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Original article

Assessment of the Impact of Oil Production Processes on the Health of the Population of Oil-Producing Areas of the Irkutsk Region

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Abstract

Introduction. The state of the population health depends on the ecological and hygienic well-being of the territory. In places with developed oil production, there is a long-term impact of pollutants on the human body and, as a result, corresponding diseases develop. This is evidenced by numerous domestic and foreign studies, but the territory of the Irkutsk region is not covered by such studies. Therefore, the work objective is to assess the impact of oil production processes on the incidence of the population of oil-producing regions of the Irkutsk region.

Materials and Methods. The source materials were the statistical indicators of overall and primary disease incidence of the population of the regions of the Irkutsk region for the period from 2016 to 2019, posted on the website of medical statistics of the Irkutsk region. For the calculation of the non-carcinogenic risk, we have used environmental monitoring data from an oil-producing company based on average daily concentrations of pollutants in oil-producing areas.

Results. It is shown that oil-producing areas are characterized by extremely high incidence rates for such groups of diseases as respiratory diseases, diseases of the circulatory system, diseases of the musculoskeletal system, diseases of the digestive system, diseases of the genitourinary system, as well as deviations in pregnancy, childbirth and the postpartum period. Infant mortality rates in these territories are up to 4 times higher than the corresponding average indicators for the Irkutsk region as a whole. The calculation of non-carcinogenic risk showed an excess over the permissible values accepted in Russia.

Discussion and Conclusions. The results of the analysis testify to the unfavorable medical and demographic situation in the territories under discussion. The pronounced excess of the incidence rate for the presented groups of diseases in the oilfield areas in comparison with the territories taken for comparison reflects the possible impact of environmental pollution on the health of the population. A connection between the growth of infant mortality in the territories under consideration and the beginning of the industrial development of hydrocarbon deposits in these places has been revealed. The contribution of oil companies to the socio-economic development of the regions, including co-financing of medical care for the population, could partially offset the negative impact of industrial processes.

Keywords: oil production, public health, overall and primary disease incidence, non-carcinogenic risk.

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Научная статья

Оценка влияния процессов нефтедобычи на здоровье населения нефтедобывающих районов Иркутской области

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Аннотация
Введение. Состояние здоровья населения зависит от эколого-гигиенического благополучия территории. В местах с развитой нефтедобычей происходит длительное воздействие загрязняющих веществ на организм человека, что в итоге влечет за собой возникновение различных заболеваний. Об этом свидетельствуют отечественные и зарубежные исследования. На территории Иркутской области такие исследования не проводились. Поэтому целью данной работы являлась оценка влияния процессов нефтедобычи на заболеваемость населения нефтедобывающих районов Иркутской области.
Материалы и методы. Исходными материалами послужили статистические показатели общей и первичной заболеваемости населения Иркутской области за период с 2016 по 2019 годы, размещенные на сайте медицинской статистики. В расчете неканцерогенного риска использовали данные экологического мониторинга нефтедобывающей компании по среднесуточным концентрациям загрязняющих веществ в районах нефтедобычи.
Результаты исследования. Показано, что районы нефтедобычи отличаются крайне высокими показателями заболеваемости со стороны систем органов дыхания, кровообращения, пищеварения, мочевыделения, костно-мышечной системы, а также по патологиях внутриутробного развития плода, при родах и в послеродовом периоде. Показатели младенческой смертности на данных территориях почти в четыре раза превышают соответствующие средние показатели по Иркутской области. Расчет неканцерогенного риска также показал превышение над принятыми в России допустимыми значениями.
Обсуждение и заключения. Результаты проведенного анализа свидетельствуют о неблагоприятной медико-демографической ситуации на обсуждаемых территориях. Выраженное превышение заболеваемости по представленным группам болезней в районах нефтепромысла, по сравнению с территориями, взятыми для сравнения, отражает возможное влияние загрязненности окружающей среды на здоровье населения. Показана связь роста младенческой смертности с началом промышленного освоения углеводородных месторождений этих мест. Вклад нефтедобывающих компаний в социально-экономическое развитие регионов, включая софинансирование медицинской помощи населению, могло бы частично компенсировать негативное влияние промышленных процессов.

Ключевые слова: нефтедобыча, здоровье населения, общая и первичная заболеваемость, неканцерогенный риск.

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Introduction. The problem of oil production impact on the health of the population is discussed at different levels. A number of studies show the negative environmental impact of oil production, affecting the health of the population [1–6].

As noted in [1], over 4 billion tons of crude oil is produced annually in the world. At each stage (extraction, storage, transportation), the environment is polluted with about 50 million tons of oil and petroleum products. Each process (exploration, drilling, production, gathering, storage, transportation of oil), under appropriate conditions, makes a change in the initial ecological state of the oil-producing area. It is believed, that the greatest environmental pollution occurs during accidental releases and spills [7, 8]. However, the problem is that the issue of using associated petroleum gas remains unresolved. The combustion products of associated petroleum gas are intensively released into the

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environment: soot, benz(a)pyrene, ammonia, nitrogen oxides, sulfur dioxide, aromatic hydrocarbons, dioxins, unburned oil. Pollutants enhance their toxic effect with simultaneous action.

Health condition of the population in most cases depends on the ecological and hygienic well-being of the territory. In territories with developed oil production, long-term exposure of the human body to harmful substances occurs and, as a result, corresponding diseases develop, pathologies appear, the risk of childhood morbidity, birth defects, miscarriages, stillbirths, oncological diseases and diseases of the endocrine, pulmonary, and cardiovascular systems increases [9–14].

The work objective is to assess the impact of oil production on the incidence of the population of oil-producing areas of the Irkutsk region. The presented work is a continuation of the authors' research in this field [15].

Materials and Methods. The source materials were statistical indicators of the overall and primary disease incidence of the population of the districts of the Irkutsk region (Katangsky, Kirensky and Ust-Kutsky districts) for the period from 2016 to 2019, posted on the website of medical statistics[1]. For comparison, similar indicators of the Kazachinsko-Lensky district of the Irkutsk region and the Irkutsk region as a whole were used as background indicators. In non-carcinogenic risk calculation, we turned to the environmental monitoring data of the oil company on the average daily concentrations of pollutants in the oil-producing areas[2].

Results. The Irkutsk region is rich in minerals: coal, iron ore, rock and potash salts, hydromineral raw materials, gold, ore raw materials, as well as significant raw hydrocarbon deposits (estimated recoverable oil resources — 2050 million tons[3]).

Hydrocarbon production is in the north of the Irkutsk region — these are the Katangsky, Kirensky and Ust-Kutsky districts. The Verkhnechonskoye oil and gas condensate field is located in the Katangsky district of the Irkutsk region, in the upper reaches of the Chona River, 1100 km from the city of Irkutsk and 420 km from Ust-Kut, is one of the largest deposits in Eastern Siberia[4]. The main fields of the Ust-Kutsky and Kirensky districts are the Yaraktinskoye oil and gas condensate field (OGCF), located 140 kilometers from the city of Ust-Kut[5]; Markovskoye OGCF is named after the nearby village of Markovo, 100 km from Ust-Kut and 60 km from the city of Kirensk; the Ichedinsky oil field occupies the territory of the Kirensky district; the Ayansky licensed subsoil plot is located on the territory of the Ust-Kutsky, Kirensky and Katangsky districts, 40 km from Kirensk[6].

Figure 1 provides population dynamics indicators of the three districts under consideration and demonstrates the situation of demographic decline of the population for the period from 2012 to 2022[7].

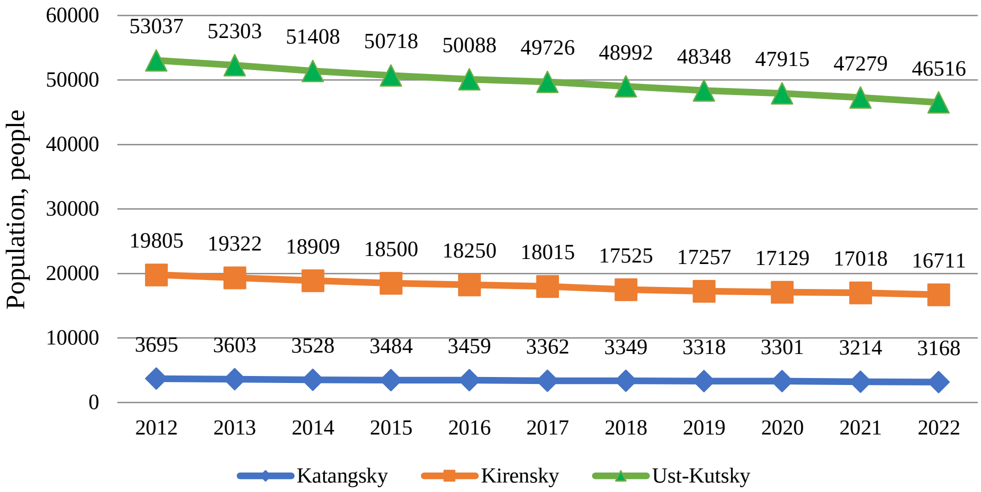

Fig. 1. Population dynamics of the Katangsky, Kirensky and Ust-Kutsky districts of the Irkutsk region

[1] *Medical statistics*. Ministry of Health of the Irkutsk Region. URL: https://miac-io.ru/uslugi-resheniya/meditsinskaya-statistika/ (accessed 25.01.2023). (In Russ.).
[2] *Arkhiv dokumentov dlya uchastiya v reitinge ekologicheskoi otvetstvennosti neftegazovykh kompanii*. URL: https://irkutskoil.ru/sustainable-development/environmental-protection/arkhiv-dokumentov-dlya-uchastiya-v-reytinge/ (accessed 25.01.2023). (In Russ.).
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[4] *Istoriya*. Rosneft. URL: https://vcng.rosneft.ru/about/Glance/OperationalStructure/Dobicha_i_razrabotka/Vostochnaja_Sibir/vcng/ (accessed 25.01.2023). (In Russ.).
[5] *Yarakstinskoe*. Edinyi fond geologicheskoi informatsii o nedrakh. URL: https://efgi.ru/object/17579691?num=1 (accessed 25.01.2023). (In Russ.).
[6] *Glavgosekspertiza odobrila proekt INK po stroitel'stvu neftegazoprovoda na Ichedinskom*. URL: https://irkutskoil.ru/press-center/glavgosekspertiza-odobrila-proekt-ink-po-stroitelstvu-neftegazoprovoda-na-ichedinskom-mestorozhdenii/ (accessed 25.01.2023). (In Russ.).
[7] *Chislennost' postoyannogo naseleniya*. Official website of the Irkutsk region for municipalities. URL: https://irkutskstat.gks.ru/ (accessed 25.01.2023) (In Russ.).

The health of the population is determined by lifestyle and socio-economic, hereditary and genetic factors, the quality of the environment and medical care [16].

To assess the health of the population of the oil-producing areas of the Irkutsk region, the incidence indicators (overall and primary) of the Katangsky, Kirensky, Ust-Kutsky districts were compared with an area close in climate, but without oil-producing facilities the — the Kazachinsko-Lensky district and the indicators of the Irkutsk region as a whole. The Kazachinsko-Lensky district is bordered in the north by the Kirensky district, in the west by the Ust-Kutsky district and the Zhigalovsky district, and in the south by the Kachugsky district. 85 % of the territory of the Kazachinsko-Lensky district is occupied by forest area, which determines the main activities of the population (logging, sawmilling, wood processing).

Initially, groups of diseases with the greatest prevalence in the studied oil-producing areas were identified for the study. To do this, we have studied the indicators of available statistics on overall incidence for the period from 2016 to 2019. Respiratory diseases turned out to be one of the most common types. The highest excess was recorded in the Katangsky district of the overall incidence indicator for this type over the corresponding indicator of the Kazachinsko-Lensky district and the Irkutsk region as a whole. In some cases, the indicators were exceeded several times, for example, in 2016 — almost 5 times, compared with the indicators in the Kazachinsko-Lensky district, and 2.4 times, compared with the indicators of the Irkutsk region as a whole.

Diseases of the circulatory system were in the second place in terms of prevalence. According to them, the overall incidence of the population in 2018 exceeded 2.1–2.4 times in the Katangsky and Ust-Kutsky districts, respectively, the indicators of the Kazachinsko-Lensky district and 1.3 times the indicators for the Irkutsk region as a whole. This is followed by diseases of the musculoskeletal system and digestive organs. The indicators for diseases occurring in the perinatal period and the number of congenital anomalies were also high in importance.

The diagram (Fig. 2) shows the average (for the period under review) indicators of overall incidence in the oil-producing areas of the Irkutsk region and in the districts taken for comparison.

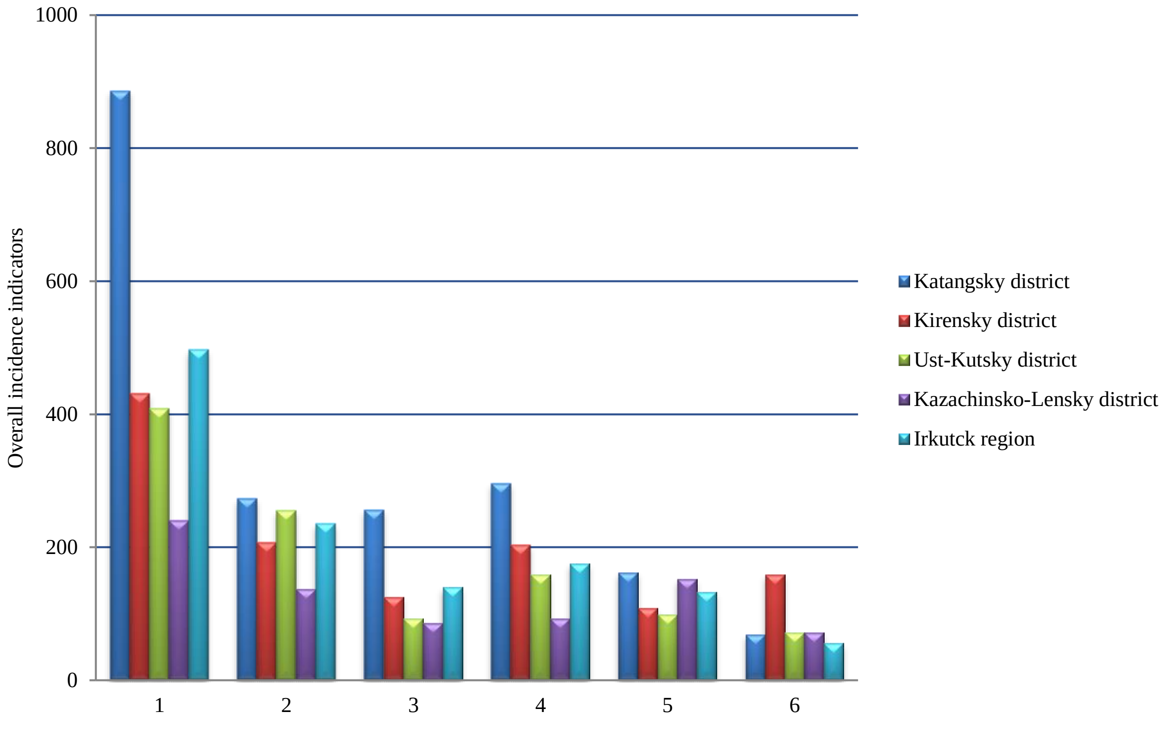

Fig. 2. Average indicators of the overall incidence of the population of the oil-producing areas of the Irkutsk region in comparison with the Kazachinsko-Lensky district and the Irkutsk region as a whole. The following categories of diseases are presented: 1 — respiratory organs; 2 — circulatory system; 3 — digestive organs; 4 — musculoskeletal system; 5 — genitourinary system; 6 — pathology during pregnancy, childbirth and in the postpartum period

From a hygienic point of view, the impact of environmental factors on the residents of the studied areas is manifested mainly in the overall incidence indicator, since the appearance of new cases of diseases is associated with the intensity of exposure to pollutants contained in the habitat of the population.

