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ASSESSMENT OF PHYSICAL DETERIORATION AND PREDICTED REMAINING LIFETIME OF METAL FRAMES OF INDUSTRIAL BUILDINGS

ӨНЕРКӘСІПТІК ҒИМАРАТТАРДЫҢ МЕТАЛЛ ҚАҢҚАЛАРЫНЫҢ ТЕХНИКАЛЫҚ ТОЗУЫН ЖӘНЕ ЖОБАЛАНҒАН ҚАЛДЫҚ ҚЫЗМЕТ КӨРСЕТУ МЕРЗІМІН БАҒАЛАУ

ОЦЕНКА ФИЗИЧЕСКОГО ИЗНОСА И ПРОГНОЗИРУЕМЫЙ ОСТАТОЧНЫЙ СРОК СЛУЖБЫ МЕТАЛЛИЧЕСКИХ КАРКАСОВ ПРОИЗВОДСТВЕННЫХ ЗДАНИЙ

Abstract. *The article analyses the problem of physical wear of metal structures of industrial building frameworks. The accumulation of damages associated with the aging of steel is considered by the example of a particular object. The results of experimental research of mechanical properties, chemical composition and structure of steel after long-term operation are given. A forecast of remaining service life of structures and their replacement is made.*
Keywords: *Steel structures, boiling steel ageing, physical wear, mechanical characteristics, estimation of technical condition, residual service life.*

Аңдатпа. *Мақалада өнеркәсіптік ғимараттардың қаңқаларының металл конструкцияларының физикалық тозу мәселесі талданады. Белгілі бір объектінің мысалында болаттың ескіруіне байланысты зақымданудың жинақталуы қарастырылады. Көпжылдық пайдаланудан кейін болатын болаттың химиялық құрамы мен құрылымының, механикалық қасиеттерінің тәжірибелік зерттеулердің нәтижелері келтірілген. Құрылымдардың қалдық қызмет ету мерзімінің болжамы және оларды ауыстыруы орындалды.*
Түйін сөздер: *Болат конструкциялар, қайнаған болаттың ескіруі, физикалық тозуы, механикалық сипаттамалары, техникалық жағдайын бағалау, қалдық қызмет мерзімі.*

Аннотация. *В статье анализируется проблема физического износа металлических конструкций каркасов производственных зданий. На примере конкретного объекта рассматривается накопление повреждений, связанных со старением стали. Приводятся результаты экспериментальных исследований механических свойств, химического состава и структуры стали после многолетней эксплуатации. Сделан прогноз остаточного срока службы конструкций и их замены.*
Ключевые слова: *Стальные конструкции, старение кипящей стали, физический износ, механические характеристики, оценка технического состояния, остаточный срок службы.*

Introduction. Intensive development of the non-ferrous metallurgy industry of East Kazakhstan took place in the post-war period of time. Since the beginning of the fifties of the last century, the main production buildings of today's flagships of the metallurgical industry have been erected – Kazzinc LLP, Kazakhmys LLP, Ust-Kamenogorsk Titanium-Magnesium Combine JSC, as well as a number of machine-building and metalworking enterprises. In those years, steel structures were often used for the construction of production facilities. The requirements for the materials of steel frames at that time were different (compared to the present). Less high-quality boiling steels obtained by melting scrap metal were widely used, as well as finished metal structures obtained during the disassembly of industrial and military facilities in Germany (special supplies from the liquidated military industry). This article discusses the problems associated with the assessment of physical wear and the possibility of further safe operation of such buildings on the example of a forge and boiler shop of a mechanical repair plant.

Materials and methods of research. To assess the technical condition of the building structures of the production building, archival data containing design materials were first studied. After that, the results of surveys conducted three times between 2004 and 2020 were analyzed [1, 11, 12]. In accordance with the current regulatory documents [2, 3], inspections of metal structures are carried out every five years. The work of the last survey included experimental studies of the properties of steel on samples cut from full-scale metal structures.

The building of the forge and boiler shop was built in several stages (Figure 1). The first stage was built in 1953 according to a project developed by the "Giprotsvetmet Institute" in 1949. It included blacksmithing departments and a boiler room. The welding department and the household building were built according to the drawings of the design department of the repair and mechanical plant, made in 1953-1963. The hardware department, oxygen ramp and ventilation with a household housing were built according to the drawings of the design department, developed in 1978-1980.

Thus, the main production part of the workshop was built 70 years ago, when the main material of metal frames of buildings was boiling steel Vst3kp. This grade of steel is confirmed by the results of chemical analysis and mechanical tests of samples cut from crane beams, trusses and columns (Tables 1 and 2).

