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DETERMINATION OF THE INFLUENCE OF AN ANTICORROSIVE LAYER ON THE STRENGTH OF LINK MINING CHAINS

OKREŚLENIE WPŁYWU WARSTWY ANTYKOROZYJNEJ NA WYTRZYMAŁOŚĆ ŁAŃCUCHÓW OGNIWOWYCH – GÓRNICZYCH

Using link mining chains is related to the proper way of selecting the type of the chain. The operational parameters of the chain are associated with a risk to the employees who operate haulage systems using scraper conveyors. A complete analysis of operational parameters is possible to be made only after relevant tests are performed. The study presents laboratory test results as well as modeling studies which allowed to determine the influence of the anticorrosive protection of the chain's surface on its operational parameters.

Keywords: transport, chain, breaking force, elongation

Eksploatacja łańcuchów ogniwowych górniczych wiąże się z właściwym sposobem wyboru stosowanego łańcucha. Parametry użytkowe łańcucha wiążą się z ryzykiem dla pracowników obsługujących układy odstawy z wykorzystaniem przenośników zgrzebłowych. Pełna analiza parametrów użytkowych możliwa jest po przeprowadzeniu odpowiednich badań. W pracy przedstawiono wyniki badań laboratoryjnych oraz badań modelowych, które pozwoliły na określenie wpływu zabezpieczenia antykorozyjnego powierzchni łańcucha na jego parametry użytkowe.

Słowa kluczowe: transport, łańcuch, siła zrywająca, wydłużenie

1. Introduction

In view of the concentration of extraction, the manufacturers of equipment supply complete haulage lines taking the output from the longwall to the surface. Optimally selected speed, conveyor's width and size of the chain allow to achieve high efficiency. Therefore, selection of a proper chain having appropriate strength and geometric parameters which meet the expectations of users constitute such a significant problem.

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Link mining chains used in mining industry are not subject to mandatory tests resulting from binding regulations. However, they are subject to control tests at the production level. One of the basic tests specified by standards: PN-G-46701 from April 1997 and DIN 22 252:2001-09 is performance of a static chain load test up to break in order to check the strength parameters. A new research subject related to tests of link mining chains was implemented in the Laboratory of Rope and Shaft Equipment of Central Mining Institute in 1980-1982. Initially, the scope of the research concerned the chain tensile tests and determination of the total breaking force as well as total elongation. In subsequent years along with the coming out standards and studies, the scope of research was expanded and adjusted to the needs of manufacturers and users of chains, so that the chains be useful for the engineering and technical staff. The scope of research and interest in this noteworthy topic results from disputes between the manufacturers and users of chains regarding reduction of operational parameters of chains protected against corrosion at the production level. In previous years, chains were supplied to customers in the so-called naturally black condition, i.e. with their surface covered with scale which is formed as a result of heat treatment and without any protection against corrosion. Due to the fact that such a surface covers with rust coating after few days, currently manufacturers protect chains for the period of transport and storage using wax-based substances, e.g. tectyl. Chains used in an aggressive mining environment which is favourable to corrosion are protected in the hot-dip galvanizing process. During the hot-dip galvanizing process, a protective coating forms on the surface of links and it consists of two layers: iron-zinc alloy and outer layer of solidified zinc. Covering the chain with an anticorrosive coating changes the coefficient of friction between particular links during the breaking test. Dynamic load variables are present in the operational practice and they occur as a result of various types of blocking of the chain placed in troughs caused by sudden rock fall, collisions with other elements of longwall equipment or due to incorrect initial chain stress. In order to fully explain the phenomena occurring in the chain during its operation, it is necessary to supplement static tests with dynamic tests. These tests can also be useful for proper selection of the chain to the specific conditions in which it will be used. The tests are described in papers (Szot et al., 2009a, 2009b).

2. Strength tests of chains

Tensile test of the link chains samples is very complex. Despite the typical tension, links of the chain cooperate on arcs. Bending and surface friction occur in this case. The thickness of the surface layer which formed during mechanical working (shot peening) and surface heat treatment or chemical heat treatment can amount to even few millimeters The analysis of values obtained from the tests allows to formulate a conclusion that chains having low friction coefficients in joints achieved as a result of lubrication or anticorrosive protection of the links' surface have lower parameters in terms of:
- breaking force,
- elongation.