The comparison of the indicators of overall and primary disease incidence of the population in the selected territories (Fig. 3) indicates a pronounced excess of incidence in the presented groups of diseases in the oilfield areas,

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compared to the territories taken for comparison, which is a reflection of the possible impact of environmental pollution on public health.

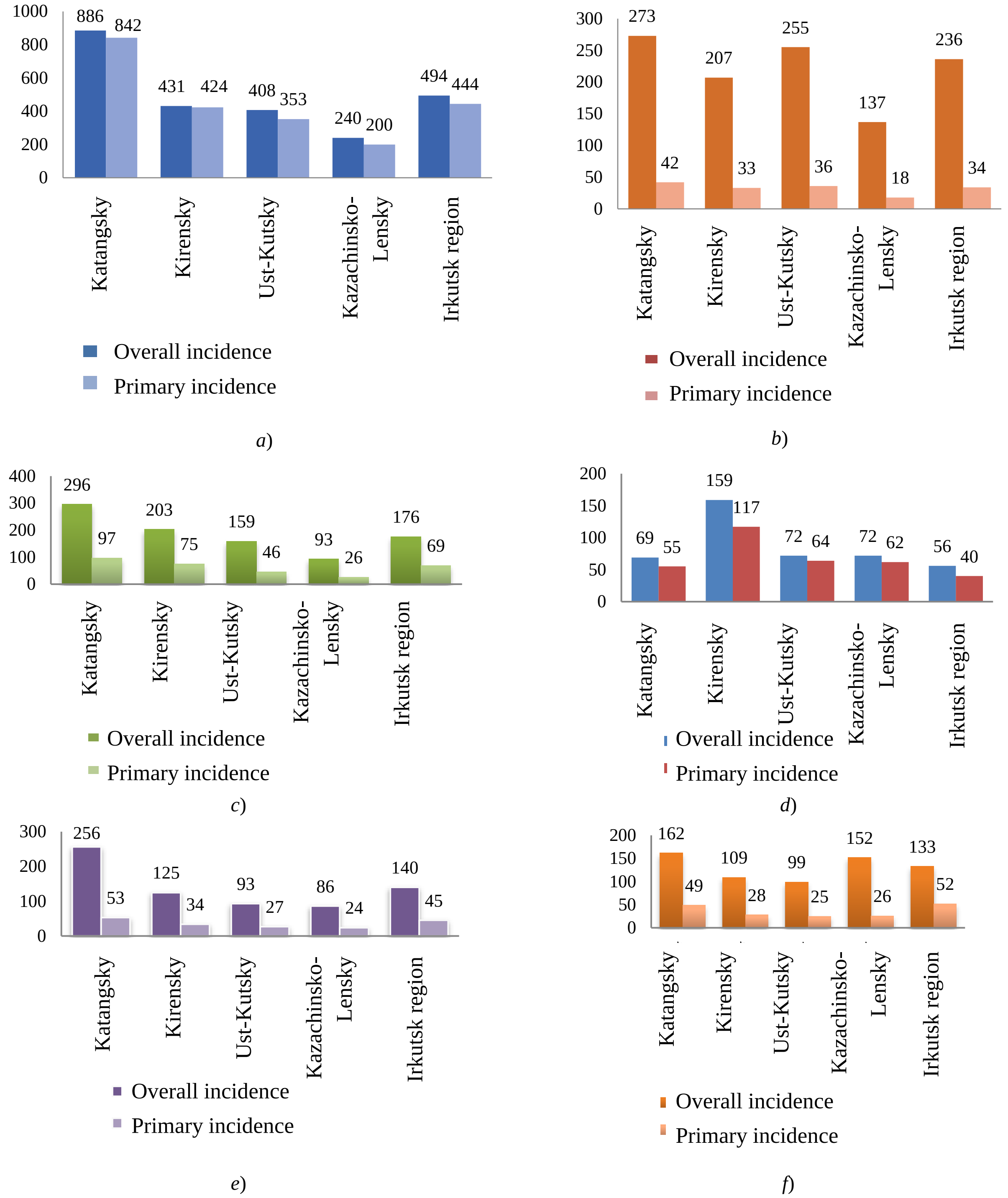

Fig. 3. Comparison of overall and primary disease incidence indicators of the population in municipalities for the following diseases:
a — respiratory organs; *b* — circulatory system; *c* — musculoskeletal system;
d — pathologies during pregnancy, childbirth and the postpartum period;
e — digestive system; *f* — genitourinary system

It is known that infants are extremely sensitive to the quality of the environment [17]. Diseases caused by environmental changes are quite common in infancy. In this regard, the dynamics of infant mortality (the number of dead children under one year per 1000 live births) in the districts of the Irkutsk region was considered. Figure 4 shows the corresponding data[8] for the period from 2001 to 2019.

[8] *Demografiya*. Irkutskstat. URL: https://irkutskstat.gks.ru/ (accessed 25.12.2022). (In Russ.).

According to the presented diagram (Fig. 4), the infant mortality rate in all areas of the oil field exceeds the level of the Irkutsk region as a whole. It should be noted that the indicators of the Ust-Ilimsky, Ziminsky, Bratsky, Bodaybinsky districts, which are also industrial districts of the Irkutsk region, also lie above the line of the Irkutsk region, but their indicators are several times lower than those of the Katangsky district (exceeding the indicators of the Irkutsk region up to 4 times in the period under review). The values of infant mortality indicators of the Kirensky district had been growing since 2011 and by 2013 they were close to the corresponding indicators of the Katangsky district. The diagram also shows the excess of infant mortality rates of the Ust-Kutsky district over the corresponding indicators of the Irkutsk region from 2006 to 2018. In the opinion of the authors, there is an obvious connection between the increase in infant mortality with the beginning of industrial development of hydrocarbon deposits in these areas (Ust-Kutsky — 2003, Katangsky — 2006, Kirensky — 2012).

During the experiment, an assessment of the non-carcinogenic risk to public health in the oil-producing areas of the Irkutsk region was carried out, using the Guidelines[9] and the environmental monitoring results of the oil company in 2018 and 2019 in the territories of the Danilovsky OGCF, Yaraktinsky, Markovsky and Ayan fields as initial data[10].

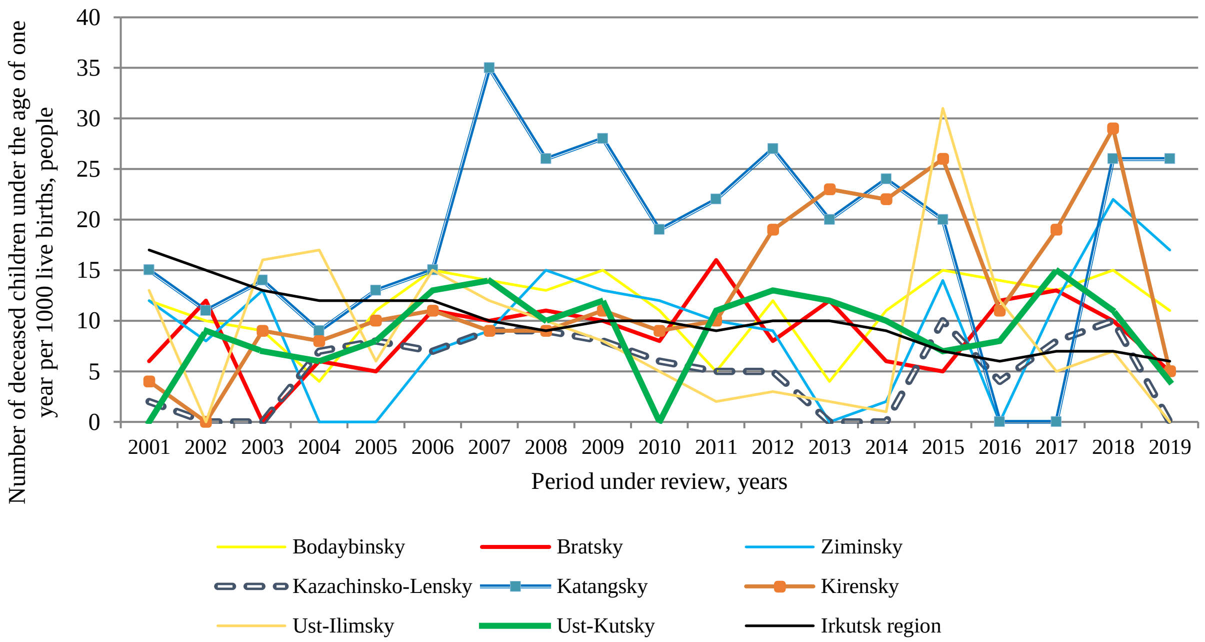

Fig. 4. Dynamics of infant mortality rates in the administrative districts of the Irkutsk region from 2001 to 2019

It should be noted that during the assessment, the average daily concentrations of pollutants averaged over the corresponding year were considered. The risk was calculated based on the fact that pollutants have a long-term effect, therefore, in accordance with the Guidelines, the largest concentration value out of two available ones was used. In accordance with the methodology, it was accepted that the daily air consumption by a person is 20 m^3/day, the average body weight of a person is 70 kg, the life time of a person is 70 years. Table 1 presents the calculation results of the probability of the development of non-carcinogenic effects on the health of the population living in the studied territories.

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Table 1

Assessment results of non-carcinogenic risk to the health of the population of the Katangsky, Kirensky and Ust-Kutsky districts from atmospheric air pollution during oil production

District	Polluting substance			Non-carcinogenic risk assessment				
	Substance	MPC_{cc} (mg/m³)	Hazard class	RFC*	RfD, (mg/kg·day)	C, (mg/m)	ADD, (mg/kg·day)	INR
Katangsky	NO_2	0.1	3	0.06	0.006	0.01	0.003	0.48
	SO_2	0.05	3	0.05	0.0025	0.05	0.015	6
	H_2S	0.008	2	0.002	0.000016	0.0012	0.00006	0.38
	Saturated hydrocarbons	50	4	0.071	20	2.1	0.63	0.03
	Suspended substances	0.035	–	0.075	0.003	0.23	0.0006	2
	Methanol	0.5	3	4	2	5.5	1.595	0.80
								Total 9.69
Kirensky	NO_2	0.1	3	0.06	0.006	0.009	0.0026	0.43
	SO_2	0.05	3	0.05	0.0025	0.06	0.00174	6.96
	H_2S	0.008	2	0.002	0.000016	0.001	0.00003	1.88
	Saturated hydrocarbons	50	4	0.4	20	2.2	0.638	0.034
	Suspended substances	0.035	–	0.075	0.003	0.54	0.00157	0.52
	Methanol	0.5	3	4	2	3.7	1.1	0.55
								Total 10.37
Ust-Kutsky	NO_2	0.1	3	0.06	0.006	0.007	0.0021	0.35
	SO_2	0.05	3	0.05	0.0025	0.03	0.00017	3.5
	H_2S	0.008	2	0.002	0.000016	0.0002	0.0000058	3.75
	Saturated hydrocarbons	50	4	0.4	20	11	3.2	0.16
	Suspended substances	0.035	–	0.075	0.003	0.51	0.0015	5
	Methanol	0.5	3	4	2	11	2	1
								Total 13.76

* ADD — the average daily dose of the pollutant absorption (mg/kg × day); C — the average concentration of the pollutant in the air (mg/m³); RfD — the reference dose of MPC (mg/m³); RFC — reference concentrations for chronic inhalation exposure.

Values of individual non-carcinogenic risk exceeding one, in accordance with the method used, mean the presence of a risk of harm to health with daily inhalation of polluted air. The greatest impact on health is the content of sulfur dioxide, suspended solids, methanol and hydrogen sulfide in the air. A comparative analysis of risks with established incidence indicators in these areas demonstrates the relationship between the content of priority pollutants in the atmospheric air and the incidence pattern of the population in the form of a significant indicator of diseases of the respiratory, circulatory and musculoskeletal systems.

The Irkutsk region is one of the ten most polluted regions of the country. It is believed that the industrial centers — Angarsk, Bratsk, Shelekhov, Zima, Irkutsk — have the greatest negative impact. However, the active development of oil fields in recent years has also begun to have a significant impact, which could not but affect the health of the population of nearby territories.

Discussion and Conclusion. The unfavorable medical and demographic situation in the territories under discussion is shown. The Katangsky district ranks first among all the considered districts and the region as a whole in terms of diseases of the respiratory system, circulatory system, musculoskeletal system, digestive organs, genitourinary system, as well as deviations during pregnancy, childbirth and the postpartum period. The Kirensky district is characterized by extremely high overall and primary indicators of deviations during pregnancy, childbirth and in the postpartum period. In this area, the indicators are exceeded by more than 2 times, compared with the rest of the territories considered. In the Ust-Kutsky district, the indicators of overall and primary incidence of the circulatory system and respiratory diseases exceed the indicators of the territories taken for comparison. There are examples in Russia when the negative impact of industrial production on the health of the population is compensated by the high level of socio-economic development of the region [18]. Perhaps such a solution to the problem would be a solution in these territories if oil-producing companies took part of the costs of financing healthcare, including the costs of attracting highly qualified medical personnel, as well as improving other socio-economic indicators of the production regions themselves.

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Original article

Development of an Approach to Assess the Consequences of Fuel-Air Mixtures Explosions Taking into Account the Development Features

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Abstract

Introduction. In the study of the problem of the impact of negative factors from explosions at gas stations on people and the infrastructure of settlements, a probabilistic approach is often used. The limitation of this approach is that when it is implemented, the concept of clutter of the surrounding space does not reflect the relationship between the area occupied by buildings and the total area affected by the shock wave. Therefore, this article is devoted to the development and justification of an approach to assessing the consequences of explosions of fuel-air mixtures (FA), taking into account the peculiarities of the development of settlements. The work objective is to develop an approach for assessing the consequences of explosions of fuel-air mixtures, taking into account the development features. The solution to this problem will facilitate decision-making for the development of effective protective measures for surrounding objects.

Materials and Methods. The authors have conducted an analytical review of the research results in the field of study and the existing approaches to assessing the consequences of explosions at filling stations (FS) and gas stations (GS), based on the specific conditions of their location on the territory of settlements.

Results. An approach has been developed to assess the consequences of explosions of fuel-air mixtures, taking into account the development features. The main causes, types of accidents with an explosion at a gas station and the scale of their consequences have been identified. Along with the theoretical justification of the issue under consideration, the authors provide a detailed description of the applied research methodology, as well as the characteristics of the objects of research, taking into account their location. When calculating the consequences of explosions of fuel-air mixtures, it was proposed for the first time to use a development density factor equal to the ratio of the area of the existing facilities to the total area of the territory affected by the shock wave. This approach justifies the need to apply additional protective measures in the areas where gas stations are located. The methods of analysis used are described in detail with justification of the reliability of the measurement results.

Discussion and Conclusion. The application of the approach proposed in the article for calculating the consequences of an explosion of fuel-air mixtures, taking into account the development density, makes it possible to control the location and the level of risk from possible explosions at gas stations in a real situation. The proposed approach for calculating the consequences allows you to quickly assess possible risks in real time and plan specific measures to minimize them in accordance with the existing situation in the area of the gas station.

Keywords: filling (gas) station, risk assessment, methodology, deflagration, explosion, calculations, experiment, development.

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Научная статья

Разработка подхода для оценки последствий взрывов топливно-воздушных смесей с учетом особенностей застройки

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Аннотация

Введение. При исследовании проблемы воздействия на людей и инфраструктуру населенных пунктов негативных факторов, возникающих при взрывах на заправочных станциях, зачастую применяется вероятностный подход. Ограничение данного подхода состоит в том, что при его реализации понятие загроможденности окружающего пространства не отражает соотношения между площадью застройки и общей площадью, подверженной воздействию ударной волны. Поэтому данная статья посвящена вопросам разработки и обоснования подхода к оценке последствий взрывов топливно-воздушных смесей (ТВС) с учётом особенностей застройки населённых пунктов. Целью работы явилась разработка подхода для оценки последствий взрывов топливно-воздушных смесей с учетом особенностей застройки. Решение данной проблемы будет способствовать принятию решений для разработки эффективных защитных мероприятий для окружающих объектов.

