



Volume 122

2024

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: <https://doi.org/10.20858/sjsutst.2024.122.16>



Journal homepage: <http://sjsutst.polsl.pl>

Article citation information:

Wieczorek, A.N., Wójcicki, M., Kalita, M., Kandzia, R. Problems of wear of the chains used in mine scraper conveyors, caused by friction and corrosion. *Scientific Journal of Silesian University of Technology. Series Transport*. 2024, **122**, 293-304. ISSN: 0209-3324.

DOI: <https://doi.org/10.20858/sjsutst.2024.122.16>.

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**PROBLEMS OF WEAR OF THE CHAINS USED IN MINE SCRAPER
CONVEYORS, CAUSED BY FRICTION AND CORROSION**

Summary. Scraper chains are the main transport cables of scraper conveyors. Problems related to the processes of destruction of link chains used in these conveyors are described. Design of scraper chains and their division into different types for use in scraper conveyors are presented. The most common damages to chains used in scraper conveyors are presented and the reasons of their wear are discussed.

Keywords: transport, link chain, flight-bar conveyor, scraper

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1. INTRODUCTION

Link chains equipped with scrapers are the basic transport and pulling component used in flight-bar conveyors for run-of-mine transport. These conveyors are the basic machines of the transport line used in the mining faces. Due to their design, they are considered to be the most resistant and intended for use in the most difficult environmental conditions, among the known solutions of tension memberless transport means [5, 13].

The wear process of flight-bar conveyor components, including chain links, is complex and depends on many factors. Regarding the environmental factors, there is a joint, synergistic interaction, which significantly reduces durability of the drive systems of transport conveyors. Cooperation of chain links with the drum, relative movement of links in the joint area, as well as extremely difficult and complex environmental conditions, which are characteristic for hard coal mining plants, determine the aggressiveness of the wear processes of link chains.

Cause-and-effect processes related to destruction processes should be considered in a holistic system, taking into account individual aspects such as friction, corrosion and fatigue phenomena. The factors that increase wear of chain links and scraper conveyor units include the following [15]:

- abrasive impact of coal and stone dust in the area of cooperation of chain links (so-called joints),
- corrosive effect of water flowing out of the goaf and coming from the cooling and spraying units,
- dynamic loads from e.g. start-ups of the conveyor drives, their uneven load, frequent overloading and blocking.

The degradation factors listed above ultimately lead to breaking the chains. Despite the use of high-quality steel for chain manufacture and specialized technologies that ensure high durability and strength requirements, decohesion of chain links is the most common type of scraper conveyor failure, which causes a great threat to working miners and generates additional costs related to downtimes caused by failures. This is especially negative, when considering the efficiency of a serial transport system in the coal mining industry, where stopping the transporting machine in the longwall face or in the roadway stops the entire mining process [11].

This article presents the problem of degradation processes of link chains in the conditions of mining processes. The most popular forms of damage, specifying the reasons for their formation and their effects, are described.

2. LINK CHAINS USED IN TRANSPORTING SCRAPER CONVEYORS

Medium-link chains are used in flight-bar conveyors. That means that the ratio of the chain pitch to the diameter of the bar from which it is made is between 3 and 4. The dimensions of the conveyor chains have been standardized. The Polish Mining Standard PN-G-46701:1997 - "Mine link chains" [10] is the current document characterizing link chains used in scraper conveyors. The links of chains are of dimensions determined by the aforementioned standard. They are shown in Fig. 1 below.

The Polish Mining Standard, based on ISO 610:1990 and DIN 22252, describes the size of the link by specifying the size $d \times p$ in mm (d - diameter of the link rod; p - pitch of the link). On this basis, a series of types of link chains for various loads was created.

In addition to the geometrical quantities contained in the standard, mining chains are defined by various mechanical quantities, the most important of which are:

- breaking load,
- calibration load,
- test load,
- elongation at breaking load,
- elongation under test load.

