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Influence of Chemical Composition of Lifting Equipment Material On Their Performance

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Abstract: The presented study refers to the use of load-handling chain slings. The theoretical calculation shows the high reliability and virtually trouble-free operation of a metal welded circuit. The introduction describes the relevance of the work and a brief historical background of the existence of this problem, as well as the terms used in the work. The next part presents a methodology for calculating the load and reliability; the quantitative values of reliability indicators, methods for obtaining them and a methodology for calculating reliability by the criterion of strength are shown. The scheme of operation of the emission spectrometer and the technology of its application are presented. In the conclusions, there are practical recommendations and coincidence of the results of the study with known facts from the materials sciences. The studies conducted by the authors demonstrate that the use of chain hangers without in-depth input control of the chemical composition of the material used can cause significant harm.

Keywords: Load capacity, materials science, composition, material, steel, chains

1. Introduction

"Ex nihilo nihil fit" is the words of the ancient Roman poet-philosopher Lucretius (98-55 BCE) meaning "Out of nothing, nothing will come". In the modern world, this phrase too often acquires its relevance if we there is a parallel with a low-quality product from which it is necessary to manufacture super-complex and responsible products. In modern conditions, quality becomes the most important competitive factor. The emerging contradictions between the complexity of the problems that arise at the enterprise related to the production of high-quality products and the methods used to solve them negatively affect the effectiveness of decisions made on product quality management. All this determines the emergence of specific requirements for quality management systems, which imply an increase in the importance of using economic and mathematical methods in making design decisions. An important element of the quality management system is the input quality control of raw materials. Input quality control, in fact, is an activity aimed at identifying and eliminating inconsistencies, which leads to an increase in the cost of specific units of products manufactured using resources subject to control [1].

In this work, the team of authors faced the problem of using low-quality chains, which required additional tests and in-depth chemical analysis to identify them. Thus, the manufacture of one unit of finished products requires more time and labor intensity. In order to achieve the necessary strength and durability of load handling devices, general requirements for designs, choice of materials and test methods are established in order to ensure that the established level of requirements is met. If chains made in accordance with the requirements are used for normal lifting operations, then there is no danger of fatigue failure. Chain failure can be caused by the wrong choice of chain class and load

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handling devices. The risk of injury from sharp edges and corners or rough surfaces when consumed is also very dangerous [2].

We consider some of the terms used in the work: according to the definitions given in [2], “Damage is an event consisting in a violation of the serviceable state of an object in operation while maintaining a healthy state”; "Failure is an event consisting in violation of the operable state of the object". It follows from the text of the above definitions that damages such as partial damage to the paintwork, small residual deformations of secondary mechanical units do not affect the operable state of the load-lifting unit and, when analyzing reliability indicators, we will not take them into account [3], [4], [5]. The study of physical (density, electrical conductivity, thermal conductivity, magnetic permeability, etc.), mechanical (strength, plasticity, hardness, modulus of elasticity, etc.), technological (fluidity, malleability, machinability, weldability, etc.) and operational properties (resistance corrosion, wear and fatigue, heat resistance, cold resistance, etc.) allows determining the areas of rational use of various materials, taking into account economic requirements. Falling loads caused by the failure of slings, such as lifting devices, chain slings or separate parts, pose a direct or indirect danger to the safety or health of people in the danger zone of the lifting mechanisms [8].

2. Methodology

To ensure resistance to aging of chains during operation, the steel must contain at least 0.025% aluminum, and the mass fraction of impurities should not exceed the figure in the Table 1.

Table 1 - Maximum mass fraction of the content of third-party elements

Element name	Maximum mass fraction, %
Sulfur (S)	0.030
Phosphorus (P)	0.030
Nickel (Ni)	0.40
Chromium (Cr)	0.40
Molybdenum (Mo)	0.15

