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A new approach to the assessment of the fatigue life of typical steel ropes

The issue of the future prediction of the technical condition of ropes during their operation is a very important issue related to the safety of use and operation of the devices. Steel wire ropes, as load bearing elements, are subject to degradation through various forms of wear during operation. Variable loads cause a complex state of stress in the wires, which translates into different tensile, twisting and surface pressures between the wires. Ropes are also exposed to difficult working conditions, e.g. corrosive environment, fatigue wear, which consequently leads to a weakening of their functional properties. Ropes, as responsible elements, require an accurate and at the same time simple way of predicting their failure-free operation in a simple and unambiguous manner.
This article concerns a new approach to determining the fatigue life of steel ropes. The issue of safety related to steel ropes has been a difficult and ambiguous issue for many years to determine without knowing the fatigue life of the object. The paper discusses experimental and practical methods for determining the fatigue life of steel ropes.

Key words: *steel wire ropes, fatigue durability, compacted ropes, wear*

1. INTRODUCTION

In the last dozen or so years, we have observed a constant increase in the quality of artistry in steel rope operation. This manifests itself in an increasing operating time even in the most difficult conditions, such as mine shafts. This applies to all typical applications of steel ropes, especially ropes used in deep mining, basic open-pit mining machines and various types of overhead crane rope systems. At the same time, the largest rope manufacturers offer new structures characterized by greater fatigue life. These new structures are usually multi-layer ropes with many strands of relatively thin wires with high tensile strength. In multi-layer ropes of some companies, e.g. Wireco, Teufelberger Arcelor Mittal, additional plastic inserts are used, which reduce the pressure values between the wires. Very often, these strands are made using the compacting process. This technology involves partial crushing of previously made strands with linear contact. The basic methods of compacting strands are presented in the text. With the advent of new steel rope designs, their wear characteristics have also changed. The most common cause of the wear of steel ropes is fatigue of the steel from which the wires are made, manifested by their cracks. Modern designs use high strength, small diameter wires, often 2160 MPa or more. This also increases the fatigue life of the wires. Combined with the reduction of contact stresses, such ropes work longer, but without the occurrence of wear factors such as fatigue scrap. This longer operation also means that such ropes, especially in humid environments in mining shaft hoists, are subject to a faster corrosion process. Ropes working in drum hoists are also subject to abrasive wear, manifested by massive cross-sectional losses mainly on the surface of the wires. In the classic operation of steel ropes, fatigue life is commonly used. This concept is explained in more detail later in the article. This parameter is descriptive but allows for comparison of rope structures in terms of the length of working time. However, it is impossible to determine the safe length of this rope operating time for specific conditions. The determinism of the steel rope wear process is also compounded by statistical uncertainty. In the operation of steel ropes, it is common practice to examine their technical condition (wear level) using various methods. Visual VT nondestructive testing and magnetic MRT testing are commonly used. The results of these tests are used to determine the type and level of wear of a given rope. This wear is understood as a loss of the load-bearing cross-section of the rope, which consequently leads to the weakening of the rope, i.e., its ability to carry loads. The value of this indicator results directly from the degree of wear, but it is difficult to determine quantitatively using non-destructive methods. The only way is to test the strength of the laid ropes and extrapolate their results to similar cases. The next chapter presents sample results of a statistical method for determining rope weakening based on the actual level of its wear. It turns out that for most types (fatigue, corrosion, abrasion) and forms (internal and external damage, symmetrically and asymmetrically located) of physical wear, the weakening of the rope is generally underestimated about the size of the loss of the rope's load-bearing cross-section. Therefore, it requires an estimate of the value by the researcher based on the results of magnetic or visual tests. This means that the appraiser must be equipped with appropriate knowledge. The authors of this article propose a new approach to assessing the operational durability of ropes. This new approach is a holistic (comprehensive) way of interpreting all operational elements that characterize the operation of a given rope. It is mainly about the accuracy and repeatability of wear assessment methods, translating these results into actual rope weakening and considering the uncertainty of estimating these indicators, meaning that the expert must be equipped with the appropriate knowledge. This is to ensure that the rope is withdrawn safely and remains with a sufficient reserve of operating time. Most regulations regarding the laying down of steel ropes deal with this problem briefly, and the laying criteria are specified point-wise. As an example, the authors give the regulations regarding ropes working in mining shaft hoists in force in Poland and South Africa. This comparative analysis shows that the criteria applicable in Poland for storing mining hoisting ropes in the final phase of their operation allow for a situation in which these ropes may significantly exceed the limit value. This is due to an underestimate of the attenuation based on the consumption estimate and a failure to consider the stochastic uncertainty of this estimate. The new proposed approach is mainly intended to prevent such a situation. Perhaps in some cases it would be necessary to revise the criteria for laying down steel ropes in mining shaft hoists in deep mining.

2. MAITENANCE PROPERTIES OF STEEL WIRE ROPES MADE WITH COMPACT STRANDS

The Polish mining industry is managed on a business basis which means maximizing profit and minimizing labor. This observation also applies to the steel ropes used in mining shaft hoists. The primary goal is the safety of their operation by applicable regulations with the longest possible operating life. Multilayer ropes with complex structures are increasingly used, including ropes with compacted strands, i.e., ropes with a longer service life than traditional ones. This generally reduces costs. In the mining industry in Poland, such ropes have been used in several dozen installations over the last dozen years. Not only do these ropes last longer, but their wear processes, especially fatigue, are different than those of the typical, popular triangle-strand ropes used previously, hence the attention that the authors of this publication devote to these ropes. They discuss some operational features of ropes made of compacted strands in more detail. To date, there has been no comprehensive research determining the impact of the structure of these ropes on their strength parameters, reliability, durability, and especially on the possibility of determining the condition during operation using the commonly used visual VT and magnetic MRT methods.

