Improving the Operational Reliability of Complex Technical Systems Operating in Corrosive Conditions

N. V. Pirumyan[1(✉)], M. G. Stakyan[1], and B. M. Yazyev[2,3]

[1] National University of Architecture and Construction of Armenia, Yerevan, Armenia
pirumyannarine@gmail.com
[2] Don State Technical University, Rostov-On-Don, Russia
[3] Kazan Federal University, Kazan, Russia

Abstract. The responsible heavily loaded structural elements (butt welds and sections of their location) of the complex technical systems, which are mainly operated outdoors, are impacted by atmospheric influences and cyclic stresses, which are caused by load fluctuations, nature vibration processes, ambient temperature and changing weather conditions. These factors cause the appearance and development of corrosion-fatigue damage and can lead to cracking and fatigue destruction of structural elements. The factors affecting on the bearing capacity of structural elements, which are occurred in a complex form, in different amounts and combinations, are classified. The surface strengthening of the junction outside surfaces and usage of anticorrosive protective plating on them are selected from a number factors. So that, to magnify fatigue strength and durability is suggested to use a strengthening technology-surface plastic deformation of welds. The physical and mechanical phenomena of the appearance and development of corrosion-fatigue processes are considered and ways to enlarge the strength and durability of elements using new corrosion-protective polymer platings (Belzona 1111) in the location of butt welded junctions are outlined. A series of techniques, e.g., static tests of steel samples with and without platings in a corrosive solution was performed and its effectiveness for application in the critical nodes was confirmed. The effectiveness of the implementation of these, process operations which enlarge the bearing capacity of the complex technical system, has been proven.

Keywords: Complex Technical Systems · Structural Elements · Corrosion · Fatigue · Cyclic Durability · Polymer plating · Strengthening · Affecting Factors

1 Introduction

The development of industry, agriculture, transport infrastructures is related to the reliability of the operation of the various purposes Complex technical systems (CTS). The extension of the CTS network is the solution of this problem, that is implemented by surmounting the difficult terrain, various natural and climatic zones and water spaces.

S. V. Klyuev et al. (eds.), *Innovations and Technologies in Construction*, Lecture Notes in Civil Engineering 307,
https://doi.org/10.1007/978-3-031-20459-3_39

As the main CTS are mainly operated in an area free of settlements, therefore the laying of the network, maintenance, technical examination, as well as scheduled maintenance of the system are relatively complex. This problem is also complemented by the peculiar properties of the CTS operation under conditions of corrosion and atmospheric influences, as well as fatigue processes associated with the cyclical loading of the network, ambient temperature fluctuations and various vibration phenomena. This factors inevitably leads to the cyclical stress–strain state in the structural elements, to the occurrence of corrosion and fatigue damage, and if there are surface and internal defects of welded junction of elements—to the development of cracks and destruction of separate structural elements [1–4].

These phenomena prescribe the requirement for the formation of the stages of development, creation and operation of the CTS, consisting of the procedures listed below: research of the location of the CTS; application of design, technological, testing, maintenance and routine repair that guarantee a given level of operability and reliable operation of the CTS [5–7].

The stages of design and technological development of the CTS are considered. The operation of CTS assumed the classification of factors causing damage and the accounting of their complex impact on the bearing capacity of the responsible structural elements of CTS [4]. It is possible to perform this by using in calculations the advanced features of the affecting factors (type and parameters of the loading mode and physical and mechanical characteristics of structural materials, terrain and atmospheric influences, as well as indicators of heat, corrosion, wear resistance and fatigue resistance of structures), as well as taking into account the influence of their complex interaction.

2 Methods and Materials

The real working conditions of the CTS are characterized by the appearance and development of various types of damages, which are continuous and complex in nature and may reduce the strength, durability and reliability of the structure. In some cases, they can result in the breakdown of the most loaded elements of the CTS, consequently—in significant downtime and reduced productivity, and to the appearance of fatigue cracks and fractures [1].