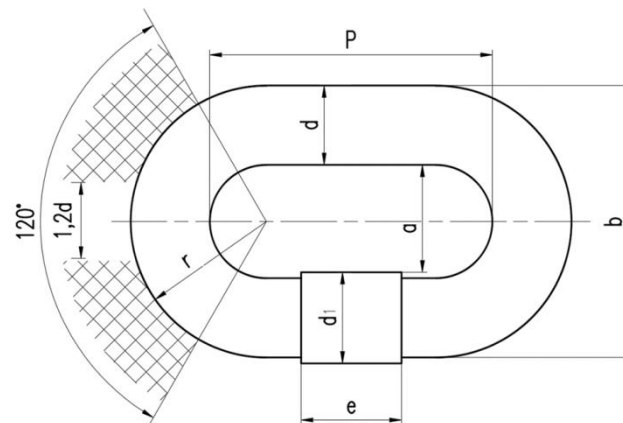


Fig. 1. Dimensions of a link in the mine chain; P- chain pitch; d - chain rod diameter; d_1 - rod diameter at the welding point; e - maximum weld width; a - minimum clearance width; b - maximum width of the link; r - radius of the link rounding (external) [10]

The breaking load is defined as the maximum force that a chain sample can bear during a breaking test on a testing machine. Examples of chain link breakage charts of various sizes are shown in Fig. 2.

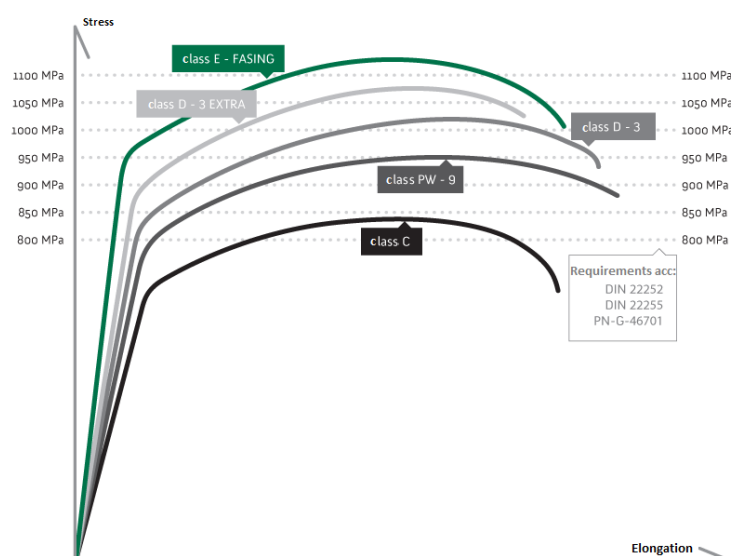


Fig. 2. Sample diagrams of breaking the mine chains of different manufacture classes [16]

A feature of mining chains that can be considered advantageous is their high elongation capacity. Together with the breaking load, the elongations are the factors determining the breaking energy of the chain. The process of elongating the chain during the test on the testing machine shows two phases - elastic deformations within the Hook's law (stresses proportional to strains) and a phase of plastic deformations, which, if exceeded, result in permanent deformation of the link [13].

Distribution of stresses in link chains (Fig. 3) is an interesting issue related to the operation of chain systems. In addition to the stresses generated by the forces tensioning the chain during the run-of-mine transport, there are also internal stresses in the links. These stresses result from the process of calibrating them, which is characteristic for the production of chains. Calibration is understood as the application of a force tensioning the chain (the so-called calibrating force), the purpose of which is to deform the links resulting in elongation of the pitch and setting it at the required level. After removing the calibrating force, a partial shrinkage of the material occurs, resulting in internal compressive stresses that have a beneficial effect on the fatigue life of the chains. In addition to determining the pitch, there are also geometric changes, especially in the joint area, which positively affects the tribological cooperation between links. The calibration load is not included in the standard and is the "know how" of mine chains manufacturers [1, 4, 11].