Against this background, monograph [1] and article [2] stood out, but they are only studies of single application cases. The basic feature that distinguishes the structures of these ropes about those used so far is the occurrence of surface contacts between cooperating wires in strands made with linear contact between the wires and then plastically deformed using various methods. Steel ropes made of compacted strands are more expensive to produce than equivalent ropes with strands with linear contact between wires. As a result of plastic deformation, strands are made of wires with linear contact in subsequent layers, creating surface contact between the deformed wires. This state is achieved by introducing significant technological changes that increase production costs in the strand production process. Several technologies are used in this process. Generally, they involve mechanical compression of the strand with linear contact between the wires in the radial direction, which causes their plastic deformation. As a result of the compacting process, the cross-section of the wires in the strand is permanently deformed. This results in a decrease in the strand's diameter, but its metallic cross-section remains the same. The wires forming the strand change their cross-section from a round one and contact each other through surface contacts. This reduces the surface stress of the wires in the strands. For example, two technologies for making compacted strands (rolling and the so-called corking) are shown in Figure 1 in the upper part of the drawing. In contrast, the lower part of the drawing shows two, most often compacted, types of strands with linear contact between wires. These are 1+6 strands and the Seale (1+9+9) construction.

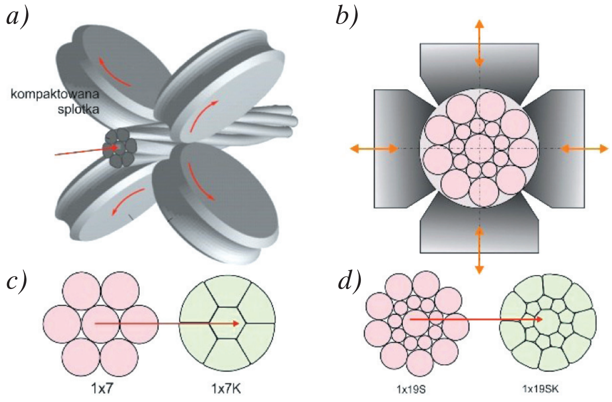

Fig. 1. Two examples of technologies for compacting strands with linear contact between wires: a) strand rolling method [3]; b) knitting method; c), d) examples of compacting 6x7 and 6x19S strands [2, 4]

The strands shown in the drawing are made with a maximum deformation of 100%. This means that all the wires in the strand are deformed so much that there is no free space between them.

The strand deformation obtained in any compacting technology is usually 6–30% and is determined by equation (1). This compression is calculated as a percentage change in the cross-section of the circle described on the strand as a result of compacting (S_0 [mm^2] – S_k [mm^2]) to the change that this cross-section would achieve if the strand were completely closed (S_0 [mm^2] – $S_{\min}$ [mm^2])

$$Z = \frac{S_0 - S_k}{S_0 - S_{\min}} \cdot 100\% \tag{1}$$

where:

S_0 – cross-section of the circle described on the strand [mm^2],

S_k – cross-section of the strand after compacting [mm^2],

$S_{\min}$ – minimum cross-section of the strand that can be obtained after compacting until the strand is completely closed [mm^2].

The greatest deformation occurs in the wires of the outer layers of the strand and decreases gradually in the wires located deeper and deeper, as they get closer to the core wire of the strand. This is also presented in finite element models of the compaction process, where the radial distribution of stress increases in compaction processes is visible [5]. In most ropes with compacted strands available on the market, the compression applied plastically only deforms the outer wires of the strands.

When the entire wire rope is subjected to crushing, the resulting rope is called a corrugated rope [6]. The compaction process reduces the diameter of the strands and the ropes made of them, an increase in the fill factor of the strand cross-section and thus in the finished rope, and a smoother external surface compared to ropes with conventional strands. This, in turn, improves the coefficient of friction between the rope and the drum or pulley. The rope's resistance to corrosion also increases. Moreover, due to the limitation of free space between the wires, surface contact improves the distribution of stresses on the cooperating surfaces. Working on the pulley, the steel wire rope is often bent, which causes higher loads at the contact between the wires, leading to slippage and, consequently, abrasive wear and material fatigue [7]. An example cross-section of a compacted rope is shown in Figure 2 [8]. It is a supporting rope marked by the manufacturer as „NRHD24CS" with external strands and a wire arrangement (1+6). The inner layer of the rope uses Seale strands in a (1+8+8) arrangement. This rope is characterized by high resistance to compression and abrasion when wound on multi-layer drums and is resistant to corrosion. Such ropes are also resistant to ovalization of the cross-section on the drum. In this construction, the strands in the layers are rolled in the opposite direction, the smooth surface of the compacted strands reduces contact stresses.

The crush size is not specified in the materials available from manufacturers and the data sheets. The compacting technology was not specified, and these two factors, production technology and crushing, have a fundamental impact on the durability of working steel ropes made using this technology. Omitting such an important parameter as crushing capacity for individual types of strands does not provide those examining and interpreting the results of e.g. magnetic tests with any additional information on how fatigue scraps may be distributed in the rope cross-section. Compared to equivalent ropes with normal strand construction, compacted ropes have less twist, lower stiffness and are more corrosion resistant. These features are desirable in drum winches of all types, but it does not necessarily increase fatigue life for shaft conditions. While examining these ropes, interpreting magnetic test results is also a problem. This is because damage occurs mainly at the contact of strand layers, and the lengths of the gaps between the ends of the cracked wires are about 1 mm, which poses a severe challenge to magnetic detection [9, 10]. An additional problem is the nature of fatigue itself. Another problem is the nature of fatigue wear itself and we will return to this issue later in the article.

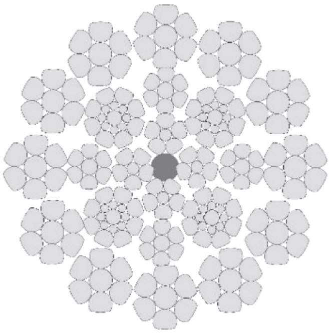

Fig. 2. Cross-section of the "NRHD24CS" type track rope [8]

3. DURABILITY OF STEEL WIRE ROPES

The fatigue durability in machine operation is intuitively obvious. However, it is quite difficult to define because it requires many detailed parameters regarding a given element: material and manufacturing technology, operating conditions and environment, nature of loads, etc. Defining the concept of durability for steel ropes is even more difficult. Below are some examples of definitions of this concept used in practice.