The number of factors affecting on the bearing capacity of structural elements is significant and, according to the principle of appearance and the nature of the impact, they can be united in the following groups:

I. Geometry and physic-mechanical condition of the CTS construction material;
II. System location surroundings and loading modes;
III. Corrosion-fatigue phenomena in CTS structural elements;
IV. Technological aspects of the construction and maintenance of CTS:

The factors include:

(1) Geometry and configuration of contours of CTS structural elements;
(2) Physical and mechanical condition of structural materials of elements;

(3) Nonstationary and cyclicity of the CTS loading mode;
(4) Environmental corrosion,
(5) Daily and seasonal ambient temperature fluctuations;
(6) Vibration phenomena (geodetic and anthropogenic) in the system;
(7) Flaws and damages of CTS structural elements;
(8) Fatigue processes in CTS structural elements;
(9) Technological methods to increase the bearing capacity of the system;
(10) Using of anticorrosive polymer plating in loaded sections of the structural elements;
(11) Rational schedule of maintenance, examination and repair work of the system.

According to the calculation scheme, adopted in the methodology of system analysis, for these 11 factors, all possible options of sets of factors are composed, depending on their number and combinations. Analysis and classification of possible options of these factors have shown that in the elements of the CTS, the most responsible are cases of combinations with 4 factors that significantly affect the efficiency of the CTS. These are: points (4) and (8)—factors of corrosion (C) and fatigue (F) processes, as well as points (9) and (10) are the factors of strengthening (S) and corrosion resistance (CR), which are opposite in nature and in total determine the bearing capacity of the CTS. Another peculiarity of significant factors—points (4), (8), (9), (10) is their presence in the vast majority of options of combinations and the level of strength and corrosion resistance of structural elements depends on their number in these combinations. Grouping of factors in combinations is carried out according to the number of inclusion of these significant factors in them:

- just one factor: F, C, S, CR—86 pcs.;
- two factors: (FC), (FS), (F CR), (CS), (C CR), (S CR)—48 PCs.;
- three factors: (FCS), (FC CR), (CS CR), (FH CR)—28 PCs.;
- four factors: (FCS CR)—1 PC.

At the second stage of the procedures, the principle of independent action of factors within the selected group was adopted, which is more often used in applied tasks for assessing the total influence effect of factors and to determine the generalized parameter of the entire group by multiplying the values of their separate parameters (the scheme of sequential influence of factors).

The aim of the study is selection of optimal technologies for increasing the bearing capacity of structural elements on the base of research and classification of complex affecting factors of CTS structural elements. To achieve that objective, it is necessary to solve the following tasks: the study of the physical and mechanical nature of corrosion and fatigue processes in low-carbon structural steels used in structural elements; the selection of the type of strengthening technique for welds; the selection of the optimal type of anti-corrosion protective plating and the technique of its usage to the welds. The mathematical model of fatigue destruction can be represented by a system of three linear equations $\lg N = F(\lg \sigma)$ corresponding to the specified sections N and σ with indices: 1, … ,3—for the initial fatigue and *1k, … ,3k; 1k, … ,3k*—for comparative corrosion-fatigue processes. The classification of the main parameters and equations of these fatigue lines is presented in Table 1.

Table 1 Equations and parameters of fatigue on the 1, … ,3, 1_k, … ,3_k and $1'_k$, …, $3'_k$ sections

