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FATIGUE LIFE TESTING OF THE ROUND LINK MINING CHAINS

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Abstract:
The material fatigue phenomenon consists of progressive material damage through the appearance and development of fractures under the influence of variable, periodically recurring stresses. Engineers designing machinery and structures to be fatigue resistant can gain useful insights about design and material properties by reviewing the literature. In this way, we can avoid costly research, but in the case of complex loading phenomena and the interaction of components, we must carry out such research. Fatigue strength calculations are less accurate than simple static calculations. The wear of link chains is concentrated in three areas, depending on the installation location and function of the individual links, namely: in the joints (the points of contact between two links), on the outer surfaces of the arches and on the outer surfaces of the straight sections of the links. During operation, chains are particularly vulnerable to wear through abrasion, corrosion and fatigue. These ageing factors, which act with varying intensity depending on the properties of the deposit, determine the service life of the chain, unless other unforeseen damage occurs, e.g. "hard" blockage of the chain. In many cases, users are guided by their own subjective criteria for assessing the technical condition of chains, which does not always lead to fully rational decisions regarding the continued use of used chains. To date, there have been no attempts to transfer the results of chain fatigue tests to behaviour of real objects. This paper presents issues related to mining chain fatigue testing. The test results presented are for both new and used chains. The experimental tests conducted at GIG made it possible to solve the problem of applying fatigue test results in industrial practice.

Key words: *chain, fatigue, safety*

INTRODUCTION

The development of devices and the related increase in power and rotation as well as the influence of negative factors such as corrosion, increased temperature, repeated overloading and long-lasting vibrations force allows designers and manufacturers to factor in the results of fatigue tests in a comprehensive manner. The surface wear of various parts, such as gears or rolling bearings, is known as contact fatigue. The wear damage of parts resulting from variable loads depends on an entire array of factors, the influence of which cannot be assessed theoretically by means of classic material strength formulas and the theory of elasticity. With regard to the above, the comprehensive consideration of fatigue strength issues is necessary in machine element design.

LITERATURE REVIEW

The connection between the effects of stress concentration and the appearance and development of fractures is the basic characteristic of fatigue as a phenomenon.

The fatigue process can be divided [1] into 3 stages:

1) initiation, which leads to the generation of microcracks,
2) microcrack development, where the combination of microcracks results in fractures,
3) sudden failure of the strained element.

The fatigue process is focused at the fracture spot, resulting in the gradual development of fatigue cracking. The remaining active cross-section gradually decreases, and once it is no longer able to withstand the external loads, the sample undergoes sudden failure.

Until recently, it was considered that chain failure as a result of material fatigue is an exception even in the case of plough chains subjected to high dynamic loads. Loads achieved under normal chain loading do not exceed the ultimate fatigue strength over a typical period of the chain operation [2]. Publications [3, 4, 5] also present the view that chain failure occurs most frequently without clear warning signs, which makes it impossible to undertake preventive actions, and is more related to factors such as excavation of material with a high stone content or operating in a highly environment. In works [6, 7, 8, 9] an attempt was made to model stress values in a link mining chain by means of numerical simulation. These studies have provided some theoretical guidance for predicting the behaviour of chains during their fast varying loading. Studies have also been carried out, e.g., in works [10, 11, 12], to verify the actual stresses in the chain under operating conditions.

Fatigue testing was incorporated into plain link mining chain quality acceptance to comply with standards [13, 14, 15]. Fatigue testing is conducted by means of a universal testing machine enabling the loading of a sample with a cyclic force. Standards define the frequency range as well as the level of the lower and upper load thresholds of a sample during a test, which ends when one of the links ruptures or when the required number of fatigue cycles is achieved. The result of a fatigue test under laboratory conditions does not reflect the level of a mine chain's fatigue strength under the conditions of actual loads occurring in a chain conveyor or plough, which is why it serves only as an additional parameter for assessing a product's quality. The test result may be impacted by the test method as well as the method of mounting the sample in the testing machine, which is why it is important to follow the procedures described in standards. For example, DIN standards note the necessity of loading the sample with a test force before beginning the fatigue test. A correct fatigue strength assessment is time-consuming, as it requires carrying out three tests per material batch. Two basic questions often arise among the end product users (mining plants):

1) Does the loading frequency in a fatigue test have an influence on the result?
2) How long can a chain remain operational when factoring in the results of fatigue testing?

