

ERYK REMIORZ<sup>1\*</sup>, STANISŁAW MIKUŁA<sup>1</sup>**THE SYNERGY OF FATIGUE, CORROSION AND ABRASIVE WEAR PROCESSES  
IN OPERATION OF MINING ROUND LINK CHAINS**

The mutual influence of fatigue processes, abrasive wear and corrosion of chain links on the functional properties of mining round link chains has been presented in this paper. Selected results of experimental investigations in the field of synergic impact of these destructive processes on the operational durability of mining chains have also been presented. The emphasis was given to the necessity of a comprehensive consideration of destructive processes that occur in various conditions of use of round link chains applied in mining machines.

**Keywords:** round link chain, fatigue cracks, corrosion, abrasive wear

## 1. Introduction

Mining round link chains are widely used in longwall machines such as scraper conveyors, coal ploughs and some longwall shearer constructions. In a longwall with a length of 300 meters equipped with a double-chain scraper conveyor and a coalplough, there are about 1800 m of round link chain. Assuming that the scraper conveyor is provided with a commonly used 34×126 chain and the plough haulage mechanism uses a typical 42×137 chain, the longwall contains almost 50 tons of round link chain made of high-grade steel. In case that a flat chain 48×152 [1] is used in a longwall scraper conveyor, the total weight of the chains in the longwall would increase to approximately 78 tons.

In the exploitation of mining link chains, three main destructive processes are distinguished, usually occurring at the same time, leading to degradation of functional properties and premature

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elimination of chains from use [2]: fatigue destruction, abrasive wear and corrosion processes. The abovementioned mechanisms of operational vulnerability combine a specific synergy characterized by a high complexity of mutual influence.

While fatigue processes are always and frequently occurring at high intensity, which results from the nature of the work of haulage chain of mining machines, abrasive wear, in particular, corrosion destruction, takes place in a very diversified range depending on the working conditions of the machines. Also, chain failures may occur under the influence of massive quasi-static overloads in cases of, for example, sudden blockages of chain haulage systems of mining machines. Currently, in connection with the use of mining chains made of high-strength alloy steels, with increasingly larger load-bearing cross-sections of links, with adequately conducted mining exploitation the static or quasi-static chain breaks occur rarely for example in emergencies. Such breaks are usually accompanied by large plastic deformations of the haulage chain over a relatively long section.

Fatigue destruction, unlike other forms of destruction of mining chains in exploitation conditions, is characterized by the fact that fatigue cracks develop in a way that does not give visible external symptoms, they occur practically without measurable deformations, which could be symptoms of progressive fatigue process. Also, the fatigue properties of chain links, as shown by numerous tests, are characterized by an unusually large dispersion of durability parameters, much higher than in the case of static breaking strength, abrasion resistance, and corrosion deterioration.

The fatigue breakthrough of one of the links of the entire long mining chain causes a sudden, forced stoppage of the machine and consequently the whole coal extraction system, while corrosive destruction and abrasive wear are of a time-increasing nature and do not cause an emergency, even if in extreme cases also lead to breaks.

Due to the classical form of the serial reliability structure of haulage chain, the useful properties of the entire long chain are determined by the elements with the lowest properties. Components of the haulage chain structure having the highest fatigue properties in the serial structure can never be entirely used. The described situation leads to a rational statement that the fatigue properties of the elements of the haulage chain should be given particular attention at the design, production and operation stages. Also, diagnostic methods of technical condition assessment should be directed to fatigue properties of all elements of chains: regular chain links and all types of connecting links that carry the full loads in any mining machines. It should be additionally taken into account that with increasing length of haulage chains, growing size of links with transport limitations in mining excavations, a constant increase in the number of connecting links in the entire chain is observed. Fatigue properties of connecting links, strongly dependent on their design, are usually significantly lower than the fatigue properties of chain links. The fatigue life of connecting links determined in normalized test conditions is also characterized by a broad dispersion of test results [3].

The dispersion of fatigue properties of chain links and connecting links, similar to the fatigue dispersion of other machine elements, is high due to the strong influence of many factors on the incubation process, microcracks development, critical gap propagation and the final fatigue breakthrough of the machine element [4]. Many of these influential factors are characterized by a strongly stochastic character resulting from the mechanism of fatigue destruction of construction materials. The additional influence of constructional and technological factors in the case of machine elements causes that there is always a certain probability of unfavourable composition of many different circumstances, which influencing in total actively reduce the properties of certain elements of the serial reliability structure with a large number of components.