Материалы и методы. Авторами проведён аналитический обзор результатов исследований в изучаемой области и существующих подходов к оценке последствий взрывов на автомобильных заправочных станциях (АЗС), газозаправочных станциях (АГЗС), исходя из конкретных условий их расположения на территории населённых пунктов.

Результаты исследования. Разработан подход для оценки последствий взрывов топливно-воздушных смесей с учетом особенностей застройки. Выявлены основные причины, виды аварий со взрывом на АЗС и масштабы их последствий. Наряду с теоретическим обоснованием рассматриваемого вопроса, авторами приведено подробное описание применённой методики исследования, а также характеристика объектов исследования с учётом их месторасположения. При расчете последствий взрывов топливно-воздушных смесей впервые предложено использовать коэффициент плотности застройки, равный отношению площади существующих объектов к общей площади территории, подверженной воздействию ударной волны. Данный подход обосновывает необходимость применения дополнительных защитных мероприятий в районах расположения заправочных станций. Подробно описаны использованные методы анализа с обоснованием достоверности результатов измерений.

Обсуждение и заключения. Применение предлагаемого в статье подхода для расчета последствий взрыва топливно-воздушных смесей с учетом величины плотности застройки даёт возможность контролировать расположение и уровень риска от возможных взрывов на заправочных станциях в условиях реальной обстановки. Предлагаемый подход к расчету последствий позволяет оперативно в реальном масштабе времени и в соответствии с существующей обстановкой в районе расположения АЗС оценивать возможные риски и планировать конкретные мероприятия по их минимизации.

Ключевые слова: автозаправочная (автогазозаправочная) станция, оценка риска, методика, дефлаграция, взрыв, вычисления, эксперимент, застройка.

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Introduction. Accidental explosions often occur at automobile gas stations located in the immediate vicinity of places where a large number of people stay. The assessment of the consequences of such explosions is relevant and extremely important. The severity of negative impacts depends primarily on the presence and quality of obstacles to the propagation of the shock wave. Subsequent assessments are necessary to carry out corrective measures aimed at reducing the impact of negative explosion factors. These include the installation of any mechanical obstacles — protective barriers, trees, shrubs, etc. The effectiveness of protective measures in quantitative terms should be sufficient to reduce the risks to the minimum permissible values. At the same time, the assessment of hazards should have a visual representation.

In practice, it is not uncommon for regulated and unregulated pedestrian crossings, various buildings or public transport stops to be located near gas stations, including multi-fuel ones. At the same time, there are often no elementary obstacles from explosive objects on the way to them that contribute to reducing the explosive load.

The danger of severe consequences in case of accidents at gas stations is confirmed by Russian and international statistics. In particular, during the period from 2005 to 2016, 2–3 fires with victims occur annually at gas stations in our country, in which 4 people are injured or killed [1]. Similar cases occur in other countries, for example, [2] describes 50 typical cases of accidents at gas stations in China over the past 20 years.

The leading approach to the study of the problem of the impact of negative factors of explosions at gas stations on people and the infrastructure of settlements is the use of well-known techniques [3] implemented in various software packages. For example, the module "Fuel-air mixtures explosions. Calculations of the affected areas during fuel-air mixtures explosions"[1] allows us to comprehensively consider all the above mentioned parameters. For practical and research purposes, the methodology makes it possible to control the entered parameters, calculation logic, and assessment of the magnitude of the consequences in case of changes in local building conditions.

To analyze hazards, the researchers use methods of analyzing modes and consequences of failures. The type and cause of equipment failure of the most frequent accidents is an explosion caused by static electricity. In this regard, effective measures are usually proposed to eliminate accidents and mitigate the consequences. The research results are aimed at ensuring the possibility of risks reduction of operating gas stations.

Scientific sources devoted to the analysis of accidents with the explosion of liquefied petroleum gases indicate that their consequences often lead to significant material losses and human casualties. Hazard analysis for deflagration and detonation mode is usually performed by the analytical method described in detail in above methodology [3]. However, more complex numerical calculation methods are also used [4]. For example, with the software[2] help, the explosion scenarios are considered in conditions of complex area development in a three-dimensional representation, including in the case of an explosion inside a building. To analyze the deflagration hazard of fuel-air mixtures, the explosion pressure and flame propagation features of a pre-mixed mixture of liquefied petroleum gases (LPG) with air can be

[1] *Modul' «Vzryv TVS». Raschety zon porazheniya pri vzryvakh*. URL: https://toxi.ru/produkty/programmnyi-kompleks-toxirisk-5/moduli-toxirisk-5/modul-vzryv-tvs-raschety-zon-porazheniia-pri-vzryvah-tvs (accessed 22.12. 2022). (In Russ.).
[2] *BREEZE ExDAM. Modeling Software for EHS Professionals*. Trinity Consultants. URL: https://www.trinityconsultants.com/software/explosion/exdam (accessed 15.09.2022).

studied numerically. For example, in a closed pipeline at elevated initial pressures and temperatures. The results of such studies allow us to identify the greatest influence on the parameters of the explosion, for example, the initial pressure. Due to the general observed trend, there is an approach to predicting accidents and their consequences using the concept of risk. Features of the risk of LPG deflagration in difficult work situations, explosion risk assessment of related procedures and devices for the development of scientific and effective explosion protection measures are considered in work of Chinese researchers [5].

Safety and risk assessments studies are increasingly being used to manage hazardous materials management activities. The resulting models in risk analysis studies can be used, for example, for land use planning or for calculating the consequences of emergencies of already existing facilities. Some works present models for calculating the consequences of fires, explosions and toxic gas emissions for people, buildings and structures. The source of such models, as a rule, is a handbook on the calculation of consequences developed for the Ministry of Housing and Environment of the Netherlands, which provides a significant number of models [6]. In foreign literature, one can find sources that reveal the basic concepts in terms of the acoustic effects of the explosion and their physical characteristics [7].

Filling stations, their multi-fuel variants, single gas filling stations are quite complex socio-technical systems with dynamic relationships between various risk factors. Currently, the causal analysis of accidents related to the explosion of fuel-air mixtures is mainly focused on the study of aspects of human fault and equipment malfunction. In [8], 28 risk factors for gas explosions were identified. Nine of them, such as a flash, an electric spark and a local accumulation of gas, are the direct causes of gas explosion. 17 factors are related to operating actions, malfunction of ventilation systems and errors in safety management. They are indirect. The probability of gas explosion increases with an increase in the number of risk factors. The risks associated with the imperfection of state policy and legislative acts are among those that are poorly subject to management. It has been established that, compared with subjective risk factors, objective factors have a higher probability of causing a gas explosion due to associated risks.

There are a number of studies devoted to the comparative explosion consequences assessment based on different approaches. For example, in [9], simplified empirical models were used to assess explosion consequences. Nevertheless, in most cases, a methodology adopted by the international community and based on probabilistic models is used to assess the degree of vulnerability of people. The calculation results using different approaches have some differences, but all reproduce the real damage and predict the explosion consequences with sufficient accuracy.

Among Russian scientists, work is also underway to systematize the results of research on the damaging effects of air shock waves during gas-air mixtures explosions. Thus, in [10], various empirical dependences of the main parameters of the air shock wave on the distance were obtained on the basis of the universal method of energy similarity. A method has been developed for calculating the power of the damaging effect for a person who is in shelters of various degrees of protection.

The simplest example of noise impact assessment during explosions of fuel-air mixtures is presented in source [11]. According to the information presented in this paper, it is possible to determine the distance from the epicenter of the explosion, at which the sound pressure level is 140 dB, which is a critical value for a human auditory analyzer.

This article is aimed at developing an approach to identify the calculated values of the probability of occurrence of an event — the impact of a shock load on a person and environmental objects due to a possible explosion of the fuel-air environment, taking into account the development features on the ground, which are determined by a specially introduced formula. Such a calculation is carried out in a single computational paradigm with the possibility to set initial parameters and visually present the results to the user.

The analysis of the previously described research materials allowed us to establish that the nature and dynamics of the behavior and consequences of emergency situations at stand-alone gas stations directly depend on the characteristics of the surrounding area. The disadvantage of the analyzed methods is the absence of a factor in the calculations that takes into account the development features of the area. The objects that need to be considered may include public transport stops, residential buildings, regulated pedestrian crossings and other gas stations. They are characterized by a close location to places of one-time congestion and even mass stay of people with a population of 50 and more people.

The authors have also analyzed another type of materials — regulatory legal acts of the Russian Federation and came to the conclusion that at present there is some legal uncertainty in the application of a number of concepts used in justifying approaches to the placement and design of gas stations on the territory of settlements. In particular, the concept of "a place of mass stay of people", introduced by the law "On Countering Terrorism"[3], means the simultaneous presence of 50 or more people in a certain place. By the Decree of the Government of the Russian Federation[4] these places were ranked in three categories: with a population of up to 200 people — the third category, up to 1000 people — the second one and more than 1000 people — the first category. An object with a mass stay of people is a building or structure (except residential buildings) in which 50 or more people can be at the same time[5]. That is, in order to justify the risk of placing a potentially hazardous object or a place with a mass stay of people, it is necessary to consider only objects with a population of 50 or more people. It is quite difficult to imagine a stop with simultaneous presence of more than 50 people with the current saturation of cities with public transport. Current documents regulating the placement of gas stations, NPB-111-98* and SP 156.13130.2014[6,7] establish specific standards for the remoteness of gas stations from certain objects, buildings and structures, public roads, etc. However, instead of the concept of "public transport stop", as a rule, the wording "place of mass stay of people" is used. Since human life is the highest value and an absolute priority in justifying any approaches, it seems advisable to reduce the threshold for the number of places (objects) of mass stay of people or introduce the concept of "a place of gathering of people" with the establishment of a number of 20 or more people. Then public transport stops, regulated and unregulated crossings, etc. will fall under this definition.

Thus, the conclusion is that the use of the established approaches to assessing the consequences of possible explosions at gas stations can lead to a revision of the standards for their location within the boundaries of settlements, the degree of their emergency protection and the protection of objects located in the zone of possible impact of negative explosion factors.

Materials and Methods. To achieve the goal set in the work we use analytical modeling of the consequences of explosions of fuel-air mixtures with building density assessment on the territory of a hazardous object. This approach makes it possible to clarify the characteristics of the type of surrounding space, expressing it not only with a qualitative, but also with a quantitative measure and substantiate the need and priority of carrying out protective measures to reduce possible risks and damage.

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[3] *O protivodeistvii terrorizmu*. Federal law of 06.03.2006 No. 35-FZ. State Duma. URL: http://www.consultant.ru/document/cons_doc_LAW_58840/ (In Russ.).

[4] *Ob utverzhdenii trebovanii k antiterroristicheskoi zashchishchennosti mest massovogo prebyvaniya lyudei i ob"ektov (territorii), podlezhashchikh obyazatel'noi okhrane voiskami natsional'noi gvardii Rossiiskoi Federatsii, i form pasportov bezopasnosti takikh mest i ob"ektov (territorii).* Decree of the Government of the Russian Federation No. 272 of 25.03.2015 (ed. 29.07.2020). Government of the Russian Federation. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/420264843?section=text (In Russ.).

[5] *Ob utverzhdenii Pravil protivopozharnogo rezhima Rossiiskoi Federatsii (s izmeneniyami i dopolneniyami).* Decree of the Government of the Russian Federation No. 1479. Government of the Russian Federation. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/565837297?section=text (In Russ.).

[6] *SP 156.13130.2014 Car refueling stations. Fire safety requirements*. Approved and put into effect by Order of the Ministry of Emergency Situations of Russia No. 221 of May 05, 2014. URL: https://docs.cntd.ru/document/1200110842 (accessed 15.12.2022). (In Russ.).

[7] *Normy pozharnoi bezopasnosti. Avtozapravochnye stantsii. Trebovaniya pozharnoi bezopasnosti. NPB 111-98**. Date of introduction 01.05.1998. Put into effect by Order of the GU GPS of the Ministry of Internal Affairs of Russia No. 25 of 23.03.1998. (In Russ.).

The methods of basic calculations are based on the use of the provisions of methodology [8], which allows determining the consequences of detonation or deflagration combustion of fuel-air mixtures containing propane, methane or gasoline. Additionally, area or length measuring instruments in 2GIS and similar programs were used. This made it possible to perform online measurements of areas or lengths on the displayed terrain.

As calculated parameters, the parameters laid down in manual [3] were evaluated, taking into account the provisions of [6]: significant or complete structural damage to buildings, the probability of eardrum rupture, survival as a result of pressure wave or lung damage. Due to the availability of mathematical logic of calculations, it is possible to implement an assessment of consequences as a result of the action of fragments as secondary factors of damage.

In total, the terrain features near seventeen gas stations located on the territory of Izhevsk, where such fuels as propane, methane or gasoline are used, were analyzed. Characteristic objects of key interest are presented in Table 1. For obvious reasons, these objects are depersonalized.

Table 1

Characteristics of the studied objects

No.	Fuel type	Features of the location, including the proximity of similar objects	Possibility of gathering of people
1.	Propane	In the line of sight there is a gas station at a distance of 95 m, next to which there is a bus stop	No
2.	Methane	Bus stop at a distance of 60 m	Yes
3.	Propane	High-rise building (5 or more floors) at a distance of 25 m	No, but the effect of secondary explosion factors — glass fragments is possible.
4.	Gasoline	In the line of sight there is a transport stop, as well as a 5-storey residential building	Yes

Results. Before performing the calculations, two tasks were set that were necessary to verify the reliability of the calculations:

– assessment of the correctness of the calculations of probabilities of the estimated parameters based on the probability function;

– assessment of the correctness of measuring areas and lengths in relation to objects on the ground.

Verification of the correctness and completeness of the solution to the first problem was performed on the conditions of solving the problem given in example No. 1 of methodology [3]. The solution to the second problem was confirmed in an experiment using a measuring "ruler" on the website of the public cadastral map of the Udmurt Republic[8]. The use of characteristic measurement points in the measurement experiment on the cadastral map showed the results of measurements along the length. Hence, the conclusion was made about the reliability of the measurement and the area on the ground. Figure 1 provides an explanation of the principle of performance of measurements. (obtained by the authors using a public cadastral map https://egrp365.org/map/?id=g2ApXz), Figure 2 provides a visual representation of the calculation result.

[8] *Public cadastral map of the Udmurt Republic EGRP 365*. Checking real estate. URL: https://egrp365.org/ (accessed 23.10.22). (In Russ.).

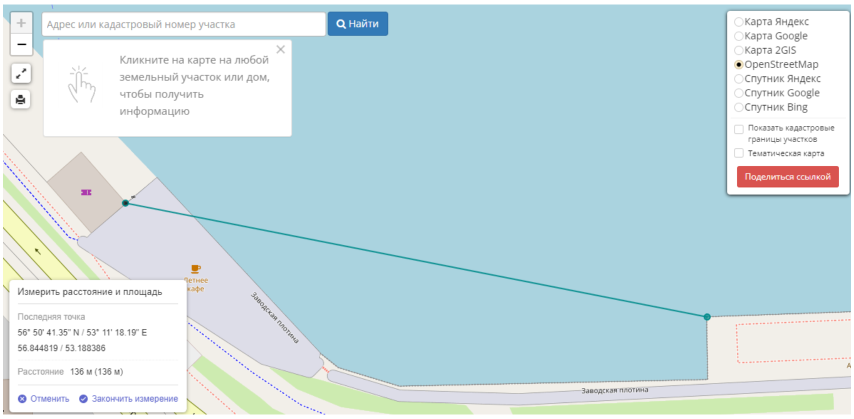

Fig. 1. Measurements on the public cadastral map

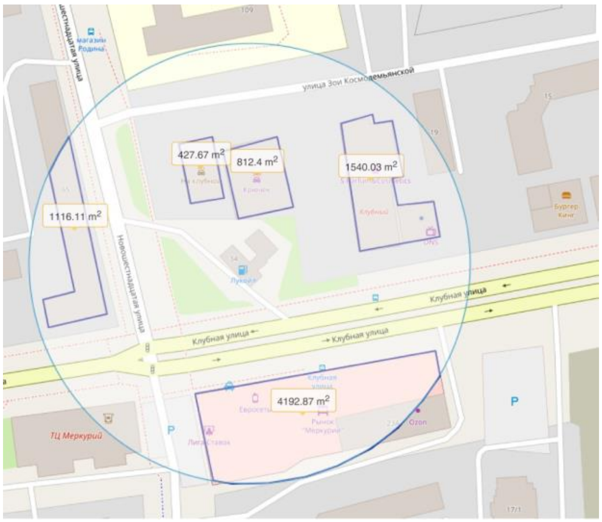

Fig. 2. Visual representation of the calculated zone, for the boundary of which the probabilities of consequences were determined

The next stage of the model experiment was the assessment of building density coefficient on the territory of the selected objects. A graphical representation of the measured areas is also shown in Fig. 2.

