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EFFECT OF WIRE MATERIAL PROPERTIES ON WIRE ROPE USE

Key words: rope diagnostics, rope damage, wire rope, wire rope devices.

Abstract: Steel ropes cannot be refurbished through repairs, and wear processes during their use are cumulative. These processes include material fatigue, aging of the core, grease, and elements made of plastics, mass losses due to friction and corrosion, structural deformation, and changes in geometry. They are designed to perform specific functions under specific conditions. When the wear level is reached that significantly affects the safety of the operation of the equipment and of the operators, the specific elements of the equipment are replaced.
The objective of the paper is to present the results of material tests on steel rope strands operated in the design systems of the basic machines used in surface mining. The presentation is focused on the ropes used in bucket wheel excavators (BWEs). These are the basic machines in surface mines and their proper operation is highly important in ensuring continuity of mining.
The authors present the results of material tests on the basis of which the conclusions were drawn about the quality of the production of steel wires that affect the rope use process.

Wpływ własności materiałowych drutów na proces eksploatacji lin

Słowa kluczowe: diagnostyka lin, uszkodzenia lin, liny stalowe, urządzenia linowe.

Streszczenie: Liny stalowe są elementami nieodnawialnymi poprzez naprawę, a w trakcie eksploatacji podlegają procesom zużyciowym o charakterze kumulacyjnym. Procesy te to zmęczenie materiału, starzenie rdzenia, smaru i elementów wykonanych z tworzyw sztucznych, ubytki masowe poprzez starcia i korozję, deformacje struktury i zmiany geometrii. Przeznaczone są do wykonywania określonych funkcji w zadanych warunkach pracy. Po osiągnięciu poziomu zużycia mającego znaczący wpływ na bezpieczeństwo pracy urządzenia i osób obsługujących i korzystających z danego urządzenia są wymieniane na nowe. Celem artykułu jest przedstawienie wyników badań materiałowych drutów lin stalowych pracujących w układach konstrukcyjnych maszyn podstawowych w górnictwie odkrywkowym. Przedstawiony materiał dotyczy lin, które pracowały w koparkach wielonaczyniowych (BWE). Urządzenia te należą do maszyn podstawowych w kopalniach odkrywkowych i ich poprawna praca ma bardzo duże znaczenie dla zapewnienia ciągłości wydobycia. Przedstawiono wyniki badań materiałowych, na podstawie których sformułowano wnioski końcowe dotyczące jakości produkcji drutów stalowych mający wpływ na proces eksploatacji lin.

Introduction

Steel ropes used in bucket wheelexcavators (BWEs) work in pulley block systems intended for lifting and lowering the mining parts of large masses resulting from the weight of the mining unit and the drive.

Rope lifting systems are commonly used in this type of equipment in surface mining in various configurations [1, 2]. The essence of the work of these ropes is drum winding / unwinding. The rope, shortening or increasing its length in a pulley system, is running on the disks and is repeatedly bent on them. This operation is best done with ropes of relatively small wire diameters made of many strands with a linear contact, which are usually coiled on a steel core. These ropes have low lateral rigidness. In some types of mining machines and in stackers, statically working ropes are used, referred to as stays. Stay ropes ensure the stability of this equipment. Ropes with high lateral rigidness and the lowest possible unwinding moment are used. Such criteria are met by single-strand or locked coil (FLCR) ropes terminated with conical handles. These ropes work as strands loaded with longitudinal forces, often in very difficult environmental, load, and atmospheric conditions. The materials used for steel ropes feature high durability, because the working conditions in these devices are very difficult. It is related to the application of new technologies for the production of strands for ropes, the ropes, as well as quality control systems of the final product. The positive effect of these processes is evidenced by repeated bending, variable loads on ropes, and sometimes the twisting of ropes on the disks in the pulley systems. Long sections of ropes and the compact design of the rope system, especially in multi-pulley systems, create a problem when performing various types of revisions, inspections, and tests of these elements [3]. The correct operation of the ropes in this type of technical facilities and their operational properties must be maintained throughout the period of operation due to the safety of use and operating costs.