The currently used chain haulage systems of mining machines based on round link chains do not allow the use of a parallel or mixed reliability structure, as is the case in a number of technical solutions in other areas, such as multi-line hoisting systems or multi-way drive systems. In this situation, the problem of fatigue processes co-occurring with corrosion damage and abrasive wear should be given special attention, using the widest possible range of possibilities to improve the service life of mining chains with construction, material, manufacturing and operation technologies using effective technical diagnostic methods.

Understanding the mutual impacts of fundamental destructive processes is of great importance, as striving to improve the usability of mining chains due to one destructive process can often have, as experience shows, a negative impact on other properties, also crucial due to the overall durability and operational reliability of haulage chains.

These issues were reflected in many projects carried out at the Department of Mining Mechanization and Robotisation (former Institute of Mining Mechanization) of the Silesian University of Technology. This article discusses selected issues in this field, with a particular focus on the synergy of fatigue phenomena, abrasive wear and corrosion processes as well as diagnostics of haulage chain under operating conditions.

## 2. Fatigue life of mining chains under corrosive conditions

High corrosion properties often characterize the environment in which the mining chains and connecting links are used. The environmental corrosiveness of underground coal mines results from high relative humidity, the presence of saline water reservoirs, elevated temperature, the presence of active compounds in the coal and other factors. In the case of using the blasting technique, additional corrosive actions result from the presence of aggressive post-blasting gases, which in combination with high air humidity additionally intensify the corrosion processes.

The mechanism of development of fatigue cracks under corrosive conditions has been the subject of many projects, mainly about construction materials, but there are no extensive tests of fatigue behavior co-occurring with corrosive interactions in the case of machine elements taking into account structural and technological factors. This applies in particular to elements of mining haulage chains made of special steels using special technological treatments.

Mining chains are subjected after heat treatment to a particular treatment called calibrating, which consists in inducing significant cold plastic deformation in the links, as a result of which a permanent state of high residual stresses is formed with a complex distribution. There are known cases of so-called corrosion cracking of chain links under the influence of internal stresses and corrosive interactions even without the participation of external load, for example in storage conditions or during longer breaks in work.

Corrosive interactions in the area of the progressive front of fatigue cracking of iron alloys can have a different effect on its development, most often strongly activating cracking. The impact of crack growth called the Rebinder effect depends on the particle size of the corrosive environment, the state of stress, the chemical composition and the structure of the steel. The Rebinder effect also occurs when the environment in which the machine elements work does not show any direct significant corrosive effects. Corrosion products that are forming in the already existing crack have a volume larger than the volume of the crack. This phenomenon additionally intensifies the effect of growth the fatigue crack.

In corrosive conditions, the fracture toughness of steel deteriorates sharply, the measure of which is the critical stress intensity factor  $K_{IC}$  [5]. The crack size is directly related to the  $K_{IC}$  value of the material, at which a total breakthrough at given stress in the load-bearing cross-section of the element occurs.

An exemplary dependence of the influence of 3,5% aqueous NaCl solution on the  $K_{IC}$  value for a steel alloy similar to the steel used for mining chains is shown in Figure 1 [6]. Deposit waters of hard coal mines often contain NaCl and other salts with similar activity and very different concentrations [7].

To determine the effect of NaCl content in the water on the fatigue life of mining chains experimental tests were carried out using a unique chain holder with a flexible cover into which the NaCl aqueous solution with different concentration was introduced (Fig. 2). The tests were carried out at a normalized level of variable loads with the frequency 8,3 Hz, realized by a testing machine type ZD100 Pu/A with a hydraulic pulsator. The number of fatigue cycles for full fatigue fracture of one of the links of five-links chain samples was counted. The holder is shown in Figure 2. It also allows the testing of fatigue life in a liquid corrosive environment with additionally blown compressed air. Due to the vibrations caused by variable loads, the solution inside the cover of the holder was intensely mixed. At the same time, the temperature of the solution was recorded which, due to variable loads, mixing the solution and the development of fatigue cracks, increased monotonically.