No.	Conditions of fatigue processes	Calculation scheme	Section of the fatigue line	N and σ * intervals		Equations of fatigue lines
				N	σ	
1	Fatigue in a protective environment (in the open air)	–	1	$N_0 ... N_{G1}$	$\sigma_{R1} \ldots \sigma_{\beta 1}$	$\lg N = C_1 - m_1 \lg \sigma$
2			2	$N_{G1} ... N_{G2}$	$\sigma_{R2} ... \sigma_{R1}$	$\lg N = C_2 - m_2 \lg \sigma$
3			3	$N_{G2} ... 10^8$	$\sigma_{R2} = const$	$\lg \sigma = \lg \sigma_{R2} = const$
4	Corrosion fatigue (comparable to points 1, 2, 3)	N1	1_k	$N_0 ... N_{G\kappa 1}$	$\sigma_{R\kappa 1} \ldots \sigma_{\beta\kappa 1}$	$\lg N = C_{\kappa 1} - m_{\kappa 1} \lg \sigma$
5			2_k	$N_{G\kappa 1} ... N_{G\kappa 2}$	$\sigma_{R\kappa 2} \ldots \sigma_{R\kappa 1}$	$\lg N = C_{\kappa 2} - m_{\kappa 2} \lg \sigma$
6			3_k	$N_{G\kappa 2} \ldots 10^8$	$\sigma_{R\kappa 1} \ldots \sigma_{R\kappa 2}$	$\lg N = C_{\kappa 3} - m_{\kappa 3} \lg \sigma$
7	Corrosion fatigue (comparable to points 4, 5, 6)	N2	$1'_k$	$N_0 \ldots N'_{G\kappa 1}$	$\sigma'_{R\kappa 1} \ldots \sigma'_{\beta\kappa 1}$	$\lg N = C'_{\kappa 1} - m'_{\kappa 1} \lg \sigma$
8			$2'_k$	$N'_{G\kappa 1} \ldots N'_{G\kappa 2}$	$\sigma'_{R\kappa 2} \ldots \sigma'_{R\kappa 1}$	$\lg N = C'_{\kappa 2} - m'_{\kappa 2} \lg \sigma$
9			$3'_k$	$N'_{G\kappa 2} \ldots 10^8$	$\sigma'_{R\kappa 1} \ldots \sigma'_{R\kappa 2}$	$\lg N = C'_{\kappa 3} - m'_{\kappa 3} \lg \sigma$

* Coordinates of the starting points of the three-link fatigue lines: $(\sigma_{\beta 1}, N_0)$, $(\sigma_{\beta\kappa 1}, N_0)$, $(\sigma'_{\beta\kappa 1}, N_0)$; $N_0 = 10$ cycles—initial durability; $\sigma_{\beta 1}, \sigma_{\beta\kappa 1}, \sigma'_{\beta\kappa 1}$—strength limits; coordinates of inflection points between $(\sigma_{R\kappa 1},\ N_{G\kappa 1})(\sigma_{R1},\ N_{G1})$, $(\sigma'_{R\kappa 1},\ N'_{G\kappa 1})$ sections of—low- and multi-cycle fatigue; $(\sigma_{R2},\ N_{G2})$, $(\sigma_{R\kappa 2},\ N_{G\kappa 2})$, $(\sigma'_{R\kappa 2},\ N'_{G\kappa 2})$—of multi-cycle and long-term fatigue

2.1 Analysis of Corrosion Processes in CTS Structural Elements

Maintenance and operating conditions of CTS are characterized by a great amount and combinations of periodically affecting factors that damage the structure or increase the efficiency of the system, with different nature and gradient of actions, as well as the duration and sequence of their manifestations.

Corrosion processes in CTS structural elements have a significant impact on the occurrence and development of corrosion and fatigue damage [8, 9]. The mounting of system and the creation of a network in an open area is accomplished by welding, therefore the welds are exposed to temperature fluctuations and the environment, which cause corrosion phenomena and accelerate the processes of occurrence and development of fatigue cracks. As a result, this results in the reduction of the endurance limit of welded junctions by 1.5 … 2.5 times, and durability—by 3 … 5 times. Simultaneously, the weakest sections are the locations of butt welds, where the stress concentration reaches up to $\kappa_\sigma = 1.8 \ldots 2.5$. As a result of the execution of the technical examination and processing of statistical data, fixed that 70 … 75% of structural elements damages and failures are of a corrosion-fatigue nature, and 20 … 25%—only from corrosion effects. So, the replacement of damaged sections of structural elements is 25 … 30% of the total mass, and 5 … 7% is irretrievably lost in the form of chemical compounds. The nature and speed of corrosion processes depend on many factors that characterize the physical and mechanical state of the surface layers of structural materials: technological features of the manufacture and processing of structural elements; the nature, duration and operating conditions of the system; temperature fluctuations and cyclical loading; contact with the environment, etc. This complex of factors requires a detailed classification and a systematic approach to assess their joint and diverse impact on the bearing capacity of the CTS structure, of which corrosion and fatigue processes are the most significant [10]. A reducing production costs, increasing the requirements of efficiency and environmental safety, as well as increasing the durability of the system are the main requirements for the conditions of trouble-free operation of structural elements [2].