Building density coefficient ρ was determined by the formula:

$$\rho = \frac{\sum_1^n S_n}{S_{ref}}, \tag{1}$$

where n — the number of measured plots; S_n — the area of one measured plot, m^2; S_{ref} — the base area, m^2.

The area of a circle with a radius of 100 m was chosen as the base area. For all analyzed gas stations, the building density coefficient does not exceed the value of 26.7 %. It should be noted that this value does not include the area of green spaces such as shrubs or trees, which in summer to a certain extent perform barrier functions due to the presence of foliage, but in winter do not lead to a decrease in the impact of an air shock wave. With a density coefficient of 26.7 %, according to definitions [3], the situation can be characterized as slightly cluttered. In practice, it is necessary to take into account the building orientation in relation to the epicenter of the explosion and the material from which it is built. Out of seventeen initial objects, four were selected as meeting the research criteria. Further, on the basis of the measured values of distances to places of possible mass stay of people, the probabilities of occurrence of events — damaging factors of the explosion of the fuel-air mixture were determined. Table 2 provides the results of research and calculations.

Table 2

Results of calculations of the model experiment

No.	Coefficient of building density / calculation radius, m	Probabilities of damaging factors, %				
		Serious structural damage to buildings, P1	Complete destruction of buildings, P2	Probability of eardrum rupture, P3	Probability of survival as a result of pressure wave, P4	Lung damage, P5
1.	0/95	84	27.1	2.2	1.4	0
2.	13.2/60	23	2.9	0.7	0.6	0
3.	22.4/25	92.6	39.6	4.4	29.1	0
4.	26.7/60	87.6	31.7	2.9	23.6	0

Based on the analysis of the results obtained (Table 2), it can be stated that the probabilities of injury to people is at a sufficiently high level, while they can be reduced by special measures — the construction of barriers to the spread of negative explosion factors.

Discussion and Conclusion. As the study has showed, the prediction of the consequences of explosions of fuel-air mixtures can be justified by the presence of characteristic terrain features near gas stations with such fuels as gasoline, propane or methane. The terrain features, as a rule, consist in the fact that in the zone of significant consequences there may be places of mass stay or congestion of people, for example, public transport stops.

From the point of view of the completeness of consequences manifestation, two options are possible:

– there may be no barrier obstacles both in winter and in summer;

– the presence of green spaces in winter has a weak barrier effect in relation to the affected objects. Identification of such dangerous objects can be carried out with a comprehensive examination of the entire territory of the settlement.

It is proved that the measurement of building density can be defined as the ratio of the area of objects enclosed in a circle of the target diameter to the area of this circle. To conduct the study, the consequences of the explosion of fuel-air mixtures were calculated based on the probability function. This approach has proven itself on the positive side, including in international practice. It is able to give accurate predictive results with lower computational costs compared to computational procedures. The novelty implemented in the project is the use of the "Ruler" module, which allows you to estimate areas and linear distances on a geographical map of the area. This module allows you to determine the building density coefficient as the ratio of the sum of the areas to the area of a circle with a radius of 100 m, although you can choose distance. In this case, the center of the circle is the "conditional" middle of the gas station. In the best case, it is necessary to take into account the relative location of buildings or structures located near the target object, which can be either "longitudinal" or "transverse" to the epicenter.

According to the measurement results for the objects observed in the framework of this study, the coefficient of their building density does not exceed 26.7 %, which makes it possible to characterize the type of surrounding space as "open" or "slightly cluttered" in accordance with [3], and thus is confirmed quantitatively.

As the calculation results show, the probability of human survival in pressure wave for two of the four gas stations is at the level of 29.1 % and 23.6 %. The comparison with the maximum permissible values is not possible due to the lack of such. However, in relation to the acceptable probability, these values are significant. The acceptable probability can be calculated as the probability value of this criterion for the distance specified in method [3]. For liquid motor fuel filling stations with above-ground tanks located outside the territories of settlements, the minimum distances from them to such objects as places of mass gathering of people should be at least 50 m.

It is proposed to introduce the concept of "a place of gathering of people" as a place where 20 or more people can be at the same time. It is proposed that it should include public transport stops, regulated and unregulated crossings, including ground, underground, etc.

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The accessibility and simplicity of the methodology with the use of open cartographic data makes it possible to carry out these types of calculations. The results of cartographic studies, along with computational procedures, have shown that currently there are those among gas stations that are characterized by the possibility of people crowding at close distances from them.

As the study has showed, the presence of conditions allowing the probability of explosions is quite common, although their implementation is episodic. Perhaps, their occurrence is due to historical reasons. The aforementioned public transport stops and similar temporary structures may not exist during the design and construction of gas stations, and may be installed by the decision of local administrations much later. The application of the proposed approach makes it possible to control their location and the level of risk from possible explosions at gas stations in a real situation.

Ultimately, the proposed approach to assessing the consequences of explosions of fuel-air mixtures allows you to quickly assess possible risks in real time and in accordance with the real situation in the area of the gas station location and plan specific measures to minimize them.

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Original article

Justification of the Need to Use the Radiation and Chemical Protection Service as Part of Special Fire and Rescue Units in the Subjects of the Russian Federation

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Abstract
Introduction. Recently, much attention has been paid to the issues of long-term development of specialized fire and rescue units of the Federal Fire Service of the State Fire Service. In this regard, there is a need to develop criteria to justify the use of a particular service as part of specialized fire and rescue units. Therefore, the objective of this study is to develop a mathematical model to justify the need to use radiation and chemical protection services as part of specialized fire and rescue units in the subjects of the Russian Federation.
Materials and Methods. Justification of the need to use radiation and chemical protection services as part of specialized fire and rescue units has been carried out using the theory of fuzzy sets. The mathematical model takes into account the climatic and geographical features of the subjects, indicators of social, technical and economic development, and the risks of emergencies and fires. It also takes into account the availability of forces and means of a Unified State system for the prevention and liquidation of emergency situations in each subject of the Russian Federation. In total, 15 indicators were selected that characterize the need to use radiation and chemical protection services as part of specialized fire and rescue units. A desirability function is defined for each indicator, which shows which values of the indicator are the most acceptable from the point of view of the need to use radiation and chemical protection services as part of specialized fire and rescue units.
Results. Using the developed model, the subjects of the Russian Federation are identified in which the need for radiation and chemical protection service as part of specialized fire and rescue units is the highest. It is proposed to create a radiation and chemical protection service of the 1st category in the Moscow, Sverdlovsk and Rostov regions, in the Krasnoyarsk and Primorsky Territories and in St. Petersburg. In 21 subjects it is proposed to use the radiation and chemical protection service of the 2nd category. In other subjects, it is proposed to assign the 3rd category to the radiation and chemical protection service.
Discussion and Conclusion. The mathematical model developed using the theory of fuzzy sets will allow a more differentiated approach to the creation of a radiation and chemical protection service as part of specialized fire and rescue units and increase the efficiency of the functioning of this service and specialized fire and rescue units as a whole. The presented model can be applied to justify the need to use other services and groups as part of specialized fire and rescue units.

Keywords: fuzzy set, specialized fire and rescue unit, emergency, fire, risk, radiation and chemical protection.

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Научная статья

Обоснование необходимости использования службы радиационной и химической защиты в составе специализированных пожарно-спасательных частей в субъектах Российской Федерации

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Аннотация

Введение. В последнее время большое внимание уделяется вопросам перспективного развития специализированных пожарно-спасательных частей Федеральной противопожарной службы Государственной противопожарной службы (ФПС ГПС). В связи с этим существует потребность в разработке критериев для обоснования использования той или иной службы в составе специализированных пожарно-спасательных частей (СПСЧ). Поэтому цель данного исследования состояла в разработке математической модели для обоснования необходимости использования службы радиационной и химической защиты в составе СПСЧ в субъектах Российской Федерации.

Материалы и методы. Обоснование необходимости использования службы радиационной и химической защиты (РХЗ) в составе СПСЧ проведено с использованием теории нечетких множеств. В математической модели учитываются природно-климатические и географические особенности субъектов, показатели социального и технико-экономического развития и риски возникновения чрезвычайных ситуаций и пожаров. Также учитывается наличие сил и средств РСЧС в каждом субъекте Российской Федерации. Всего отобрано 15 показателей, характеризующих необходимость использования службы РХЗ в составе СПСЧ. Для каждого показателя определена функция желательности, которая показывает, какие значения показателя являются наиболее приемлемыми с точки зрения необходимости использования службы РХЗ в составе СПСЧ.

Результаты исследования. С использованием разработанной модели определены субъекты Российской Федерации, в которых потребность в службе РХЗ в составе СПСЧ наиболее высокая. Службу РХЗ 1-го разряда предлагается создать в Московской, Свердловской и Ростовской областях, в Красноярском и Приморском краях и в г. Санкт-Петербурге. В 21 субъекте предлагается использовать службу РХЗ 2-го разряда. В остальных субъектах предложено присвоить службе РХЗ 3-ий разряд.

Обсуждение и заключения. Разработанная с использованием теории нечетких множеств математическая модель позволит более дифференцированно подходить к созданию службы РХЗ в составе СПСЧ и повысить эффективность функционирования данной службы и СПСЧ в целом. Представленная модель может быть применена для обоснования необходимости использования других служб и групп в составе СПСЧ.

Ключевые слова: нечеткое множество, специализированная пожарно-спасательная часть, чрезвычайная ситуация, пожар, риск, радиационная и химическая защита.

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Introduction. Specialized fire and rescue units of the Federal Fire Service of the State Fire Service (hereinafter referred to as SFRU) in the territorial garrisons of fire departments are assigned the tasks of extinguishing xs in settlements and facilities, carrying out emergency rescue, diving and other special engineering works related to the elimination of fires, the elimination of the consequences of technogenic and natural emergencies [1, 2].

According to the standard staffing table (Order of the Ministry of Emergency Situations of 21.03.2014 No. 129 "On Amendments to Order of the Ministry of Emergency Situations of Russia of 30.12.2005 No. 1027 and Invalidation of the Orders of the Ministry of Emergency Situations of Russia and Certain Provisions of the Orders of the Ministry of

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Emergency Situations of Russia") the following services and groups may be part of SFRU:

– diving service;

– medical and psychological service;

– telecommunications and communications service;

– engineering service;

– radiation and chemical protection service;

– fire extinguishing and emergency rescue service;

– cynological group;

– pyrotechnic work group;

– technical support and maintenance group;

– robotics and unmanned aerial vehicles group.

Currently, much attention is paid to the issues of the SFRU long-term development [2]. In this regard, it became necessary to formulate criteria for justifying the use of a particular service as part of the SFRU.

The study objective is to develop a mathematical model using the theory of fuzzy sets [3-6] to determine the need to use the radiation and chemical protection service (RCP) as part of the SFRU to ensure fire safety and protect territories from emergencies in the subjects of the Russian Federation.

The RCP service in the SFRU of Chief Directorates of the Ministry of Emergency Situations of Russia for the subjects of the Russian Federation is created to ensure safety measures and improve the SFRU readiness for emergency situations to extinguish fires, eliminate emergency situations at facilities with chemically hazardous substances, as well as extinguishing fires and conducting primary emergency-rescue works related to them at facilities with radioactive substances and other sources of ionizing radiation.

Materials and Methods. In order to develop a mathematical model, a list of indicators was formed that characterize the need for the use of SFRU and individual services (groups) of SFRU in the subjects of the Russian Federation. A total of 34 indicators were selected. From these indicators, those that characterize the need to use the RCP service are highlighted. All indicators are divided into three groups.

Natural-climatic and geographical features of the subject characterize the following indicators:

– area of the territory;

– seismic hazard;

– presence of mountain ranges;

– social, technical and economic factors, which include the following indicators:

– share of industrial production in the total volume of production;

– degree of depreciation of basic production assets;

– length of highways;

– length of railways;

– number of radiation-hazardous objects;

– number of chemically hazardous objects;

– number of explosive and fire-hazardous objects.

The third group includes the risks of emergencies and fires, as well as indicators characterizing the availability of forces and means of the Russian System of Prevention and Response to ES (RSChS) in the considered and neighboring subjects of the Russian Federation:

– average distance to the nearest SFRU, in which there is a RCP service;

– average distance to the nearest unit of the RSChS forces, in which there is a RCP service;

– presence of the RCP service in the SFRU in the subject of the Russian Federation under consideration;

– risk of emergencies related to chemical and radiation hazards;

– risk of emergencies related to explosions, collapses.

For each indicator, a desirability function is determined [7, 8], the values of which lie in the range from 0 to 1. The desirability function demonstrates which values of the indicator are the most acceptable from the point of view of the need to use the RCP service as part of the SFRU.

If, with an increase in the value of the indicator, the demand for the RCP service increases, the desirability function has the form:

$$\mu_1(x) = \begin{cases} 0, & x < x_1, \\ \frac{x - x_1}{x_2 - x_1}, & x_1 \le x \le x_2, \\ 1, & x > x_2. \end{cases} \quad (1)$$

If a higher value of the indicator corresponds to a lower demand for the RCP service, the desirability function has the form:

$$\mu_2(x) = \begin{cases} 1, & x < x_1, \\ \frac{x_2 - x}{x_2 - x_1}, & x_1 \le x \le x_2 \\ 0, & x > x_2. \end{cases} \quad (2)$$

Boundary values of x_1 and x_2 are determined by analyzing statistical data for each indicator. Functions $\mu_1(x)$ and $\mu_2(x)$ are used for indicators, the values of which change continuously.

To formalize the indicators set at the qualitative level, linguistic assessments of the degree of expressiveness of the indicator are used. The desirability function for such indicators takes discrete values.

For the "seismic hazard" indicator, the desirability function has the form:

$$\mu_3(\mathrm{y}) = \begin{cases} 0, & \mathrm{y} < 6, \\ 0{,}2, & y = 6, \\ 0{,}4, & y = 7, \\ 0{,}6, & y = 8, \\ 0{,}8, & y = 9, \\ 1, & y \ge 10, \end{cases}, \quad (3)$$

where value y characterizes the presence in the subject of the Russian Federation of settlements with the specified seismic intensity for the C degree of seismic hazard (according to the set of rules of SP 14.13330.2011 "Construction in Seismic Areas").

For the "presence of mountain ranges" indicator, the desirability function has the form:

$$\mu_4(z) = \begin{cases} 0, & z = 0, \\ 0{,}25, & 0 \le z < 0{,}2, \\ 0{,}5, & 0{,}2 \le z < 0{,}4, \\ 0{,}75, & 0{,}4 \le z < 0{,}6, \\ 1, & z \ge 0{,}6, \end{cases}, \quad (4)$$

where value z characterizes the share of the territory of the subject of the Russian Federation occupied by mountain ranges.