To answer these questions, the authors carried out a cycle of fatigue tests under laboratory and industrial conditions. Due to the difficulty of obtaining samples of a 42x137 chain and the magnitude of the lower and upper force values, a 34x126 chain was selected for fatigue testing to determine the effect of load frequency on fatigue life. In-service chain testing was carried out on the 42x137 chain, samples in question were taken during operation and tested in the laboratory. The high price of the chain does not make it possible to carry out fatigue tests for a large number of specimens, which allows the use of known methods for evaluating test results.

LABORATORY TESTS

The laboratory tests were conducted on a 34x126 chain based on standard PN-G-46701.

The adopted criterion was that the value obtained during the fatigue test, at forces applied to each sample, must be at least as per class C – 70,000 fatigue cycles as per the manufacturer's declaration provided in Table 1.

Table 1
Normative requirements on mechanical properties of 34x126 class C chains

Surface condition	In natural black condition	Protected against corrosion
Tensile strength	1450 kN	1305 kN
Elongation at rupture	14%	11.2%
Bending resistance	34 mm	
Hardness	From 345 HBW to 385 HBW	
Impact resistance	57 J	
Fatigue life	70,000 cycles	

Tests were conducted for the assessed chain to determine its composition. The results are presented on a graph in Fig. 1. The 23 MnNiCrMo5-4, 1.6758 reference material composition is compliant with standard [13].

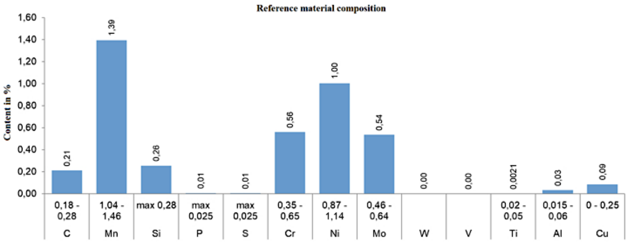

Fig. 1 Chemical composition of the tested chain

The tests were conducted using a ZD 100 testing machine equipped with a pulsator for fatigue testing. The force registration was performed by means of an HBM TYP 1-P3MB/500 bar pressure sensor connected to the machine's hydraulic system, and the displacement was recorded by means of a SENSOPART TYP FT 80 RLA-500-S1L8 laser sensor. The chain temperature was monitored using a thermal camera. All the data was registered using an HBM QuantumX MX840B amplifier with a frequency of 150 Hz.

The following test conditions were defined based on standard [14]:

- The stress at the lower load threshold should be 50 N/mm^2,
- The stress at the upper load threshold should be 250 N/mm^2.

10 chain samples were subjected to testing, where the loading frequency was controlled within 4.2 to 12 Hz for the load limit values. The test results are presented in Table 2.

Table 2

Results of fatigue testing of 34x126 class C chain

Sample number	Load limit values [kN]	Loading frequency [Hz]	Number of cycles until failure
1	91-454	12	72,400
2	91-454	11	86,500
3	91-454	9.6	70,000
4	91-454	9	81,100
5	91-454	9	108,200
6	91-454	9	126,100
7	91-454	9	80,100
8	91-454	4.2	31,500
9	91-454	4.2	77,700
10	91-454	4.2	78,000

The charts displayed in Fig. 2 represent an example sample loading course within the scope of load value and elongation amplitude recording.