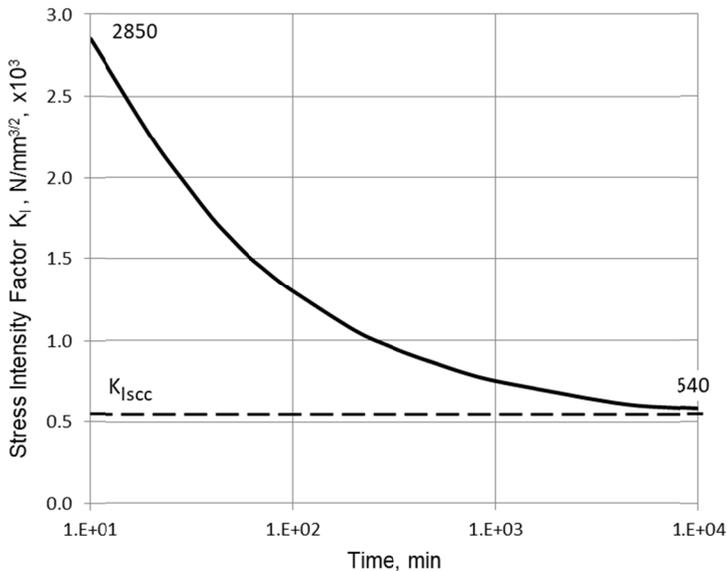


Fig. 1. Influence of the action time of an aqueous solution of 3.5% NaCl on the value of critical stress intensity for steel on mining chains

Figure 3 presents exemplary results of fatigue tests of the chain link samples in the NaCl aqueous solution environment. The attention is drawn to the substantial decrease in fatigue life of chains treated with the NaCl solution and the increased spread of the test results. The fatigue

breaks of chains in a corrosive environment occurred mainly in the transition zone of arches into the straight sections of links with fatigue centers located inside the link profile, while at the same time increased the number of breakthroughs in the axis of links and the zone of welds. During the tests, the temperature of the system on the surface of the flexible cover of the holder in relation to the ambient temperature was measured (Fig. 4). There was a significant increase in the temperature of the solution during fatigue tests in the period of fatigue crack development, which indicates a substantial process of energy dissipation during fatigue chain cracking, especially in the final period of fatigue cracks in the chain samples. Some increase in temperature following the break of the chain link results from the heat being taken up by the solution from the crack zone.

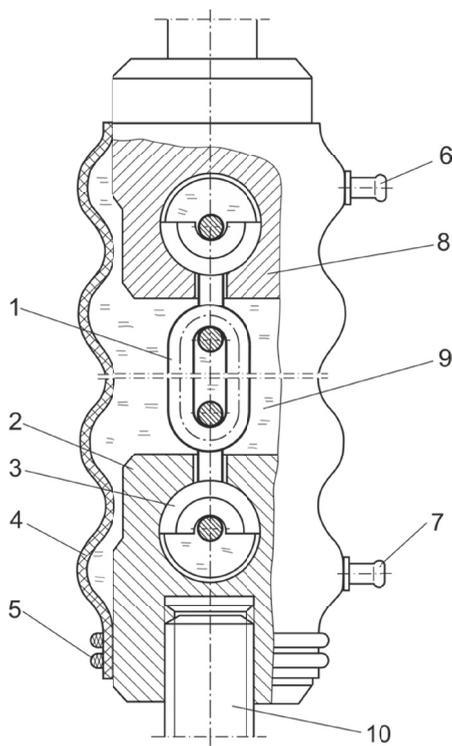


Fig. 2. Special holder for testing strength properties of link chains in a corrosive environment:  
 1) chain sample, 2) bottom hull, 3) half-link fastening, 4) rubber cover, 5) pressure rings,  
 6),7) inflow and outflow of corrosive agent, 8) top hull, 9) space filled with a corrosive environment,  
 10) screw fastening the holder to the testing machine

Due to the short testing time (several hours), and therefore the short time of the corrosive environment used in the research, the observed corrosion losses of the chain links material were negligible, regardless of the concentration of NaCl in the water.

The problem of anticorrosion protection of mining chains has been the subject of many projects carried out in various universities and chain manufacturers. Hot-dip galvanised chains with increased corrosion resistance especially in the presence of reservoirs containing chlorides

and sulfur compounds are offered for use. However, the use of hot-dip galvanising in addition to a significant increase in costs is associated with a drop in breaking strength and fatigue life tested in standard conditions in atmospheric air. The ecological aspect is also essential, the abraded zinc layer gets into the coal, and after burning together with the exhaust fumes pollutes the atmosphere. Zinc as one of the heavy metals with increased concentration poses a threat to human health.

Another solution is the use of coatings containing zinc powder in suspensions of organic compounds. The agent increasing the corrosion resistance of mining chains and reducing the friction resistance is phosphating, which is useful especially at the initial stage of use and in storage conditions [3].