The classic definition of fatigue durability of steel ropes is the operating time, or the number of cycles, worked by a steel rope under specified conditions until it reaches destruction or a specified level of wear [11]. In practice, the strength definition of fatigue durability is more often used. This is the steel rope's operating time (working resource), determined by the number of operating cycles or operating time until its complete destruction, achievable in specific environmental conditions with variable loads.

Theoretically, having data on the fatigue life of a steel rope should solve the basic operational problem: when to replace the rope with a new one. The answer to this statement is that before this deadline (or after a certain number of cycles have been completed). This means that is very difficult to obtain any knowledge about this value.

There are several ways to determine the fatigue life of steel ropes, with the most important presented below.

The maintenance method uses spreadsheets of the number of wire breaks as a function of time [12].

The laboratory method uses fatigue machines to perform fatigue life tests in controlled conditions. It is possible to experimentally determine the relationship between the number of visible wire cracks and the remaining strength of the rope [13]. Such research is expensive and time-consuming. They usually concern a small sample of ropes and do not consider specific shaft conditions. An example of such research is shown in Figure 3 [3]. The graphs show rope wear, expressed in the number of fatigue scraps, as a function of the number of cycles worked. The blue graph shows the wear curve of a rope with a diameter of 50 mm and a 6x36WS construction. The red graph shows the wear curve of an equivalent rope with a diameter of 50 mm made of compacted strands of 6x36WSK construction. Although there is no data on the amount of crushing and the compaction method, the charts show the typical course of wear of ropes with compacted strands about ropes with ordinary strands. The fatigue wear process of ropes with compacted strands takes place so that for approximately 2/3 of the ropes' operating time, the wires practically do not break. Fatigue accumulates in the wire material invisibly and fatigue cracking of wires begins after this phase, but is usually violent, often characterized as „explosive". The reason for this form of rope wear over time is well described by computer models of rope fatigue wear described below. This also means that the person examining the rope over a long period has no information that the fatigue wear process is taking place. Moreover, in compacted strands, the wires do not spread over long distances when they break, and the gaps between the ends do not exceed 1 mm. If the magnetic method is used to assess the level of wear, such damage is very poorly visible in the signal of LD type inductive sensors.

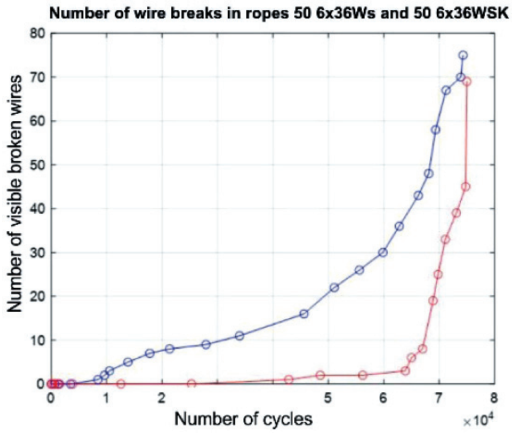

Fig. 3. Example of fatigue life tests for steel ropes of the same design made of plain round strands (blue) and partially compacted strands (red) [3]

Methods of mathematical approximation of the rope wear a time series describing this process using various techniques and then extrapolating the determined function. Among other ARIMA-type processes, econometric methods such as the harmonic weights or exponential smoothing method are used [4, 14].

Figure 4 presents the results of fatigue life tests as a specific rope level of wear [14]. This approach was proposed for the first time in diagnosing steel ropes in mining shaft hoists.

This innovation combines three concepts: fatigue life, operational wear and weakening caused by a decrease in the breaking force of the rope. The charts were prepared based on the results obtained during fatigue testing of ropes. The degree of wear was determined based on the so-called signal of the integrated MD8 defectograph [15, 16]. The lower curve shows a rapid non-linear decline in fatigue life with wear level. Unfortunately, there is no data on the type of rope tested, the tests themselves, the assessment error, and the method of determining durability. The graph shows that rope wear, which corresponds to a weakening estimated at 25%, is accompanied by a decrease in fatigue life of over 90%. The graph also shows that the decrease in fatigue life is very rapid in the first phase of rope operation, only to slow down in the final phase. This behavior of steel ropes was difficult to explain until the development of a method for computer modeling of the fatigue process of steel rope wear [17].

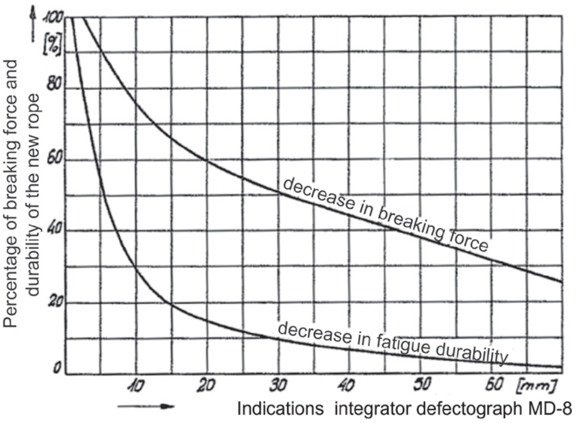

Fig. 4. Decrease in fatigue life and weakening of the rope as a function of its wear [14]

Fatigue wear modeling involves iterative computer models based on the Wöhler fatigue hypothesis (for wires) and the Palmgren–Miner (PM) cumulative hypothesis (the principle of adding stresses in individual wires). Among others, such models have been described in monograph [4]. An exemplary result of such model tests is presented in Figure 5. It presents two realizations of the change in rope wear, expressed as the number of fatigue cracks in wires appearing depending on the number of cycles worked. In these models, the level of rope wear measured by the number of fatigue scraps is equivalent to weakening. The graphs were obtained using a fatigue wear model of a 34x7 multi-layer rope, made of identical wires with a wire strength of R_m = 1900 MPa, of different quality of workmanship, characterized by a large spread of loads on individual wires (blue color) and increased quality of workmanship (red color). These models well reflect the nature of the wear process, especially of multi-layer ropes made of compacted strands. It can be seen in the drawing 5 that this quality variable significantly extends the operating time of ropes made in this way compared to ropes of lower quality. Figure 6 shows the same implementations of the fatigue wear process, but as a change in fatigue life as a function of the weakening of these ropes. This corresponds to the lower graph in Figure 4. The presented graphs confirm the thesis presented in this article that ropes of high quality of workmanship, but with equal stress values in individual wires, in the first phase of their operation exhaust the fatigue life resources faster than ropes with a lower quality of work-manship.