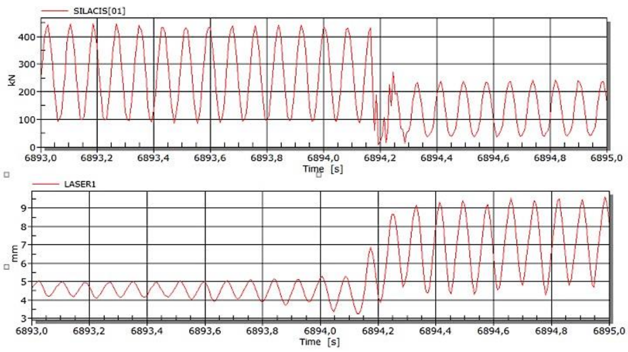

Fig. 2 Graphs of load (upper) and amplitude (lower) values over time

No significant changes were observed when analysing the courses of chain loading and displacement during the test. At the final test stage, failure is preceded by a visible loading decrease and a displacement amplitude increase, which confirms the character of the fatigue process. Temperature recording for the assessed chain link exhibited a rise in the tested object temperature together with the increase in the chain loading frequency during the test and frequency distribution with the results presented in Fig. 3.

The fatigue test results obtained across all 10 samples qualified the chain as fit for operation and highlighted the sample loading frequency to have no influence on the results. The sample loading frequency was found to have an influence on temperature with an increase in temperature being observed as the sample loading frequency increased.

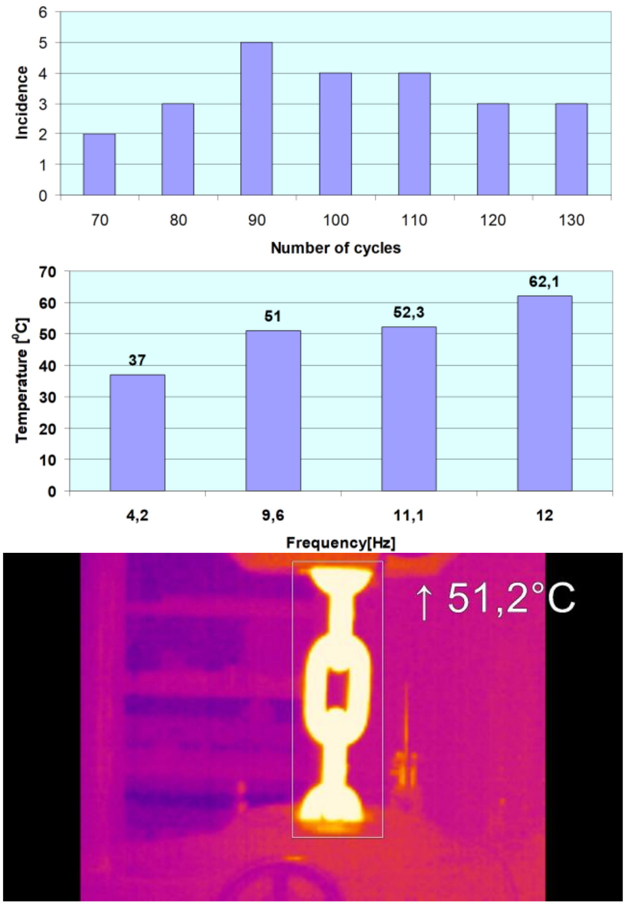

Fig. 3 Graph of sample temperature increase as function of loading frequency

CHAIN FATIGUE TESTING DURING OPERATION

On the one hand, plough chain life depends on the quality of the product, or alternatively its construction. On the other, the chain is subjected to varied operating conditions impacting its operating life. Hard stops of the ploughing system close to the drive, with peak loads that develop over a time measured in milliseconds, may lead to sudden chain failures.

The subject of the conducted tests were plough chains with a nominal link diameter of 42 mm in brand new condition as well as used chains with a known run time in a longwall in a GH-1600-1 plough, manufactured similar to standard DIN 22252:2012 [14] by three different manufacturers. The chain's geometric parameters are presented in Table 3.