The method of system analysis logically approves the selection and compilation of 10 calculation schemes for determining coefficients $K_{\sigma k}$, K_{Nk}, which are taking into account a different combination and number of Influencing factors, and the formation of their functions $K_{\sigma k} = f(N)$ and $K_{Nk} = \phi(\sigma)$. Taking into account the two-link type of fatigue lines, these calculation schemes are classified and separately presented in zones of limited ($N_{Ri} \leq N_{G1}$) and long-term ($N_{Ri} > N_{G1}$) endurance (Tables 2, 3). The changes presented in Table 3 are as follows: during open air tests in the $N_{Ri} > N_{G1}$ zone, the fatigue line of flat samples takes a horizontal position, which changes the structure of the parameters of the calculation schemes (Table 2, points 1, 5–7).

2.2 Application of Strengthening Technology in CTS Elements Welded Joints

The development of the CTS network in an open area is accompanied by an increase in the scope of welding work. The ensuring of necessary operability, durability and reliability of the entire system are depending on quality of welding work. Considering that the main types of defects and damages are located on the section of butt welds and cause stress concentration, reducing the physical and mechanical characteristics of the

Table 2 The structure of the coefficients of corrosion $K_{\sigma k}$ and K_{Nk} (for $N_{Ri} \leq N_{G1}$)

For $N_{Ri} \leq N_{G1}$ $N_{Ri} \leq N_{G1}$											
No.	Test series comparison	Groups options	Open air corrosion coefficient $K_{\sigma k}$			Open air corrosion coefficient K_{Nk}			Factors impact		
			$K_{\sigma ki}$	Ratio	Ratio σ_{Ri}	K_{Nki}	Ratio	Ratio N_{Ri}	Types and groups of factors		Legends*
1	N2-N1	I	$K_{\sigma k1}$	σ_{R2}/σ_{R1}	< 1	K_{Nk1}	N_{R2}/N_{R1}	< 1	Corrosive environment—open air		CE-A
2	N2-N5	II	$K_{\sigma k2}$	σ_{R2}/σ_{R5}	> 1	K_{Nk2}	N_{R2}/N_{R5}	> 1	Stress concentration	(in corrosive environment)	SC (CE)
3	N3-N5		$K_{\sigma k3}$	σ_{R3}/σ_{R5}	> 1	K_{Nk3}	N_{R3}/N_{R5}	> 1	Strengthening		S (CE)
4	N4-N5		$K_{\sigma k4}$	σ_{R4}/σ_{R5}	> 1	K_{Nk4}	N_{R4}/N_{R5}	> 1	Coating		C (CE)
5	N3-N1	III	$K_{\sigma k5}$	σ_{R3}/σ_{R1}	< 1	K_{Nk5}	N_{R3}/N_{R1}	< 1	Corrosive environment—open air-stress concentration- strengthening		CE-A-SC-S
6	N4-N1		$K_{\sigma k6}$	σ_{R4}/σ_{R1}	< 1	K_{Nk6}	N_{R4}/N_{R1}	< 1	Corrosive environment—open air—stress concentration—coating		CE-A-SC-C
7	N5-N1		$K_{\sigma k7}$	σ_{R5}/σ_{R1}	< 1	K_{Nk7}	N_{R5}/N_{R1}	< 1	corrosive environment—open air—stress concentration		CE-A-SC
8	N3-N2	IV	$K_{\sigma k8}$	σ_{R3}/σ_{R2}	< 1	K_{Nk8}	N_{R3}/N_{R2}	< 1	Stress concentration-strengthening	(In corrosive environment)	SC- S (CE)
9	N4-N2		$K_{\sigma k9}$	σ_{R4}/σ_{R2}	< 1	K_{Nk9}	N_{R4}/N_{R2}	> 1	Stress concentration- coating		SC-C(CE)
10	N3-N4	V	$K_{\sigma k10}$	σ_{R3}/σ_{R4}	> 1	K_{Nk10}	N_{R3}/N_{R4}	> 1	Strengthening—coating		S -C (CE)

Table 3 The structure of the coefficients of corrosion $K_{\sigma k}$ and K_{Nk} (for $N_{Ri}. > N_{G1}$)