Nevertheless, they work longer hours. The irregularities in both graphs result from stochastic dispersion of loads on individual wires. They are different in each calculation cycle, but they are random in terms of the postulated quality of workmanship. The experimentally determined fatigue strength and wear of compacted steel ropes and the relationship between the number of visible wire cracks and the remaining rope strength are presented in [18]. Fatigue life modeling allows one to obtain this type of information and other information that other methods do not allow, such as the impact of the quality of the rope, the method of making the wires, the unevenness of the loads on individual strands etc. The wear curves for the example in Figures 5 and 6 are presented together in Figure 7, but as a function of the ropes operating time (number of cycles). It is also presented as a linear function of the change in fatigue life for examples of the same ropes made of high and lower quality. The linearity of these characteristics results from the adopted operating time variable as the number of cycles. As seen, model tests can be carried out until the „rope breaks" due to the achieved weakening, which is not possible in real conditions, because the ropes are previously laid down at a weakening level of approximately 20%. The results obtained by numerical simulation according to [4] also confirm the observations that the weakening of the rope at the level of 20% of the rope breaking force is synonymous with a decrease in fatigue life of even more than 90%. This is extremely important in the context of the criteria for laying down mining shaft hoist ropes in force in Poland. As can be seen in Figure 7, ropes of higher quality work even many times longer than ropes of average quality, but when their weakening exceeds 20% (the value of deposition of supporting ropes of mining shaft hoists according to WUG regulations), the remaining fatigue life is much lower. This is extremely important due to the increasing use of ropes with compacted strands for supporting ropes.

The structure of these ropes favors averaging the loads transferred to individual wires and strands. As a result, this leads to better equalization of stresses between individual wires and strands. This explains the unusual fatigue wear characteristics of a rope with compacted strands, shown in Figure 3. Compacting the strands equalizes the transfer of loads, including variable loads. The material fatigue of individual wires accumulates without any externally visible effect, so after reaching the maximum work resource described by the Palmgren–Miner hypothesis, it leads to a fatigue crack in accordance with the Wöhler equation. The stress intensity factor can determine the growth rate of fatigue cracks according to the Paris equation [19]. Compared to ropes made of ordinary strands, the operating time of compacted ropes is longer, but more rapid in the last phase.

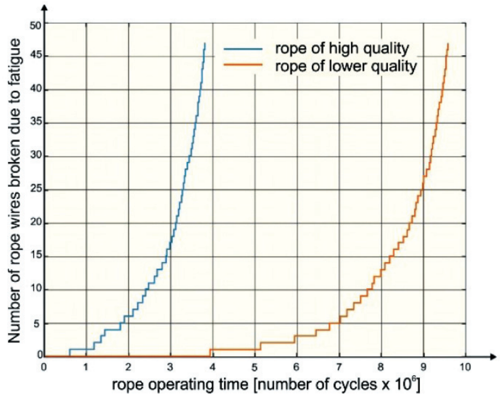

Fig. 5. The course of wear of ropes of various quality as a function of the number of cycles performed based on the results of numerical simulation according to the iterative model [4]

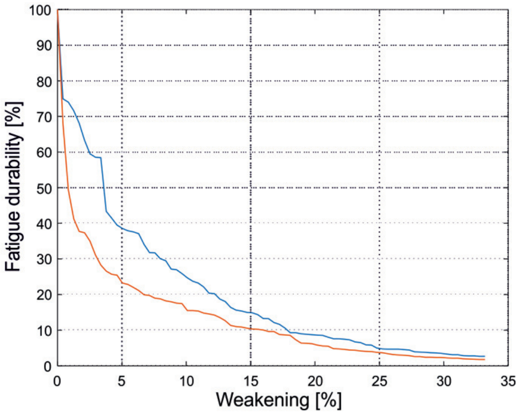

Fig. 6. Decrease in fatigue life of ropes with a wear pattern as in Figure 5 as a function of its weakening (based on the results of numerical simulation according to the iterative model [4]

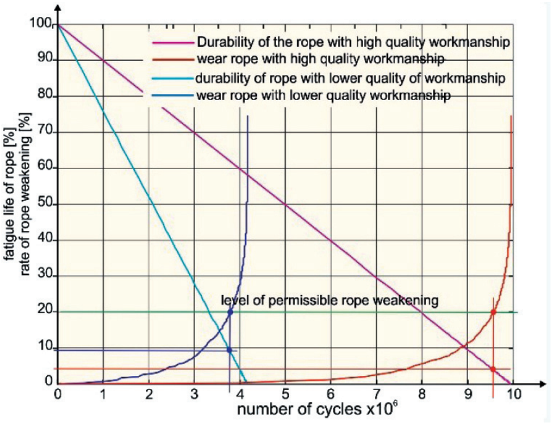

Fig. 7. Decrease in fatigue life and wear of ropes of different quality of artistry as a function of operating time (based on the results of numerical simulation according to the iterative model [4])

The method of calculating fatigue life as a guaranteed number of cycles to achieve the deposition criterion involves using a regression equation with parameters estimated based on testing a specific rope in laboratory conditions on a fatigue machine. This method was developed at the Technical University of Stuttgart [20] and recommended by the rope manufacturer CASAR. In general, the method o calculating the fatigue life of a rope in this way for given operating conditions is known. Still, the values of numerous coefficients used in the formulas have not been published.