Table 3

Nominal dimensions of the chains subjected to assessment

Nominal diameter d, mm	42
Pitch t, mm	137
Internal width b1, mm	48
External width b2, mm	139
Measuring length 5 x t, mm	685

Standard [3] defines the mechanical property requirements for plough chains (Table 4).

Table 4
Plough Chain Mechanical Property Requirements - standard DIN 22252

Surface condition	In natural black condition	Protected against corrosion
Tensile strength	2220 kN	1998 kN
Elongation at rupture	14%	11.2%
Bending resistance	42 mm	
Hardness	From 345 HBW to 385 HBW	
Impact resistance	57 J	
Fatigue life	70,000 cycles (lower force 139 kN, upper force 693 kN)	

According to standard DIN 22252, the material should be selected in a way ensuring the fulfilment of its remaining requirements. However, the minimum grade of steel should be 23MnNiCrMo5-2. 1.6541 per DIN 17115 [16]. The results of chemical composition tests are presented as a chart in Fig. 4.

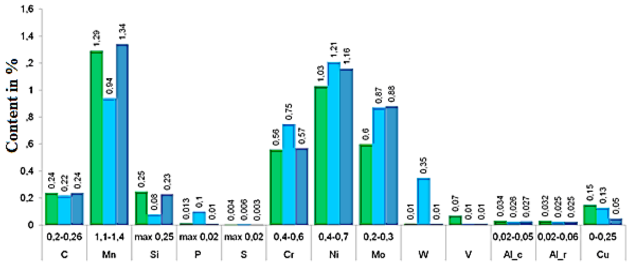

Fig. 4 Chemical composition of the tested chain

The x axis displays the 23MnNiCrMo5-2. 1.6541 reference material composition per DIN 17115 [16]. The chemical composition in terms of molybdenum and nickel content considerably exceeds the values defined in standard [8]. The content of chromium and manganese for the samples in question is also in the upper range.

Before inspecting their practical operation, fatigue tests were conducted on three chain samples per manufacturer. The fatigue test was carried out using a lower force of 139 kN and upper force of 693 kN. The new chain samples achieved the minimum standard-required number of 70,000 cycles (Table 5) and clearly exceeded the values recommended in standards [14, 15].

Table 5
New chain fatigue test results

Manufacturer 1			
Sample number	20-60-20	20-60-21	20-60-71
Achieved number of cycles	222161	234513	280314
Manufacturer 2			
Sample number	20-60-58	20-60-60	20-60-74
Achieved number of cycles	224665	203611	188724
Manufacturer 3			
Sample number	20-60-54	20-60-55	20-60-56
Achieved number of cycles	192808	201186	197101

The control tests of used chains were performed within the scope of fatigue testing on chain strands delivered to GIG, obtained from an operational longwall, with known runs in minutes and times of operation as presented in Table 6.

Table 6
Periods of chain operation in the longwall

No.	**Manufacturer**	**Installation date**	**Removal date**	**Run/ minutes**
1	Manufacturer 1	20.08.2020	11.10.2020	19214
2	Manufacturer 2	11.10.2020	20.11.2021	16867
3	Manufacturer 1	20.11.2020	20.01.2021	21884
4	Manufacturer 3	20.01.2021	19.03.2021	17202

The supplied samples were subjected to another series of fatigue tests. The results of fatigue cycles achieved for the used chains are included in Table 7.

Table 7
Used chain fatigue test results

Manufacturer 1 19214 minutes			
Sample number	20-60-57	20-60-61	20-60-72
Achieved number of cycles	117181	132651	156416
Manufacturer 2 16867 minutes			
Sample number	20-60-59	20-60-62	20-60-63
Achieved number of cycles	148151	156117	136987
Manufacturer 1 21884 minutes			
Sample number	20-60-64	20-60-65	20-60-73
Achieved number of cycles	137703	129388	136237
Manufacturer 3 17202 minutes			
Sample number	20-60-100	20-60-106	20-60-107
Achieved number of cycles	77805	87450	115118

The tested used chains achieved the number of fatigue cycles exceeding 70,000, just as required for new chains by standard DIN 22252. Given the similar characteristics of the tested chains, the loss in fatigue life can be considered collectively with regard to all the tests. The trend of all the tests conducted for the three manufacturers' chains operating from 20.08.2020 to 19.03.2021 is presented as a chart in Fig. 5. It demonstrates that the average operation time required to achieve the standard threshold of 70,000 fatigue cycles is about 32,000 minutes.