In technical facilities of such large masses and dimensions as the basic mining machines, the ropes, both working in the boom vertical movement systems and the sway ropes, determine the stability of the machine. Excessive wear of ropes and their improper use increase the risk of failure, which can cause irreparable damage to the entire machine. In critical situations, the ropes must be replaced immediately. Most often, however, this is related to the reaching of a certain level of wear. Wearing processes cause various types of damage during the use of ropes, and their knowledge allows for safe use and rational management of rope replacement. In the further part of the work, the systems of pulley blocks and the factors that affect the durability of ropes are discussed in general. With the ropes put away as a result of excessive wear, metallographic examinations of sections with the strongest wear, and reference sections were performed. Metallographic examinations of strands of used ropes are relatively rarely performed, although the quality of strands largely determines the future performance of the ropes. The results of the tests presented in the article gave the basis for formulating conclusions on the wear processes in ropes of bucket wheelexcavator systems, with particular emphasis on the quality of strand production.

1. Rope systems in surface mining machines

The pulley system is a set of discs placed on a common axis as one movable and one motionless block in which the rope travels (wraps) around the discs. As a result, there is a change in the position of the movable block; and, depending on the number of rollers, the benefit is that it can lift larger masses than would result from the breaking force of a single rope. Thus, pulley systems can be designed for very large loads, and this is determined by the number of branches of rope strings used in the block system. In consequence, loads can be achieved up to thousands of tons, as with the largest cranes, e.g., for putting up drilling platforms. The appropriate flexibility of the system is ensured by cooperating steel ropes of specific design. The main disadvantage of the multi-disc system is in large dimensions and masses of the elements, mostly depending on the diameter of the ropes used. The rope design has a major effect on the service life of the entire rope system. The process of rope wear in pulley systems depends on many parameters, including the diameter of the discs, the construction method, the dimensions of the rope groove, and the bending direction. The latter factor is presented in Figure 1.

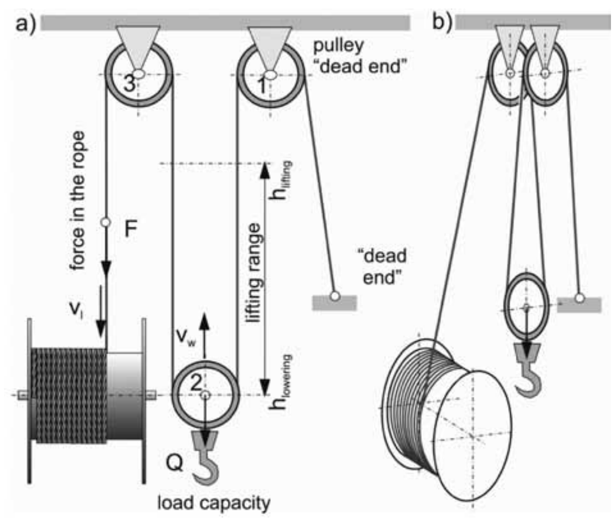

Fig. 1. Basic pulley block systems with a single rope: a – the rope bent in two directions, b – the rope bent in one direction [4]

During the movement of the bucket wheel excavator (lifting or lowering), the length of the rope section changes between the individual disks. As a result of changes in the length (shortening or lengthening) of the individual sections of the rope, an additional moment of turning is created. The value of the moment of rope untwisting increases during the shortening of the length of its section (the distances between the rope wheels). When the value of the moment of turning is greater than the moment of friction on the rope wheel, the rope twists and the moment of untwisting decreases. At the same time, the rope's lay length in the other branch of the rope decreases. In the area of the upper rope pulleys, further sections of the rope feature an increased moment of turning. As a result of this phenomenon, there is a differentiation in the length of lay length of the ropes working in their respective branches. This applies to practically all wire rope designs operating in pulley systems. The mechanism that lay length to the change (differentiation) of the length of lay length of the rope operating in pulley systems is shown in Fig. 2. This mechanism has an effect on changes in the angles of the inclination of wires in strands and also introduces additional variable tangential stresses that accelerate the fatigue wear process.

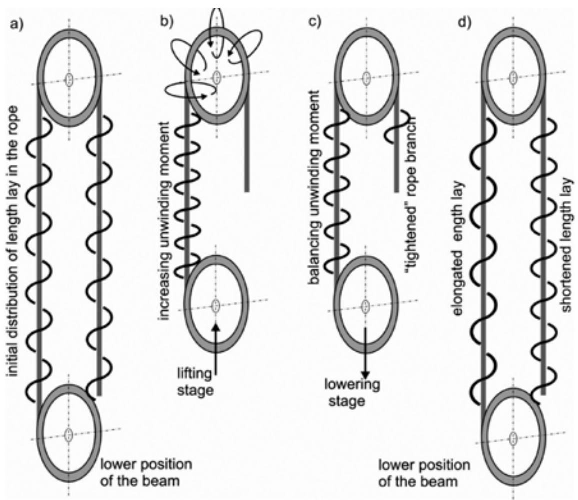

Fig. 2. Differentiation of lay length in wire ropes working in pulley systems; *a* – uniform distribution of lay length in all sections of the rope, *b* – shortening of the lay length along with shortening of the rope branch, occurrence of increased unwinding, *c* – when unwinding force is larger than moment of friction on the rope pulley, the rope twists and the other branch of the rope is tightened, *d* – stabilisation during the downward travel, with different rope l lay length

