EVALUATION OF THE MECHANICAL PROPERTIES OF STEEL WIRE ROPE DURING ITS OPERATION IN THE MINING INDUSTRY

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ABSTRACT

The control of the technical condition of the lifting steel ropes is important for the safe operation and for the correct functioning of the machines in which they work.

Most often, the stresses in the ropes depend on the tension force, the construction and diameter of the rope, the number of wires in the rope, etc. All these factors are important in the control and monitoring of a given lifting rope during operation, to adequately and timely assess the quality of the rope, its remaining operational resource, and from there to assess its working capacity.

The research is aimed at evaluating the performance and reliability of a real working wire steel rope intended for the mining industry. The behaviour of a real working rope was followed for different periods of time until it was retired, and results were obtained for its real operational properties, in comparison with those before use.

The breaking force and tensile strength of the rope wires, as well as their plasticity, flexibility and resistance to bending throughout the period of in-service monitoring, were determined.

Keywords: steel wire rope, mechanical properties, wire tensile testing, wire bending test, safety factor of ropes, service life.

INTRODUCTION

The development of modern industry is characterized not only by an increase in the volume and assortment of production, but also by an improvement in its quality indicators. High quality requirements are placed on metal products, which is a prerequisite for increasing their service life, the reliability of structures, machines and mechanisms. A thorough and comprehensive study of the properties and the behavior of metals under various operating conditions, as well as establishing their compliance with certain standard requirements, is imperative [1 - 3].

Steel ropes are widely used in several industries such as: mining, metallurgy, construction, transport, etc. Today, they are basic structural elements of many machines and facilities, offering a universal and economical solution to almost all problems related to the transmission of mechanical energy through traction. They are used to drive cranes and elevators, build overhead lines, bridges, highways and other metal structures.

Steel wire ropes are an important element of lifting and transporting machines. The control of their technical condition is important in terms of their safe operation and the correct functioning of the machines in which they work [4 - 7]. The standards for the quality and performance of steel ropes are regulated in a number of national and international regulations and standards. They specify the technical requirements for the ropes and the methods for testing and controlling their quality [8 - 14].

The aim of the present work is to investigate and evaluate the mechanical characteristics of a hoisting steel wire rope intended for the mining industry, evaluating its residual resource, serviceability and reliability during operation.

Steel wire ropes during the period of use are subjected to the combined effect of many factors, such as cyclic and variable loads, significant frictional forces endure shocks and vibrations, often work at high speeds, etc. The service life of steel ropes depends on the correct choice of rope for a specific application, on the correct installation, operation and maintenance. Failure to meet any of the listed requirements will inevitably lead to reduced service life or emergency failure.

The most common reasons for the retirement of the hoisting steel wire ropes are analysed in [15]: - wear in the places of contact between the ropes and the lifting drums and the roller;

- lack of lubrication for extended periods; - prolonged exposure to heat and moisture;

- the fatigue of the material as a result of the constantly repeated bending of the rope;

- the overloading of ropes caused by excessive tension or excessive impact load;

- mechanical damage to the rope because of crushing, dragging or shearing, bends, due to improper installation, etc.

The control of the technical condition of the lifting ropes is of considerable importance for their safe and reliable operation. It is carried out by visual observation of the ropes and by destructive and non-destructive methods for their testing.

Visual control is easy and gives quick and direct results. However, it is not enough. It does not provide a quantitative assessment of the degree of wear damage to the individual wires of the rope. Furthermore, the total number of broken wires, both on the surface and inside the rope, cannot be determined by visual observation. Through visual control, the integrity of the wires making up the outer layer of the rope can be assessed, such as: - the presence of broken outer wires is detected, as a result of repeated bending of the rope (fatigue) or uneven contact with the rollers and drums (abrasion); - traces of significant wear can be found on the periphery of the rope; - traces of corrosion can be detected, which is one of the most dangerous and difficult to identify problems.

During the visual control, a change in the diameter of the rope can be detected by measuring it and comparing the obtained result with data from the manufacturer or with the results of an initial measurement carried out before the use of the rope. The steel rope must be replaced with another one if the reduction in its diameter is greater than the permissible reduction defined in the standard BDS ISO 4309 and regulations for load-lifting ropes [14].

The destructive control of the ropes is carried out in laboratory conditions. In most cases, a section of the rope is used in the tests. The main destructive methods for testing ropes are described in standards [13, 19 - 23]. An analysis of the results of mechanical tests of steel ropes has been made in [16 - 18].