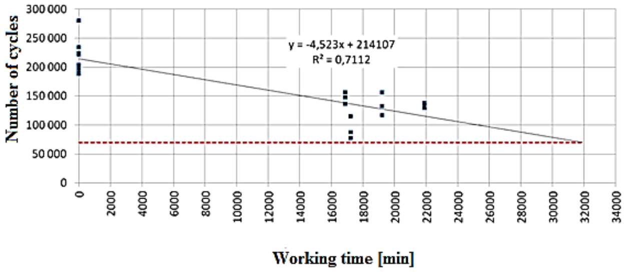

Fig. 5 Trend graph of a fatigue endurance decrease as a result of chain operation

Therefore, it was decided to place the chains back into operation, in agreement with the chain user. The tested chains operated twice in the longwall, first installed as part of the longwall extraction and then combined into a single strand and installed for 17640 minutes of operation as part of testing. The total chain operation time is a sum of the two runs, and the results of the runs are presented in Table 8.

Table 8
Periods of chain operation in the longwall

No.	Manufacturer	Original installation date	Original operation time [min]	Total operation time [min]	Test installation date	Removal date
1	1	20.08.2020	19310	36950	18.04.2021	05.06.2021
2	2	11.10.2020	16867	34507		
3	3	20.01.2021	17242	34882		
4	3	20.01.2021	17242	34882		

Given the similar characteristics of the tested chains, the loss in fatigue life can also be considered collectively with regard to all the tests. The test trend for all the three manufacturers' chains is presented in Fig. 6.

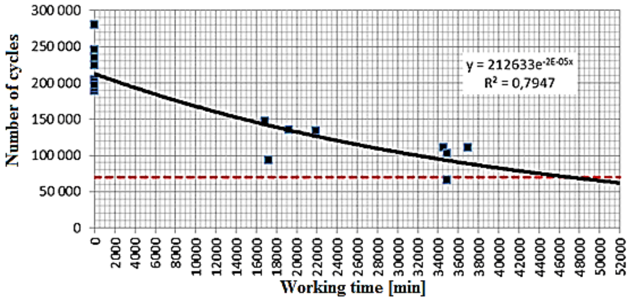

Fig. 6 Trend graph of a fatigue endurance decrease as a result of chain operation

Factoring in the test results obtained after the additional runs confirmed the nonlinear nature of the variations in fatigue life characteristics. After fitting an exponential function to the results, it can be predicted that the general run required to achieve a fatigue life of 70,000 cycles for the plough chain, as provided by the DIN standard, equals about 47,000 minutes.

INFLUENCE OF GEOLOGICAL CONDITIONS ON CHAIN EXPLOITATION

The bottom of the longwall, where the chains were operated, was composed mainly of a compact and medium-bedded grey mudstone and weakly and medium-bedded grey claystone, locally also compact light grey fine-grained sandstone. In the immediate and main roof, there was medium-bedded grey mudstone and light grey fine-grained compact sandstone. Higher up, there was medium-bedded grey mudstone, medium-bedded grey claystone, as well as coal from seam 385/1, which was also locally present in the main roof. The entire parcel to be mined was located within a deposit classified as water hazard grade I. The working site of the chain classified as grade II climatic hazard had an ambient temperature greater than 31°C and did not exceed 33°C. Table 9 shows changes in geometry of the chains during operation.