Table 1. Chemical composition of steel samples

№	Chemical composition, %									Brand of steel
	C	Mn	P	S	Si	Cr	Ni	Mo	Ti	
1	0.18	0.50	0.017	0.016	0.04	0.01	0.03	0.002	0.0002	St.3kp
2	0.14	0.46	0.024	0.021	0.01	0.02	0.06	0.006	0.0002	St.3kp
3	0.10	0.31	0.026	0.025	0.01	0.19	0.55	0.006	0.0002	St.2kp (with increased content of Ni)
STATE STANDARD 380-2005	0.14-0.22	0.30-0.60	≤0.040	≤0.050	≤0.05	≤0.30	≤0.30	–	–	St.3kp
	0.09-0.15	0.25-0.50	≤0.040	≤0.050	≤0.05	≤0.30	≤0.30	–	–	St.2kp

Boiling steel is characterized by a sharp heterogeneity of carbon, sulfur and phosphorus content, called liquation [13]. In addition to this drawback, there are defects in the crystal lattice – the absence of iron and carbon atoms in the nodes where they should be in accordance with the ideal structure of the metal. The absence of atoms is called vacancies [4].

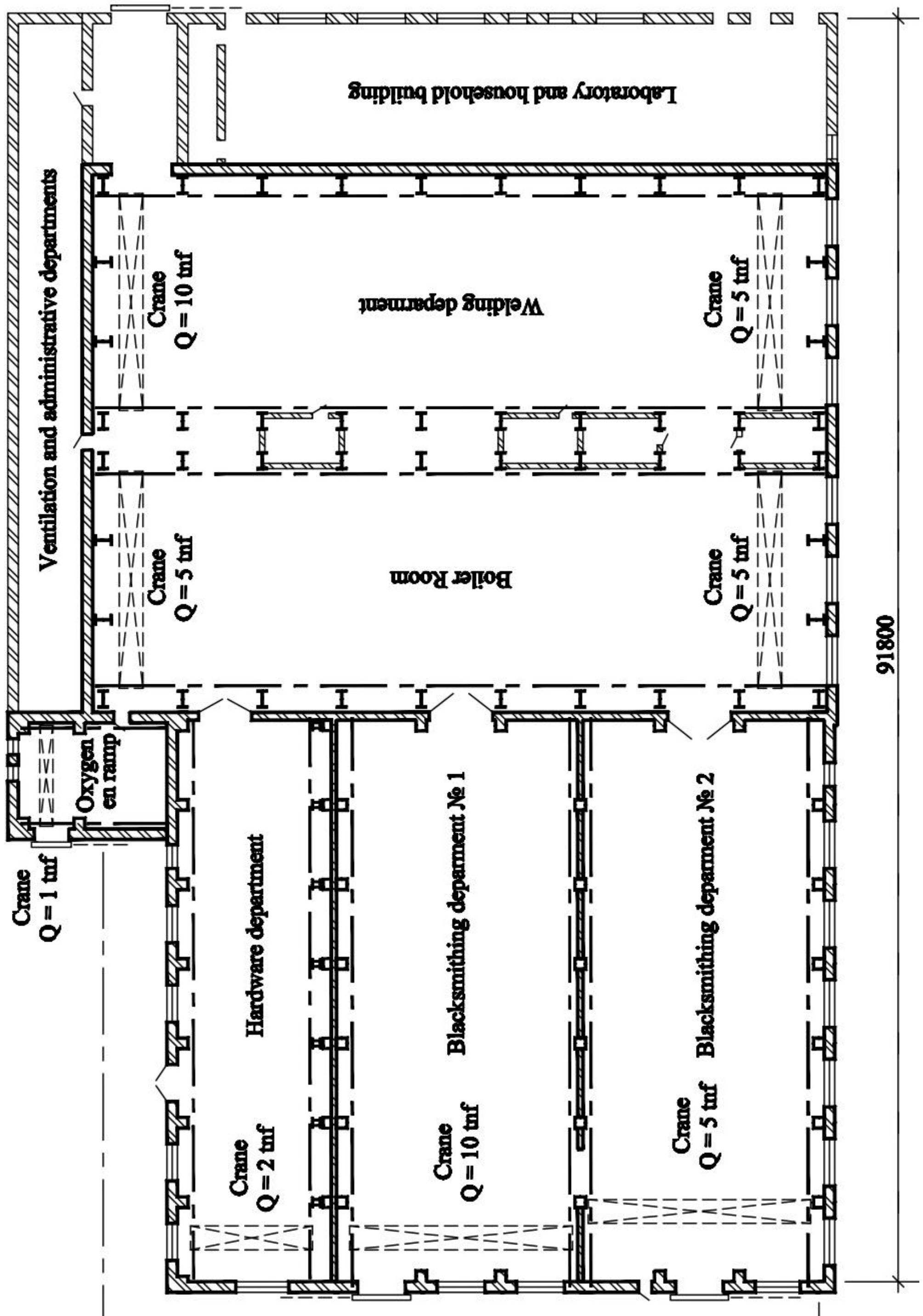

Figure 1. Schematic plan of the workshop

When steel is working under load, vacancies can move and concentrate in one place, forming dislocations that lead to the appearance of microcracks. Signs of such heterogeneity and concentration of dislocations can be seen in the photo provided by the laboratory of the analytical and technical control service of the enterprise (Figure 2).

Figure 2. Microstructure of boiling steel

Another negative property of boiling steel is aging. It is characterized by a decrease in plastic properties – an increase in the yield strength over time. Steel becomes prone to brittle fracture, which can lead to the collapse of metal structures. The formation of cracks in metal is facilitated by the variable operating temperature of structures and dynamic loads that create crane and seismic impacts [5].

According to the results of mechanical tests, it was found that the yield strength of steel samples was increased by 30.5 – 48.1% compared to the state standard for steel, which confirms the aging of steel (Table 2).

Table 2. Comparison of actual values of mechanical characteristics of steel

№ sample	Construction	Ultimate strength, kgf/mm^2	Yield strength, kgf/mm^2	The ratio of yield strength to ultimate strength	Increase in yield strength, %
1	Support strut of the truss	41.5	28.4	0.684	30.53
2	The lower belt of the crane beam	50.5	35.3	0.699	33.4
3	Crane branch of the column	50.5	39.2	0.776	48.09
STANDARD 380-2005	–	medium 41.8	medium 21.9	0.524	–

When examining the crane beams of the boiler room in 2012, cracks were found in the metal of the walls of the I-beams, which were reinforced by welding lamellae (Figure 3). In 2020, cracks appeared in the welds of the attachment points of the upper belts of crane beams to the columns in the welding department. This confirms the need to replace crane beams, since the period of operation of such structures is no more than 50 years.