The cyclic change in the lay length has, therefore, a significant impact on the formation of local fatigue failures. The change in the lay length in a given branch is dynamic and results from the scope of operation of the pulley system. This lay length leads to local damage in the sections with the greatest change in the lay length [5]. In consequence of the mechanism that adds variable shear stresses, this factor has a significant impact on fatigue durability due to the change of lateral rigidness. The extension of the lay length causes the gaps between the strands to decrease and the rope rigidness increases. Such a change in rigidness increases the values of stresses from bending. The shortening of the rope lay length causes the destruction of the rope core and the increase of stresses from tensile forces in the rope wires as shown in Figure 3.

Ropes in which the length of the lead changed locally have a different modulus of elasticity in different sections. They also wear faster, because their changed lateral rigidness and lay length produce the frequent occurrence of spiral deformation (the corkscrew) and the "basket" deformations. In pulley systems, these deformations are very common and constitute one of the main reasons for the protection of such ropes.

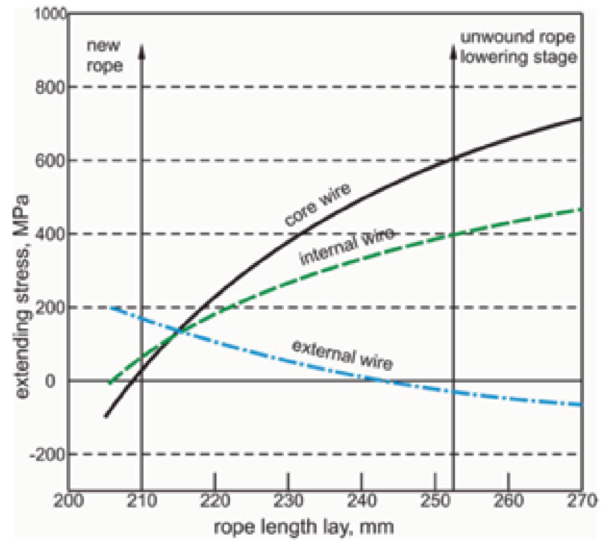

Fig. 3. Expanding stresses in rope wires dependent on change in rope lead

This has a fundamental impact on the distribution of rope wear along its length, because the sections of the rope moving at higher speed will be subject to more bends. In the zones of rope bending, energy dissipation occurs due to deformations of the wire of the rope and friction losses during the movement of the wire strands relative to each other. It is on the discs that fatigue wear occurs in the form of wire cracking as a result of bending. The wear of ropes on the pulleys is also due to the vibrations of individual strands that arise at the moment of stopping or starting operations. The rope sections that are next to each other and on the track of the rope rollers (wheels) are exposed to fatigue, plastic deformation, and fretting. These sections then wear down similarly to the wear of stay ropes, that is, at the ends (in the support points).

Stay ropes are also subject to wear processes but of a radically different nature. The main factor is corrosion and the cracking of individual wires around the conical handles. The main drawback of the stay systems in bucket wheel excavators is the unevenness of the loads of ropes operating in parallel. The result is a non-linear extension of wire ropes under load. In ropes, like in other objects, non-linear wear occurs [6]. This factor depends very much on the properties of the rope, such as the tensile strength of wires, the type of design, the compactness of the structure, or environmental factors such as humidity and temperature. Each rope, having a different modulus of elasticity on which depends the rigidness of the rope, is elongated by a different length. This parameter consequently leads to the differentiation of loads in stay ropes. The equation for the absolute elongation depending on the initial parameters of the rope is as follows:

$$\Delta L = \frac{F}{E \cdot S} \cdot L_0 ,$$

where
ΔL – absolute elongation, mm,
F – longitudinal load of the rope, N,
E – longitudinal modulus of elasticity, MPa,
S – cross section of the rope, mm^2,
L_0 – initial length of the rope, mm.