For $N_{Ri}. > N_{G1}$ $N_{Ri}. > N_{G1}$										
No.	Test series comparison	Groups options	Open air corrosion coefficient $K_{\sigma k}$			Open air corrosion coefficient K_{Nk}			Factors impact	
			$K_{\sigma ki}$	Ratio	Ratio σ_{Ri}	K_{Nki}	Ratio	Ratio N_{Ri}	Types and groups of factors	Legends*
1	N2-N1	I	$K_{\sigma k1}$	σ_{R2}/σ_{RG1}	< 1	K_{Nk1}	N_{R2}/N_{G1}	> 1	Corrosive environment—open air	CE-A
5	N3-N1	III	$K_{\sigma k5}$	σ_{R3}/σ_{RG1}	< 1	K_{Nk5}	N_{R3}/N_{G1}	> 1	Corrosive environment—open air—stress concentration—strengthening	CE-A-SC-S
6	N4-N1		$K_{\sigma k6}$	σ_{R4}/σ_{RG1}	< 1	K_{Nk6}	N_{R4}/N_{G1}	> 1	Corrosive environment—open air-stress concentration—coating	CE-A-SC-C
7	N5-N1		$K_{\sigma k7}$	σ_{R5}/σ_{RG1}	< 1	K_{Nk7}	N_{R5}/N_{G1}	> 1	Corrosive environment—open air-stress concentration	CE-A-SC

*Note. * Symbols: **A**—in the open air, **CE**—in the corrosive environment, **SC**—with stress concentration, **S**—strengthening, **C**—with protective coating* material (strength and endurance limits, hardness, recrystallization of microstructure, tempering and aging from variable temperatures T = 250 … 1100 °C, etc.), the need to reduce the effects of these damages, by using various physical and technological procedures (hydrodynamic, temperature, supersonic, high-frequency electricity, laser exposure, plastic deformation, etc.), must become priority [10]. Of these technological procedures for CTS structural elements, the most acceptable is the technique of surface plastic deformation (SPD) of the weld section, which is a relatively simple and affordable method by using a special tool with rolling balls or rollers operating according to the kinematic scheme of the planetary friction mechanism. The break-in rollers (balls) under the action of normal force smooth out the surface micro-roughness of the weld and form a deformed layer with residual compression stresses compensating for the influence of external load, which ultimately leads to a decrease in the stress state in the seam [11].

Previously performed researches indicate that the widespread usage in structural elements the low-carbon and low-alloy structural steels, which are easily amenable to plastic deformation and have a relatively low cost, after performing strengthening techniques leads to an increase in endurance limits by 50 … 70%, and cyclic durability by 3 … 4 times, also ensuring the cost-effectiveness of the installation of a system [12].

The efficiency of SPD prescribes the necessity of a wide application of this method in order to regulate the stress state in the weld and in the transition section to the main metal, which remains the main cause of the appearance and development of fatigue damage. The effectiveness of the impact of strengthening processes can also be increased by preliminary grinding of the seam surface in order to remove defects and irregularities of welding work, which creates favorable conditions for influencing the stress concentration, hence increasing the bearing capacity of the seam [13].