The standard BDS EN 10218-1 presents the general test methods for steel wire and wire products. It includes tests for tension, twisting, bending, coiling, pressure, corrosion, hardness testing, hardenability, fatigue, wire shape determination, artificial aging, non-destructive testing and more [13].

In destructive testing, most often a piece of the rope is used, which is subjected to various test methods. Tensile testing is the most used method, as it provides complete information on the mechanical properties of the material. A tensile test determines the strength and plastic characteristics of the rope but does not give an idea of its quality as a whole. In this case, the use of non-destructive testing methods, is particularly appropriate. Through them, information can be obtained about the condition of the rope along its entire length, without having to dismantle it. The combination of destructive and non-destructive methods gives complete and clear information about the properties and possible damage of the steel ropes during the period of operation.

Non-destructive material testing methods are based on physical phenomena and effects and are used to control the quality of equipment, machinery, etc. Through them, imperfections and defects obtained during production or operation are detected and sized, which is used in evaluating the resources of the facilities. The criteria for evaluating the technical condition of the rope in non-destructive methods are: the loss of metal from the total cross-section of the wires and the presence of local defects, such as broken or deformed wires [24]. Zhou describes the most widely used methods for non-destructive testing of steel ropes and proves that non-destructive testing is particularly important in the evaluation of steel ropes during their operation, ensuring their reliability and safety [25].

EXPERIMENTAL

Object of the study

Steel wire ropes are an important load-bearing component in hoisting machinery. The manufactured steel ropes, depending on their purpose, must meet certain requirements described in detail in the ten parts of the European standard BDS EN 12385 [8 - 12]. The standards specify the materials, the requirements for the production and testing of ropes, as well as the minimum values of the breaking force, the dimensions and strength of the ropes, etc. For example, for general lifting applications, ropes are manufactured in accordance with the European standard BDS EN 12385-4 [10]. Establishing compliance with the standard requirements of a rope is proof that a certain level of rope quality, safety and reliability has been reached.

Steel wire rope has a unique design - it consists of several steel wires that form separate bundles twisted in a spiral around the core, Fig.1. The main requirement of the steel rope is to achieve the maximum load capacity with a relatively small diameter, to be sufficiently flexible, durable and to have a small mass per unit length [26]. To achieve these rope requirements for a particular application, the construction of the rope is essential. The different materials from which the rope is made, and the different constructions of wires and bundles will provide different properties (strength, flexibility, resistance to bending, fatigue, etc.) of the rope for a particular application [27].

In the present study, the tests were carried out on a steel wire rope intended for use in a lifting machine for transporting people and goods. The rope is right crossed, with a diameter of 33 mm and has a 6x36 construction, schematically presented in Fig. 2, i.e. the rope is made of 6 bundles, each with 36 wires or a total of 216 wires. In each bundle there are wires with 3 different diameters, d. The construction of the bundle is 1 + 7 + (7 + 7) + 14, i.e. the bundle is made up of central wire bundle (1 wire with d = 1.8 mm), internal wires for the bundle (7 wires with d = 1.1 mm and (7 + 7) wires with d = 1.5 mm) and external wires for the bundle (14 wire with d = 1.8 mm). Depending on the diameter, d, the number of wires in the whole rope is: with d = 1.1 mm - 42 pcs., with d = 1.5 mm - 84 pcs., and with d = 1.8 mm - 90 pcs.

The rope was suspended in the lifting machine (cage-crossbeam) in September 2020. Upon delivery of the rope, tests were carried out establishing the initial (before use) mechanical characteristics of the rope. The length of the working part of the tested rope from the guide pulley with a diameter of 3000 mm to the lowest position of the cage and shaft is 400 m. The maximum static load of the rope, including the own weight of the rope, determined according to the Technical Safety Regulations is 84366 N [7].