Stay rope systems where there is an uneven load are more likely to fail. Therefore, in practice, it is necessary to strive for balancing loads in stay systems. This problem in parallel stay systems is solved by the following:
– The construction of independent tension systems,
– The construction of systems for compensating the elongation of individual stay ropes,
– The pre-tensioning of ropes, and
– The use of ropes with very high values of safety coefficients.

It is necessary to precisely make ropes and pre-stretch them for use in the stay systems of bucket wheelexcavators in surface mining. This is achieved in the process of the production of stay ropes; however, the result may be neutralised by deformation during transport, winding ropes on drums with improper diameters, etc. Stay systems can only work properly in conical handles in which the possibility of length differentiation is minimised. The difference in the length of the rope sections affects the value of the loads transferred by individual ropes as shown in Figure 4.

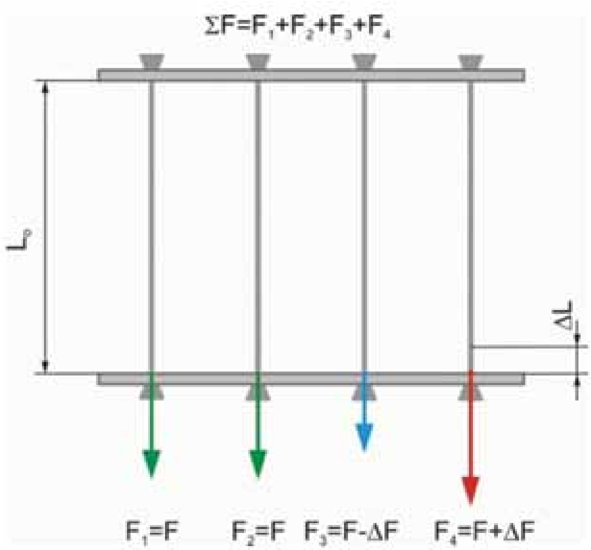

Fig. 4. Effect of the length of the rope in parallel systems on the loads

The figure above shows the situation in which two ropes were loaded with the same force F, the third rope was loaded with a lower force (F-ΔF), and the fourth rope was, in consequence, overloaded (F + ΔF). Such a case of uneven load can in fact be found only by measuring forces in ropes.

Twisted (spiral, closed, or semi-closed) ropes have a much larger rigidness modulus compared to wire ropes, and it is in a much wider range of variations depending on the design, material for wires, production technology, etc. All in all, the wire geometry determines this, wire execution, diameter, etc. in the individual layers. In multi-rope systems, a lower value of the elastic coefficient causes greater elongation at the same load, and vice versa. Stay ropes must be made precisely, the length must be measured to millimetres, and their transport and installation must be properly supervised, so that their geometry is not affected. Changing the geometry causes a change in the diameter of the rope, the wires move, and this generally disrupts the rope's structural parameters. Changing the rope geometry caused by the change in rope lay length affects its fatigue resistance and determines the change in the value of the elastic modulus [7, 8]. The varied length of rope sections is also a cause of different loads in ropes. This has a major impact on the forms and characteristics of vibration of ropes in the individual stays. In practice, in most cases, the vibrations of stay ropes are caused by the oscillation of the lower anchor point. For such a system, the following methods of vibration reduction are possible:
– Vibration damping in the place of the lower fixing,
– A change in the natural frequency of ropes, and
– Increasing the internal damping coefficient.

These vibrations cause a bending moment, the highest value of which occurs in the area of the lower handles, as a result of which the rate of fatigue wear in these places is greater. This is particularly dangerous due to the difficulty of observing damages in this place, which are hidden in the conical handle.

2. Material tests

The authors of this paper obtained sections of ropes of various wear characteristics during the replacement of stay ropes in one of the bucket wheelexcavators working at KWB Bełchatów, and we had the possibility of performing comprehensive tests. The replacement of the rope set was made after finding numerous cracks in the area of the lower conical attachment of the ropes. The non-destructive testing carried out before removing the ropes, performed with visual and ultrasonic methods, allowed us to conclude that the damage occurs both in the outer layer of ropes and in the inner layers, and it is located in the place right after the entrance of the rope to the conical holder. Sections of stay ropes were selected for testing, and the sampling locations are shown in Figure 5.