Table 9
Changes in geometry of the chains during operation

	Nominal diameter	Diameter tolerance	Manufacturer 1	Manufacturer 2	Manufacturer 3
Working time [min]	-	-	36950	34507	34882
Nominal diameter D [mm]	42	±1.1	39.36 (-7.8%)	39.03 (-7.9%)	39.34 (-7.7%)
Pitch t [mm]	137	±1.4	138.20 (+1.0%)	138.30 (+0.9%)	137.60 (+0.4%)
Internal width b1 [mm]	48	min	49.60 (+1.8%)	49.70 (-1.4%)	50.30 (+3.1%)
External width b2 [mm]	139	max	128.00 (-4.0%)	129.30 (-3.7%)	127.60 (-5.3%)
Weld diameter d_s [mm]	< d+3% > d-2%		40,86 (-6,1%)	40.62 (-6.8%)	40.93 (-4.6%)
Weld length [mm]	< 0.7 d		26.00	25.80	26.30
Measuring length 5 x t [mm]	685	±1.4	687.20 (+0.4%)	688.00 (+0.4%)	686.20 (+0.2%)

In all cases, a loss of link cross-section due to frictional wear of the outer surface of no more than 8 per cent was observed. There was also an increase in pitch and gauge length of no more than 1%. Changes in geometry recommended by the manufacturers to qualify the chain for replacement: diameter: -30%, pitch: +3.5%. Good geological conditions had no negative impact on the frictional wear of the chains. Due to the short operating time of the chains, no corrosion process developed on their surface.

THE INFLUENCE OF MECHANICAL DAMAGE ON FATIGUE LIFE

The chain user delivered link fragments for analysis, which constituted the results of plough chain failure during the studied time of operation. Selected pictures of link macro fractures and surface conditions are presented below in Fig. 7.

Fig. 7 Ruptured chain link

In most of the fracture cases, the point of fatigue cracking initiation was the top of the indentation generated on the inside of the link as a result of its displacement and the impact tension of the link by adjacent links. The exception are Thiele chain links, which fractured as a result of:

- cracking initiation from the indentation on the outside in the area of friction influence at the weld (Thiele 10.03.2021), Fig. 8,

Fig. 8 Ruptured chain link

- cracking at the link curve (Thiele 18.03.2021), characterised by a very large focal point of fatigue fracture – a long time of fracture development, Fig. 9.

Fig. 9 Ruptured chain link

It was therefore decided to examine the influence of mechanical deformation on fatigue life. An indentation was identified on the inside of a supplied used chain strand link. After subjecting a sample taken from this area to fatigue testing, the result obtained was 20,342 cycles. This is considerably lower compared to the strands with normal operational wear. Cracking developed at the indentation, which is displayed in Fig. 10 used Thiele chain link cracking at the indentation.

Fig. 10 Ruptured chain link

An indentation was identified on the inside of a supplied used chain strand link also in the case of chains transferred back into operation. After subjecting a sample taken from this area to fatigue testing, the result obtained was 25,343 cycles. This is also considerably lower compared to the strands with normal operational wear. The chain is presented in Fig. 11.

Fig. 11 The chain after fatigue testing

The resulting fatigue fractures presented in Fig. 7-11 are in line with typical fatigue damage fractures, and the mechanism and nature of their formation is consistent with those described in the literature [17, 18, 19, 20].

FATIGUE SAFETY FACTOR

A plough chain loading analysis performed for the chain samples in question was presented in [21]. The cycle character was of pulsating tension (pulsating positive cycle). The average calculated parameter values indicate a similar character of the load cycles on both sides of the plough in terms of load stability and cycle asymmetry. The basic differences being the maximum stress values occurring during the cycle. Example force peaks recorded during the measurements are presented in Fig. 12.