EXPERIMENTAL

Steel ropes are an important element of hoisting machines. Unlike other machine parts that operate at unlimited fatigue strength, constant bending steel wire ropes always have a limited-service life [28]. Therefore, they must be regularly inspected and tested so that they can be replaced before damage or emergency failure

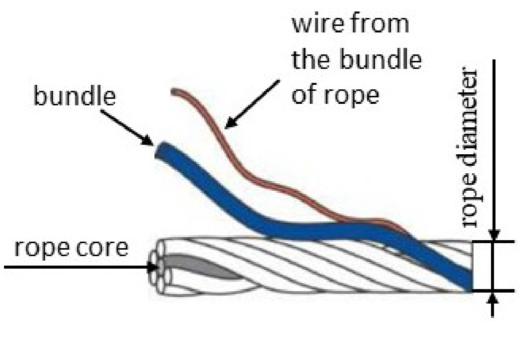

Fig. 1. Schematic representation of the design of steel wire rope [https://www.ariadna-bg.com/].

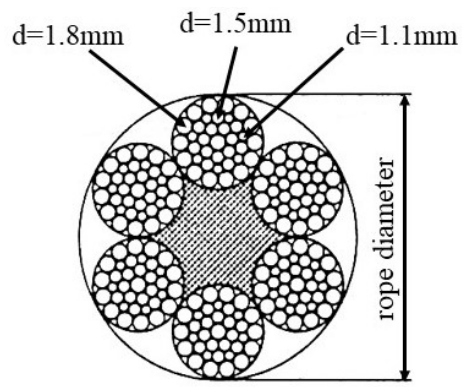

Fig. 2. Schematic representation of the structure of the investigated steel rope 6x36; d - diameter of the wires making up the rope bundle in mm.

occurs. The control of their technical condition is important in terms of their safe operation and the correct functioning of the machines in which they work. The standards for the quality and performance of steel ropes are regulated in a number of regulations and standards presented above. They also specify the methods for testing and quality control of the ropes.

The purpose of the present work is to determine the change in the mechanical properties of a steel rope during its operational period. To evaluate the serviceability and reliability, as well as the residual life of the rope when resuspended in the lifting cage, standard static tension and bending tests were carried out in the work. Initially, the mechanical properties of the rope before hanging it in the cage (new rope) were determined, and then their change during operation was followed.

Tensile tests to determine the breaking force of the wires and the tensile strength of the rope, as well as the bending tests of the wires (to establish their plasticity, flexibility and resistance to bending) were carried out every 6 months throughout its service life - from the moment of its suspension in the cage until its removal from use. In case of non-compliance with the load safety factor with the normative requirements, the rope is removed from use. The obtained results of the conducted research are presented in Table 1, 2 and 3.

Comparative analyses were made with the initial mechanical characteristics of the rope (before use), and the results of each subsequent control were compared with the results of the previous rope test.

RESULTS AND DISCUSSION

The steel ropes used in the mining industry must have good flexibility, resistance against unravelling and durability. In addition, ropes must be able to operate at high speeds, withstand shock, vibration and other cyclic and variable loads.

The construction of the steel rope investigated in the work is such that the wires during operation work with close bearing tolerances relative to each other. When the rope is bent around a roller, at the point of the bend, the wires slide relative to each other and are adjusted at the place of bending, absorbing the difference in length between the inner and outer parts of the rope, which occurs when bending around the roller [15]. The sharper the bend, the greater the movement of the wires, the greater the deformations of the wires.

The ropes are subjected to cyclic loading due to the large number of bends when passing through the guide and deflection pulleys and through the drums of the hoisting machines. As a result, a sudden damage to the rope is reached due to breakage of wires [29, 30]. The breaking of the steel wire ropes does not occur suddenly but is preceded by the breaking of the outermost wires, which is easily visible during visual inspection. In this case, the rope is immediately out of use, preventing accidents.

Analytical models have been developed over the years to predict the mechanical behaviour of steel ropes, based on knowledge of the material behaviour, geometry and construction of the ropes – reviewed in detail by Ghoreishi [31]. Modern research is aimed at modelling and simulating the relevant load conditions of the ropes and from there predicting their service life, using the capabilities of various computer technologies and software [26].

Most often, the stresses in the ropes depend on the tension force, the construction and diameter of the rope, the number of wires in the rope, etc. [24, 32]. All these factors are important when testing ropes and affect the properties of the rope and its residual life. Some of the above reasons for broken rope can be avoided with proper operation and maintenance of the rope, but others that are related to the physical nature of the metal and the processes of friction, wear and fatigue that occur during operation on the rope, cannot be avoided. Therefore, frequent inspections (control) of the ropes are mandatory. Through them, the quality of the rope is assessed, the current properties of the rope, its working capacity and its remaining operational resource are established, and this is a guarantee for its problem-free and accident-free operation. The control of steel ropes is expressed in initial (before operation) and subsequent periodic investigation of the change in the mechanical properties of the rope, as well as after the rope is out of use.