The voltage in the chain link is unevenly distributed [9]. On the outer side of the link, it significantly exceeds the rated voltage. The rated stress values are calculated based on the fact that the breaking force is distributed over the entire cross-sectional area of the link. The design value of working load limit *(WLL)*, t, is calculated by the following formula:

$$WLL = \frac{0.5\pi 200 d^2}{1000g} \mathrm{WLL} = \frac{0.5\pi 200\mathrm{d}^2}{1000\mathrm{g}}, \tag{1}$$

where *WLL* is given in tons; g is the free fall acceleration. The value of manufacturing proof force (*MPF)* is based on exact design values using the following formula [10]:

$$MPF = \frac{0.5\pi 500 d^2}{1000} \mathrm{WLL} = \frac{0.5\pi 200\mathrm{d}^2}{1000\mathrm{g}}. \tag{2}$$

The breaking force value is based on exact design values using the following formula:

$$BF_{min} = \frac{0.5\pi 800 d^2}{1000} \mathrm{WLL} = \frac{0.5\pi 200\mathrm{d}^2}{1000\mathrm{g}}. \tag{3}$$

Figure 1 shows the dependence of the elongation of one chain link on the load applied to it. It is easy to see in the graph that when the chains are operated without exceeding the carrying capacity, the links do not elongate [11]. Round link chains must be used when designing chain slings. The safety factor of the chain in relation to the load of a separate branch of the sling must be at least 4 [12].

The probability of failure-free operation of the product during the cycle in the general case $P(t)$ and its standard deviation (*SD*) in the general case is determined by the following formulas:

$$P(t) = \prod_{j=1}^{n} P_j(t)\, \mathrm{WLL} = \frac{0.5\pi 200\mathrm{d}^2}{1000\mathrm{g}}, \tag{4}$$

$$\sigma_{P(t)} = P(t) \sqrt{\sum_{j=1}^{n} \left[\frac{\sigma_{P_j(t)}}{P_j(t)}\right]^2}\, \mathrm{WLL} = \frac{0.5\pi 200\mathrm{d}^2}{1000\mathrm{g}}, \tag{5}$$

where n is the number of j-th components of the product; $P_j(t)$ is uptime probabilities (*UP*) of *j*-th component of the product; $\sigma_{P(t)}$ is *SD* of *j*-th component of the product.

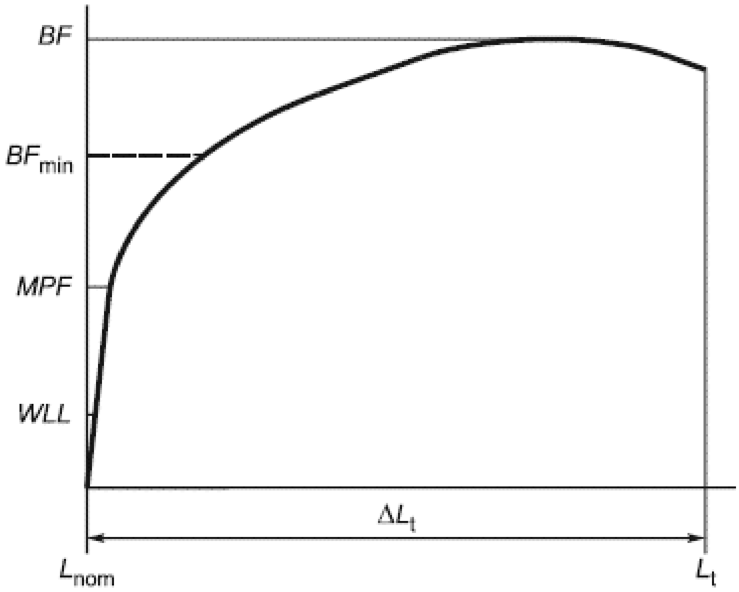

Fig. 1 - BF is the breaking force; $BF_{min}$is the specified minimum breaking force; MPF is the manufacturing proof force; WLL is the working load limit; ΔL_t is the total elongation at break

