ as a function of the number of exhaust cycles, rope 1 set 3 [6].

6. Conclusions
On the basis of the assessment, the following conclusions can be drawn [6]:

- Support ropes operated in shaft hoists of the analyzed underground mine, they wear mainly due to corrosion. To extend their service life, increase the frequency of relubrication of the ropes.
- Support ropes working in hoisting equipment with the machine located on the frame wear not only as a result of corrosion, but also as a result of wire strokes of the outer layer. This is due to the design of the hoisting device in which the rope runs on the steering wheel at a certain angle.
- Steel-rubber equalizing ropes working in shaft extracts of the analyzed underground mine wear out mainly as a result of corrosion. It comes to it especially 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.
- Ropes of the same construction, working in the same shaft lift, but greater labor rates are subject to greater elongation.
- In each of the shaft hoists analyzed, the ropes were extended the most in the first 6 months of operation. The elongation is from 62% to 90% of the total elongation.
- Ropes of the same structure, working longer in the same shaft hoist, are more elongated. After working the same number of cycles, the relative elongation is similar.
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