The present work is based on obtained real experimental data on the mechanical behavior of the investigated steel rope.

An indicator of the quality of the rope is the calculated load safety factor [4, 5, 23,]. When testing a new rope, before hanging it, as well as during repeated tests, the load safety factor is determined as the ratio between the total breaking force of the wires of the rope that have passed the tensile and bending tests and the maximum static load, including the self-weight of the rope. A rope in service shall be removed and replaced if, on retesting, its load safety factor is found to be less than 6, which is the value of the factor for ropes used in lifting people and loads [7].

Monitoring of the steel wire rope found that the actual service life of the wire rope was 42 months. In this operational period, every 6 months, control laboratory tests of the mechanical properties of rope samples were carried out and the current load safety factor of the rope was determined. The rope was hung in the lifting cage in September 2020. The first inspection to establish the quality of the rope during operation was carried out in March 2021, the second - in September 2021 and so on every six months. In March 2024 it was found that the calculated load safety factor is below the accepted minimum permissible value for ropes intended for suspension in machines for transporting people. As a result, the rope was removed from the lifting cage and scrapped according to the relevant order specified in Ordinance No. 31/27.12.1996 [6].

Visual inspection performed in the seven control tests showed no broken wires on the surface. Corrosion was found on the wires with a diameter of 1.8 mm, which are external to each bundle of the rope.

Mechanical tensile tests were performed according to BDS 16750-88 [4] and BDS EN ISO 6892-1 [19], and the obtained results were compared with the minimum values specified in BDS EN 12385-4+A1 [10]. It was established that the tested strength characteristics of the rope in the initial test and in the subsequent seven control tests correspond to the requirements of the standard. The tests were carried out at room temperature, with the length of the rope untwisted, the strands grouped by diameter and each strand tested. The results of the tensile tests of the wires of the tested rope before and during operation are presented in Table 1. There are no wires that failed the tensile test, according to technical requirements.

It was found that after each subsequent six-month service period, the total breaking force of the rope decreased, but remained within the allowable limits. It was found that the tensile strength of the 1.1 mm and 1.5 mm diameter wires remained relatively constant over the service period, compared to the decreasing tensile strength of the 1.8 diameter wires, Fig. 3. The wires with a diameter of d = 1.8 mm are located on the outer surface of the bundles of the rope. They are in direct contact with the rollers of the lifting machine and experience the greatest sign-changing deformations intensified by

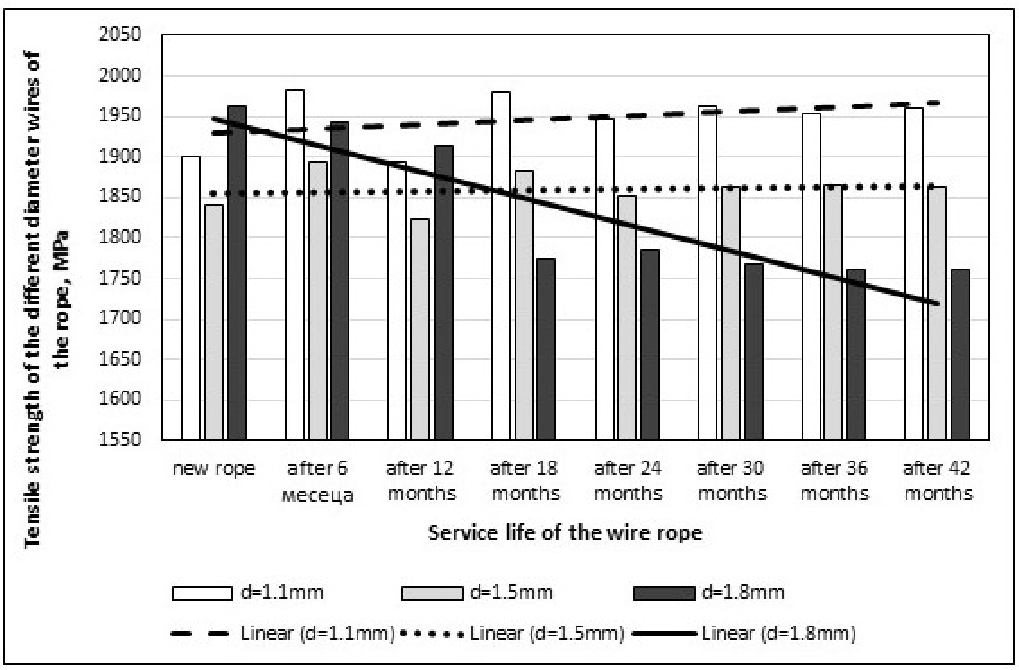

Fig. 3. Tensile strength of the wires of the rope depending on the service duration.