The reliability of the mechanism is determined by the safety margins, therefore, *UP* of *j*-th component of the kit and its *SD* is calculated by the following formulas:

$$P_j(t) = P_{\Pi j}(x)\text{WLL} = \frac{0.5\pi 200\text{d}^2}{1000\text{g}}, \quad (6)$$

$$\sigma_{P_j} = P_j(t)\sqrt{\left[\frac{\sigma_{P_n(x)}}{P_n(x)}\right]^2}\,\text{WLL} = \frac{0.5\pi 200\text{d}^2}{1000\text{g}}, \quad (7)$$

where $P_{\Pi j}(x)$ is the reliability indicator of *j*-th component of the set, calculated according to the criterion of strength; $\sigma_{P_n(x)}$ – *SD* $P_n(x)$. According to the statistics of Rostekhnadzor [13], occupational injuries and accidents at lifting structures are in third place (after injuries in the coal and mining industry) and amount to about 90 accidents per year. The above statistics indicate the need to find additional methods to reduce accidents and improve the safety of the fleet of lifting units. The limit states for the loss of bearing capacity include limit states that lead to the complete operational unsuitability of the lifting equipment or to the complete (partial) loss of the bearing capacity of the design elements of its metal structure (destruction, formation of significant cracks, loss of stability, transition to a variable system due to deformations and destruction, etc.) [14]. Quantitative values of reliability indicators $\text{P}_{\Pi\text{j}}(\text{x})$ and $\sigma_{\text{P}_{\text{nj}(\text{x})}}$ are calculated by the following formulas [15]:

$$P_{\Pi j}(x) = \prod_{i=1}^{m} P_i(x), \quad (8)$$

$$\sigma_{P_{nj}(x)} = \sqrt{\sum_{i=1}^{m} \sigma_{P_i(x)}^2}, \quad (9)$$

where $\text{P}_\text{i}(\text{x})$ and $\sigma_{\text{P}_\text{i}(\text{x})}$ is the probability of non-destruction of *i*-th of component of element *j*-th of the set of its SD, calculated by the following formulas [16]:

$$P_i(x) = 0.5 + \Phi(x_i), \quad (10)$$

$$\sigma_{P(x)} = \frac{1}{\sqrt{2\pi}} e^{-\frac{x_i}{z}}, \quad (11)$$

where $\Phi(X_i) = \frac{1}{\sqrt{2\pi}}\int_0^{x_i} e^{-\frac{t^2}{2}}$ is the tabular Laplace function; $x_i = \frac{\widetilde{\sigma_{T_1}} - \sigma_{g\,max_i}}{\tilde{S}\widetilde{\sigma_{T_1}}}$ is the argument of Laplace function, where $\widetilde{\sigma_{T_1}}$ is the estimation of the mathematical expectation of the yield strength of the material of *i*-th element; $\tilde{S}\widetilde{\sigma_{T_1}}$ is *SD*, $\widetilde{\sigma_{T_1}}$ is accepted in accordance with Industry standard 92-0264; $\sigma_{g\,max_i}$ is the material stress in the dangerous section of *i*-th element.

Thus, *UP* per cycle for the chain is taken equal to 1.0, with *SD* equal to 0, since the safety margins of the elements are higher than the minimum allowable [17], [18]. The problem of multicriteria optimization is to find a vector of target variables that satisfies the imposed constraints and optimize a vector function whose elements correspond to the target functions. These functions form a mathematical description of the satisfaction criterion and, as a rule, contradict each other. This problem arises in many fields of science, and its solution can be applied to many complex mechanical components and devices [19]. For a more structural description of the methodology used, we summarize:

1. Preliminary theoretical data on the chemical composition of the applied chain must meet the requirements of Table 1; (if this requirement is met, then we go to step 2);
2. Determination of calculated values of acting loads according to formulas (1), (2) and (3);
3. Determination of the margin of safety, in case of failure to meet the requirement $\frac{BF}{WLL} \geq 4$, it is necessary to additionally calculate the reliability indicators using formulas (8), (9), (10) and (11).

For example, we take six arbitrary chain link diameters 4, 10, 16, 22, 28 and 45 and calculate WLL, MPF and BF values for them using formulas (1), (2) and (3):

Table 2 - Estimated values *WLL, MPF* and *BF*

Link diameter, mm	*WLL*, t	*MPF*, kN	*BF*, kN
4	0.511	12.566	20.106
10	3.195	78.539	125.663
16	8.181	201.061	321.699
20	12.783	314.159	502.654
28	25.056	615.752	985.203
45	64.717	1590.431	2544.69

Based on the data obtained, the margin of safety is $\frac{BF}{WLL} \geq 4$. The requirement is met and therefore additional calculation of reliability indicators is not required. In some cases, when it comes to the probabilities of failures, for example, due to the impact of a seismic shock or an attempt to lift a load above the design capacity, calculation methods are used to analyze models of lifting units. Before suggesting such methods of analysis, it is necessary to take into account the methods for detecting failures in operation, as well as the criteria for the inadmissibility of certain types of characteristic damage encountered in practice. The chain sling is classified as M2 mechanism; therefore, the minimum margin of safety is 3. From which it follows that, according to the Table 3, the use of a chain according to GOST 818 EN meets all the necessary requirements [11].