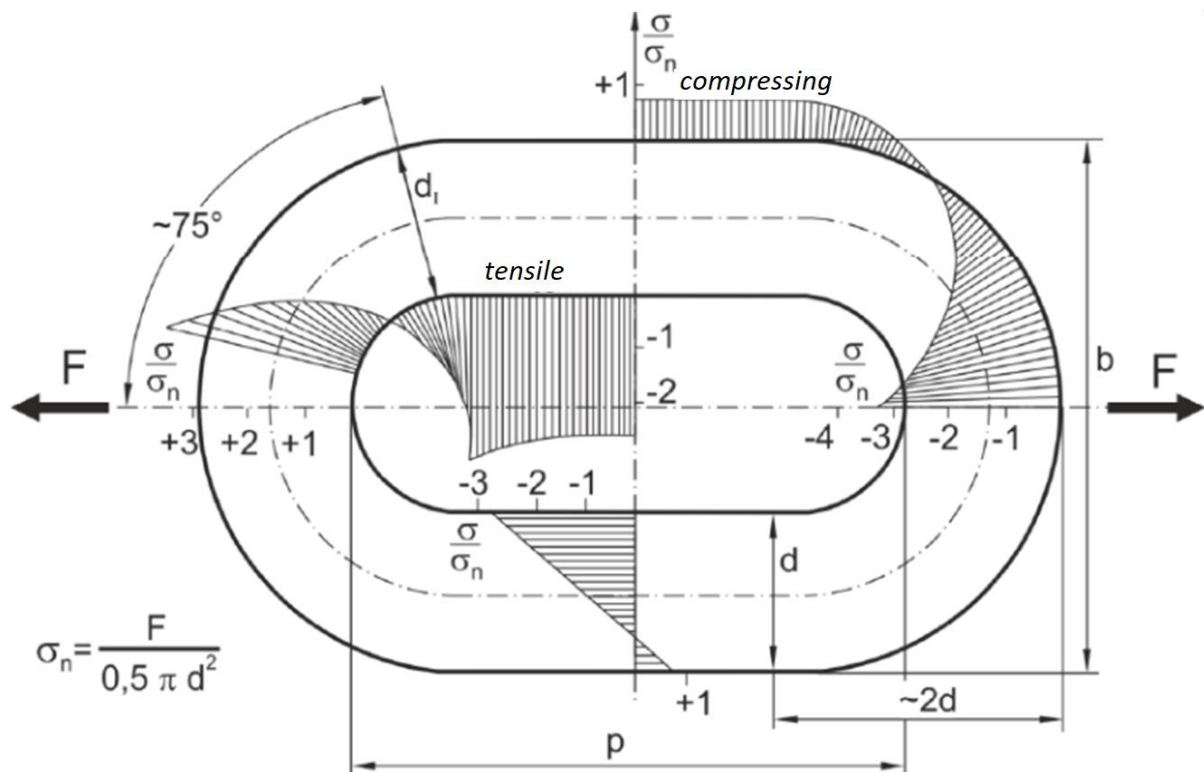


Fig. 3. Distribution of stresses in a mine chain link [9]

3. DEGRADATION PROCESSES OF LINK CHAINS

Chain failures are associated with several characteristic leading processes. The most important of them are:

1. Abrasive wear
2. Corrosion.
3. Synergistic phenomena (e.g. tribocorrosion).
4. Fatigue of the material.

The following sections describe the impact of the above-mentioned causes on mining chain degradation.

3.1. Abrasive wear

During the cooperation of links with the drum and cooperation among the links in the joint area, abrasive wear is the dominant cause of degradation. When analyzing the chain-chain drum kinematic system, three following basic friction nodes can be distinguished (Fig. 4):

- area of cooperation of the front torus of the horizontal link with the bottom of the drum (Item A),
- area of cooperation of the horizontal rear link torus with the flank of the tooth (Item B),
- chain joint area - horizontal and vertical link contact zone (Item C) [15].

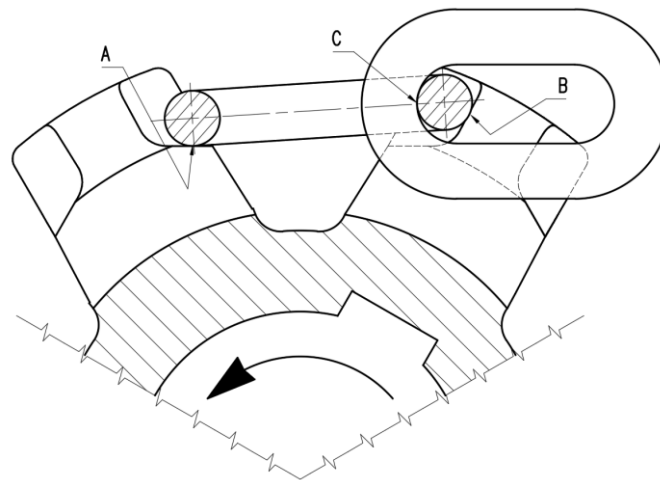


Fig. 4. Friction nodes in the chain-chain drum kinematic system
(Item A - front torus in the bottom of the drum, Item B - rear torus on the tooth flank,
Item C - cooperation of links in the joint) [15]