This phenomenon has been included in the provisions of the standard DIN 22 252:2001-09 which allow to reduce the breaking force of chains protected against corrosion by 10% and their elongation by 20% with respect to the values given in the standard. Polish standard PN-G-46701 does not have such a provision and that is why there are continuous disputes between the manufacturers and customers.

The so-called Rebinder effect occurs as a result of using anticorrosive coatings on the links of mining chains and it consists in a burst activity of molecules of surface active substances permeating into the surface layer of metal as described in papers (Szot et al., 2009a, 2009b). Reduction of requirements for the breaking force by 10% and for chain elongation by 20% is assumed with regard to raw chains.

3. Results of laboratory tests

The most important data are obtained from experimental tests carried out on samples using probabilistic methods of analyzing their results. It provides a lot of new information on the quantitative and qualitative influence of various factors on mechanical properties of chains and the obtained data can be used to develop mathematical models. Therefore, a sequence of tests was carried out for the purpose of this paper, the aim of which was to determine such major values as the maximum breaking load and elongation for this load. These tests consisted in breaking raw chains and chains coated with Tectyl coating.

Table 1 shows results of the tests carried out for the samples of a chain 34×126 class D. They have been taken from one production batch and some part of them was coated with Tectyl.

TABLE 1

Results of static tensile tests

Raw samples			Samples coated with Tectyl		
Sample no.	Breaking force [kN]	Elongation %	Sample no.	Breaking force [kN]	Elongation %
06-168-2	1840.3 ±20.6	19.7	06-168-1	1677.3 ±18.7	13.0
06-168-3	1794,8 ±20,0	17.5	06-168-6	1713.0 ±19.1	12.9
06-168-4	1833.1 ±20.5	17.5	06-168-7	1691.3 ±18.9	13.4
06-184-5	1858.2 ±20.8	22.1	06-168-8	1711.4 ±19.1	11.8
Average:	1831.6	17.7	**Average:**	1698.2	12.8

As in case of thin rope elements, there is no clear yield point R_e in the diagrams presenting chain tension (Fig. 2 up to break $P_L = f(DL)$. Due to a significant elongation of brand new chains, it is impossible to determine the conventional proportional limit and yield point as in case of wires or rods.

During the quantitative evaluation of obtained test results, a decrease both of the breaking force (Fig. 1) and elongation can be noticed. Random measurement errors and scatter of forces as well as elongation of chains of the same size are caused by random factors occurring in the complex production process.

The breaking work was calculated from the obtained test diagrams for particular samples. The graphic interpretation of this breaking work is shown in Fig. 2.

Hatched field below the curve can be expressed by formula 1:
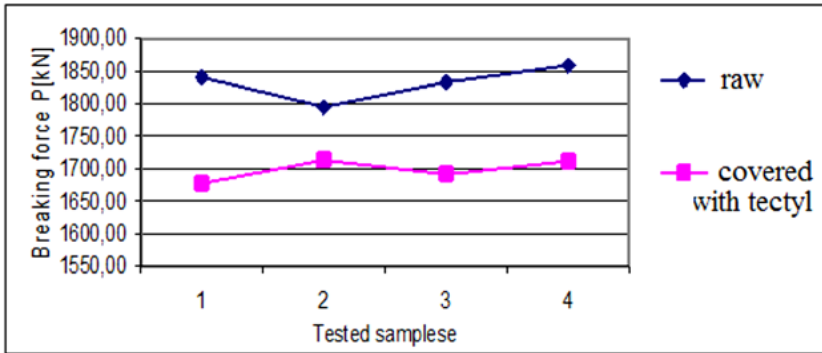
$$W = \int_0^l F dl \qquad (1)$$