Table 3 - Mechanisms classification

Chain purpose	Group of classification (mode) of the mechanism according to Industry standard 4301/1	
	M1, M2	M3-M8
Cargo	4	6

Since the safety margins of the chain, in accordance with [20], are higher than the minimum allowable ones, the probability of their non-destruction is close to unity and its reliability indicators in terms of the strength parameter are:

$$P_{\Pi}(x) = 1.0;\ \sigma_{P_n(x)} = 0.0, \quad (17)$$

The probability of non-destruction of the chain P(t) and its *SD* according to formulas (4), (5) is:

$$P(t) = 1;\ \sigma_{P(t)} = 0, \quad (18)$$

To check the chemical composition, we can use the following equipment: atomic emission spectrometers implement the principles of atomic emission spectral analysis in their work. These instruments are the most common analytical instruments in the world and in Russia. They are intended for analysis (most often elemental analysis) of the composition of various substances in various aggregate states.

Often, spectrometers are called optical-emission spectrometers (optical-emission spectrometers or OE-spectrometers). This name is used to emphasize the difference from X-ray fluorescence spectrometers (X-ray fluorescence spectrometers or XRF Spectrometers). The principle of operation of the latter is also based on the registration of the emission spectrum, but of a different wavelength range: X-ray, not optical. Also, such instruments are sometimes called simply emission spectrometers. In addition, names are widely used that explicitly indicate the type of spectrum excitation source used:

- spark or arc spectrometer with a spark or arc source of excitation of spectra;
- ICP Spectrometer is an atomic emission spectrometer with a spectrum excitation source in the form of inductively coupled plasma;
- for spectrometers with laser sources of excitation of spectra, the names laser or laser-spark spectrometer are used.

Non-destructive testing refers to such a procedure for controlling the properties and parameters of an object, in which the suitability of the object for further use and operation is not violated. From this point of view, some types of spectrometers are related to non-destructive testing devices (for example, mobile spark spectrometers). Although they leave traces of spark erosion on the object with a depth of several microns and a diameter of less than 10 mm, the suitability of the object for further use and operation, as a rule, is not violated. On the other hand, for example, ICP spectrometers in their classical version are used for spectral analysis of samples in the liquid phase. Therefore, the spectral analysis of solid samples with these devices requires their preliminary chemical dissolution, i.e. destruction. However, if ICP spectrometers equipped with a spark or laser ablator are used for the analysis of solid samples, then such a combined atomic emission spectrometer can again be classified as a device for nondestructive testing. The principle of operation of an optical emission spectrometer is quite simple. It is based on the fact that the atoms of each element can emit light of certain wavelengths (spectral lines), and these wavelengths are different for different elements. In order for atoms to emit light, they must be excited by heating, electric discharge, laser or in some other way. The more atoms of a given element are present in the analyzed sample, the brighter the radiation of the corresponding wavelength will be.

3. Results

After the positive results of the theoretical calculation presented in the previous section, we can proceed to the practical application of the selected circuit. Based on the operational load, we chose State Standard GOST EN 818-2-8-22h66 chain. Comparison with another circuit is shown in the Table 4.

Table 4 - Circuit comparison

Chain	Link diameter, mm	BF, kN	Weight 1 m, kg	Cost of 1 m, rubles
GOST EN 818-2-8-22h66	20	502	9	3 950
20h60-T(8) GOST 30188-97	20	504	8.6	5 690

With similar geometric and lifting parameters, the choice was made in favor of a cheaper component. Chains must have a manufacturer's certificate of their testing in accordance with the regulatory document according to which they are manufactured. In the absence of the specified certificate or for other reasons, tests of a sample of the chain must be carried out to determine the breaking load and check for compliance with the dimensions of the normative document. The chain shall be tested with a load of 1.25 times its rated pulling force for 10 minutes [20]. To use the chain as a part of a load-lifting product, we must additionally make sure of the following:

- availability of a certificate;
- need for additional testing.