4. LEVEL OF WEAR AND WEAKNESS OF STEEL WIRE ROPES

The wearing of steel ropes is an inevitable process of degradation of their physical, geometrical and operational properties. Wear is caused by fatigue processes, corrosion, losses caused by abrasion and loss of basic geometrical features such as: diameter [mm], stroke length [mm], longitudinal and transverse stiffness, lubricant properties, core wear. The level of rope wear is an assessment of this wear based on the number of visible wire scraps, change in rope diameter [%], change in stroke length [%], elongation [%], size of wire cross-section losses due to wire abrasion [mm^2], loss of ferromagnetic cross-section [mm^2, %,], loss of load-bearing cross-section of the rope [mm^2, %,], lubrication condition, core condition, torque, etc. This assessment is objective when the examiner uses apparatus methods, e.g. magnetic testing. This assessment may be subjective if the assessor uses only visual methods and treats magnetic testing only as a tool for determining the most worn part of the rope. From the operational point of view, the best measure of the level of wear is to determine the loss of the load-bearing cross-section of the rope [mm^2, %]. Such a measure would lead to determining the weakening of the rope according to Equation (2) as a decrease in the rope's ability to transfer longitudinal loads due to changes in wear.

$$\Delta F = \frac{F_{rz0} - F_{rz}}{F_{rz0}} \cdot 100\% \tag{2}$$

Unfortunately, the weakening of the working rope can only be determined indirectly based on visual tests (number of broken wires) or magnetic tests (degree of rope wear determined according to the PN-92/G-46603 standard). Both methods are not accurate – the visual method is subjective. In addition, the quantitative relationship between the weakening and wear, as defined in this way, is regressive and subject to significant uncertainty. The accuracy of this relationship depends on the level of rope wear, the distribution of damage, the design, diameter, type of wear, and the method of assessing the degree of wear. Rope wear significantly impacts its weakening, but there is no clear relationship between these values. It is, therefore, advisable to determine the relationship between weakening and wear based on the results of controlled tests. They should be concerned with the basic forms of wear in specific applications of steel ropes. The only rational way is to determine the level of rope wear for a given value and the corresponding weakening. It should be noted that rope weakening measures its ability to transfer longitudinal force. It can only be precisely determined based on the actual value. For the final results to make stochastic sense, at least a dozen such tests for one type of rope and a given type of damage would have to be performed. This affects the costs and causes such tests to be performed rarely, and their results are reluctantly published. Below are examples of such test results performed in South Africa [21] and statistically developed by the authors of this article. The results of the tests carried out in South Africa consisted of breaking entire sections of ropes of different constructions, in which artificial damage was done by cutting wires in different numbers and different configurations. Other results presented below are tests carried out entirely by the authors of this article. The tests covered several different constructions of steel ropes with different forms of wear. The tests consisted of assessing the level of wear of ropes using the magnetic method with the MD120 defectograph per the PN-92/G-46603 standard and then breaking the wires to determine the actual weakening of a given section of the rope according to Equation (2). Below are examples of results from such tests.

It should be noted that in the literature on the problems of assessing the condition of ropes, the authors of this study have yet to encounter such an approach. Example results of the authors' tests are presented in Figures 8–11. They refer to different construction solutions of ropes used in mining hoists, mainly drum hoists. The drawings show at the top – a description, symbol and sketch of the rope cross-section, and at the bottom, a graph of the regression relationship: weakening [%] versus wear [%]. In the graphs on the vertical axis, the abbreviation LBS stands for weakening (Loss of Metallic Section) [%], and the abbreviation LA stands for wear (Loss of Area) [%]. The graphs also include the equation of the first-degree linear regression model, and the value of the linear determination coefficient determined for this regression model.

Figure 8 shows a linear model of the relationship between the weakening and wear of a Fishback rope (a popular rope used and manufactured in South Africa in deep lifts, similar to the rope shown in Figure 2). The modelled wear of the rope is caused by cut wires in triangular strands at the interface of the layers. The damage is evenly distributed across the cross-section of the rope. This wear model corresponds to this type of rope's typical fatigue wear process, mainly manifested by broken wires occurring at the interface of the strand layers. The weakening of the rope was determined based on tests of breaking sections of ropes in their entirety about a brand-new rope. The slope coefficient in this regression model is 1.001, i.e. the level of rope wear for this case corresponds to weakening. Due to the scatter of results, there is an uncertainty in the weakening estimate with a standard deviation of 2%. The dashed lines also show the 95% confidence interval limits on the graph.

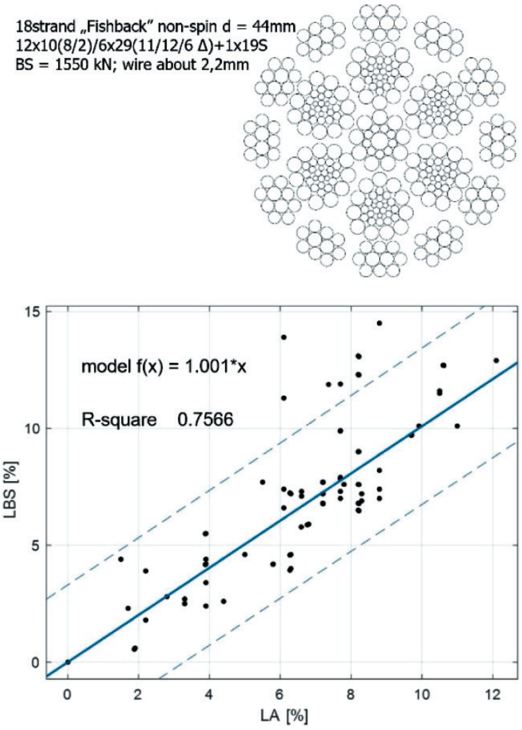

Fig. 8. Relationship between weakening and wear of steel ropes caused by cut wires at the interface of strand layers determined on the basis of strength test results ([21], statistical analysis: authors of the publication)

Figure 9 shows a linear model of the relationship between the weakening and wear of a Ribbon rope (a popular rope used and manufactured in South Africa in deep lifts, similar to the rope shown in Figure 2). The modelled wear of the rope is caused by cut wires lying on the surface of the strands' outer layers. The damage is evenly distributed around the circumference of the rope. The weakening of the rope was determined based on tests of breaking sections of ropes in their entirety about a brand new rope. The slope coefficient is 2.41, i.e. the level of weakening of the rope for this case is, on average, 2.41 times higher than the wear.