Fig. 1. The dependence of the value of braking force for the non-protected
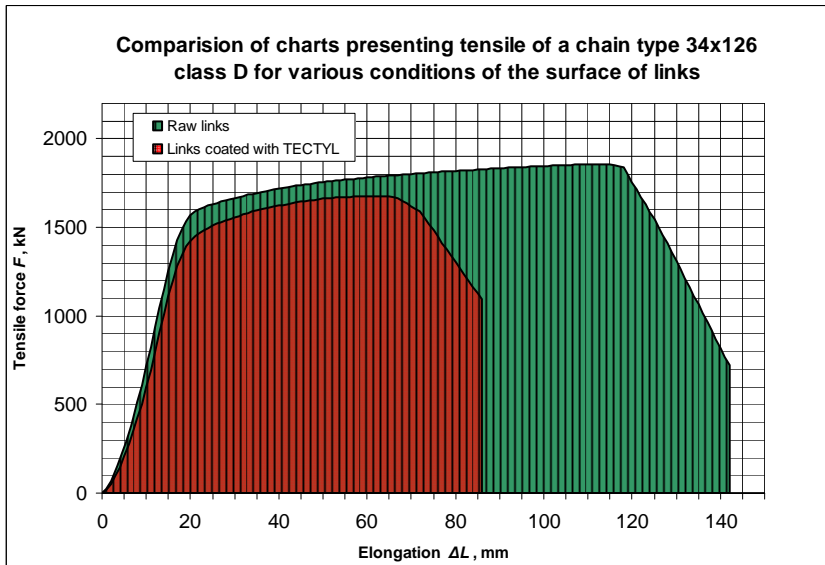and protected against corrosion samples

Fig. 2. Dependencies $F(\Delta l)$

In case of a static tensile test, the work is a process related to the change of potential energy into kinetic energy and heat energy. Analyzing the graphic interpretation of the results of static load test without using mathematical assessment methods, a decrease of breaking work can be noticed. It results from a decrease of imposed force value and increase of elongation. Table 2 include calculated breaking work values for particular chain samples. Calculating the average values for a particular chain population, a decrease of the average breaking work by 38.38% is noticeable. Breaking work determines the ability of the chain to absorb energy and dissipate it during operation of the conveyor.

Values of breaking work for particular tests

Raw samples			Samples coated with Tectyl		
Sample no.	Breaking force [kN]	Breaking work [kJ]	Sample no.	Breaking force [kN]	Breaking work [kJ]
06-168-2	1840.3 ±20.6	189.8	06-168-1	1677.3 ±18.7	115.9
06-168-3	1794,8 ±20,0	168.4	06-168-6	1713.0 ±19.1	119.2
06-168-4	1833.1 ±20.5	177.4	06-168-7	1691.3 ±18.9	119.9
06-184-5	1858.2 ±20.8	220.2	06-168-8	1711.4 ±19.1	110.7
Average:	1831.6	188.95	Average:	1698.2	116.43

According to the assurances of manufacturers of chains, after removal of the protective layer of the chain, its two parameters, such as breaking force and elongation should return to their previous values. Therefore, additional tests were carried out and a chain protected against corrosion as well as a chain cleaned using sand-blast method of the same production batch were subject to load. The test results are shown in Fig. 3. In this case, the chain also does not keep its parameters according to the provisions of the standard concerning their acceptable values. It may be caused by maintaining the same value of friction coefficient as for the sample covered with an anticorrosive layer.
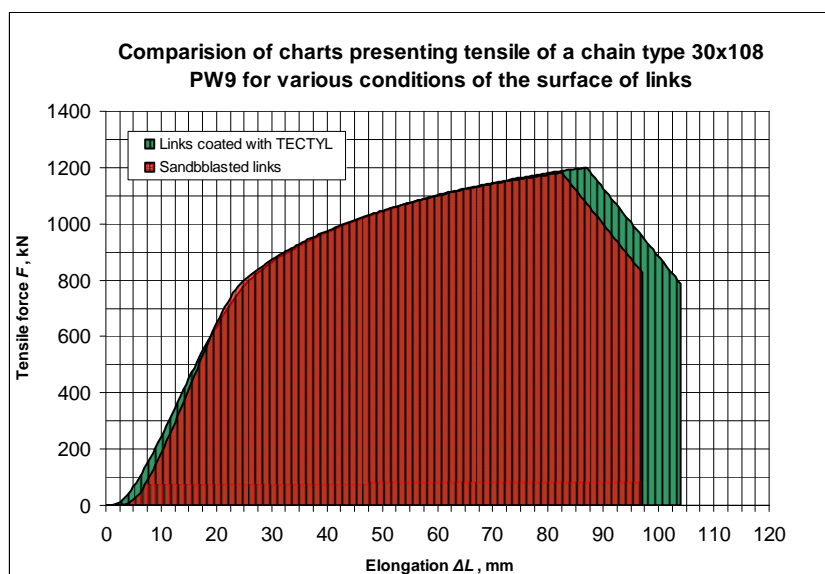

Fig. 3. Comparison of attempts to break the chain protected against corrosion
and chain with removed anti-corrosion layer

4. Numerical analysis

In order to verify the laboratory tests, numerical analyzes of the mining chain have been performed, which determine the influence of a friction coefficient μ between links on the tensile strength of a chain. A numerical model of a mining chain 18×64 was created, which was subject to strength analyzes based on the Finite Element Method.