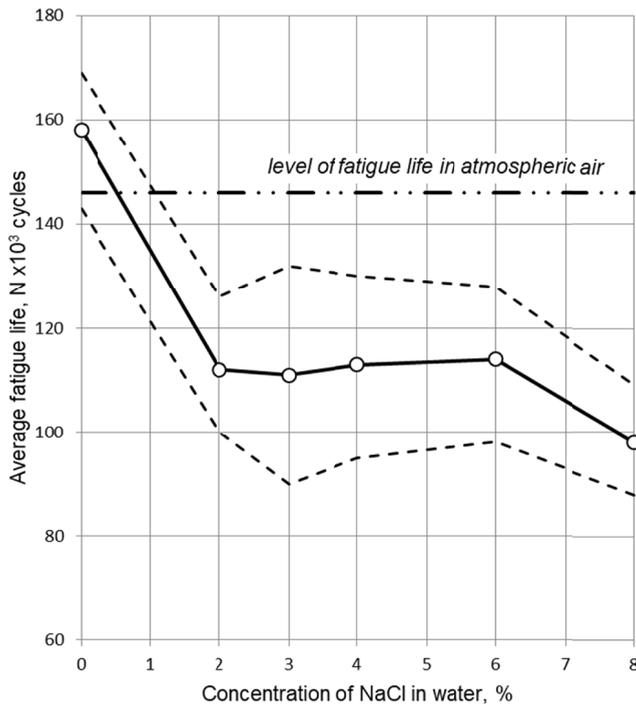


Fig. 3. Results of studies on the effect of NaCl concentration in water on the average fatigue life of five-link chain samples size  $\varnothing 18 \times 64$ ; the scatter of the test results is marked with a dashed line

Figure 5 presents the results of investigations on the impact of mine water exposure time on fatigue life of phosphated chains, phosphated after previous shot peening and chains without protective coatings for fatigue life of chains [3]. The phosphating treatment is simple and carried out at the temperature of  $95 \div 98^\circ\text{C}$  so it can be easily repeated in the course of operation, for example during the allocation of wall equipment to a new longwall.

Attempts to cover the chains with agents based on organic compounds, ultimately forming a protective layer with a waxy consistency are at the stage of testing. In the case of covers of this type, other critical functional properties should also be expected to deteriorate. Investigations show that chains coated with TECTYL show a decrease in static breaking strength by  $7 \div 8\%$ ,

decrease in elongation breaking by up to 28% and a significant reduction in fatigue life determined in standard conditions [8].

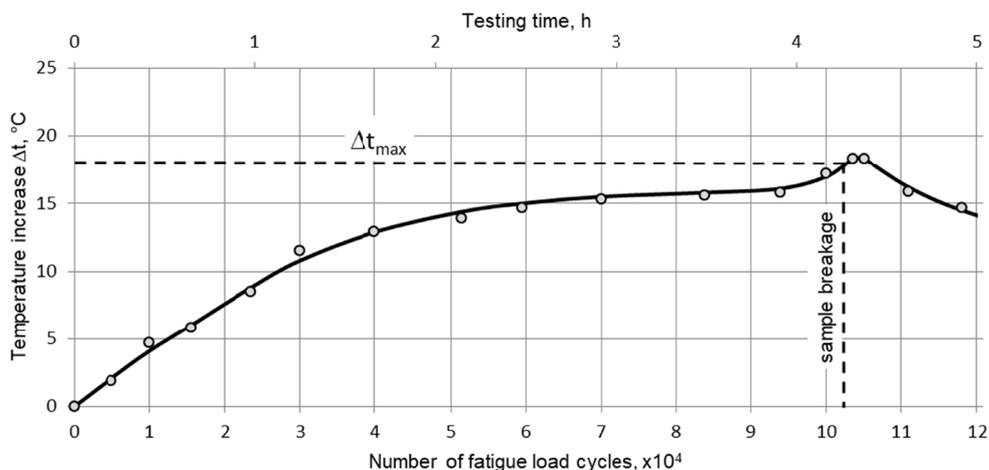


Fig. 4. Example of the course of the temperature increase measured on the surface of the device for chain samples fatigue tests in corrosive conditions as a function of the number of load cycles from the start of the test to the full fatigue breaking of the chain size 18×64 class C