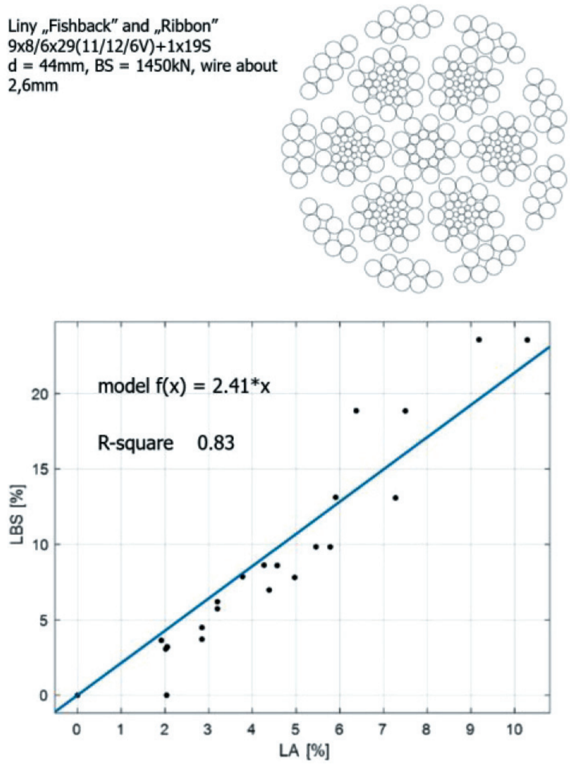

Fig. 9. Relationship between weakening and wear of steel ropes caused by cut wires on the strand surface determined on the basis of strength test results ([21], statistical analysis: authors of the publication)

Figure 10 shows a linear model of the relationship between the weakening and wear of a rope with a triangular strand structure. This popular rope is used in deep hoists in drum and multi-rope devices with friction drives. The tested rope operated in a multi-layer winding system on the drum. It showed only differentiated abrasive wear with abrasions exceeding one-third of the outer wire diameter over the entire circumference. Rope wear was determined based on tests of the entire length of the rope after it was removed from the device. The tests were performed with an

MD120 defectograph, interpreting only the signal of the LMA Hall sensor zeroed about the cross-section of the non-working rope (a section of the rope from the vicinity of the driving drum). Rope weakening was estimated based on tests of whole rope sections, about a section of the rope from the vicinity of the drum, which showed no wear. The slope coefficient of the linear regression model is 1.43, which means that the rope weakening level for this case is, on average, 1.43 times higher than the wear level. It should be noted that the low value of the linear determination coefficient. This means that the rope weakening level is not only determined by the loss of the metallic cross-section caused by abrasion but also by the nature of the distribution of this loss in the cross-section and along the length, which cannot be determined based on the LMA sensor signal.

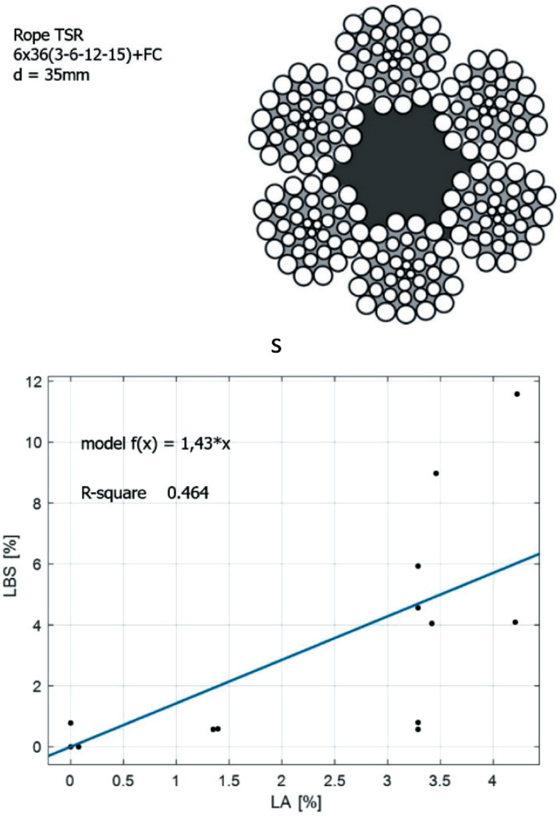

Fig. 10. Relationship between weakening and wear of steel wire ropes caused by wire abrasion on the strand surface (statistical analysis: authors of the publication)

Figure 11 shows a linear model of the relationship between the weakening and wear of a single-lay rope. This famous rope is used as a guy rope for tall free-standing structures or as a cable rope in floating cranes and primary machines in opencast mining. The tested rope showed only corrosive wear at the contact of wire layers. Rope wear was determined based on tests of the entire length of the rope with an MD120 defectograph using only an LD inductive sensor and the pulse summation method over a section of 30 rope diameters. Rope weakening was estimated based on tests of all wires from different rope sections about the section showing no wear. The slope coefficient is 2.14, which means that the rope weakening level for this case is, on average, 2.14 times higher than wear.