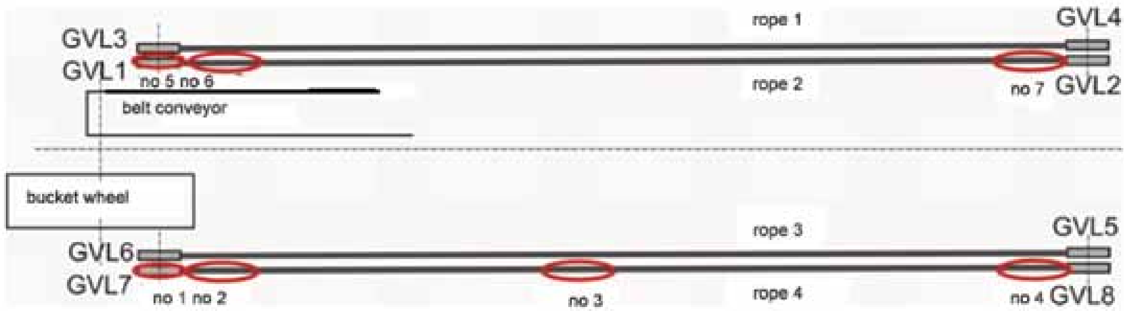

Fig. 5. The stay rope system with the marked places of rope sampling for strength and metallographic tests [9]

The samples for further testing were identified as follows:

Section No 1: the GVL7 thimble cone, in which there were a total of nine broken wires,

Section No. 2: the rope with a fragment of the GVL7 thimble cone,

Section No. 3: the sample of the rope from the central part, without any damage,

Section No. 4: the rope with a fragment of the GVL8 thimble cone,

Section No. 5: the thimble cone of the GVL1 thimble,

Section No. 6: the rope with a fragment of the GVL1 thimble cone,

Section No. 7: the rope with a part of the GVL2 thimble.

The provided sections were prepared for strength and metallographic tests. It is interesting to note that, during these works, the rope design was found to be different from the entries in the documentation of the machine from which they were removed. The stay ropes used in the bucket wheel excavator featured different diameters of round wires, different heights and widths of shaped wires, as well as one layer of wires less than specified in the documentation. These structural parameters have a fundamental impact on the transverse rigidness of the rope and its flexibility. In this case, these parameters were changed to a substantial extent, which could have affected the premature rope replacement. During the preparation of the samples for the testing, each layer of wires was labelled as shown in Figure 6. It was also found that there was excessive elastic energy, as apparent from the "broom effect" shown in Figure 7.

Material tests were carried out on the sections of the ropes shown in Figure 5 as Nos. 2, 3, 6, and 7. Samples for testing were properly prepared and the microstructure assessment and the resulting wire cracks were performed [10]. In addition, structural tests were carried out and the chemical composition was examined. The largest number of tests of samples was performed for Section 2, in which the largest number of damages was found at the stage of sample preparation. A total of 62 test samples were prepared for this section. A much

Fig. 6. The stay rope cross sections: after cutting off the thimble (left) and with the marked layers of wires to be included in the testing (right) [9]

Fig. 7. The "broom effect" after cutting off the layers of the wires [9]

smaller number of samples (23 pieces for each section) were prepared for the remaining sections of the ropes.

The preliminary inspection was carried out for the samples provided to select the samples with visible distribution fracture on a part or in the whole cross-section (tearing).

As a result of the metallographic examinations, the largest number of the defects of this type was found for Section 2, in which there were numerous distribution and tearing fractures on a fragment or in the whole cross-section. Only in Section 3 was there no tearing or fractures found in any of the examined layers of wires.

In Section 6, numerous cracks and tears were observed in each layer examined. Fig. 8 presents the microstructure of the breakthrough for a torn sample from Section 6 in the layer of shape wires. The observed fractures were partial in the wires with a circular cross-section and similar in shape to the letter Z (Z wires).

No fractures or cracks were found in the wires prepared from Section 7. After this examination, 3% etching and observation were performed under a light microscope, where a very fine pearlitic structure was observed in the wires. The structure was homogeneous and indicated that it was a typical microstructure of the wire from which ropes with high mechanical properties are made. Only in a few places on the fractures was the presence of small areas (grains) of the ferrite found. A pearlitic structure indicates that the tested wire was made of steel with eutectoid composition (C = 0.77 % wt).

Fig. 8. Crosswise cross-section of the shape wire with visible micro cracks [11]

In shape wires, areas of plastically deformed pearlite were observed (Figure 9). These deformations indicate that the Z shape of the wires was provided after the pearlitic conversion in the patenting process. Microcracks were observed in the area of the deformation of the pearlite structure.