4.1. Model tests

Model strength tests were carried out numerically using the Finite Element Method (FEM) (Rusiński, 1994; Rakowski & Kacprzyk, 1996). The essence of this method is a division (discretization) of a complex system into a finite number of elements, then the analysis of a single element the behaviour of which is determined by a finite number of parameters and finally recombining all elements in order to examine the response of the whole system. The main assumptions of the method are based on the fact that it is easier to study and understand the response of a single element and then combine the whole system in order to examine its response than to study the system as a whole (Chmielewski & Nowak, 1996; Dyląg et al., 1996; Szuścik & Kuczyński, 1998).

From the point of view of a user, modelling in modern FEM systems comes down to an entry of geometry of the entire tested system and determination of parameters of its particular parts, such as material properties, sectional parameters and in case of a non-linear analysis – stress strain curves. The geometry of the system can be created or imported from CAD software. A burdensome discretization, especially in case of complex models, is often performed automatically or semi-automatically under the user's control. After the required input parameters are entered, it is necessary to determine the type of load and support of the model. Among others, the values of internal forces automatically converted to equivalent stresses are obtained from the calculations.

Computer programs operating on the basis of FEM, calculate not only dislocation and internal forces but also equivalent stresses according to Huber-Mises-Hencky hypothesis pursuant to the general formula (Dyląg et al., 1996; Szuścik & Kuczyński, 1998):

$$\sigma_{red} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x\sigma_y - \sigma_x\sigma_z - \sigma_y\sigma_z + 3\cdot\left(\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2\right)} \qquad (2)$$

Comparing the obtained maximum values of equivalent stresses with limit values for a particular material, it is possible to obtain in a simple and inexpensive way the answer to the question concerning the correctness of the designed structure. Therefore, according to the abovementioned hypothesis, equivalent stresses constitute a criterion which is mostly used for calculation of the structure using the FEM analysis.

4.2. Analysis of strength

Numerical analyzes were carried out for a mining round chain model 18×64, according to PN-G-46701 standard. The model included two complete links and two half links to which a boundary conditions were applied (Fig. 4). The model constructed in such a way excluded the impact of support (Saint-Venant's Principle) on the result for two middle links.

Analyzes were to reflect the essence of a stand test concerning tensile of a chain, taking into account the variability of the friction coefficient parameter μ. This coefficient was the only
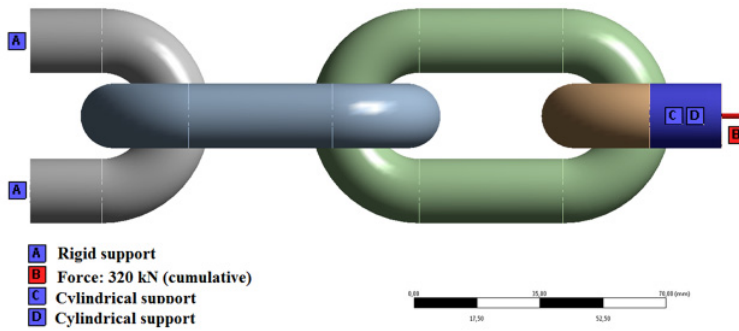
Fig. 4. A general view of a round mining chain model 18×64 with boundary conditions

variable in the following analyzes and thus, it excluded the impact of other factors on the final results. What is more, in order to improve the convergence of results, the finite element grid was concentrated within the areas were the links had contact (Fig. 5).
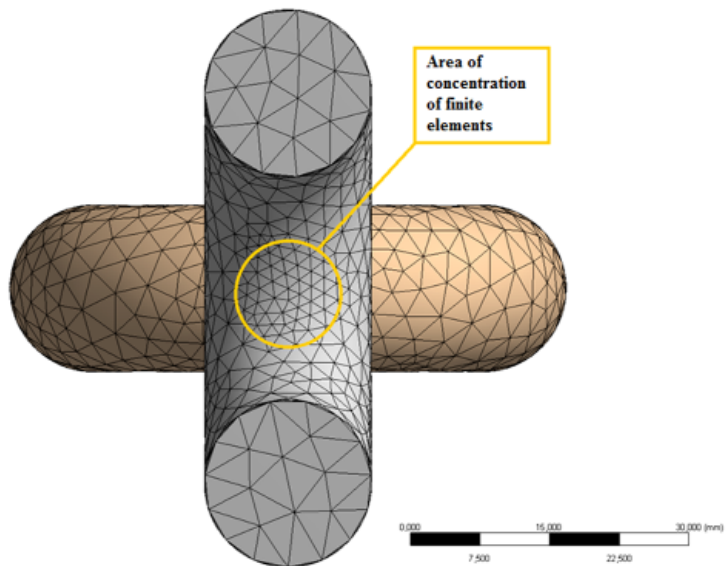