For each of the mentioned friction nodes, tribological wear is observed, caused by the cooperation of contacting surfaces, often additionally intensified by rock dust abrasion. In the case of contact at Items A and C (Fig. 4), wear is caused by the rolling of the links in the joint and positioning the front horizontal torus of the link in the bottom of the socket. During the cooperation among the links in the chain joint, the contact point of the links moves, which results in the lowering of the vertical link in the inter-tooth groove. This causes a rolling motion as part of two links in cooperation with the simultaneous slipping of the front torus in the bottom of the socket. In addition, lowering the vertical link is accompanied by rolling and partly

slipping in the chain joint. The long-term effect of the described phenomena is a wear deforming the seat bottom, tooth flank and the corresponding zones on the horizontal link (Fig. 5).

Cooperation in the area of the joint and abrasion of these zones, in turn, causes an increase in the pitch of the link chain. This results in the rear torus (Fig. 4, B) resting on the tooth flank instead on the bottom, which often leads to the rear torus sliding over the tooth flank towards the bottom of the drum, resulting in wear of the tooth flank and the referring contact zone on the link. The literature [13, 14] distinguishes three following classes of cooperation of the link in the pocket of the sprocket wheel:

- nominal toothing, when the pitch diameter of the chain wheel is congruent with the chain pitch and while the chain is running on the wheel, the horizontal link entering the toothing simultaneously contacts the surface of the preceding socket. At this point, there is no movement of the link in the wheel socket, which generates cooperation with the highest efficiency,
- special toothing, when the chain pitch is smaller than the pitch on the pitch diameter of the wheel. With this type of toothing, the torus of the rear horizontal link cooperates with the tooth coming out of toothing. The remaining teeth, in turn, do not have contact with the horizontal links on the flanks until they leave toothing of the preceding link,
- normal toothing when the chain pitch is greater than the expected chain wheel pitch on the pitch diameter. In such a situation, during the rotation of the wheel, the torus of the horizontal link slips along the flank of the tooth until it settles in the bottom of the socket. The wear of the tooth flank further leads to a shift of the contact point of the torus of the front horizontal link with the bottom of the socket towards the centre of the socket. This leads to the contact points of the link with the bottom of the socket approaching the edge of the slot under the scraper. This is accompanied by a decrease in the contact surface of the front torus with the bottom of the socket [15].

Increasing the chain pitch and reducing the chain wheel pitch by settling the link in the abrasion of the bottom of the drum socket leads to incorrect cooperation of the described kinematic pair. This generates an increase in dynamic loads, which intensifies fatigue and friction wear [3, 15].

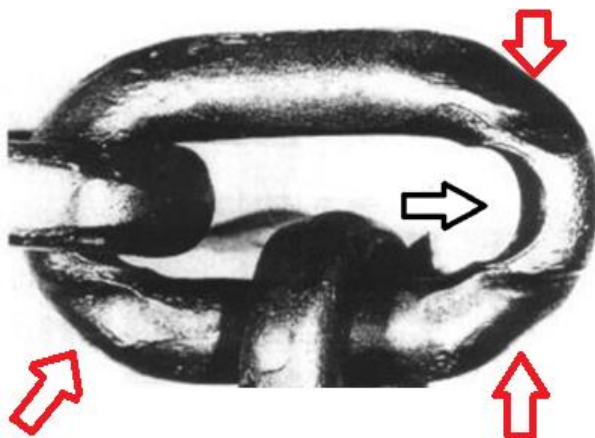


Fig. 5. Wear area of chain link joint (black arrow) and wear area of chain link contact zone (red arrows) [8]