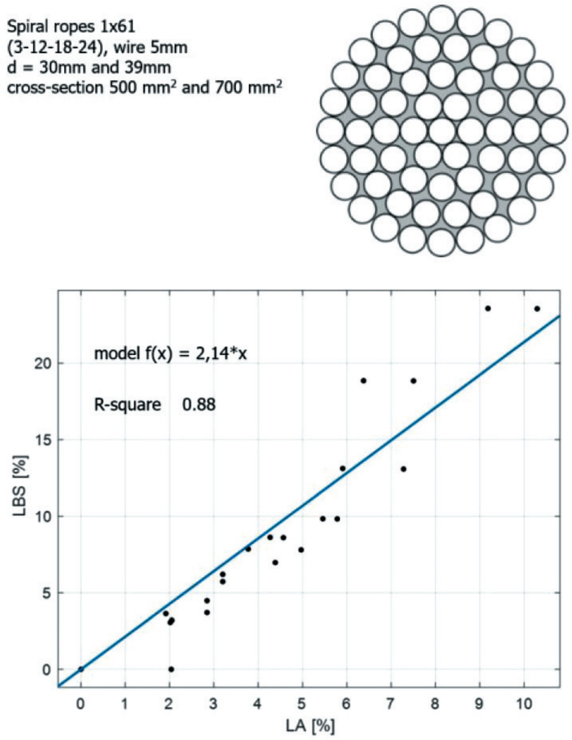

Fig. 11. Relationship between weakening and wear of steel ropes caused by wire abrasion on the strand surface (statistical analysis: authors of the publication

5. STOCHASTICAL ESTIMATION OF THE WEAKENING OF STEEL WIRE ROPES BASED ON THEIR DETERMINED WEAR LEVEL

The presented examples of relationships between the value of weakening of steel ropes and their level of wear indicate a significant influence of the type (form) of wear and the distribution of damage in the cross-section of the rope on the relationship between these relationships and the size of the statistical uncertainty of determining this relationship. These results indicate a significant share of the random factor in the estimated wear and weakening value. This means that, for example, wear in the form of scrap wires of the same number but located inside the rope and on its surface has a diametrically different effect on the value of weakening. The same is true for the form of wear. The same numerically determined wear caused by corrosion causes a weakening different from that caused by abrasions or scrap wires. Since the criterion of weakening decides the disqualification of a rope, the above aspects should be considered by experts. It is much easier to consider the influence of randomness, as shown above. This is illustrated in Figure 12, which is an example of such conclusions, to not only determine the average weakening level based on the estimated level of wear, knowing the relationship between wear => and weakening, but also the probability of underestimating this weakening level. This example presents a situation in which the expert assessed, based on his wear tests, the wear of a multilayer rope caused by wire scrap lying at the contact of the layers, e.g. at 20% loss of the load-bearing cross-section. In the case of hoisting devices used in Poland, the value of the criterion for laying down lifting ropes is a 20% decrease in the safety factor, equivalent to 20% weakening. The question remains whether the rope should be laid down or not. For this case, the weakening-wear relationship presented in Figure 8 is known (linear model $f(x) = 1.001 \cdot x$), i.e. the average weakening equals the determined wear. It remains to consider only the random scatter of these values additionally. Since the regression equation was determined with an uncertainty of 2%, because that is the standard deviation, it is possible to determine the probability of underestimating this weakening, i.e. the probability of occurrence of weakening greater than 20%. In Figure 12, this probability is shown by the yellow field and is exactly 50%. At the same time, the chance that the weakening of the rope is less than 20% is less than 50%.

On the other hand, the probability that the actual level of weakening is 18–22% is about 68%. This figure also shows that with 95% probability, the weakening of the rope exceeds 24%, i.e. significantly, by as much as 4%, the value specified in the regulations. Since the wear of the rope will only increase, the expert should decide to replace the rope or extend its operating time, but additional tests of its technical condition should inform this.

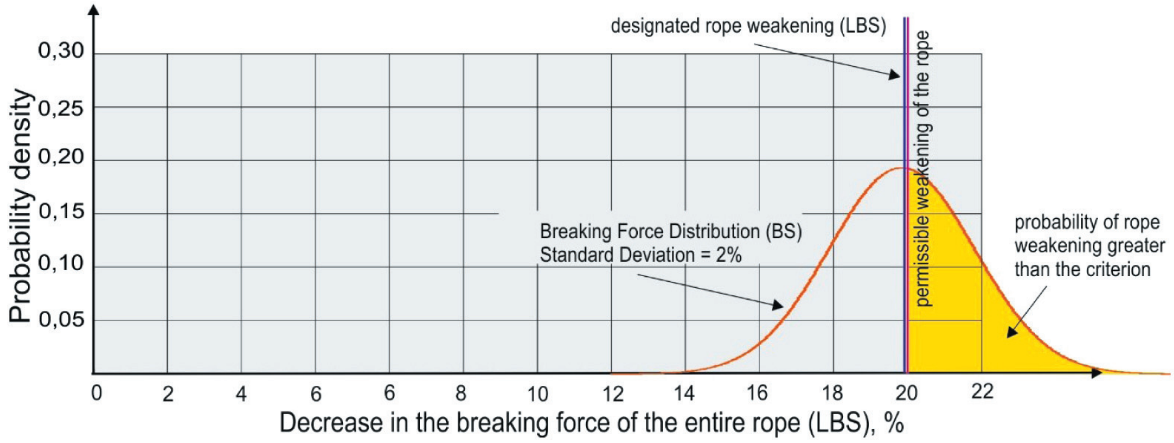

Fig. 12. Illustration of the stochastic interpretation of rope weakening for a given level of wear caused by crack damage occurring at the junction of strand layers

6. SUMMARY

1. Model tests of fatigue wear processes of steel ropes show that the criteria for laying down supporting ropes of mining shaft hoists used in Poland [WUG regulations, safety factor decrease by 20%] show that these ropes have a reserve of fatigue life of less than 10% at the time of laying down.
2. The criteria for laying down supporting ropes of mining shaft hoists used in Poland [WUG regulations] compared to others, e.g. used in South Africa [22, 23], are point-wise and do not take into account the influence of random factors affecting all stages of rope making and rope operation. These factors inevitably lead to statistical uncertainty in estimating the wear level and, thus, the weakening value of the working ropes.
3. Model studies of fatigue wear processes of steel ropes show that one of the critical factors influencing their operating time is the quality of their artistry, understood as the use of technologies during rope production that reduce the spread of loads on individual wires and strands of the rope. This observation applies especially to modern multi-layer ropes, ropes with plastic inserts, and ropes made of compacted strands.