Figure 3. Reinforcement of crane beams with cracks by lamellas

The aging time of steel is several decades. Aging accelerates under the action of dynamic loads and temperature changes. These factors exacerbate the danger of brittle destruction.

Since the beginning of the sixties of the last century, boiling steel of the st3kp brand was allowed to be used in steel frames only for columns that perceive static loads [14]. They are assigned to group 3. Structures of group 1 (crane beams) and group 2 (trusses) are not allowed to be made of boiling steel. Similar requirements for steel have been preserved in the new regulatory documents of the Republic of Kazakhstan (paragraph 2.2 of the national annex [6] to the Eurocode [7]).

With an increase in the seismicity of the zone from 2005 to 7 points in Ust-Kamenogorsk and Ridder, the use of boiling steel is prohibited for frame columns [8].

The danger of brittle destruction of steel lies in its suddenness, due to the simultaneous combination of several factors (dynamic impact, overload, low temperature, long aging time). With increasing aging time, the risk of destruction increases.

Results and treir discussion. Currently, it is possible to guarantee the safe operation of the building for a period of no more than 3-5 years. The reason for this is the accelerated accumulation of damage in the metal structures of the supporting frame made of currently prohibited boiling steel. This is confirmed by the cracks found in the structures and attachment points of crane beams in 2012-2020, as well as the results of a laboratory study of samples cut from the frame structures.

At the first stage of testing samples cut from full-scale frame structures, chemical analysis of steel of crane beams (7 samples) and coating trusses (4 samples) was performed. It was found that the chemical composition of the steel complies with the STANDARD 380-2005 standard for the st3kp brand.

At the second stage, mechanical tests of large-sized samples were carried out on one of the support strut of the truss, the lower belt of the crane beam and the crane branch of the welding department column. Along with the chemical composition that confirmed the grade of steel Vst3kp and Vst2kp, mechanical characteristics were determined – tensile strength, yield strength, elongation, relative contraction and toughness. As noted above, mechanical tests showed an increased yield strength value compared to the state standard (Table 2) by 30.53-48.09%, which confirms the aging of steel.