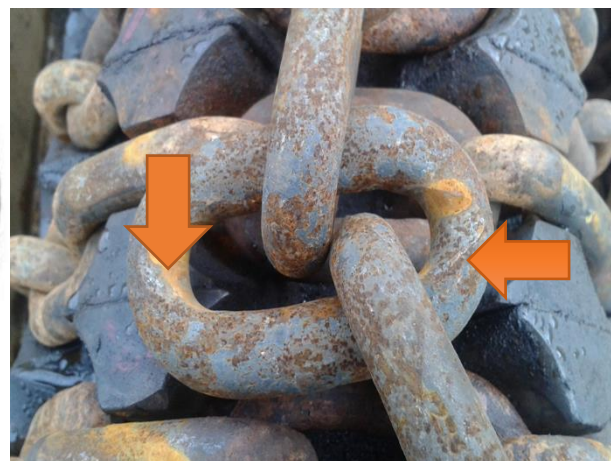


Fig. 6. Visible areas of abrasive wear in the area of the link joint

In the case of vertical links, apart from the abrasion processes (against the conveyor trough – Fig. 8), there are also changes in the structure of the link material. The rubbing surface of the chain links warms up as a result of friction processes and then cools down intensively as a result of transferring heat energy to the other parts of the machine and as a result of cooling with water-laden run-of-mine (or the environment). The cyclical heating and cooling in favourable conditions causes the formation of a martensite layer (called in the literature the friction martensite) characterized by high hardness and brittleness, and thus susceptible to cracks when the link is overloaded. These damages have numerous surface cracks perpendicular to the surface and to the slip direction (Fig. 7). These cracks are often sharp notches, and they are the beginning of cracks leading to the link destruction [11].

3.2. Corrosion

Corrosion phenomena significantly affect the link chain operation. The mechanism of electrochemical corrosion appears as a result of the following features of the contacting media:

- corroding metal is a conductor, and its surface is never completely homogeneous,
- water in which metal corrodes is not chemically clean; is a solution of various electrolytes and exhibits ionic conductivity depending on the concentration and mobility of the ions contained in it.

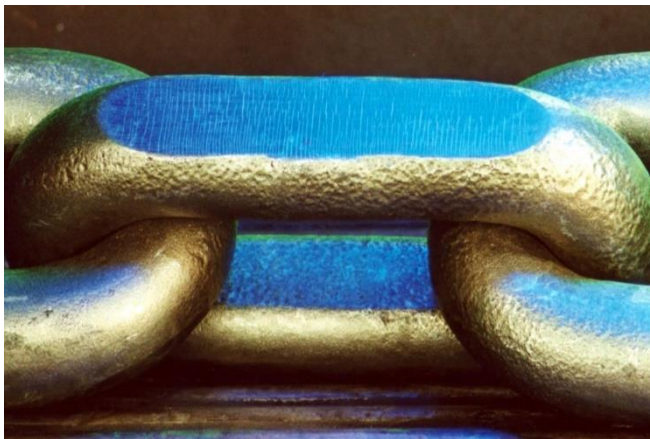


Fig. 7. Cracks meshing formed as a result of the formation of the so-called friction martensite [8]



Fig. 8. Link abrasion on the conveyor trough [15]

In the case of a difference between the potentials of the metal surface fragments, galvanic cells are formed, also called corrosion cells, in which the following reaction takes place on the anode:



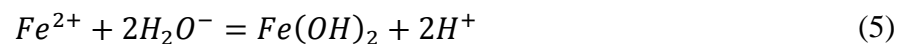
At the cathode, as a result of dissociation, hydrogen is released according to the following reaction:



As a result of the addition of electrons from the cathode, another reaction takes place:



Electrode reaction products may enter into secondary reactions generating insoluble iron oxides:



Chain link corrosion is especially dangerous if the fatigue cracks appear on the link's surface. In such a case, extensive corrosion pits may appear, the propagation of which is further intensified by the increased chemical activity of the work environment (Fig. 9). The result of this process are corrosive separation cracks in the links. In addition, in a strongly corrosive environment, a significant decrease in the critical stresses that initiate development of cracks is observed. Therefore, the fatigue wear of links operating in a corrosive environment progresses faster. Examples of corrosive effects on mine chain links are presented in Fig. 10 [9].