For the "availability of the RCP service in the SFRU" indicator, the desirability function has the form:

$$\mu_5(r) = \begin{cases} 0, & if\ the\ \mathrm{RCP}\ service\ is\ created, \\ 1, & if\ there\ is\ no\ \mathrm{RCP}\ service. \end{cases} \quad (5)$$

The integral assessment of the need to use the RCP service in the SFRU in the subject of the Russian Federation is determined by the formula:

$$W = \sum_{m=1}^{3} \beta_m w_m, \quad (6)$$

where β_m — weight coefficient for the m-th group of indicators.

Generalized w_m estimator for the m-th group of indicators for the subject of the Russian Federation is determined by the formula:

$$w_m = \sum_{k=1}^{N_m} \alpha_{km} \mu_k(x_k), \quad (7)$$

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where N_m — number of indicators in the *m*-th group; α_{km} — weight coefficient for the *k*-th indicator in the *m*-th group; μ_k — desirability function for the *k*-th indicator; x_k — value of the *k*-th indicator for the subject of the Russian Federation.

To determine weight coefficients for each group of indicators, the method of pair-wise comparisons based on the linguistic scale of assessments was used [9, 10]. When comparing the *i*-th and *j*-th indicators, a_{ij} score is set depending on the degree of importance of these indicators from the point of view of the need to use the RCP service in the SFRU from 1 (if the indicators are equally significant) to 9 (if the *i*-th indicator is strictly preferable to the *j*-th). The assessment of the comparison of the *j*- th indicator with the *i*- th i has the inverse value of $1/a_{ij}$.

As an example, Table 1 shows a matrix of pair-wise comparisons for indicators characterizing social, technical and economic features of a subject of the Russian Federation. The names of the indicators are given in Table 2.

The desired values of weight coefficients α_1, α_2, ..., α_N for each group of indicators are the solution to the optimization problem

$$S = \sum_{i=1}^{N} \sum_{j=1}^{N} \left(a_{ij}\alpha_j - \alpha_i\right)^2 \rightarrow min;\ \sum_{i=1}^{N} \alpha_i = 1, \quad (8)$$

which is found by the method of indefinite Lagrange multipliers [11]. Optimization problem (8) is reduced to a system of *N*+1 linear equations, the solution to which is the desired weight coefficients α_i and the Lagrange multiplier *λ*.

Table 1

Matrix of pair-wise comparisons for indicators characterizing social, technical and economic features of the subject of the Russian Federation from the point of view of the need to use the RCP service in the SFRU

№ пок.	1	2	3	4	5	6	7
1	1	1	0.33	0,50	0.25	0.25	1
2	1	1	0.33	0,50	0.25	0.25	1
3	3	3	1	3	1	1	5
4	2	2	0.33	1	0.33	0.33	1
5	4	4	1	3	1	1	4
6	4	4	1	3	1	1	4
7	1	1	0.20	1	0.25	0.25	1

Table 2 shows the type of desirability function and its parameters, the calculated values of weight coefficients α_{km} for the indicators included in each group, as well as weight coefficients β_m for each of the three groups of indicators.

Table 2

Parameters of the desirability function and weight coefficients for indicators characterizing the need to use the RCP service in the SFRU

No.	Indicator name	Function	Value x_1	Value x_2	Weight coefficient α_{km}
Natural-climatic and geographical characteristics (β_1 = 0.127)					
1	Area of the territory, thousand km^2	$\mu_1(x)$	20	200	0.583
2	Seismic hazard	$\mu_3(x)$	–	–	0.258
3	Presence of mountain ranges	$\mu_4(x)$			0.159
Social, technical and economic characteristics (β_2 = 0.222)					
1	Share of industrial production in the total volume of production, %;	$\mu_2(x)$	20	50	0.063
2	Degree of depreciation of basic production assets, %	$\mu_1(x)$	40	60	0.063
3	Length of highways, thousand km	$\mu_1(x)$	5	20	0.239
4	Length of railways, thousand km	$\mu_1(x)$	0.5	2	0.084

No.	Indicator name	Function	Value x_1	Value x_2	Weight coefficient α_{km}
5	Number of radiation-hazardous objects, units	$\mu_1(x)$	0	5	0.247
6	Number of chemically hazardous objects, units	$\mu_1(x)$	30	100	0.247
7	Number of explosion- and fire-hazardous objects, units	$\mu_1(x)$	50	150	0.057
Risks of emergencies and fires (β_3 = 0.651)					
1	Distance to the nearest SFRU, in which there is a RCP service, km	$\mu_1(x)$	50	500	0.075
2	Distance to the nearest RSChS unit, in which there is a RCP service, km	$\mu_1(x)$	50	500	0.075
3	Availability of the RCP service in the SFRU	$\mu_5(x)$	–	–	0.703
4	Risk of emergencies related to chemical and radiation hazards, year^{-1}	$\mu_1(x)$	0	0.2	0.085
5	Risk of emergency situations related to explosions, collapses, year^{-1}	$\mu_1(x)$	0	0.4	0.061

Results. The developed mathematical model was applied to determine the need to use the RCP service as SFRU part to ensure fire safety and protect territories from emergency situations in the subjects of the Russian Federation. The values of indicators of socio-economic development of the subjects are determined according to the data of the Federal State Statistics Service. The number of hazardous objects in the subjects is determined using data [12]. The risks of emergencies are determined based on the analysis of data on the types of sources of occurrence and nature of emergencies in the subjects of the Russian Federation for the period from 2010 to 2021.

At the first stage, the subjects of the Russian Federation were identified, in which it is necessary to use the 1st-class SFRU. For these subjects, the condition must be met:

$$W \geq W_{\text{гр}} = \frac{2W_{max}+W_{min}}{3}, \quad (9)$$

where W — value of the integral indicator of the need to use the SFRU in the subject of the Russian Federation; W_{min} and W_{max} — the minimum and maximum values of the integral indicator among the subjects of the Russian Federation. Boundary value $W_{\text{гр}}$ was obtained equal to 0.650.

According to the calculation results, the 1st-class SFRU is proposed to be used in six subjects of the Russian Federation: in the Moscow, Sverdlovsk and Rostov regions, in the Krasnoyarsk and Primorsky Territories and in St. Petersburg. In all the 1st-class SFRU, the RCP service is assigned the 1st class.

At the second stage, for the rest of the subjects of the Russian Federation, the values of the indicator "average distance to the nearest SFRU" were determined, taking into account the 1st-class SFRU, and the values of the integral indicator of the need to use the RCP service in the SFRU were calculated.

The 2nd-class RCP service is proposed to be used in the SFRU, if the condition is met:

$$W_{\text{РХЗ}} \geq W_{\text{РХЗ,гр}} = \frac{2W_{\text{РХЗ},max}+W_{\text{РХЗ},min}}{3}, \quad (10)$$

where $W_{\text{РХЗ}}$ — value of the integral indicator of the need to use the RCP service in the SFRU in the subject of the Russian Federation, $W_{\text{РХЗ},min}$ and $W_{\text{РХЗ},max}$ — the minimum and maximum values of the integral indicator among the subjects of the Russian Federation in which there is no 1st-class SFRU. Boundary value $W_{\text{РХЗ.гр}}$ was obtained equal to 0.759.

In the remaining subjects of the Russian Federation, it is proposed to use the 3d-class RCP service in the SFRU.

The obtained values of the integral indicator of the need to use the RCP service in the SFRU in the subjects of the Russian Federation $W_{\text{РХЗ}}$, are shown in Fig. 1. It is proposed to use the 1st-class RCP service in 6 subjects of the Russian Federation (highlighted in red in the figure), the 2nd-class RCP service — in 21 subjects (highlighted in yellow), the 3d-class RCP service — in 58 subjects (highlighted in green).

The calculation results based on a mathematical model are compared with the actual presence of the RCP service in the SFRU in the subjects of the Russian Federation. For this purpose, information was collected from the Chief

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Directorates of the Ministry of Emergency Situations of Russia in the subjects of the Russian Federation on the availability and need for the RCP service as part of the SFRU.

Of the subjects included in the red group, the RCP service was not created only in the SFRU of St. Petersburg.

Of the subjects included in the yellow group, the RCP service in the SFRU was created in 19 subjects out of 21.

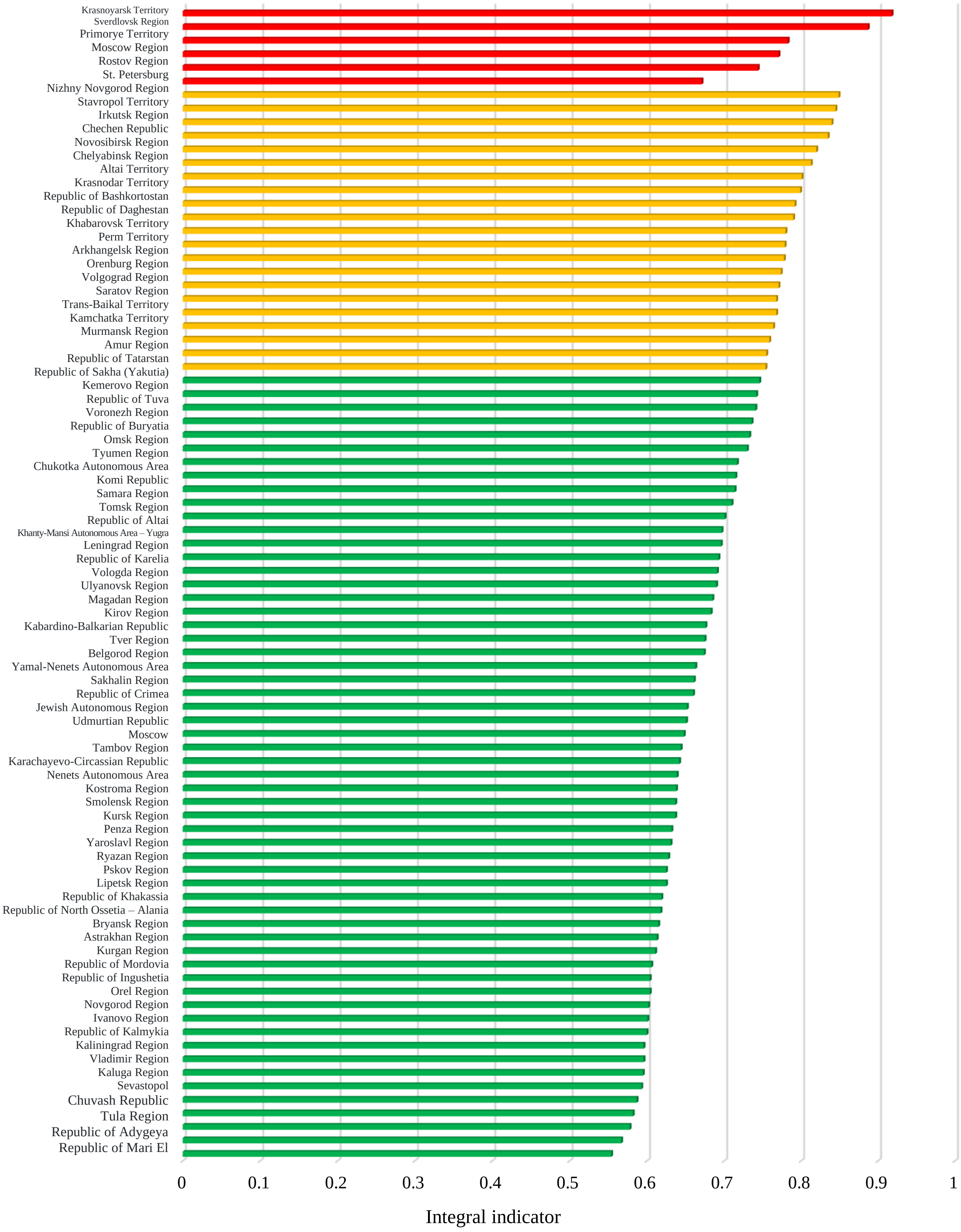

Fig. 1. Distribution of the subjects of the Russian Federation according to the integral indicator of the need to use the RCP service in the SFRU in the subjects of the Russian Federation

Of the subjects included in the green group, there is a RCP service in the SFRU in 40 subjects of the Russian Federation out of 58, 9 subjects declared the need to create a RCP service, 5 more subjects in which this service was created declared no need for it.

The existence of a statistical relationship between the calculation results based on a mathematical model and the actual presence of the RCP service in the SFRU in the subjects of the Russian Federation was verified using the χ^2 Pearson criterion [13, 14]. The results can be displayed as a conjugacy table (Table 3).

Table 3

Conjugacy table to verify the relationship between the calculation results based on a mathematical model and the actual presence or declared need for the RCP service in the SFRU in the subjects of the Russian Federation

Group name	Number of subjects of the Russian Federation in which		Total number of subjects of the Russian Federation
	RCP service has been created or there is a need to do it	RCP service is missing or there is no need	
Red group	5	1	6
Yellow group	19	2	21
Green group	44	14	58
Total	68	17	85

The value of χ^2-statistics for two-field Table 3 is 2.11. The critical value of criterion χ^2 for two degrees of freedom at a significance level of 0.05 is 5.99. The calculated value is less than the critical one, which indicates that there is no relationship between the calculation results based on the mathematical model and the actual presence of the RCP service in the SFRU in the subjects of the Russian Federation. This indicates that the RCP services as part of the SFRU are currently created without taking into account the risks of emergencies and fires and other features of the subjects of the Russian Federation. The use of the approach proposed in the article will allow for a more differentiated approach to the creation of the RCP service as part of the SFRU and increase the efficiency of the functioning of this service and the SFRU as a whole.

Discussion and Conclusion. The mathematical model based on the theory of fuzzy sets has been developed to justify the need for a radiation and chemical protection service as part of specialized fire and rescue units to ensure fire safety and protect territories from emergencies in the subjects of the Russian Federation. The model takes into account the climatic and geographical features of the subjects, indicators of social, technical and economic development, and the risks of emergencies and fires. It also takes into account the presence of forces and means of RSChS in the considered and neighboring subjects of the Russian Federation.

It is proposed to assign a class from the 1st to the 3rd to each SFRU, depending on the scale of the tasks to which the SFRU is involved, taking into account the risks of emergencies and fires. Similarly, it is proposed to assign classes for services and groups as part of the SFRU.

On the basis of the developed model, the calculations of the integral assessment were carried out to justify the need to use the RCP service in the SFRU for each subject of the Russian Federation. The subjects of the Russian Federation are identified in which the need for the RCP service as part of the SFRU is the highest. In these subjects, it is proposed to use the RCP service of the 1st and 2nd classes.

The developed model can be applied to substantiate the need to use other services (groups) as part of the SFRU.

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Original article

Fire Resistance of a Building Element with Intumescent Fire Protection: Standard Assessment and Express Analysis

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Abstract
Introduction. The paper considers the problem of fire resistance assessment of building structures with intumescent fire protection. For the results reliability, a fire test should be carried out only when the intumescent coating at the facility is ready, which will make it possible to detect hidden factors of violation of its quality and prevent collapse in case of a possible fire. The work objective is to test the express analysis of intumescent coatings in comparison with standard methods for fire resistance assessment.

Materials and Methods. The elements of building structures covered with fire-resistant intumescent paint Defender M Solvent with different diluent content were studied. The fire resistance of the coatings was determined by two methods. The first one is an express analysis. The following indicators were recorded:
– general appearance of the coked cellular material (CCM);
– swelling coefficient;
– CCM compressive and shear-tear strength of the boundary layer.
The second one is a standard approach according to the requirements of ISO 834-75 (GOST 30247.0-94). The indicators were:
– time to reach the critical temperature;
– critical deflection during heating.

Results. In addition to the above indicators, testing also took into account the amount of diluent. The CCM swelling coefficient, CCM compression force, tensile strength and density were considered. The revealed patterns are systematized in a table. The obtained indicators were compared with the technical requirements for the material. The period during which the steel substrate of the sample reaches a critical temperature is recorded. It is established that with an increase in this time, the coefficient of swelling of the protective layer (CCM) and its shear-tear strength increases. At the same time, the values of compressive strength and CCM density decrease. When the intumescent paint is diluted beyond the norm, the fire protection parameters deteriorate and the fire resistance limit R45 is not reached. The research results are visualized in the form of diagrams. They confirm that the express analysis makes it possible to reasonably judge the suitability or unsuitability of the paint for fire protection, if the required fire resistance limit is R45.