Fig. 5. A view of the finite elements grid; a visible place of grid concentration within places where the links have contact

The material implemented to the analysis was corresponding with the standard grade of steel used for links of mining chains, according to the specification of DIN 17115. A material model which was characterizing the standard parameters of steel grade S355J2+N in a bilinear manner was adopted for the purpose of the analyzes. Fig. 6 shows a diagram created on the ba-
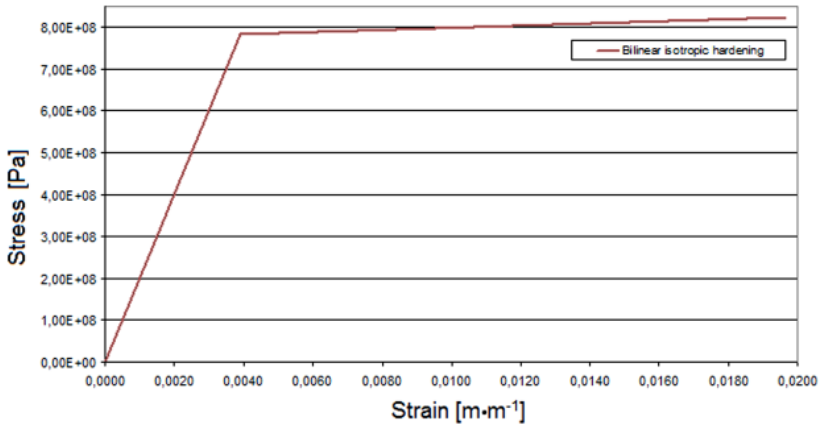
Fig. 6. Material model of steel grade S355J2+N – bilinear diagram Stress-Strain

sis of materials characteristics of steel grade which was used during the analysis, while Table 3 includes basic data used to create the above-specified diagram. The first line on the graph (from 0 to R_e) corresponds to the work of material with regard to resilience and the second line (from R_e to R_m) characterizes the material work with regard to yield.

   Due to the nature of the analyzes as well as lack of detailed materials characteristics, the results for the tensile force equal to 320 kN were adopted as a point of comparison. In case of all samples tested experimentally with regard to tensile, this force did not cause destruction of the sample.

TABLE 3

Material data for the steel used in numerical analyzes

Steel grade	Young model [GPa]	Poisson's ratio	Yield point R_e [MPa]	Static module [GPa]
S355J2+N	200	0.3	785	2.26

   As it was mentioned above, tensile force of $F = 320$ kN applied so that it was increasing in time was adopted as a basic load of the chain.

   Among others, deformations of the model, stress components and their distribution were obtained as a result of the calculations. Fig. 7 shows an example distribution of equivalent stresses determined according to Huber hypothesis for one of the tested sections. Exemplary deformations of the model are shown in Fig. 8.