At the same time, the impact strength of steel determined for the same samples exceeds the standard value for st3sp steel by 32.7-40% (for st3cp steel, the impact strength is not normalized). This may be due to the insufficient number of samples (the impact strength was determined for only two samples), as well as the fact that in the post-war period, open-hearth steels obtained by remelting from war metal (armored steels), which were usually designated as st3kp, were used in construction. This explains the increased content of alloying additives in the chemical composition of individual samples (Table 1).

To exclude emergency situations, according to the results of surveys in [1, 11, 12], the following measures were justified:

1. The need for priority replacement of crane beams. Sudden brittle destruction caused by aging of boiling steel and loss of elastic-plastic properties is dangerous for them. Usually the period of operation of such structures is no more than 50 years.

2. The need to replace the enclosing structures of the coating in the boiler and welding departments, made of small-sized and unreliably fixed plates and fragments of translucent structures.

3. Changing the roof profile due to the inability to provide external drainage of atmospheric precipitation.

4. The need to strengthen the foundations made of masonry on low-grade mortar, found when placing new technological equipment. Obviously, this type of foundations for walls is typical for the blacksmith's department. Therefore, the placement of new forging equipment in it, which creates dynamic loads, can cause the destruction of the brickwork of the walls.

5. Elimination of design flaws. The building as a whole does not meet the mandatory requirements of modern design standards for facilities located in earthquake-prone zones [8]. Correction of structures will require replacement of brick walls, strengthening of foundations, replacement of the coating structure in the boiler and welding departments, installation of additional frame columns and foundations for them to create antiseismic seams.

In this regard, the building of the forge and boiler shop in accordance with clause 4.16 [9] is of limited use for category 3, when the total cost of rehabilitation of the facility will be from 50% to 85% of the book (market) value. Such costs may exceed the cost of building a new forge and boiler shop, therefore they are unprofitable and impractical.

The technical condition of the building structures of the building depends on the amount of physical wear. In this case, the normative calculation method published in [10] is applicable. The physical wear of the Fi as a percentage is determined by the formula:

$$F_i = \frac{500 \cdot K_i \cdot \left(1.036^{\frac{t}{5}} - 1.036^{\frac{0}{5}}\right)}{\ell n 1.036},$$

where Ki = 0.0056 for the building of the capital group 1; t – is the actual age of the building from the moment of commissioning in 1953, when t = 0, to the present.

Substituting the actual age of the oldest part of the building t = 70 years into this formula, we get physical wear of 50.73%. In 2026, the age of the building will be 73 years, the actual wear will be 53.5%. According to Table 3.55 [10], with actual wear from 41% to 60%, the technical condition of the building is estimated as unsatisfactory; approximate the cost of major repairs (in % of the replacement cost) will be 37% – 90%.

This indicator is consistent with clause 4.16 of the code of rules [9], according to which the technical condition is of limited use for category 3, when the total cost of rehabilitation of the object will be from 50% to 85% of the book (market) value.

Conclusions. Considering that physical wear was defined as the average value for all building structures and engineering networks of a building, it is possible to approximately determine the wear of individual elements based on the methodology described in [15]. The specific weight of the element as a percentage was approximately taken at its actual cost as part of the total construction costs, and wear was taken based on the results of the last survey of the building [1]. Physical wear is presented in Table 3. Here, the remaining service life of the building elements is determined until they are completely worn out.

Table 3. Physical wear of the forge and boiler shop building and the projected service life of structural elements and internal technical systems

Structural element of the building	Specific gravity of the element, %	Wear of the element, %	Total depreciation, % for 2023	Remaining service life, years	Estimated replacement year (full wear and tear)
Foundation	5	30	1.5	6	2030
Exterior walls	12	60	7.2	3	2026
Columns	8	30	2.4	6	2030
Coating Farms	12	60	7.2	3	2026
Internal walls and partitions	4	50	2.0	4	2028
Coating Plates	10	90	9	3	2026
Roof	6	50	3	4	2028
Crane beams	10	90	9	3	2026
Window blocks	4	30	1.2	3	2026
Door blocks	3	30	0.9	3	2026
Stairs	3	30	0.9	6	2030
Floors	5	50	2.5	3	2026
Exterior decoration	3	50	1.5	3	2026
Internal technical systems	10	50	5	3	2026
Other elements	5	30	1.5	3	2026
Total $Ф_и$	100		54.8		

Aging of boiling steel inevitably leads to brittle fracture, which has been studied by domestic and foreign scientists [16, 17, 18, 19]. For structures with high physical deterioration, ageing aggravates the danger of collapse [20, 21].

Thus, the building as a whole is subject to demolition and replacement with a new design solution that meets the conditions of modern production technology.

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