Discussion and Conclusions. In comparison with the results of the application of standard techniques, the effectiveness of the express analysis technique and the correctness of the results of the assessment of intumescent fire protection were confirmed. In construction conditions, an express CCM analysis will be sufficient to determine the quality of an intumescent fire retardant coating.

Keywords: fire resistance, intumescent coating, coked cellular material, express analysis method, tensile strength, critical temperature, swelling coefficient, fireproof structures.

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Научная статья

Огнестойкость строительного элемента с интумесцентной огнезащитой: стандартная оценка и экспресс-анализ

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Аннотация

Введение. Рассматривается проблема оценки огнестойкости строительных конструкций с интумесцентной огнезащитой. Для получения достоверных результатов нужно проводить огневое испытание только после полной готовности интумесцентного покрытия на объекте. Такой подход позволит выявить низкое качество материала и предотвратить обрушение при возможном пожаре. Цель исследования — испытание экспресс-анализа интумесцентных покрытий в сравнении со стандартными методами оценки огнестойкости.

Материалы и методы. Исследовались элементы строительных конструкций, покрытые огнезащитной интумесцентной краской Defender M Solvent с различным содержанием разбавителя. Огнестойкость покрытий определяли двумя методами. Первый — экспресс-анализ. Фиксировались следующие показатели:

– общий вид пенококса (ПК);

– коэффициент вспучивания;

– прочность ПК на сжатие и на сдвиг-отрыв приграничного слоя.

Второй — стандартный подход согласно требованиям ISO 834–75 (ГОСТ 30247.0–94). Показатели:

– время достижения критической температуры;

– критический прогиб при нагревании.

Результаты исследования. Кроме заявленных выше показателей тестирование учитывало также количество разбавителя. Рассматривались коэффициент вспучивания ПК, сила сжатия ПК, предел прочности и плотность. Выявленные закономерности систематизированы в табличном виде. Полученные показатели сопоставлялись с техническими требованиями к материалу. Зафиксирован период, в течение которого стальная подложка образца достигает критической температуры. Установлено, что с увеличением этого времени повышается коэффициент вспучивания защитного слоя (ПК) и его прочности на сдвиг-отрыв. Одновременно уменьшаются значения прочности на сжатие и плотности ПК. При разбавлении интумесцентной краски сверх нормы ухудшаются параметры огнезащиты и не достигается предел огнестойкости R45. Итоги изысканий визуализированы в виде диаграмм. Они подтверждают, что экспресс-анализ позволяет обоснованно судить о пригодности или непригодности краски для огнезащиты, если требуемый предел огнестойкости — R45.

Обсуждение и заключения. В сопоставлении с результатами применения стандартных методик подтверждена эффективность методики экспресс-анализа и корректность результатов оценки интумесцентной огнезащиты. В условиях стройки экспресс-анализа ПК будет достаточно для определения качества интумесцентного огнезащитного покрытия.

Ключевые слова: огнестойкость, интумесцентное покрытие, пенококс, метод экспресс-анализа, предел прочности, критическая температура, коэффициент вспучивания, пожаробезопасные конструкции.

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Introduction. Intumescent coatings are widely used in the design of relatively fireproof reinforced concrete and steel structures. This explains the interest of researchers in assessing the fire retardant effectiveness of such materials [1–3]. The publications criticize uninformative methods based on standard fire resistance tests. To solve the problem, comprehensive approaches are proposed to study the effectiveness of intumescent coatings that swell under the action of fire [1, 2]. They must meet certain standards. In academic research, it is difficult to establish the compliance of the material with industrial standards. There are two main reasons for this:

– the necessary stationary equipment is usually not available;

– the experiments require a long time and significant resources (in particular, energy).

However, the authors of [4, 5] use some industrial standards — curves of nominal temperature and time. Let us note that the parameters of a real fire in a modern building may differ significantly from the nominal curves defined in industrial standards [6–8]. Nevertheless, industrial standards remain the main guideline. The international standard for fire resistance testing of building structures ISO 834-75 (GOST 30247.0-94)[1] defines general requirements for methods of fire exposure to establish limit conditions.

Research and development of intumescent coatings take place in different conditions. Different test equipment is involved. This allows you to quickly check new formulations of coatings [4, 5, 9, 10], conduct tests in non-standard fire conditions [11, 12] and measure additional parameters [13, 14]. Most authors pay attention to the strength and adhesion of the paint itself, not paying attention to the mechanical properties of coked cellular material (CCM). However, the finished paint layer is not fire protective. It is more correct to present it as a stock of materials for the formation of such protection, i.e. for transformation into another material — coked cellular material. The authors of publications [15–17] investigated the strength of coked cellular material on stationary laboratory equipment.

The effectiveness of the coating is determined mainly by the thickness of the intumescent layer and the degree of dilution of the finished paint immediately before application. All this affects the quality of the CCM — the thickness of the layer and the density. Modern standards do not allow establishing these indicators during external examination of the paint layer, measuring its thickness and fixing conditional adhesion [18].

The authors of the presented work have developed an express analysis method that allows you to quickly identify the actual suitability of fire protection. At the same time, simple and inexpensive equipment is used, there is no need for special laboratory conditions and high energy costs. The quality of fire protection can be determined directly on the building structure [19, 20].

The work objective is to substantiate the effectiveness of the express method developed by the authors for evaluating the effectiveness of intumescent coatings of building structures. The proposed approach is tested and compared with standard methods for fire resistance assessment.

Materials and Methods. When testing fire retardant properties of elements of a metal building structure, three different variants of intumescent (swelling) material were used:

– mid-priced paint Defender M Solvent OOO "Laboratoriya "Evrostil" with the parameters stated in the technical documentation (composition 1);

[1] *GOST 30247.0-94 (ISO 834-75). Elements of building constructions. Fire-resistance test methods. General requirements*. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/9055248 (accessed 10.04.2023). (In Russ.).

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– the same paint, diluted by orthoxylene (6 % of weight), which slightly exceeds the maximum stated in the technical documentation (composition 2);

– the same paint, excessively diluted with orthoxylene — 10 % of weight. (composition 3).

Let us note that excessive dilution is often found in practice. We are talking about cases when the viscosity of the paint is corrected using unsuitable, cheap coating equipment or it is excessively diluted in order to save paint [18]. According to the instructions, the dilution should not exceed 5 %.

As part of the work, two types of structures were protected.

1. Hot-rolled I-beams with parallel flanges No. 12 (GOST R 57837-2017). The thickness of the finished paint coating layer after drying is 1–1.2 mm. The vertically oriented structure (column) in the furnace was tested for fire retardant efficiency according to the parameter "time to reach the critical temperature".

2. Beams of the 35SH1 grade with a length of 4.2 m with a thin-layer fire retardant coating of 0.87 mm. The loaded beam horizontally oriented in the furnace was tested for fire resistance of the structure according to the parameter "critical deflection during heating".

The coatings after application to the structures were dried until the diluent was completely removed — 10–14 days at a temperature of +20 °C and a humidity of no more than 80 %. The tests were carried out for each sample according to the developed method of express analysis [19], after which the coatings were restored at the test sites. Further, the tests were carried out for each sample in a flare furnace according to GOST R 53295-2009[2] and GOST 30247.1-94[3].

The test results using the express analysis method were evaluated according to the following indicators:

– CCM general appearance;

– swelling coefficient;

– CCM compressive strength;

– CCM shear-tear strength of the boundary layer with a thickness of 1 mm from the substrate (according to the method described in [19]).

Additionally, the CCM density was measured in the laboratory.

The time of reaching the critical temperature of the protected material according to GOST R 53295-2009 was estimated. For this purpose, a temperature curve was constructed — the dependence of the critical temperature of the steel substrate on the time of the fire test. Test conditions:

– ambient temperature — +18° C;

– relative humidity — 30 %;

– air velocity — less than 0.5 m/s.

The average temperatures in the fire chamber of the furnace did not exceed the permissible deviations. Fire resistance of the structure before reaching the maximum permissible deformation of the beams under fire exposure was determined in a special horizontal furnace. Beams with coatings were tested under a point load of 16 tons every 1/3 span. During the tests, the time of occurrence of the limiting states and their type, the temperature in the furnace, the temperature on the unheated surface of the sample, the deformation of the beam, and the temperature regime in the chamber were recorded.

Results. After conducting fire tests according to the standard methodology and express analysis methodology [19], the samples were examined and their physical and mechanical parameters were measured. The results are summarized

[2] *GOST R 53295-2009. Fire retardant compositions for steel constructions. General requirement. Method for determining fire retardant efficiency*. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/1200071913 (accessed 10.04.2023). (In Russ.).

[3] *GOST 30247.1-94. Elements of building constructions. Fire-resistance test methods. Loadbearing and separating constructions*. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/9055247 (accessed 10.04.2023). (In Russ.).

in Table 1. The results of CCM density measurements not provided for by the express analysis methodology are also presented [19].

Table 1

Test results of intumescent fire protection by express analysis and according to GOST R 53295-2009

Parameter	Composition 1	Composition 2	Composition 3
Amount of diluent in IP, % wt.	0	5	10
Time to reach the critical temperature of the substrate (+500 °C), min	47	34	27
CCM swelling coefficient	36	17	11
CCM compression force outside gas bubbles, with an indenter with a diameter of 3 mm, g.wt	6	14	27
CCM compressive strength, g.wt/cm^2	86	200	360
CCM shear-tear strength of the boundary layer from the substrate, g.wt/cm	78	56	42
CCM density outside large gas bubbles, g.wt/cm^3	0.28	0.44	0.51
CCM density taking into account large gas bubbles, g.wt/cm^3	0.28	0.14	0.45

Fig. 1 shows the fire resistance test in a standard furnace and the formation of coked cellular material from intumescent paint compositions 1-3 on a metal column of I-section.

a) *b*)

Fig. 1. Fire test result in a standard furnace of I-beam column with an intumescent coating of composition 1:
a — 10 minutes after the start of firing; *b* — after 30 minutes

Let us consider the test results by the standard method. When the sample coated with composition 1 is heated, after 47 minutes, the limit state is fixed according to the parameters "time to reach the critical temperature" (Fig. 2) and "critical deflection during heating" (Fig. 3). This confirms the compliance of composition 1 with the time stated in the technical documentation for reaching the critical temperature (45 min).

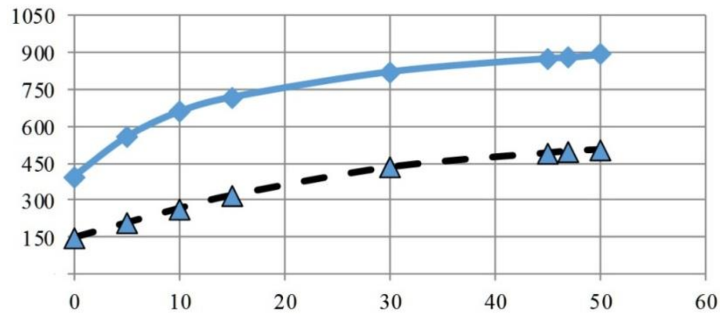

Fig. 2. Time to reach the critical temperature of the sample coated with composition 1 (without dilution). The solid line is the heating temperature; the dotted line is the surface temperature under the CCM layer. The vertical axis shows the temperature (°C), the horizontal axis shows the time (min)

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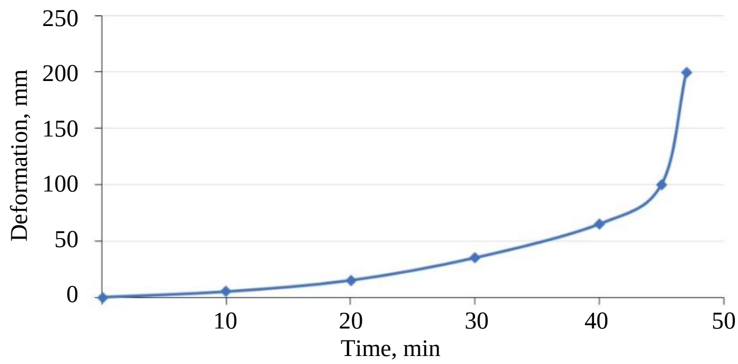

Fig. 3. Dependence of sample deflection with a fire retardant coating of composition 1 (without diluent) on the time of thermal exposure in the furnace fire chamber

The express analysis results regarding the compliance of the fire retardant composition with the technical documentation (CCM swelling coefficient, see Table 1) indicate the correctness of the proposed methodology.

When testing a sample coated with composition 2 according to the standard procedure, the time to reach the limit states was 34 minutes (Fig. 4). That is, the tested material does not comply with the technical documentation. The composition cannot be used for fire protection if the required fire resistance limit is R45.

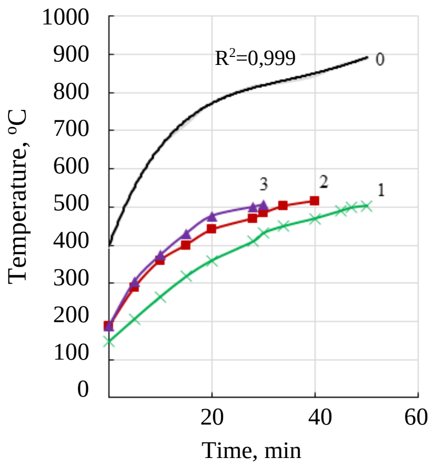

Fig. 4. Dynamics of temperature changes in the fire chamber (curve 0) and the temperature of the protected surface during the testing of samples 1-3 (curves 1-3)

The results of the tests using the express analysis method confirm the unsuitability of the paint, despite the fact that the coefficient of swelling of the coating exceeds the minimum value specified in the regulatory documentation. The resulting CCM is externally heterogeneous, large gas cavities are noticeable. The CCM layers outside of these defects have increased strength and density, as well as relatively low adhesion to the protected material.

Tests of sample 3 gave the following results. The steel substrate reaches its limit state after 27 minutes when tested according to the standard procedure (Fig. 4). This indicates the unsuitability of composition 3 according to the indicator "time to reach the critical temperature" (45 min). This fact was confirmed by the results of tests by the express method. The CCM is heterogeneous, there are large gas cavities. The strength and density of the CCM layer outside these defects is increased, the adhesion to the protected material is low.

The express analysis allowed us to establish that at a given critical deflection value of 200 mm, the loss of bearing capacity in sample 1 was observed after 47 minutes, in sample 2 — after 42 minutes, in sample 3 — after 35 minutes.

Therefore, the longer the heating time of the steel substrate of the sample to the critical temperature, the higher the coefficient of swelling of the CCM protective layer and the lower the index of the CCM compressive strength (Table 1, Fig. 5).

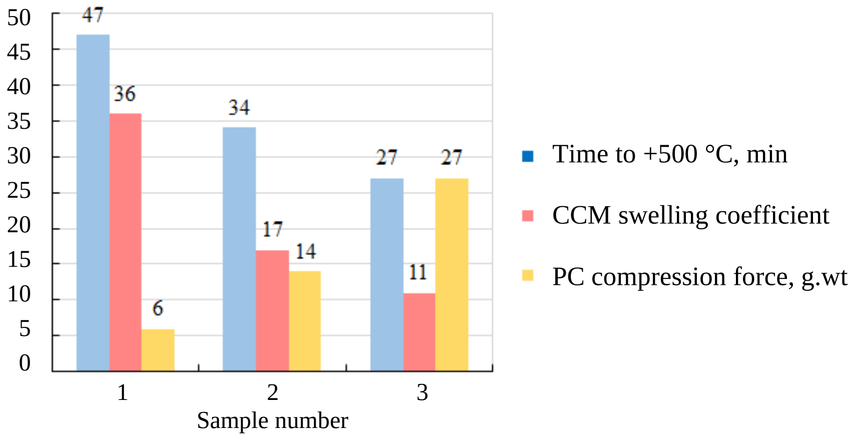

Fig. 5. Results of fire resistance tests according to GOST 30247.0-94 (time to reach the critical temperature of the substrate) and by express analysis (CCM swelling coefficient, CCM strength)

The relatively high compressive strength of CCM, established by the express analysis method for sample 3, assumes a high density of CCM (Table 1) and an increase in the thermal conductivity of the protective layer, which reduces the time to reach the critical temperature of the substrate and is confirmed by the test results according to GOST 30247.0-94.