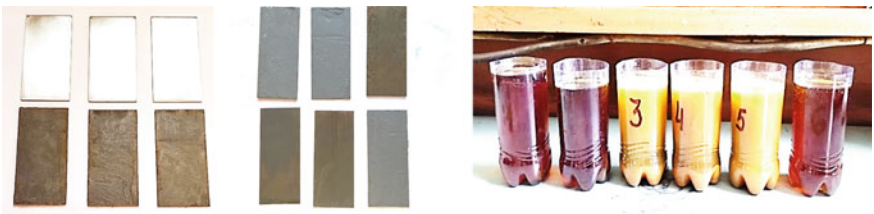
3 Results and Discussion

The process of corrosion of responsible elements of the CTS abruptly reduces the reliability and operability of the system, which requires the use of new effective instruments and methods to increase the corrosion resistance of these elements. One of the concrete solutions to increase anticorrosive properties is the application of new highly effective protective coatings on loaded sections of system, which, interacting with surface micro-irregularities, fills their micro-depressions and micro-defects of welds and by simple technological operations increases the corrosion resistance of system. To apply these coatings, the outer surface of the seam is subjected to a preliminary examination to eliminate welding defects and to create surface micro- irregularities, then thoroughly cleaned and degreased to increase the degree of adhesion of the coating to the seam surface. After the coating is applied, it is exposed to pressure for its final formation. These operations are usually performed at $T \geq 5$ °C ambient temperature and at the absence of precipitation, and to increase the degree of adhesion after 2–4 h of its application, approximately 2 h the coating is treated with an air heater at T = 60 … 100 °C. It is recommended to start the work of the structural elements after 4.0 … 0.5 days (if the welding work is performed, respectively, at ambient temperatures T = 5 … 30 °C), and in the presence of volatile chemical compounds, gases and dust in the environment—after 5.0 … 1.0 days.

To assess the influence of corrosion and the possibility of application of effective anti-corrosive coatings, comparative static corrosion resistance tests were performed on flat metal samples made of structural steel *St10*, which were accurately weighed, thoroughly cleaned and degreased before testing. The newest polymer material of the Belzona 1111 FN10132 (SuperMetal) brand was used as an anticorrosive coating, which, according to the results of production tests, shows:

- high level of corrosion resistance—under influence of alcohols, gases, hydrocarbons, technical and vegetable oils, various types salt solutions, pure- and seawater;
- satisfactory level—with organic and inorganic acids of medium concentration (up to 50%);
- unsatisfactory level—with the same acids, but in a high concentration ($\approx$ 95%).

Of the 6 tested samples (N1, … N6), three were the initial options (*NN* 1, 2, 6), and on the rest ones (*NN* 3, 4, 5), according to the coating technology from the Belzona 1111 material, strong anticorrosive protective layers were created (Fig. 1b). Corrosion resistance tests were carried out in a 10% aqueous solution of $FeCl_3$ for 24 h and at the temperature of T = 20 °C.



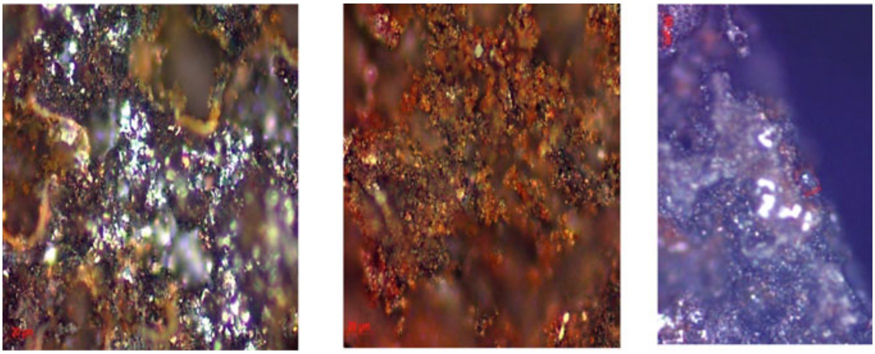
(a) (b) (c)

Fig. 1 Tests of flat steel samples in a corrosive solution with 10% $FeCl_3$ **a** before testing: *NN 1, 2, 6*—initial samples, *NN 3, 4, 5*—with an anticorrosive coating; **b** samples after testing; **c** the state of the corrosive solution after testing

For samples *NN 1, 2,* 6 changes in the microstructure of the surface layers and a decrease in the initial mass in the range of 4.5 … 10.0% are observed. The study of the surface condition of these samples on a *ZEISS AXIO VERT* A1 electron microscope (magnification × 1000 times) indicates the presence of corrosion damage with a depth of 20 … 22 mm, which in the sequel may become center for the development of corrosion-fatigue cracks (Fig. 2). For samples NN 3, 4, 5, these defects are not observed, which proves the high efficiency of applying this durable anticorrosive coating.

4 Conclusions

Reducing the design time of new CTS involves the clarification of the parameters of the affecting factor, based on the analysis, classification of their operating conditions and loading modes, by using productive design and technological measures that allow



(a) (b) (c)

Fig. 2 Surface microstructure after static tests on samples *NN 1, 2, 6* **a** and *NN 3, 4, 5* **b**; **c** surface cracks in samples *NN 1, 2, 6*

determining and using their limit values. Simultaneously, the presence of a significant number of diverse factors (11 pieces) acting together and with various combinations predestine the task of their study and classification by the applying the principle of system analysis. These factors are presented in 4 groups. The features of the expression of the most significant factors—stress concentration, the corrosive effect of the environment and fatigue phenomena, as well as strengthening and corrosion protection techniques, which in most cases come into a single composition, are considered as a total.