There are many parameters that affect water properties. These include pH, water hardness, chlorine content and other chemicals. To determine the corrosiveness of water, laboratory tests, which include a physicochemical analysis of water, are required. There are also various indicators that help in assessing water corrosiveness. An example of such an indicator is the S coefficient described in [7]. It is based on the guidelines of EN 12502-3:2004. To calculate the coefficient during laboratory tests, the content of chloride anion Cl^- , sulfate anion SO_4^{2-} , hydrocarbon anion HCO_3^- and nitrate anion NO_3^- should be determined. The S coefficient is calculated from the following relationship [7]:

$$S = \frac{c(Cl^-) + c(NO_3^-) + 2c(SO_4^{2-})}{c(HCO_3^-)} \quad (8)$$

The cited standard specifies two ranges of impact of water aggressiveness in the context of steel components:

- $S < 0.5$ – low probability of pitting corrosion,
- $S > 3.0$ – high probability of pitting corrosion.



Fig. 9. An example of a corrosion pit on a cross-section through the parent material of a chain link [8]

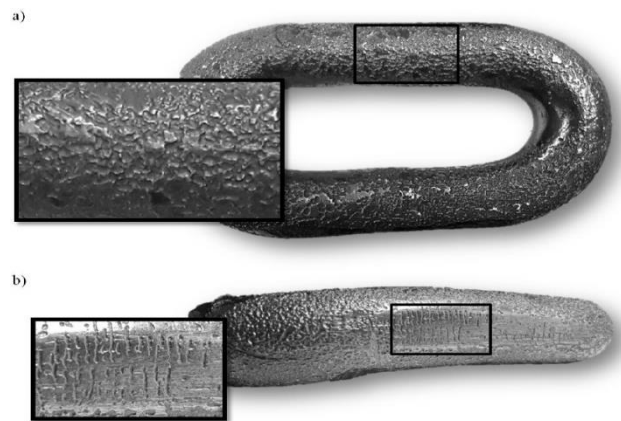


Fig. 10. Chain link corrosion: a) surface pitting, b) fatigue cracks intensified by corrosive environment [11]

3.3. Tribocorrosion

Tribo-chemical wear is another known wear mechanism for conveyor chain links. It is defined as the formation of surface reaction layers as a result of tribo-chemical reactions. These surfaces, due to the abrasive mechanisms, are removed opening the newly reacting surface with the environmental substances (e.g. mine water). This reactivity is explained by the plastic deformation of the friction surface, which generates local density changes, causing the migration of electrons from places with shear stresses to the places with tensile stresses (where the potential is negative). Temperature may be another catalyst for tribo-chemical reactions of differences resulting from the heating of rubbing surfaces. Electrons then migrate from the regions of higher temperature to regions of lower temperature. As part of the tribo-chemical wear, the oxide layer is removed and then recreated on the surfaces of the cooperating components. It is classified as a normal type of wear, and its intensity is insignificant in stabilized conditions. With the increasing corrosiveness of the environment of the cooperating components (e.g. in the presence of saline water), this process is significantly intensified by the impact of hard products of wear, which take the role of hard abrasive grains. In the literature, the term tribocorrosion wear is used to describe the form of combined wear intensified by the synergistic action of abrasive and corrosive agents (fig. 11). There is a synergy of factors that jointly enhance chain degradation, what significantly accelerates its damage. The presence of hard metal oxides getting into the abrasive as a result of the joint action of abrasive and corrosive processes causes the synergy effect [3, 12, 15].

3.4. Fatigue of the material

Corrosion pitting, micro-cracks or abrasion-mechanical damage are usually the initiators of fatigue degradation of links. There are several phases in the fatigue failure process. The first phase is the incubation of microcracks formed during the operation of conveyor chains. The next phase is development (deepening) of microcracks until the so-called critical value. After reaching the micro-cracks critical value, a stage of their rapid progress takes place, finally leading to the next phase, i.e. to a fracture in the critical cross-section (Fig. 12). In the aspect of

mine link chains, these fractures usually occur in several characteristic places (Fig. 13), which results from the distribution of stresses caused by significant tensile forces [6, 9].