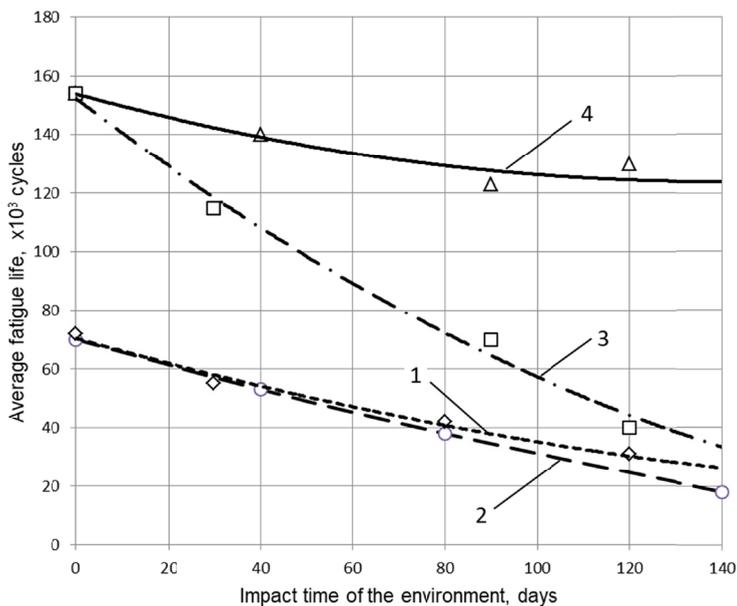


Fig. 5. Influence of the duration of the corrosive environment of mine water on fatigue life of chains subjected to various treatments: 1) chains serially subjected to constant atmospheric conditions and periodic exposure to mine water, 2) chains serially treated with mine water, 3) shot blasted chains not subjected to any corrosion protection, 4) shot-blasted and then phosphated chains

A new proposal to improve the resistance of mining chains to corrosive interactions in the presence of NaCl aqueous solutions is the application of Zn-Al coatings to the surface of chain links treated as the final treatment of the mining chains production process. Two-stage dip coating of chains in Zn-Al bath with 5% Al content allows obtaining excellent corrosion protection effects tested in a standard salt chamber in which the NaCl solution was sprayed in the water wetting the surface of the 23HGNMA steel chain size  $\varnothing 18 \times 69$  [9]. The two-stage coating, in this case, consists of pre-dip coating in a Zn bath, and then in a bath with a eutectoid composition containing 5% Al for a treatment time of 30 seconds in each bath. The layer obtained in this way, with a variable chemical composition, showed better resistance to penetration of the anti-corrosion coating than conventional zinc coating, even after 1000 hours of testing in a salt chamber. Noteworthy is the short treatment time and its high efficiency, despite about three times lower layer thickness than in the case of a typical galvanising. In this case, it is expected to have a smaller impact on the structural changes of the chain links material and relaxation of internal stresses in the links formed during the process of chains calibration. The lower consumption of zinc also leads to a reduction of costs and a reduction of the ecological hazard. There is a need for more extensive experimental and operational tests in this area.

In the described situation, the problem of adequate and acceptable for technical, economic and ecological reasons a way to improve the durability of mining chains under the corrosive conditions that take place in many coal mines remains to be solved.

### **3. The impact of abrasive wear on the durability of the mining chain links**

Abrasive wear often accompanies fatigue failure. Both destructive processes enter into complex relations, usually intensify each other, accelerating the degradation of useful properties of the mining haulage chains. Cases, where wear processes increase fatigue life, are rare and can happen, for example, when moderate abrasion processes remove this surface layer of an element in which fatigue microcracks are nucleated. If only wear losses in the area of cross-sections carrying loads are considered, for example, wear losses on straight sections of chain links may even cause some increase of breaking strength, regardless of whether they are one-sided or double-sided. Wear losses in the joints of the links always significantly reduce the strength of the chains and their fatigue life [3].

The proper cooperation of chain links with the teeth of sprocket also has a significant impact on the wear of the haulage chains of the mining machinery. This problem is presented, for example, in the works [10-14].

The coexistence of abrasive wear and fatigue was the subject of many experimental studies carried out at the Faculty of Mining and Geology at the Silesian University of Technology. Figure 6 shows an instrument cooperating with a hydraulic pulsator enabling fatigue tests of chains with frictional wear in cell joints. At low spring tension (3), a classic fatigue test is carried out simultaneously with two chain samples, which allows direct comparison of two material variants or subjected to various technological treatments. At the given increasing spring tension as a result of variable loads, the cyclic chain deflection of the links in the joints occurs. When the loading force of the fatigue cycle is tending to a minimum, the chain samples are deflected, while as the force increases, the "straightening" of the chain sample takes place, thus imitating the behaviour of the chain links on the sprocket. By choosing the relation between the spring tension and the

amplitude of the loading force, it is possible to directly assess the fatigue and wear properties of the two chain samples for example with various anti-wear coatings.