   A graphical interpretation of the results for all tested cases are shown in diagrams in Figs 9, 10, 11 and 12.
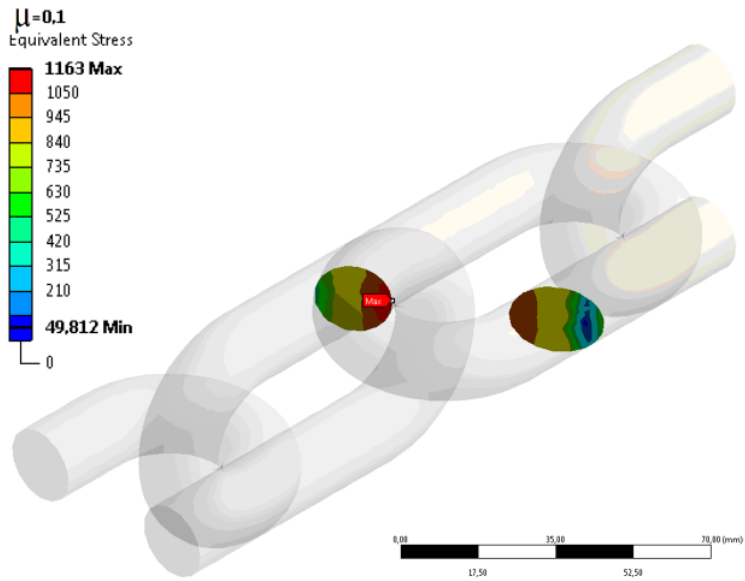
Fig. 7. Distribution of equivalent stresses in the tested section of a chain link
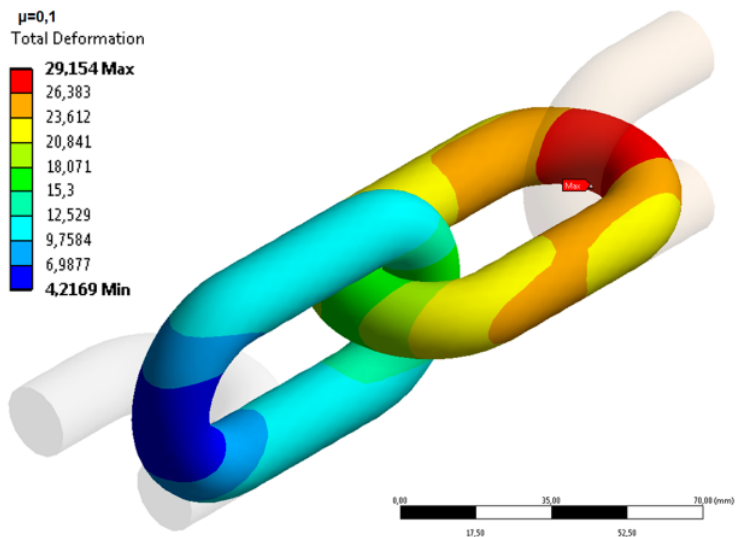(stress in Mpa, without deformation)

Fig. 8. Deformation of structure in the tested system of chain links
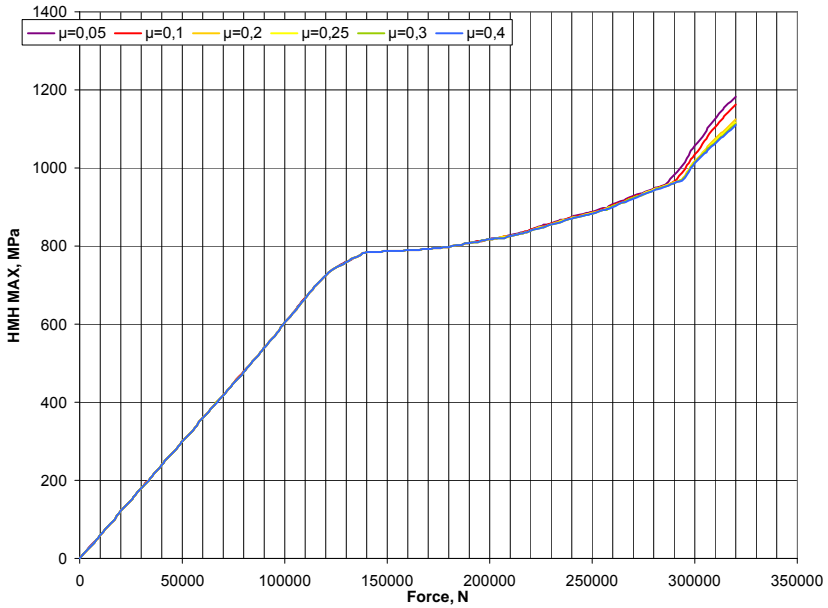(displacement in mm, deformation scale 10×)