In the case presented in this paper, the presence of a certificate of performance confirmation did not convince the group of authors of the high quality of the chains. The Figure 2 shows part of the test circuit for checking the load with an increased factor. During testing, the link located on the hook was deformed (Figure 3), when the test was repeated, the link broke. Figure 4 shows the process of performing an inspection with an optical emission spectrometer. Sample types that can be tested with it include samples from molten material, primary or secondary metal fabrication. Of the total number of 10 manufactured samples, one sample was tested, that is, 10%. Based on the negative results of checking one sample, the entire batch was rejected, and a claim was sent to the chain manufacturer about non-compliance with the stated requirements. During the input control of the circuits, these deviations were not identified, which indicates the need for a deeper analysis during the input control.

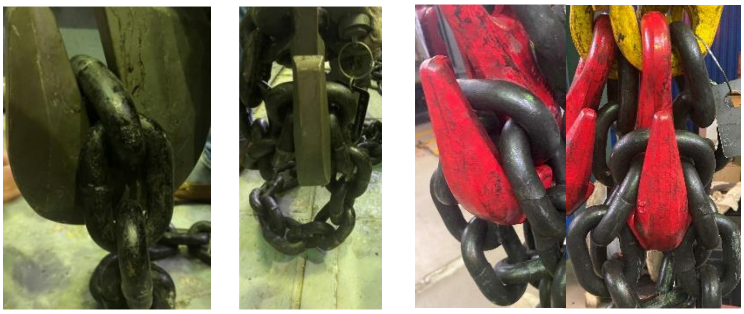

Fig. 2 - Test scheme

Fig. 3 - Link deformation

4. Discussion

When evaluating the conformity of flexible elements of load-handling devices made of short-link load-lifting chains, the following control methods are used:

a) visual;
b) instrumental.

Visual control consists of:

a) in the assessment of compliance with the passport data of the load-handling device and (or) regulatory documents:
- chains and existing markings;
- design of the connections of the end links of the chain with the mating elements of the load-handling device.

b) inspecting the chain along its length and at the points of connection with the mating elements of the load-handling device for the presence of defects determined by the human eye, or using optical instruments (10x magnifying glass).

The instrumental control method is a measurement of the chain parameters: diameter and length of the links, decrease in the diameter of the links with obvious signs of wear, as well as the length of the slings, chain branches and the difference in their lengths in multi-branch slings due to residual elongation after running in. Measurements are made using a universal measuring tool. Branches of chain slings and elements of other lifting devices from chains are subject to rejection if the following defects and damage are found:

a) absence of a tag or marking on it (for branches and elements replaced during operation);
b) link break;
c) cracks, tears, delamination of metal in chain links;
d) curvature (curvature, deformation) of chain links;
e) elongation of the chain link more than 3% of the original size;
f) decrease in the diameter of the chain link due to mechanical or corrosive wear, local dents or nicks by more than 10% of the original one;
g) gouges from gas cutting or flashing from welding;
h) damage resulting from thermal exposure or electric arc discharge.

A multi-branch sling made of steel rope is subject to rejection if the difference in the length of the branches due to residual elongation is more than 3% after running in, a chain sling is more than 1%, and a sling on a textile basis is more than 6%. After an analytical assessment of the damage, it became necessary to check the composition of the material from which the chain suspension was made. For these purposes, an optical emission spectrometer was used. One part of the electromagnetic spectrum used in an optical emission spectrometer includes the visible spectrum and a part of the ultraviolet spectrum. The wavelength ranges from 130nm to 800nm. The spectrometer can analyze a wide range of elements from lithium to uranium in solid metal samples, operating with a wide concentration range, very high confidence, high accuracy and low detection limits. (Figure 4, Figure 5).