The microstructure of the fragments of the anticorrosion galvanic coating for the tested wires was examined. In the wires from the outer layer, numerous cracks propagating from the steel / Zn layer boundary into the steel were observed, which is the result of the mechanical fatigue processes during operation. The propagation direction of the fractures was both parallel and perpendicular to the boundary. The shape and size of the cracks observed on the fractures perpendicular to the wire axis are varied. Selected fragments of the examined sections are shown in Figures 10 and 11. In many cases, the propagation of the fractures along the boundaries of a few ferrite grains in the subsurface areas was observed. Moreover, numerous delaminations (separation of the Zn layer from the base) on the upper Zn / steel layer were noticed. Strong cracks were reported in all of the analysed areas of the near-surface Zn samples. These cracks, in the presence of a rather complex condition of stresses that could have occurred, especially in the outer layers of the rope, may be the originating points of fatigue cracks.

The analysis of the chemical composition was carried out with an analyser (SEM-EDS) of X-ray characteristic radiation energy induced in the sample by an electron beam. Selected analyses of the chemical composition are shown in Figures 12 and 13.

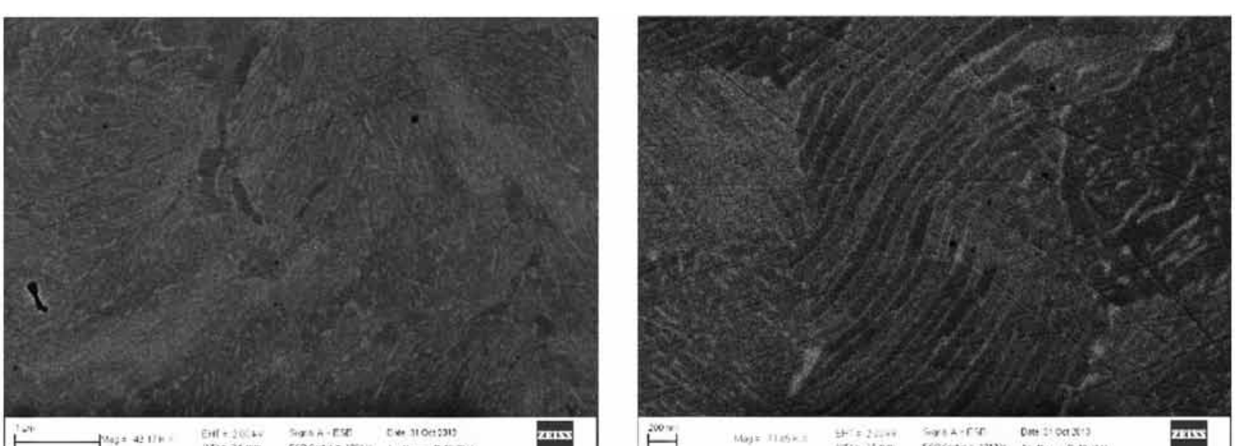

Fig. 9. Transverse cross-section of non-etched shape wire with deformed pearlite [11]

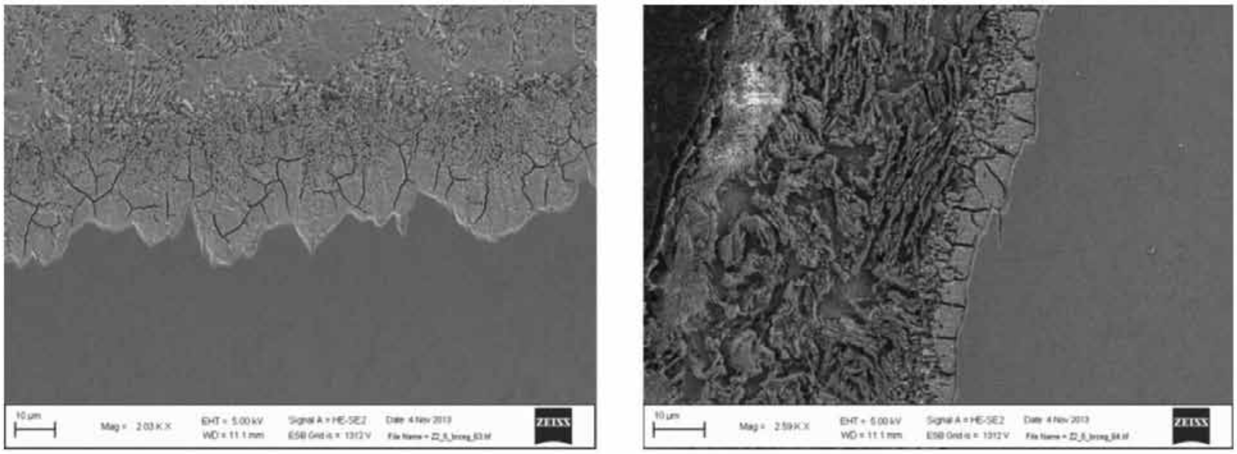

Fig. 10. Transverse cross-section, non-etched, with visible structure of the Zn layer with numerous microcracks [11]