Fig. 9. A diagram presenting a change of the maximum value of equivalent stress in the tested section in power function, depending on the change of the friction coefficient value μ
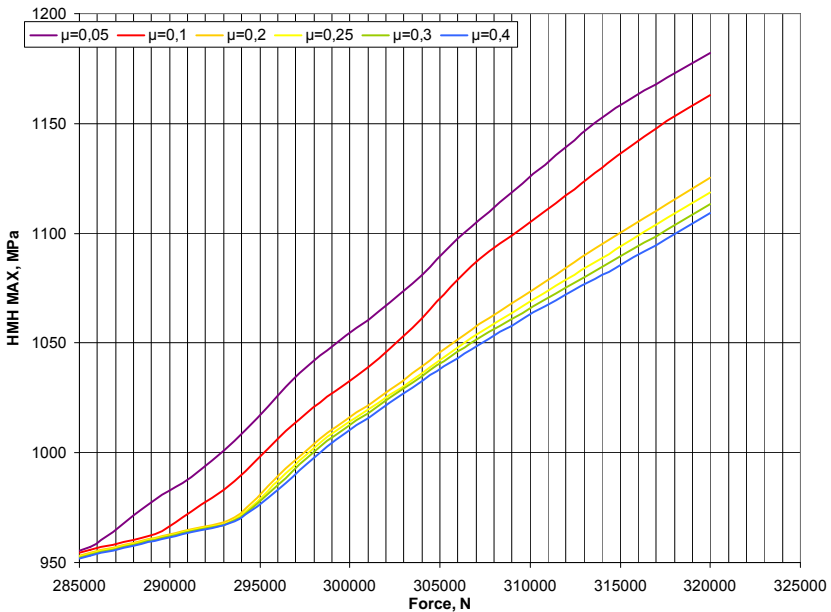

Fig. 10. A diagram presenting a change of the maximum value of equivalent stress in the tested section in power function, depending on the change of the friction coefficient value μ
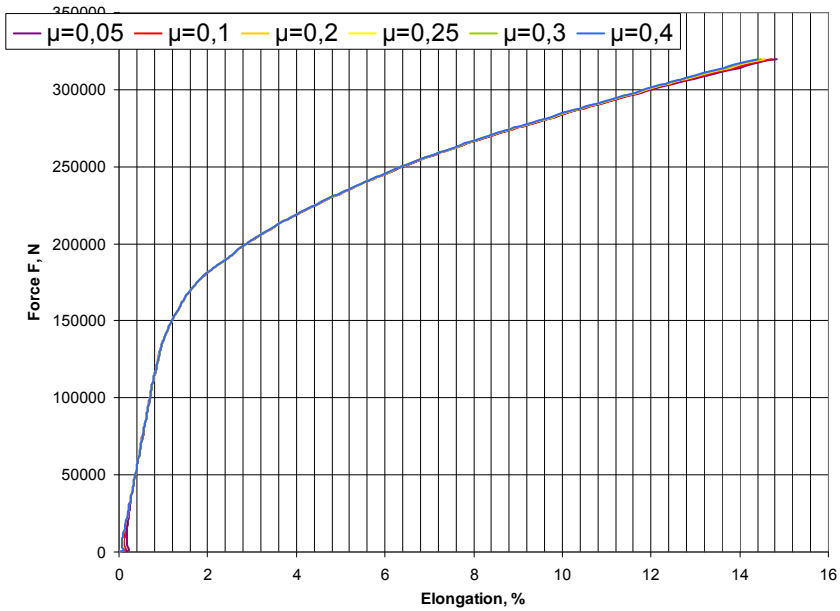
Fig. 11. A diagram presenting the force transmitted by the kinematic system in elongatiion function, depending on the change of the friction coefficient value μ
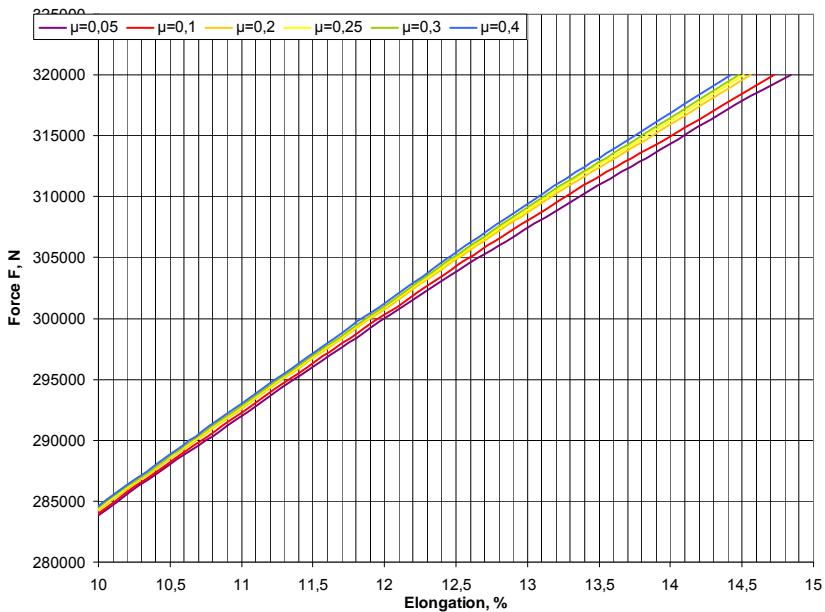