Another test stand that allows testing abrasive wear phenomena in joints involving fatigue and the ability to take into account the effect of corrosion is shown in Figure 7 [15]. When rotating the element (5), cyclic deflection of two chain samples occur depending on the length of the element arm. The chain samples are simultaneously stretched longitudinally by the lever system (4) with a constant force depending on the weight of the weights or with the variable force provided by the corresponding electrohydraulic system. During the tests, the chain samples can be cooled by direct air streams from the fans.

Figure 8 presents examples of test results obtained using the experimental stand, regarding the influence of chain calibration force on the average intensity of abrasive wear of links in joints measured by the increase in the chain pitch. As the calibration force increases, the intensity of chain links wear also increases because of the geometrical features of the links in the contact zone change strongly in such a way that the range of rolling of cooperating links diminishes and the range of slip increases. Therefore, the opposing effect of the calibration force on the functional features of mining chains is revealed. The fatigue life of chains, determined in standard conditions, increases with the increase of the calibration force which is caused by the higher value of the internal compressive stresses created during the calibration process in the critical zones of the chain links.

For original investigations on the process of wear of chain links in joints, the experimental stand with tilting head is used (Fig. 9) [16].

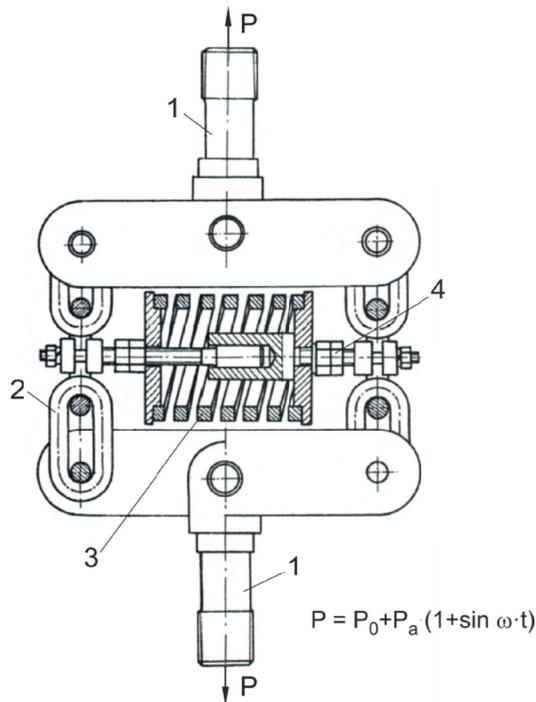


Fig. 6. Test stand with a spring tension system, cooperating with a hydraulic pulsator:  
 1) fastening screw, 2) chain sample, 3) spring, 4) adjustment nut

Particularly high intensity of wear of chains links measured by the increase of pitch in operational practice can be observed in the initial period of operation of haulage chains. This forces the machine operators for frequent and cumbersome procedures commonly known as „shortening the chain“. In fact, the length of the chain as a result of these treatments practically does not change, only the number of links in the chain decreases. For example, the average link pitch increase by 0,2%, which often takes place after a short time of use. In the case of an armoured face conveyor, 300 m long (i.e. 600 m of a single chain) is a necessity to „shorten“ the chain by approx. 1,20 m. Increased wear intensity of the links in the joints at the initial stage of operation results from huge local contact pressures on a small “not matched” surface and reduced wear resistance of the links surface layer, which is often decarbonised and covered with oxides during the heat treatment of chains.

Some reduction in the intensity of wear of chain links in joints at the initial stage of operation can be achieved by using two-stage calibration of chains in the process of their production [3].

The first, preliminary calibration should be performed before heat treatment, when the material in the joint area has a lower hardness. The contact surface then increases due to the plastic deformation of the alloy of the chain links in the joints, resulting in a reduction of the maximum contact pressures. The second, basic calibration should be performed at a much higher load after heat treatment operations to form a favorable state of residual stresses in the chain links. Selection of calibration forces at both stages should be carried out by trials to obtain the maximum final effect. That allows shaping the functional properties of the chains depending on the purpose, thus maximizing the resistance to abrasion or fatigue life.