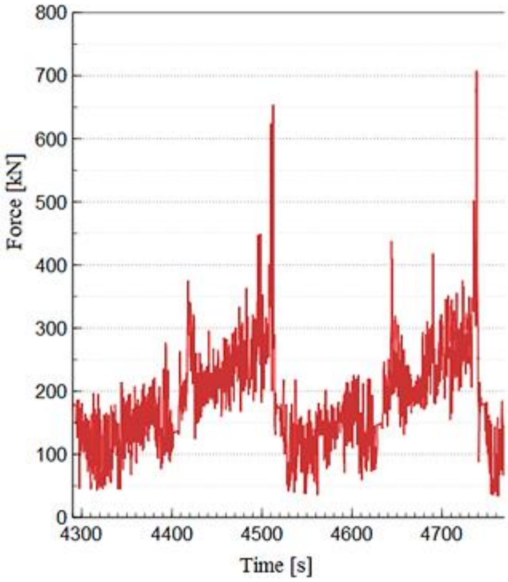

Fig. 12 Example of loads recorded during industrial tests

Values of force peaks recorded during changes in a direction of plough operation are presented in Table 10.
Measured values are close to the upper force level specified by the standard which is 693 kN for this type of chain. In all performed tests a load stability coefficient was within $1 < \chi < \infty$ and a load asymmetry coefficient was within $0 < R < 1$, which confirms the type of cycle [22].

Table 10
Maximum force values

Main drive side		Auxiliary drive side	
Force [kN]	Stress [MPa]	Force [kN]	Stress [MPa]
663.4	239.4	555.9	200.6
615.4	222.1	628.3	226.8
630.8	227.7	655.9	236.7
653.0	235.7	654.8	236.3
707.3	255.3	692.8	250.0
777.5	280.6	661.1	238.6
644.4	232.6	631.0	227.7
595.3	214.8	643.4	232.2
636.4	229.7	647.7	233.8
Average values			
658.2	**237.5**	**641.2**	**231.4**

The commonly acknowledged fatigue strength threshold [22, 23, 24, 25] in pulsating tension cycles with a given maximum stress is:

$$Z_{rj} = 0.55 \cdot R_m$$

where:
R_m – tensile strength, MPa.

Considering the stress concentration in the link layers, the chain breaking stress occurring in its limbs is lower than the material R_m. Standard DIN 22252 defines the breaking stress at a level of 800 MPa. This level was confirmed by way of tensile testing for both the new and used chains.

For a new chain, the safe stress level is Z_{rj} = 440 MPa. The highest stress recorded during regular operation was 194.5 MPa. This means that a correctly used chain operates with a fatigue safety factor of:

$$n_{rz} = 2.26$$

which places the chain within the range of 2.0-2.3 intended for structural steel.

For a chain subjected to a fluctuation of forces at intervals of about 90 seconds, resulting in a stress of even 280.6 MPa, the factor is:

$$n_{rz} = 1.56$$

The fatigue testing of a dented chain revealed that the influence factor [26, 27] of a notch generated by such damage relative to the average life of the chain is:

$$\beta_k = 93458/20342 = 4.59$$

After factoring in the notch influence, the safety factors are 0.49 and 0.34 respectively. This means that the occurrence of notches considerably lowers the operational safety of a chain from the perspective of its fatigue life.

CONCLUSIONS

On the basis of conducted laboratory and industrial tests, we can express the following conclusions that will be useful for entities utilising mining chains.

1. The fatigue tests conducted for brand new samples revealed no influence of the sample loading frequency on the test results. The increase in loading frequency leads to an increase of the sample temperature.
2. The laboratory tests conducted according to the procedures provided in standard DIN 22252 on samples of used chains demonstrated no reduction in strength parameters in terms of fatigue life. According to the predictions resulting from fatigue testing, the estimated fatigue life for chains used in longwalls is 47,000.00 min.
3. The primary reason for premature chain failure during operation are indentations generated as a result of link damage. It leads to the generation of a notch decreasing the fatigue life Z, with the deficiency determined by the notch influence factor β_k. According to the tests conducted for the supplied sample, the factor was β_k = 4.59.
4. The fatigue safety factor for used chains was n_{rz} = 2.26, which is a correct value compliant with those adopted in literature, which confirms the correct selection of the chain and its appropriate operational loading.
5. The tests conducted confirmed the positive influence that molybdenum has on chain fatigue life.

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