Fig. 12. A diagram presenting the force transmitted by the kinematic system in elongatiion function, depending on the change of the friction coefficient value μ

5. Methods of reducing the negative effect of the protection against corrosion

The purpose of verification of the model analysis was to show that the friction coefficient value has a significant influence on the reduction of the braking force and elongation as well as to point out that there are anticorrosive substances which reduce the negative effect of anticorrosive preservatives. Therefore, an additional series of tests was carried out for the chain 18×64 made of material grade S355J2+N.

Two preservatives specially developed together with the manufacturer of the abovementioned anticorrosive substances were applied as a preservative. The coatings of the chain were protected against corrosion using two substances AntyCor BPS for which the resulting coatings differ in friction coefficient value. Additionally, in order to meet the requirements of chains' manufacturers, the use conditions of those substances were determined:
- no need to maintain the cleanliness class of the protected surface,
- a possibility of applying on a visible corrosion,
- adjusted to the work in C5 environment,
- good adhesion of the coating to the substrate,

6 samples of chains were tested where the samples:
- number 1 and 2 were coated with anticorrosive substance AntyCor BPS series SK,
- number 3 and 4 were coated with anticorrosive substance AntyCor BPS series B-5,
- number 5 and 6 were not protected against corrosion.

The test results are shown in Table 4 the samples after the tests are shown in Fig. 13.

TABLE 4

Results of static tensile tests

Sample no.	Series	Breaking force value [kN]	Standard breaking force [kN]	Change in percentage [%]
6	3	412	410	+ 0.5
5		415	410	+ 1.2
4	2	396	410	- 3.5
3		396	410	- 3.5
2	1	402	410	- 2.0
1		405	410	- 1.2

It can be noticed during the quantitative assessment that in case of the applied anticorrosive substances, the breaking force value is reducing, however its value is significantly lower than in case of chains protected with wax-based substances (Tectyl).
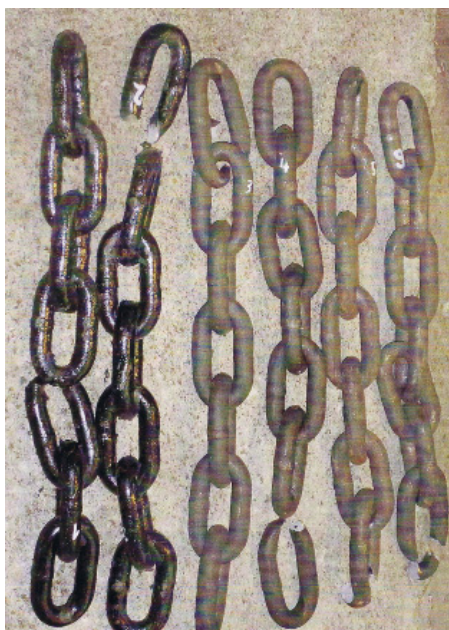
Fig. 13. Samples of the chain after the tests

4. Summary and conclusions

For the purpose of this study, a series of laboratory tests and numerical calculations were performed, verifying the impact of a change of the friction coefficient μ between the mining chain links on its breaking strength. As a result of the numerical analyzes and laboratory tests, the following conclusions can be drawn:

- within the tested scope, a significant impact of friction between links on the load capacity of the chain could be observed,
- in case of model tests, a particularly large difference was noticed within the range between $\mu = 0.1$ and $\mu = 0.2$, a load capacity difference of ca. 6.5% was noticed at a maximum tested ceiling,
- laboratory tests confirm the model tests and the load capacity difference of 6.0% was noticed,
- there is a significant decrease of breaking work for the chains protected against corrosion 38.4%,
- there is a possibility to select anticorrosive substances in order to reduce their negative influence,

The tests showed that chains are generally produced correctly, however the manner of their protection and non-uniform European regulations cause problems with the proper interpretation of test results. The test results were submitted to the manufactures in order to use them in the production processes.

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