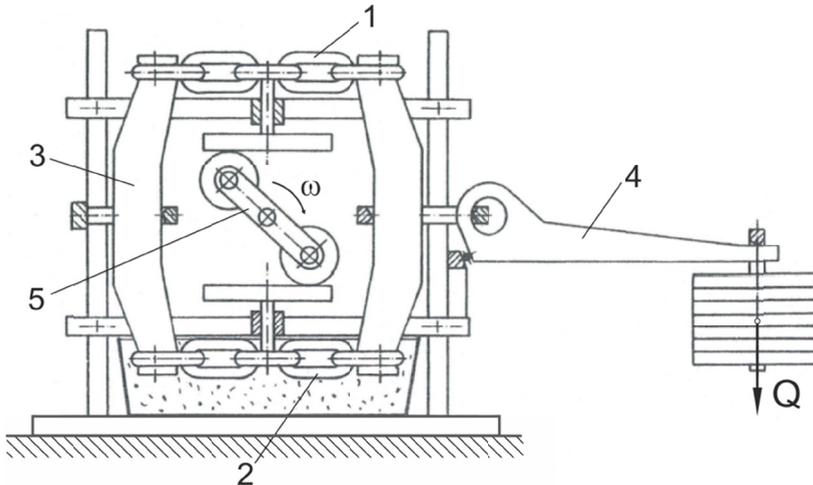


Fig. 7. Test stand with a forcing cam mechanism and lever loading system of the chain sample:  
 1), 2) chain samples, 3) lever, 4) lever loading system, 5) chain links deflection system

During operation of longwall scraper conveyors and especially of modern coal ploughs, the intense friction of straight sections of haulage chain links with cooperating elements leading to significant temperature gradients in the friction zone is observed. As a result, a specific mechanism of chain links destruction takes place. It consists in creating on the straight sections

of chain links a layer with strongly changed metallographic structure. So-called friction induced martensite means a layer with a very fragile structure [17]. Under the influence of large variable chain loads, this layer breaks and creates a specific, often quite dense, grid of shallow cracks perpendicular to the direction of chain movement.

In operational practice, such cracks often go unnoticed due to corrosion and specific rolling as a result of high contact pressures. Some of these cracks develop deeper into the cross-section of the chain link leading to breakthroughs and chain breaks. Cracks in the friction martensite zone are often places of deep corrosion pits leading to corrosion cracking of chain links. This phenomenon is additionally favoured by the increased chemical activity of plastically deformed zones and the complex state of internal stresses induced by intense friction. Figures 10 and 11 show, respectively, the image of the described friction fractures on the straight sections of the chain links and the view of the chain link with friction cracks and corrosion pits in the places of previous friction cracks.

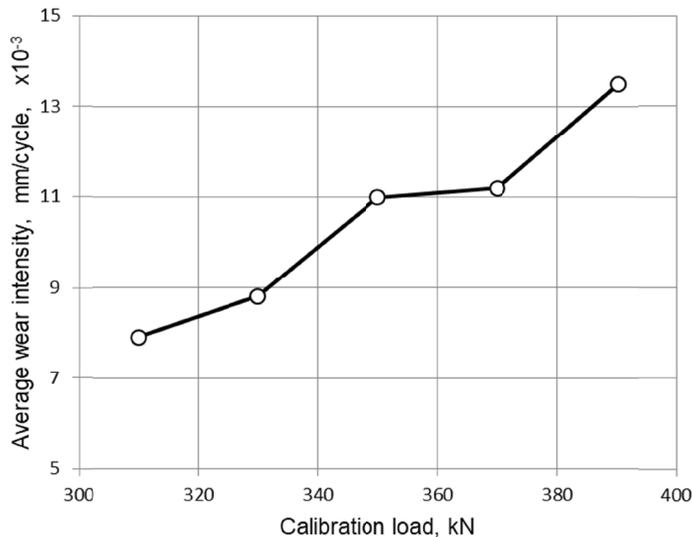


Fig. 8. The dependence of the average intensity of chain link wear on the calibration load for steel 23HGnMA

In the case of coal plough haulage chains, the described friction cracks are additionally particularly intensified due to the cyclical variation of the direction of slip on the straight sections of the chain links. The additional tensile stresses in the upper layer of the chain links induced by friction have an alternating swinging character, so they are more dangerous from the fatigue point of view than in the chains of scraper conveyors, where the slip has one primary direction. Alternating slip favours the growth of already existing surface cracks, which promotes the development of corrosion pits. In these cases, the synergy of the primary destructive processes (friction, fatigue, corrosion) of the mining chains is particularly vivid.