Any link fracture, in the case of a serial transport system in a coal mine, causes downtime in mining and thus large economic losses. Both production plants and designers of link chains are searching for opportunities to modernize the solutions offered, in terms of increasing durability, strength or corrosion resistance. Therefore, the problem of chain degradation processes in mine scraper conveyors is still valid. Reducing the failure rate of scraper conveyors by eliminating downtimes resulting from chain damage translates into lower hard coal mining costs.

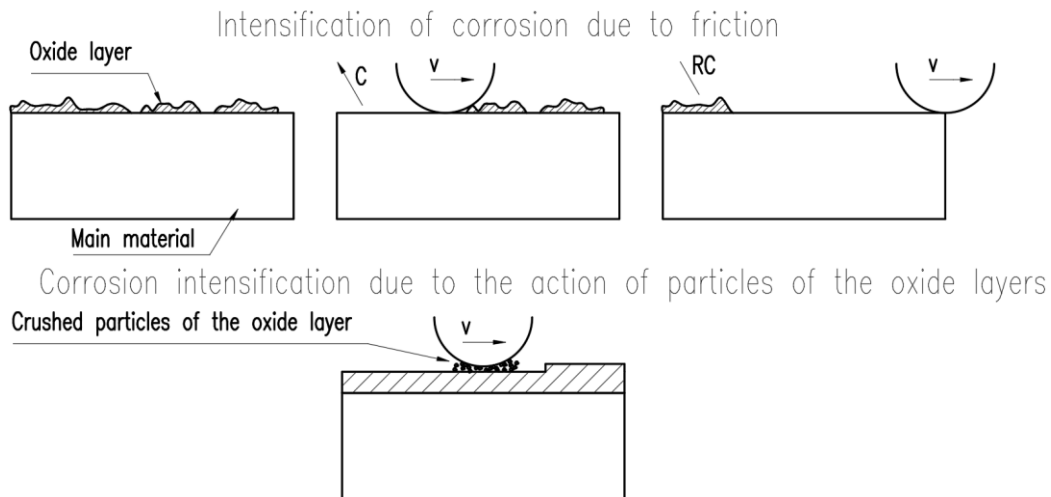


Fig. 11. Mechanism of tribocorrosion wear (v -speed vector, C -corrosion; RC -reoxidation) [2]



Fig. 12. Fatigue fracture of a chain link [8]

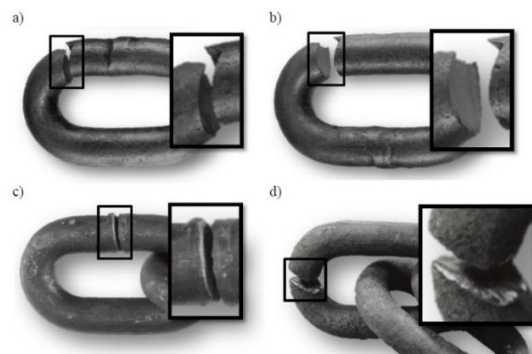


Fig. 13. Typical places of fractures :
 a) fracture in the arc on the side of the weld (approx. 50%),
 b) fracture in the arc on the opposite side (approx. 30%),
 c) fracture in the weld (approx. 15%),
 d) fracture in the link axis and other forms of fractures (about 5%) [11]

4. CONCLUSIONS

Analysis and testing the processes causing the chain degradation is of key importance in the prediction of potential damage and further development of scraper conveyor designs. The article describes the most common forms of damage to the chains of scraper conveyors working in transport units in hard coal mines.

In the case of these components, the most common destructive processes are: abrasive wear, corrosion, and fatigue processes. In mining practice, damage caused by the combined action of wear and corrosion is also observed, which is usually referred to as the process of tribocorrosion.

As the analysis of the state of knowledge presented in the article shows, in many works this process is mentioned as one of the most important destructive factors, but there are no results of laboratory tests and in environmental conditions that would present measurable wear values on the basis of which it would be possible to determine the predicted durability of chains for given environmental conditions. This fact is the basis for the authors to undertake further research on the process of their destruction in the conditions of the combined action of environmental factors.

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Received 05.10.2023; accepted in revised form 02.12.2023



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