Fig. 4 - Control methods

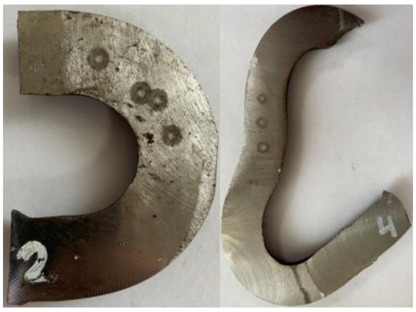

Fig. 5 - Controlled samples

The result of the check is shown in the Figure 6, where it is clearly seen that the content of the elements according to the Table 1 is not satisfied. For the control check of the spectrometer, a sample was taken from steel 12G2S GOST 27772-88 (Figure 7), which confirmed the accuracy of the device.

	Fe	C	Si	Mn	Cr	Mo	Ni	Al
Min		0,0000	0,0000	0,0000				
Max		0,220	0,550	1,60				
1	98,2	H 0,242	0,372	0,919	0,0163	0,0227	0,124	< 0,0050
2	98,2	H 0,253	0,346	0,931	0,0174	0,0271	0,121	< 0,0050
3	98,1	H 0,248	0,415	0,947	0,0230	< 0,0020	0,128	< 0,0050
4	98,1	H 0,235	0,366	0,986	0,0179	< 0,0020	0,121	< 0,0050
Cp.	98,1	H 0,244	0,375	0,946	0,0187	0,0124	0,124	< 0,0050

Fig. 6 - Spectrometry result of the deformed sample

	Fe	C	Si	Mn	Cr	Mo	Ni	Al
Min		0,0900	0,0500	1,30	0,0000		0,0000	
Max		0,150	0,800	1,70	0,300		0,300	
1	97,6	H 0,155	0,504	1,43	0,0363	< 0,0020	0,130	< 0,0050
2	97,5	H 0,152	0,520	1,48	0,0479	< 0,0020	0,133	< 0,0050
3	97,6	0,144	0,519	1,44	0,0403	< 0,0020	0,131	< 0,0050
4	97,6	H 0,153	0,511	1,41	0,0363	< 0,0020	0,132	< 0,0050
Cp.	97,6	H 0,151	0,514	1,44	0,0402	< 0,0020	0,132	< 0,0050

Fig. 7 - Spectrometry result of the controlled sample

The content of carbon and alloying elements determines the properties of steels. The composition of the alloys contains iron, carbon, magnesium, silicon, manganese, phosphorus, sulfur, etc. The amount of one component in relation to the total mass determines viscosity, ductility, strength and hardness of the metal. Carbon steels are classified by chemical composition, manufacturing method, purpose and degree of deoxidation. The production technology does not completely remove impurities from steel. They occupy a small percentage, but are present in all carbon steels. The carbon content separates steel into carbon steel and alloy steel. The production of metal welded circuit is not a complex production and does not require any conditions for itself, such as clean rooms [21]. It has long been automated at a high level.

Load chains are also used for transporting complex and special loads over different distances and in difficult weather conditions [22], [23], [24]. The mechanical properties of steel depend on the amount of carbon. An increase or decrease in the carbon content, even in hundredths of a percent, predetermines the scope of the metal. When more carbon is added to steel, the alloy becomes hard, strong and elastic. When it reduced, it improves its ductility and impact resistance. The low content of silicon (Si) in the test sample indicates a lack of elastic properties and corrosion resistance. A low chromium (Cr) content may indicate reduced strength and reduced ductility, which is why a break occurred.

5. Conclusion

As the study showed, the presence of accompanying product quality certificates is not always its guarantor. Theoretical calculation does not always correspond to operational values. With a fourfold margin of safety, detailed incoming control is required, up to the chemical composition, which entails an expansion of the staff of enterprises and the emergence of chemical analysis laboratories. As an option for solving this problem, there is a tightening of the set of rules and requirements for manufacturers of lifting chains and alloys, as well as the introduction of penalties for violations of quality and manufacturing technology. In other words, the tightening of input control measures is an extensive development path, leading to overspending of resources within the framework of the joint activities of the supplier and the consumer; and supplier evaluation and related activities to improve their quality management systems is an intensive path that saves resources. The completed sequence of actions can be used as a technique for conducting input control at heavy engineering enterprises to identify low-quality material. The presented sequence can be finalized to a ready-made methodology, which requires an in-depth analysis of the results.

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