Discussion and Conclusion. The express analysis of fire resistance of intumescent coatings proposed by the authors was tested on I-beam building structures. The results were compared with a similar test according to GOST 30247.0-94. The comparison demonstrated the correctness of the authors' approach.

The results of the tests for both methods are divided into three groups. The first category includes the results obtained for coatings with high-quality undiluted fire retardant paint that meet the requirements of regulatory documentation in all respects. The second is the results of testing coatings that do not provide the specified fire retardant parameters. At the same time, the CCM coefficient of swelling and its adhesion to the substrate decreases, strength and density increase. The third group is characterized by significant deviations from the required parameters. Based on the results obtained, it can be argued that the assessment of CCM parameters by the express analysis method in the conditions of a construction object is sufficient to decide if the intumescent coating is suitable or unsuitable for fire protection.

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Original article

On the Issue of Assessing the Levels of Noise and Vibration Impacts on Workers of Industrial Enterprises of the Republic of Kazakhstan

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Abstract
Introduction. Ensuring safe and comfortable working conditions is one of the most important tasks in the organization of modern production processes that have a direct impact on employee productivity, injuries and occupational diseases. Despite all the efforts made both at the state and departmental levels, the current state of occupational safety and health of industrial workers in the Republic of Kazakhstan continues to remain at an insufficiently high level. The main cause of occupational injuries and occupational diseases is the impact on working personnel of dangerous and harmful production factors, one of which is an increased level of noise and vibration from production equipment. The authors analyze statistical data on the number of cases of injuries, their types and causes of occurrence in workers by sectors of the economy of the republic. The influence of noise and vibration on the health of workers is considered. It is found that an increased level of noise and vibration effects causes injuries to a lesser extent, and occupational diseases to a greater extent. The work objective is instrumental measurement of noise and vibration levels in the workplaces of production sites of a machine-building enterprise and assessment of working conditions there to develop effective measures to reduce the harmful effects on the health of workers.
Materials and Methods. Statistical data on occupational injuries and occupational diseases were used as basic information, as well as the results of instrumental measurements of the level of noise and vibration effects on workers using the methods set out in GOST ISO 9612-2016 and GOST 31319-2006, taking into account Order of the Minister of Health of the Republic of Kazakhstan of February 16, 2022 No. KR DSM-15 "On approval of hygienic standards to physical factors that have an impact on a person".
Results. The results of the conducted research allowed us to conclude that about 22.6% of workplaces at production sites are characterized by harmful and dangerous working conditions in terms of noise and vibration effects on workers.
Discussion and Conclusion. Based on the results of the study, a plan of priority measures was developed to reduce the harmful effects of increased noise and vibration in the workplace. The authors also recommend a special working regime, benefits and additional payments to employees for working conditions that do not meet safety requirements.

Keywords: occupational health and safety, occupational injuries, occupational diseases, workplace, dangerous and harmful production factors, noise, vibration.

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Научная статья

К вопросу оценки уровня шумовых и вибрационных воздействий на работников промышленных предприятий Республики Казахстан

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Аннотация

Введение. Обеспечение безопасных и комфортных условий труда является одной из наиболее важных задач в организации современных производственных процессов, оказывающих непосредственное влияние на производительность труда работников, травматизм и профессиональные заболевания. Несмотря на все усилия, предпринимаемые как на государственном, так и на ведомственном уровнях, современное состояние безопасности и охраны труда (БиОТ) работников промышленных предприятий в Республике Казахстан (РК) продолжает оставаться на недостаточно высоком уровне. Главной причиной производственного травматизма и профессиональных заболеваний является воздействие на работающий персонал опасных и вредных производственных факторов, одним из которых является повышенный уровень шума и вибрации от производственного оборудования. Авторы анализируют по отраслям экономики республики статистические данные о количестве случаев травматизма, их видах и причинах возникновения у работников. Рассмотрено влияние шума и вибрации на здоровье работающих, при этом установлено, что повышенный уровень шумовых и вибрационных воздействий в меньшей степени вызывает травматизм, а в большей — профессиональные заболевания. Целью данного исследования является инструментальное измерение уровня шума и вибрации на рабочих местах производственных участков машиностроительного предприятия и оценка условий труда там для выработки действенных мер по снижению вредного воздействия на здоровье работников.

Материалы и методы. В качестве базовой информации использованы статистические данные по производственному травматизму и профессиональным заболеваниям, а также результаты инструментальных измерений уровня шумовых и вибрационных воздействий на работников с использованием методик, изложенных в ГОСТ ISO 9612-2016 и ГОСТ 31319-2006 с учетом приказа министра здравоохранения Республики Казахстан от 16 февраля 2022 года № ҚР ДСМ-15 «Об утверждении гигиенических нормативов к физическим факторам, оказывающим воздействие на человека».

Результаты исследования. Результаты проведенных исследований позволили сделать вывод о том, что около 22,6 % рабочих мест на производственных участках характеризуются вредными и опасными условиями труда по уровню шумовых и вибрационных воздействий на работников.

Обсуждение и заключения. По итогам исследования был разработан план первоочередных мероприятий по снижению вредных воздействий повышенного уровня шума и вибрации на рабочих местах, а также рекомендованы особый режим труда, льготы и доплаты работникам за условия труда, не отвечающие требованиям безопасности.

Ключевые слова: безопасность и охрана труда, производственный травматизм, профессиональные заболевания, рабочее место, опасные и вредные производственные факторы, шум, вибрация.

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Introduction. Guarantees of ensuring safe working conditions at enterprises in the Republic of Kazakhstan are established at the state level: article 24 of the Constitution of the country declares the right of every citizen "... to working conditions that meet the requirements of safety and hygiene ...", and article 31 proclaims that the State aims to

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"... protect the environment favorable for human life and health"[1]. Explaining these provisions, the Labor Code of the Republic of Kazakhstan defines that the safety of workers is understood as the level of their protection from the effects of hazardous and harmful production factors (workplace hazards, WH), and safety is ensured by the compliance of the labor process and the production environment with the requirements of safety and labor protection[2]. The above aspects are also fixed by other regulatory legal acts of the country in the field of safety and labor protection [1].

Nevertheless, according to the data of the Industrial Safety Committee of the Republic of Kazakhstan, out of 1.6 million workplaces checked in 2019, 373 thousand workers were exposed to hazardous and harmful production factors, that is, every fourth employee (22.3 %) was employed in production with the presence of workplace hazards[3]. Figure 1 shows the statistical data on the number of deaths and victims of accidents at work in the republic from 2017 to 2021 [2, 3].

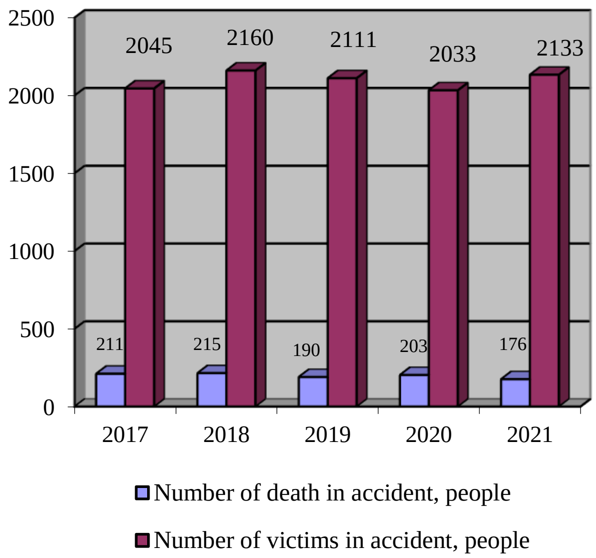

Fig. 1. Indicators of occupational injuries in the Republic of Kazakhstan from 2017 to 2021

In general, in the Republic of Kazakhstan and its regions in recent years, there have been no positive changes in the direction of occupational injuries reduction; its level remains quite high. According to the data presented in Fig. 1, it can be seen that in 2021, as a result of accidents, 176 people died at work (in 2017 — 211 people). Even if the mortality rate decreased by 16.5 %, this is explained not by an increase in the level of safety and labor protection of workers, but by the downtime of enterprises due to quarantine, as well as the subsequent shut down of some of them in the period from 2019 to 2021. The number of industrial injuries, on the contrary, has increased — from 2,045 people in 2017 to 2,133 people in 2021, or by 4.3 %.

Another negative side of industrial injuries is its high material consequences, or losses to the country's economy, data on which are presented in Fig. 2.

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[1] *Constitution of the Republic of Kazakhstan*. Official website of the President of the Republic of Kazakhstan URL: https://www.akorda.kz/ru/official_documents/constitution (accessed 05.11.2022).
[2] *Labor Code of the Republic of Kazakhstan*. No. 414-V dated November 23, 2015. URL: https://kodeksy-kz.com/ka/trudovoj_kodeks.htm (accessed 06.04.2023).
[3] *Results of work for 2020, 2021*. Official website of the Industrial Safety Committee of the Ministry of Emergency Situations of the Republic of Kazakhstan. URL: https://www.gov.kz/memleket/entities/kpb/documents/details/198142?lang=ru (accessed 06.11.2022).

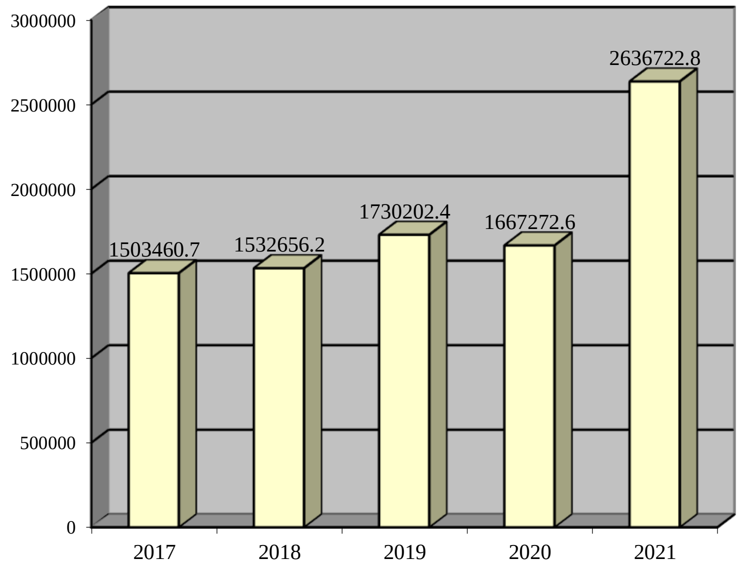

Fig. 2. Material consequences from accdents in the Republic of Kazakhstan
from 2017 to 2021, thousand tenge

In 2021, these losses amounted to 2 billion 636 million 722.8 thousand tenge in the Republic (or at the exchange rate of the Central Bank of the Republic of Kazakhstan 383 million 802.4 thousand rubles of the Russian Federation).

Let us consider in more detail the causes of the occurrence of accidents at industrial enterprises of the Republic of Kazakhstan in 2021 (Table 1)[4,5].

Table 1

Number of workers killed and injured due to accidents in the Republic of Kazakhstan in 2021[4]

Cause of the accident	Number, people.	
	injured	killed
Impact on the victims of an increased level of dust and air pollution of the air of the production environment	10	1
Violation of safety requirements in the operation of vehicles	54	10
Violation of traffic rules requirements	165	20
Accidents and other emergencies	63	13
Unsatisfactory organization of work	266	26
Poor technical condition of buildings, structures and shortcomings in the organization of workplaces	34	3
Shortcomings in the organization of employee training in the rules and requirements of safety and labor protection	41	5
Absence or non-use of personal protective equipment by victims	19	1
Increased noise exposure	1	–
Presence of workplace hazards and their impact on victims	88	14
Exposure to elevated levels of ionizing radiation	1	–
Absence or non-use of collective protective equipment	11	–
Violation of the norms and rules of industrial and labor discipline by the victims	39	9
Violation of safety and labor protection rules	276	19
Violation of the established work and rest regime by the victims	6	–
Gross negligence by the victims	688	61
Impact of increased physical activity	3	–
Design flaws or the use of faulty equipment	25	1
Gross violation of technological regulations and processes	17	3
Others	63	4

[4] *Health statistics*. Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan. URL: https://stat.gov.kz/ru/industries/social-statistics/stat-medicine/publications/ (accessed 08.11.2022).
[5] *Occupational safety and health for 11 months of 2022*. Official website of the Committee of Labor and Social Protection of the Population of the Republic of Kazakhstan. URL: https://www.gov.kz/memleket/entities/lspm/activities/292?lang=ru (accessed 08.11.2022).

Thus, according to the data provided, it can be concluded that the main causes of deaths and injuries at work were violations of the requirements and rules of safety and labor protection by the personnel of enterprises, shortcomings in the organization of work, the presence of workplace hazards in the workplace and their impact on workers, and so on. Thus, in 2021, the unsatisfactory organization of work was the cause of the death of 26 and injury to 266 workers, and violations of basic rules of safety and labor protection by workers — 19 and 276 people, respectively. One of the main causes of industrial injuries at the enterprises of the republic was the gross negligence by the victims themselves in the performance of their duties (for this reason, 61 people died and 688 people were injured).

At industrial enterprises, along with other workplace hazards, the most common negative production factors are noise and vibration [2, 4, 5]. Thus, every third employee of enterprises works in conditions of noise and vibration that specifically affect the human body. A large number of various technological equipment has been installed at production sites and workplaces, which, being a source of increased noise and vibration, has a negative impact on the health and general well-being of workers [3, 6-8]. For these reasons, which can be partially attributed to the indicators presented in Table 1, such as increased noise levels, exposure to workplace hazards, lack of individual and collective protective equipment, design flaws and operation of faulty machines and mechanisms, 16 people died and 144 people were injured in 2021.

However, the increased level of noise and vibration cause injuries to workers to a lesser extent, and to a greater extent — the occurrence of occupational diseases, as evidenced by the data in Table 2.

Of the 351 identified cases of occupational diseases of workers in the republic as a whole, 167 (47.5 %) were occupational diseases, the cause of which was an increased level of noise and vibration, which caused the victims to develop vibration disease, conductive and sensorineural hearing loss, bilateral sensorineural hearing loss, bilateral mixed conductive and sensorineural hearing loss.

Materials and Methods. The basis for conducting research to assess the level of noise and vibration from the equipment were the workplaces of the production sites of the Ural Plant for the production of transformers. The research was carried out according to the methods set out in GOST ISO 9612-2016 "Interstate standard. Acoustics. Noise measurement for the purpose of evaluating human exposure to noise"[6], GOST 31319-2006 "Vibration. Measurement and evaluation of human exposure to whole-body vibration. Practical guidance for measurement at the workplace"[7], taking into account the provisions of Order of the Minister of Health of the Republic of Kazakhstan No. KR DSM-15 dated February, 16, 2022[8]. In the course of instrumental measurements of noise and vibration, the following instruments and equipment were used: a sound level meter (sound level measuring device) of the ATT-9001 brand and a vibration parameter meter (vibrometer) of the Vibrotest-MG4.01 brand.

Table 2

Number of employees who received occupational diseases in 2021[4]

Name of occupational disease	Number of victims, people
Total for the Republic of Kazakhstan, including:	351
impact of vibration	73
sensorineural and conductive hearing loss	46
bilateral conductive hearing loss	1

[6] GOST ISO 9612-2016. *Interstate standard. Acoustics. Noise measurement for the purpose of evaluating human exposure to noise. Method of measurements at workplaces*. URL: https://online.zakon.kz/Document/?doc_id=39455237 (accessed 10.11.2022). (In Russ.).