4. Laboratory and operational tests of the weakening of the supporting ropes of mining shaft hoists in connection with the nature of wear processes indicate an underestimation of the level of weakening based on wear tests using visual and magnetic methods, especially for corrosion, abrasion and uneven distribution of wire scraps in the cross-section of the rope.
5. The authors of this article propose carrying out comprehensive tests of ropes made of compacted strands after they have been withdrawn from service to assess the effectiveness of currently used wear assessment methods in precisely determining the actual weakening of these ropes based on strength tests.

References

[1] Hankus J.: *Liny wyciągowe nośne o powierzchniowym styku drutów*. GIG, Katowice 2003.

[2] Kubiś B., Olszyna G., Szade P., Tytko A.: *Fatigue Life of Compacted Wire Ropes for Applications in Deep Mining*. Management Systems in Production Engineering 2023, 31, 1: 95–101, https://doi.org/10.2478/mspe-2023-0012.

[3] Kubiś B.: *Wpływ wstępnej deformacji splotek w linach kompaktowanych na ich trwałość i parametry wytrzymałościowe*. GIG, Katowice 2019 [unpublished doctoral thesis].

[4] Tytko A.: *Liny stalowe*. Wydawnictwo Naukowe PWN, Warszawa 2021.

[5] Erdönmez C.: *Analysis and design of compacted IWRC meshed model under axial strain*. International Journal of Mechanics and Materials in Design 2020, 16: 647–661, https://doi.org/10.1007/s10999-019-09481-x.

[6] Chen L., Magliulo M., Elig M., Beex L. A.A.: *A mechanical model for compaction of strands for wire ropes*. International Journal of Solids and Structures 2023, 269. https://doi.org/10.1016/j.ijsolstr.2023.112178.

[7] Kumar K., Goyal D., Banwait S.S.: *Effect of key parameters on fretting behaviour of wire rope*. Archives of Computational Methods in Engineering 2020, 27: 549–561, https://doi.org/10.1007/s11831-019-09326-y.

[8] Tobys J., Kocur G.: *Protokół NR 35/PZ/2016/P-S z oceny przydatności lin nośnych przed ich zastosowaniem w górniczym wyciągu szybowym awaryjno-rewizyjnym szybu SG-2 KGHM "Polska Miedź" S.A. Oddział Zakład Górniczy "Polkowice-Sieroszowice" w Polkowicach*. Polkowice 2016 [unpublished].

[9] Carbogno A., Pypłacz J., Nowacki J.: *Liny kompaktowane w górniczych wyciągaczach szybowych*. Hutnik – Wiadomości Hutnicze 2013, 80, 1: 17–20.

[10] Nowak M., Lipiński L.: *Problemy eksploatacji lin nośnych o powierzchniowym styku drutów.* W: *Bezpieczeństwo pracy urządzeń transportowych w górnictwie*, red. A. Tytko, M. Wójcik. Centrum Badań i Dozoru Górnictwa Podziemnego sp. z o.o., Lędziny 2015: 73–80.

[11] Kawecki Z., Stachurski J.: *Defektoskopia magnetyczna lin stalowych*. Wydawnictwo Śląsk, Katowice 1969.

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

[13] Szade P., Szot M., Kubiś B.: *Thermoelastic effect in compacted steel wire ropes under uniaxial loading*. Quantitative Infra-Red Thermography Journal 2020, 18, 4: 252–268, https://doi.org/10.1080/17686733.2020.1768495.

[14] Hansel J.: *Podstawy teoretyczne prognozowania czasu pracy lin stalowych*. Zeszyty Naukowe AGH, Elektryfikacja i Mechanizacja Górnictwa i Hutnictwa, nr 84, Kraków 1977.

[15] Ridge I.M.L., Tytko A.: *Use of magnetic NDT to determine the lay length of a stranded wire rope*. Journal of The British Institute of NDT 2001, 43, 12: 806–813.

[16] Tytko A.: *Application of signal analysis in magnetic testing of wire ropes*. Workshop of Nondestructive Testing of Material and Structures. AMAS Course – NTM'02, Polish Academy of Sciences. Warszawa, 20–22 maja 2002.

[17] Tytko A.: *Modelowanie zużycia zmęczeniowego i diagnostyka lin stalowych*. Rozprawy, Monografie, Nr 65. Wydawnictwa AGH, Kraków 1998.

[18] Costello G.A.: *Theory of Wire Rope*. Springer, New York 1997.

[19] Paris P.C., Erdogan F.: *A critical analysis of crack propagation laws*. Journal of Basic Engineering 1963, 85: 528–533.

[20] Feyrer K.: *Wire Ropes: Tension, Endurance, Reliability*. Springer 2007, https://doi.org/10.1007/978-3-540-33831-4.

[21] Van Zyl M.: *Discard criteria for mine winder ropes. Final Report GAP502*. Research Agency MIKE VAN ZYL INCORPORATED, SA 2000, https://mhsc.org.za/sites/default/files/public/research_documents/Gap%20502%20Discard%20criteria%20for%20mine%20winder%20ropes%20Report_0.pdf [1.02.2023].

[22] SABS 0294: *Proposed Code of practice for the performance, operation, testing and maintainace of drum winders relating to rope safety*. South African Bureau of Standards, SA Pretoria 1998.

[23] SABS 0293: *Code of Practice for the Condition Assessment of Steel Wire Ropes on Mine Winders*. The South African Bureau of Standards, SA 1999.

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