Table 1. Tensile tests results.

	d*, mm	Total number of wires in the rope	Breaking force of wires; min - max, kN	Total breaking force of all wires, kN	Cross-sectional area of all wires, mm^2	Tensile strength, MPa
New rope	1.1	42	1.74 - 1.86	75899	39.89	1900
	1.5	84	3.14 - 3.36	272914	148.36	1840
	1.8	90	4.69 - 5.11	449111	228.91	1962
after 6 months of use	1.1	42	1.81 - 1.98	79068	39.89	1982
	1.5	84	3.19 - 3.45	281566	148.36	1893
	1.8	90	3.79 - 5.16	445707	228.91	1942
after 12 months of use	1.1	42	1.70 - 1.93	79674	39.89	1893
	1.5	84	3.00 - 3.33	270932	148.36	1824
	1.8	90	4.65 - 4.95	438055	228.91	1913
after 18 months of use	1.1	42	1.79 - 1.98	79022	39.89	1981
	1.5	84	3.15 - 3.43	278810	148.36	1883
	1.8	90	4.58 - 5.14	406467	228.91	1775
after 24 months of use	1.1	42	1.76 - 1.97	77665	39.89	1946
	1.5	84	3.10 - 3.39	274895	148.36	1852
	1.8	90	4.54 - 5.16	408792	228.91	1785
after 30 months of use	1.1	42	1.80 - 1.94	78294	39.89	1962
	1.5	84	2.99 - 3.39	276387	148.36	1863
	1.8	90	4.49 - 5.11	404486	228.91	1767
after 36 months of use	1.1	42	1.77 - 1.96	77940	39.89	1954
	1.5	84	3.15 - 3.40	276720	148.36	1865
	1.8	90	4.52 - 5.15	403299	228.91	1762
after 42 months of use	1.1	42	1.78 - 1.95	78215	39.89	1961
	1.5	84	3.06 - 3.42	276250	148.36	1862
	1.8	90	4.52 - 5.03	403034	228.91	1761

** d - diameter of the wires in the rope bundle, mm*

friction and corrosion processes.

The bending tests of the new rope and of the rope samples during the subsequent seven controls were carried out according to the Bulgarian standard BDS 5021-83 [21]. The method consists of repetitively alternating bending between parallel cylindrical rollers of a specimen clamped at one end between the jaws of the testing apparatus, counting the number of bendings until fracture of the specimen. The test results of all wires of different diameters are presented in Table 2.

Table 2 also shows the minimum allowable number of bends to failure that a wire of the rope of a specific diameter must withstand in order to be considered to have passed the bend test, according to the technical requirements for steel ropes defined in the normative documents. It has been found that the resistance of the wires to bending decreases with the passage of time in service. More and more wires fail the bending test. The comparative analysis shows that after the first 6 months, failed bending tests were 1.8 % of all wires, after 12 months of use the percentage of wires that failed the bending test increased five times - 9.3 %, and at the end of the service period - the percentage is 30.6 %. It was found that the wires from the outer layer of the bundles that failed the bending test were the first to contact the rest of the lifting machine and were subjected to the

Table 2. Bending test results.

	d, mm	Total number of wires in the rope	Permissible number of wire bends until failure	Number of wire bends until fracture, min - max	Number of wires failed the bend test	Evaluation of the wires that failed the bending tests, %
New rope	1.1 1.5 1.8	42 84 90	20 10 12	25 – 33 13 - 17 12 - 17	0 0 0	0
after 6 months	1.1 1.5 1.8	42 84 90	20 10 12	24 - 38 12 - 19 8 - 17	0 0 0	1.8
after 12 months	1.1 1.5 1.8	42 84 90	20 10 12	25 - 34 14 - 18 4 - 15	0 0 20	9.3
after 18 months	1.1 1.5 1.8	42 84 90	20 10 12	17 - 31 13 - 19 6 - 16	1 0 20	9.7
after 24 months	1.1 1.5 1.8	42 84 90	20 10 12	20 - 36 12 - 17 7 - 16	0 0 15	6.9
after 30 months	1.1 1.5 1.8	42 84 90	20 10 12	21 - 32 12 - 23 5 - 19	0 0 22	10.2
after 36 months	1.1 1.5 1.8	42 84 90	20 10 12	19 - 30 13 - 18 9 - 16	1 0 29	13.9
after 42 months	1.1 1.5 1.8	42 84 90	20 10 12	12 - 28 12 - 18 5 - 14	9 0 57	30.6