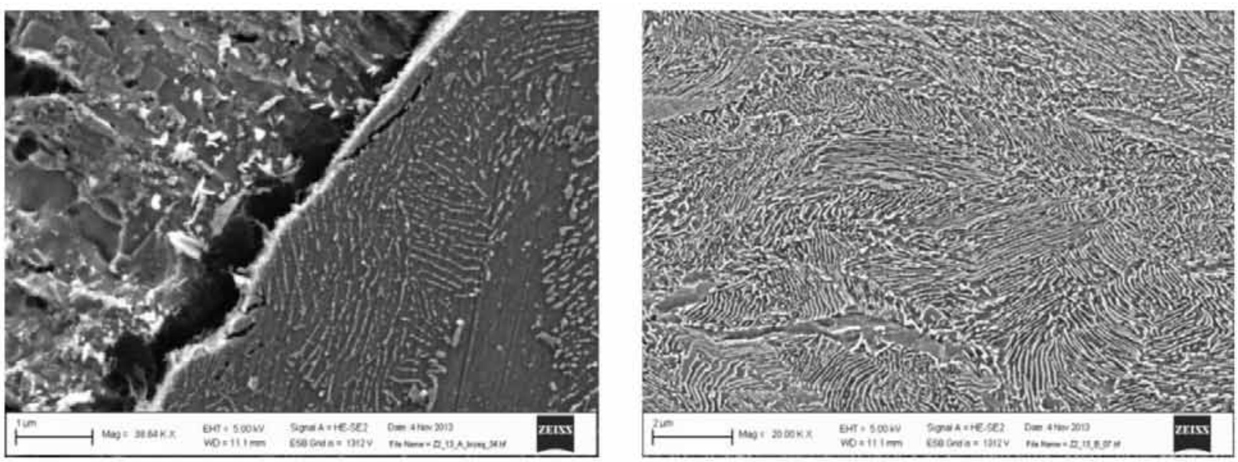

Fig. 11. Transverse cross-section, etched, with visible pearlitic structure and lamination in the surface area with the zinc layer [11]

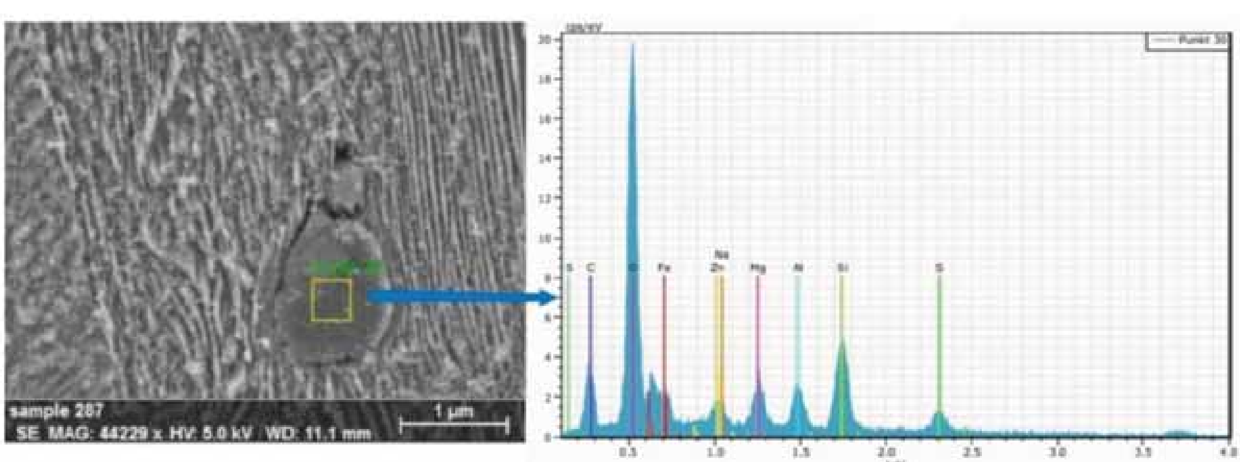

Fig. 12. Transverse cross-section, non-etched, and its analysis of the chemical composition with non-metallic inclusions, with the x-ray radiation energy spectrum [11]