The mechanism of appearance and development of corrosion-fatigue damages, which, unlike other factors, working in the entire range of durations of limited and long term endurance, has been studied. To increase the bearing capacity of structural elements the application of a new corrosion-resistant polymer plating of the Belzona 1111 brand is recommended. The numbers of static corrosion-proof tests in a $FeCl_3$ corrosion solution were performed, which confirmed the effectiveness of using of this plating.

So that, to increase the resistance to corrosion fatigue of structural elements butt welded junctions, which are significant stress concentrators, the technique of surface plastic deformation of welds has been applied, where, due to the appearance of residual compression stresses, the effect of working loading of CTS has been largely compensated and the fatigue resistance of structural elements has been increased [14].

Acknowledgements. This work is realized in the framework of the “Preservation and development of the research laboratory of natural-mathematical modeling of construction tasks” and “Preservation and development of the research laboratory of construction and urban economy” programmes financed by Science Committee of Republic of Armenia.

References

1. Chibukhchyan, G., Stakyan, M., Chibukhchyan, O.: Improving the carrying capacity of structural elements of vehicles by the corrosive strength criterion. J. Mach. Manuf. Reliab. **48**, 551–556 (2019). https://doi.org/10.3103/S1052618819060037
2. Ibatullin, I.D.: Kinetics of fatigue damage and destruction of surface layers. Samara (2008)
3. Pirumyan, N.V., Stakyan, M.G.: Measures to increase the building steel structures' bearing capacity. IOP Conf. Se.: Materials Sci. Eng. **913**(1–6), 022006 (2020). https://doi.org/10.1088/1757-899X/913/2/022006
4. Korolov, V., Vysotskiy, Y., Filatov, Y.: Design criteria of reliability and safety in the design of corrosion protection of structural steel. EUROCORR-2014. The European Corrosion Cogress: "Improving materials durability: from cultural heritage to industrial applications", Pisa (2014)
5. Kogaev, V.P.: Calculations for strength under stresses variable in time. Mashinostroenie, Moscow (2003)
6. Krastev, D.: Improvement of corrosion resistance of steels by surface modification, pp. 295–316. IntechOpen, London (2012). https://doi.org/10.5772/33247
7. Orlov, B.N.: Innovative technologies for ensuring the reliability of working elements of machines and equipment. Moscow (2013)
8. Pirumyan, N.V., Stakyan, M.G.: Asessment of corrosion fatigue strength of gas-transport system constructions under atmospheric forcing. IOP Conf. Se.: Materials Sci. Eng, **698(**1–6), 022077 (2019). https://doi.org/10.1088/1757-899X/698/2/022077
9. Bazhenov, Y.V., Bazhenov, M.Y.: Fundamentals of reliability and operability of technical systems. Publishing House of the VlSU, Vladimir(2017)
10. Kirpichev, V.A., Saushkin, M.N., Smyslov, V.A.: On mathematical modeling of fields of plastic deformations arising from various types of strengthening treatment. Mat. Mod. Phys., Economy. Tech. Social. Systems and Processes: Proceedings of XVII International Conference. Ulyanovsk, pp. 116–117 (2009)
11. Pirumyan, N.V., et al.: Mathematical modeling of the process of reduction of the material consumption of gas transmission system elements. Key Engineering Materials **906**, 115–123 (2022). https://doi.org/10.4028/www.scientific.net/kem.906.115
12. Dashchenko, A.F., Kravchuk,V.S., Iorgachev, V.D.: Bearing capacity of strengthening of machine parts. "Astroprint", Odessa (2004)
13. Gubanov, V.F.: Parameters of roughness of smoothed surfaces. Strengthening Technologies and Coatings **11**, 6–9 (2010)
14. Zharskiy, I.M., et al.: Technological methods for ensuring the reliability of machines. Higher School, Minsk (2010)