greatest destructive effect of the applied cyclic loads. These wires are the first in the bundle to show reduced plasticity, because of the plastic deformation experienced during service. As the period of service increases, traces of wear and corrosion are also noticeable on the outermost wires in the bundle, which leads to an increase in the number of the wires that did not pass the test (Table 2).

An assessment of the quality, efficiency and safety of the rope used is the calculated load safety factor. Before operating the rope, the calculated load safety factor is 9.5. It is found that it also decreases over the period of use, Table 3. The load safety factor decreases from 9.5 to 8.2 after the first year of operation, maintaining this value during the following 12 months. After the second year of operation, the rope load safety factor decreases, reaching a value of approximately 7 during the next 12 months. During the rope monitoring and regular mechanical tests that were carried out, it was found that after 42 months of operation on the rope in the lifting cage, the results of the control tests are unsatisfactory. The obtained load safety factor, after the last inspection, is 5.5, and the normatively accepted minimum value is 6. This indicates that the tested rope has exhausted its operational resource and does not meet the standard requirements and should be removed from service.

Table 3. Load safety factor.

	Number of wires that passed the tensile and bending tests	Rope breaking force - total breaking force of all the wires that passed the breaking and bending tests, N	Load safety factor
Permissible load safety factor - 6 Maximum static load, incl. the own weight of the rope - 84366 N Total number of wires in the rope - 216			
New rope	216	797926	9.5
after 6 months	212	787536	9.3
after 12 months	196	687720	8.2
after 18 months	195	687150	8.1
after 24 months	201	688446	8.2
after 30 months	194	652748	7.7
after 36 months	186	616912	7.3
after 42 months	150	462306	5.5

CONCLUSIONS

Monitoring of a steel wire rope operating under real conditions in the mining industry has been carried out. The monitoring was carried out before the suspension of the rope (new rope) and then - every 6 months until its end of use (7 control tests were carried out).

Monitoring consists of visual and destructive control. During the monitoring, standard tensile tests and technological bending tests of the wires were carried out. For the entire service period, the strength characteristics of the rope and its constituent wires, as well as their plasticity and resistance to cyclic bending, have been determined and evaluated.

Comparative analyses were made with the initial mechanical properties of the rope (before use), as well as with any previous test to establish the residual resource of the rope, its efficiency and safety. Compliance of the characteristics of the used steel rope with the requirements specified in the relevant European standards concerning the quality and safety of steel hoisting ropes has been established.

Visual inspection found that during the service period, the surface of the outer wires for each bundle deteriorated. There are traces of corrosion, and in the last control tests - of wear and tear as a result of friction of the rope in the rollers. During the monitoring and evaluation period, no broken strands of the rope are detected. The obtained results show that the rope was used correctly, according to the normative requirements.

As a result of tensile and cyclic bending tests of the wires, experimental data on the mechanical properties of steel rope were obtained, analysed and compared. The breaking forces of the wires and the rope, respectively the tensile strength and the number of bends, of the wires, which the wire can withstand until it breaks, are determined. The load safety factor was calculated after each control test. According to the standard requirements for steel ropes, the investigated characteristics are of fundamental importance in determining the quality, reliability and applicability of the ropes.

The comparative analysis of the obtained mechanical properties and the calculated load safety factor, for the whole service life of the rope of 42 months, shows that the steel rope, when used correctly, can work efficiently and safely for at least 2 years, during which the 6-month monitoring is mandatory. During the next period of operation, control tests should continue every 6 months. In order to establish the quality of the rope along its entire length and/or to confirm the need for its retirement, it is recommended to carry out a non-destructive control of the rope.

The correct use of steel ropes and regular monitoring to identify changes in the structure and properties of the ropes is a guarantee of avoiding production problems and unwanted sudden accidents or incidents.

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