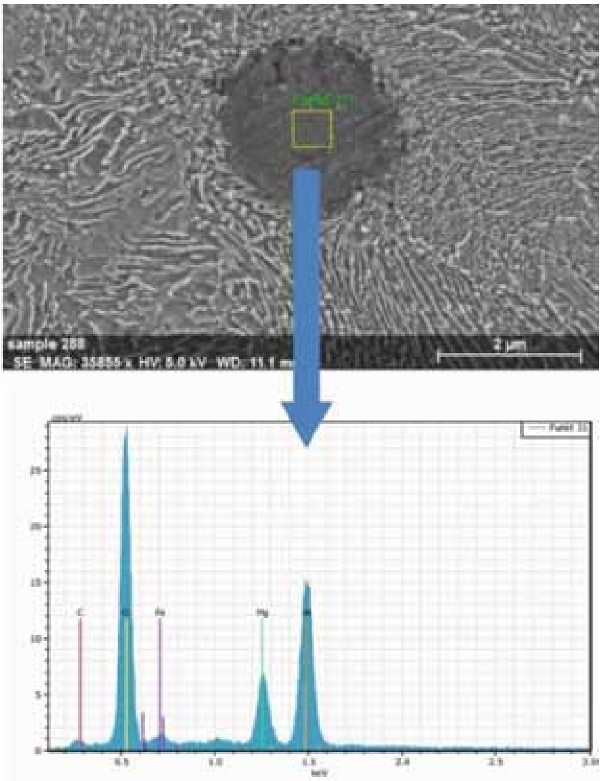

Fig. 13. Transverse cross-section, non-etched, and its analysis of chemical composition with inclusions, x-ray radiation energy spectrum, SEM+EDS [11]

The analysis carried out on a larger area showed the presence of such elements in steel as manganese, silicon, and carbon. The analysis of the chemical composition of the galvanized layer on the surface of the wire was also performed. The chemical analysis confirmed the presence of Zn only in the surface layer. The analysis of non-metallic inclusions present in the steel showed them only to be manganese sulphides.

Summary

On the basis of the quality assessment, it was concluded that the material for the wires from which the stay ropes of the bucket wheelexcavator were made was of ordinary metallurgical purity, in terms of the number of non-metallic inclusions. The non-metallic inclusions present in the steel are mainly manganese sulphate (MnS). They do not have much effect on the strength properties and durability of wires.

The very fine pearlite microstructure (visible only under the scanning microscope) is correct for such structural elements as wires for steel ropes. This structure, obtained after patenting by the manufacturer of rope wires, proves the eutectoid composition of steel (C = 0.77% by weight). This structure was found in all of the wires from which all of the excavator's stay ropes were made. The analysis of the chemical composition of the material from which the excavator stay ropes were made revealed the presence of only basic elements, such as C, Mn, and Si. The very fine pearlite structure in all the examined wires is homogeneous, which indicates that it was visible only under the scanning microscope and not under the light microscope.

The metallographic examinations resulted in the conclusion that the very fine pearlitic structure indicates a small gap between the Re and Rm boundaries in the tension characteristics of the wires. Therefore, in the process of rope production and the application of successive layers of Z-shaped wires, the yield strength Re was not reached. In reference to the above, the shaped wires from which the stay ropes were made were deformed only elastically. The cracking wires moved and resulted in the disturbance of the heliacal system structure over a considerable length of the rope.

The microstructure observed in the cross-section (fracture) transverse to the wire axis is homogeneous. The areas visible in the etched fracture are those of plastically deformed pearlite for the Z shaped cross-section wire samples. This deformation is the result of cold forming after the patenting, giving the Z shape of the wire's cross-section.

Numerous microcracks propagating from the Zn / steel layer deep into the steel from the boundary are most frequently observed in the samples from the external layers. These are fatigue effects, as a result of the wire operating in the three-axis condition of cyclic variables.

The examinations have shown that the stay ropes used in the basic machines in surface mining wear only around the lower thimbles, and wire cracks occur in the outer layers.

In the operational practice for stay ropes, these cracks are caused by the vibrations of the rope of low rigidness and the occurrence of large bending moments in the end (the conical handle). We are dealing here with a complex stress condition, which causes a reduction in rope durability. As a result, the application of even very high quality wire materials does not provide protection against accelerated wear, because the rope structure may be changed or additional operational loads may occur, e.g., the vibrations of unequally loaded branches of ropes in this case.

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