In the Department of Mining Mechanization and Robotisation of the Silesian University of Technology, experimental methods for revealing cracks initiated by friction during operation us-

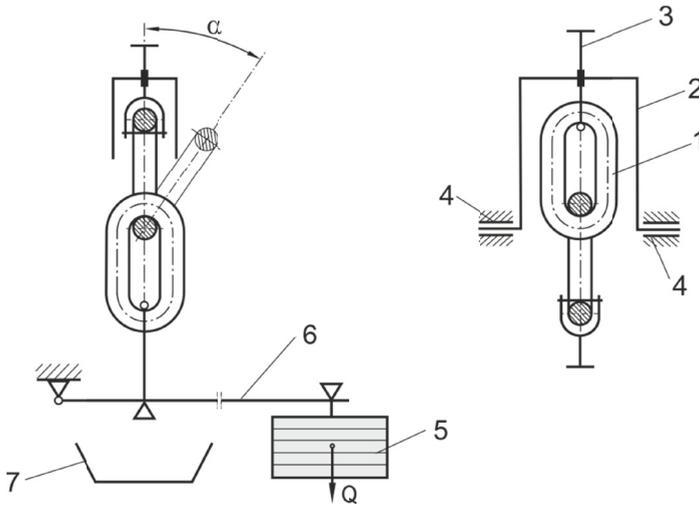


Fig. 9. Test stand with a tilting head for testing the chain wear process: a) schematic diagram, b) general view, 1) chain sample, 2) tilting head, 3) adjustment screw, 4) tilting head bearings, 5) weights, 6) lever system, 7) container for wear products

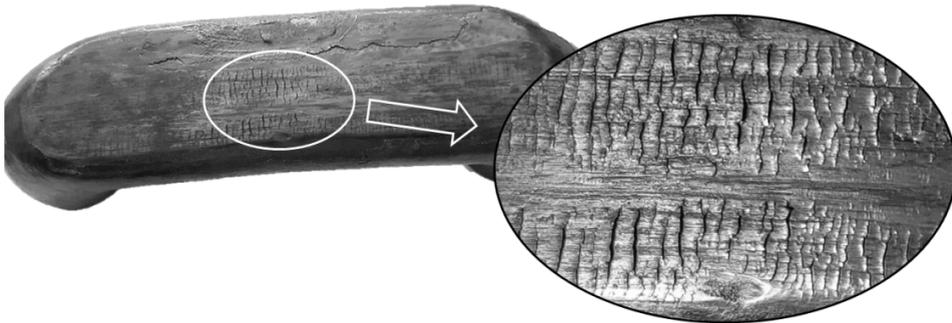


Fig. 10. An example of friction cracks on the straight section of the mining chain link

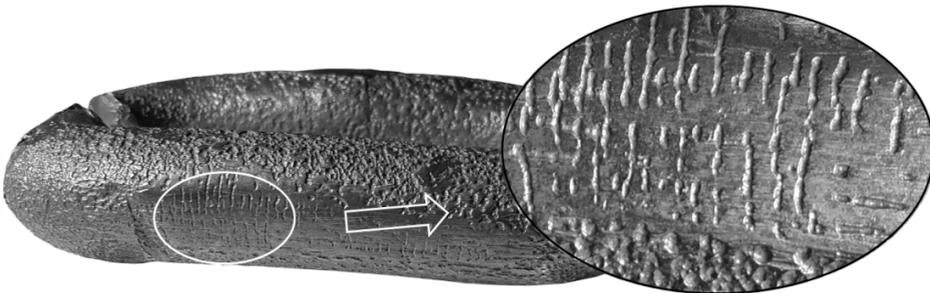


Fig. 11. Chain link with friction cracks and corrosion pits

ing effective diagnostic methods were developed [18]. Methods of revealing such types of cracks based on the use of magnetic phenomena are particularly useful. It has been proposed to adopt the magnetic-powder method in the wet variant for the efficient detection of chain links cracks in operation. Work is also being carried out on securing mining chains, in particular of haulage chains in coal ploughs, against the described friction and fatigue destruction.

## 4. Summary

Mining round link chains are a crucial element of longwall machines such as armoured scraper conveyors, coal ploughs and longwall shearers with chain haulage systems. The breaking of the chain links of these machines leads to the stopping of the coal extraction in the longwall which results in significant economic losses. The repair of this type of failure is usually complicated and time-consuming, mainly when the break occurs in the bottom race of the conveyor pan line or a closed pipeline guide of the cutting machine haulage chain.

The mining round link chains, during operation in a longwall, are subject to the mutual adverse impact of fatigue processes, abrasive wear and corrosion damage, which leads to a reduction in their functional properties. These processes combine a specific synergy characterized by a high complexity of mutual influences.

In the Department of Mining Mechanization and Robotisation (former Institute of Mining Mechanization) of the Silesian University of Technology, many experimental studies were carried out in the field of synergistic impact of these destructive processes on the operational durability of mining round link chains. Attention was paid to the necessity of a comprehensive consideration of destructive processes that occur in various conditions of use of round link chains in longwall mining machines.

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