[7] GOST 31319-2006. *Vibration. Measurement and evaluation of human exposure to whole-body vibration. Practical guidance for measurement at the workplace*. URL: https://online.zakon.kz/Document/?doc_id=30979214 (accessed 10.11.2022). (In Russ.).

[8] *Ob utverzhdenii gigienicheskikh normativov k fizicheskim faktoram, okazyvayushchim vozdeistvie na cheloveka*. Order of the Minister of Health of the Republic of Kazakhstan No. KR DSM-15 dated February 16, 2022. Information and legal system of regulatory legal acts of the Republic of Kazakhstan. URL: https://adilet.zan.kz/rus/docs/V2200026831 (accessed 10.11.2022).

unilateral sensorineural hearing loss with normal hearing in one ear	2
bilateral sensorineural hearing loss	22
mixed conductive and sensorineural hearing loss	20
bilateral unspecified mixed conductive and sensorineural hearing loss	1

By comparing the measured parameters of the actual values of noise and vibration with the maximum permissible levels (MPL), a working conditions class (WCC) was assigned to workplaces according to the "Rules of mandatory periodic certification of production facilities according to working conditions"[9]. According to the above Rules, depending on the degree of deviation of the actual levels of workplace hazards from hygienic standards, working conditions were divided into four classes according to the degree of harmfulness and danger: 1 — optimal, 2 — acceptable, 3 — harmful and dangerous (with subclasses 3.1, 3.2, 3.3 and 3.4 depending on the degree of excess over the standards), 4 — unacceptable.

Results. The results of the studies conducted to assess the level of noise and vibration effects on humans from the operation of production equipment are presented in Tables 3 and 4.

Table 3

Results of the study of the level of noise and vibration effects on workers

No.	Name of the produc-tion site	Workplace characteristics	Total number of WP	Noise, dBA			Vibration, dB			WCC
				MPL	Measured level	Excess over the MPL	MPL	Measured level	Excess over the MPL	
1	Areas No. 1 and No. 2 of the assembly shop	Foreman of insulation materials	15	No more than 80	71.3	None	No more than 97	83.1	None	2
		Machine operator (plasma cutting of metal)	3	No more than 80	69.7 70.1 70.5	None	No more than 97	81.3 80.6 82.1	None	2
		Machine operator (transverse metal cutting)	9	No more than 80	90.7 90.4 89.8 90.3 91.8 90.5 91.2 92.1 91.1	+10.7 +10.4 +9.8 +10.3 +11.8 +10.5 +11.2 +12.1 +11.1	No more than 97	102.3 101.9 102.4 101.5 102.4 101.5 101.5 102.4 101.6	+5.3 +4.9 +5.4 +4.5 +5.4 +4.5 +4.5 +5.4 +4.6	3.2 3.2 3.2 3.2 3.2 3.2 3.2 3.2 3.2
		Machine operator (metal slitting)	3	No more than 80	90.3 89.2 90.4	+10.3 +9.2 +10.4	No more than 97	101.7 100.9 100.2	+4.7 +3.9 +3.2	3.2 3.2 3.2
		Sheet bending machine operator	3	No more than 80	70.3 69.2 70.4	None	No more than 97	83.2 82.1 82.4	None	2
		Machine operator (guillotine scissors)	3	No more than 80	88.7 89.5 87.8	+8.7 +9.5 +7.8	No more than 97	100.7 99.6 100.8	+3.7 +2.6 +3.8	3.2 3.2 3.2
		Carpenter (woodworking machine)	2	No more than 80	78.1 77.1	None	No more than 97	92.3 90.9	None	2
		Argon arc welding welder	7	No more than 80	71.9	None	No more than 97	81.1	None	2
		Charge maker	9	No more than 80	70.7 70.4 69.8 70.3 71.8 70.5 71.2	None	No more than 97	82.3 81.9 82.4 81.5 82.4 81.5 81.5	None	2

[9] *Pravila obyazatel'noi periodicheskoi attestatsii proizvodstvennykh ob"ektov po usloviyam truda*. Order of the Minister of Health and Social Development of the Republic of Kazakhstan No. 1057 dated December 28, 2015. Information and legal system of regulatory legal acts of the Republic of Kazakhstan. URL: https://adilet.zan.kz/rus/docs/V1500012743 (accessed 10.11.2022).

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No.	Name of the produc-tion site	Workplace characteristics	Total number of WP	Noise, dBA			Vibration, dB			WCC
				MPL	Measured level	Excess over the MPL	MPL	Measured level	Excess over the MPL	
					72.1 71.1			82.4 81.6		
2	Area No. 3 of the assembly shop	Transformer assembler	23	No more than 80	70.3	None	No more than 97	81.7	None	2
3	Welding and painting area	Electric welder (welding machine)	13	No more than 80	69.1	None	No more than 97	81.4	None	2
		Painter	13	No more than 80	60.4	None	No more than 97	64.8	None	2
		Driller (drilling machines)	4	No more than 80	84.2	+4.2	No more than 97	98.9	+1.9	3.1
4	Mechanical area	Turner (turning workstation)	8	No more than 80	91.7 92.5 91.8 92.5 93.4 92.8 91.9 91.4	+11.7 +12.5 +11.8 +12.5 +13.4 +12.8 +11.9 +11.4	No more than 97	100.4 101.2 100.1 101.4 100.7 99.8 100.2 101.4	+3.4 +4.2 +3.1 +4.4 +3.7 +2.8 +3.2 +4.4	3.2 3.2 3.2 3.2 3.2 3.2 3.2 3.2
		Miller (milling machines)	2	No more than 80	84.8 84.1	+4.8 +4.1	No more than 97	98.4 99.3	1.4 1.3	3.1 3.1
5	Winding and wire section	Winder NN	11	No more than 80	68.9	None	No more than 97	80.4	None	2

Table 4

Generalized results of WCC assessment in the workplace by the level of noise and vibration effects on workers

Name of the production site	Number of WP	Number ofworkers on WP	Distribution of the number of WP by WCC						
			class 1	class 2	class 3				class 4
					3.1	3.2	3.3	3.4	
Areas No. 1 and No. 2 of the assembly shop	45	28	–	30	–	15	–	–	–
Area No. 3 of the assembly shop	23	23	–	23	–	–	–	–	–
Welding and painting area	30	18	–	26	4	–	–	–	–
Mechanical area	10	6	–	2	8	–	–	–	–
Winding and wire section	11	11	–	11	–	–	–	–	–
Totsl:	119	86	–	92	12	15	–	–	–

More clearly, the results of the assessment of working conditions at the workplaces of the production sites of the plant by the level of noise and vibration effects on workers and their certification according to WCC are presented in Fig. 3.

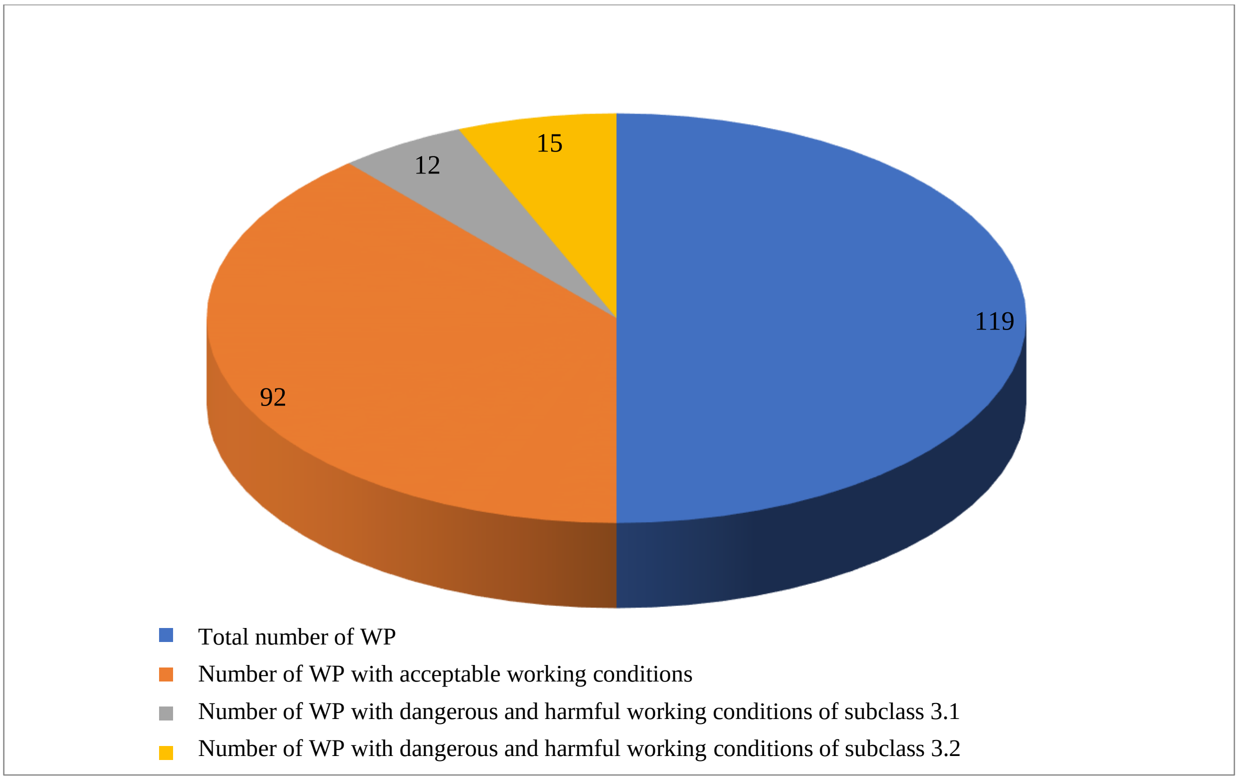

Fig. 3. Results of working conditions assessment at workplaces and their certification according to WCC

Discussion and Conclusion. According to the data presented in Table 4 and in Fig. 3, it can be seen that 27 out of 119 workplaces, or 22.6 % of their total number, are characterized by the presence of workplace hazards in terms of noise or vibration factors, as well as their combined influence. However, it is often difficult, and sometimes impossible, to completely localize or eliminate increased noise and vibration levels of equipment, machines and mechanisms, as well as other workplace hazards, in real production conditions, since they are an accompanying part of technological processes. Moreover, this problem is characteristic not only for Kazakhstan, which many domestic scientists and specialists explain with outdated equipment and backward technologies, but also for industrially developed Western countries [9–14]. Nevertheless, the parameters of noise and vibration, as well as the degree of their impact on employees, should be constantly monitored, and if a negative impact is detected, technical and organizational measures to reduce them to safe levels should be developed and implemented in a timely manner.

The results of the research revealed another problem, which is that the certification of workplaces of the production sites of the plant, previously carried out by an accredited organization, did not reveal any deviations in working conditions from the acceptable ones, and according to its results, all workplaces were assigned the 2nd class. The fact is that accredited organizations are engaged in certification of workplaces, with which the employer enters into a contract for its conduct and pays for all work, therefore, in the results obtained, such organizations do not reflect the actual state of affairs, but the wishes of the employer [15].

Since, according to the results of the research, part of the workplaces of the plant's production sites was assessed according to WCC as corresponding to subclasses 3.1 or 3.2, i.e. characterized by harmful and dangerous conditions in terms of noise and vibration effects, the personnel engaged in the labor process at these places, in accordance with the current labor legislation of the Republic of Kazakhstan, have the right to a number of benefits and compensations.

When calculating wages, determining work and rest regimes in accordance with these benefits and compensations, it is necessary to provide:

a) additional payments to the basic rate up to 10 % (according to Paragraph 1 of Article 105 of the Labor Code of the Republic of Kazakhstan) for work in conditions of exposure to workplace hazards (increased noise and vibration);

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b) additional annual leave for at least six days (Paragraph 1 of Article 88 of the Labor Code of the Republic of Kazakhstan);

c) reduction of working time — no more than 36 hours per week (Paragraph 2 of Article 69 of the Labor Code of the Republic of Kazakhstan), and the working shift — no more than eight hours;

d) two intra-shift breaks during the shift (Paragraph 1 of Article 82 of the Labor Code of the Republic of Kazakhstan), included in working hours, lasting no more than 20 minutes. 1.5–2 hours after the start of the shift and after a break for rest and meal (lunch);

e) a break for rest and meal approximately in the middle of the shift lasting no less than 30 min. (as a rule, the duration is set as one hour.) (Paragraph 1 of Article 81 of the Labor Code of the Republic of Kazakhstan).

Recruitment proposals:

– age of employees — at least 18 years old;

– prohibition on the employment of women and adolescents (Subparagraph 2, Paragraph 1 and Subparagraph 4, Paragraph 2, Article 26 of the Labor Code of the Republic of Kazakhstan).

It provides for the following mandatory medical examinations: preliminary (indicating contraindications for hiring if there are workplace hazards at the workplace) — before concluding an individual employment contract and periodic — once every two years.

A plan of technical measures was developed for the implementation at production sites and workplaces of the plant to reduce the increased noise and vibration effects on workers from production equipment.

The results of the conducted research allowed us to conclude that about a quarter of the workplaces at the production sites of the plant are characterized by dangerous and harmful working conditions in terms of noise and vibration effects on workers from production equipment, therefore, the working regime, benefits and additional payments to workers for working conditions that do not meet safety requirements were recommended. Providing employees with safe and comfortable working conditions, including such factors as increased noise and vibration, helps to reduce the potential risks of injuries and occupational diseases and, as a result, to increase the overall efficiency of labor activity and labor productivity.

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Original article

Production Facilities Safety Assessment According to the Maximum Values of Machines Reliability

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Abstract
Introduction. At the stage of designing technical devices and performing appropriate strength calculations of metal structures, sufficiently large reserves of strength are taken, which, theoretically, exclude any failures of parts. In fact, the machines work with frequent failures. Of interest are undiagnosed failures that lead to a critical decrease in safety, especially at hazardous production facilities. It is assumed that the previously applied approaches of selective determination of the maximum (minimum) reliability value, based on point estimates of the distribution parameters of the two-parameter Weibull law, lead to an overestimation of the calculated indicators of the probability of failure-free operation, i.e. underestimation of risk. Therefore, the work objective is to consider an approach to assessing the risk of operating production facilities in a situation of accidental occurrence of dangerous and undiagnosed failures in systems.
Materials and Methods. Methods for technical devices safety assessment based on probability theory were used in the work, and the probability of machine failure was determined based on the well-known method of reliability theory. This method consists in calculating and constructing distribution functions of random variables (load-bearing capacity and loading) that influence the occurrence of failure. The level of increase in the reliability index was determined, leading to frequent unpredictable failures of technical devices (machines) and a decrease in the safety of their operation.
Results. The signs of inconsistency of strength calculations based on overestimated safety margins, which in theory exclude failures of parts and machines in general, are identified and substantiated. A new approach to risk assessment of operating production facilities in a situation of accidental occurrence of dangerous and undiagnosed failures by safety systems has been developed and implemented. An algorithm for determining the three parameters of Weibull's law for a population based on sample data has been developed. The resource distribution densities of the boom of the single-bucket excavator EK-14 are constructed. The recommendations are given to increase the probability of failure-free operation to 0.9989.
Discussion and Conclusion. The results of the conducted research allow us to substantiate a new approach to risk assessment of operating production facilities in the event of dangerous and undiagnosed failures of basic parts by safety systems, leading to negative consequences.

Keywords: industrial safety, safety, reliability, maintainability, durability, persistence, failure, machine, resource.

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Научная статья

Оценка безопасности производственных объектов по предельным значениям безотказности машин

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Аннотация
Введение. На этапе проектирования технических устройств и выполнения соответствующих прочностных расчетов металлоконструкций принимаются достаточно большие запасы прочности, теоретически исключающие какие-либо отказы деталей. В действительности машины работают с частыми отказами. Интерес вызывают недиагностируемые отказы, приводящие к критическому снижению безопасности, особенно на опасных производственных объектах. Предполагается, что ранее применяемые подходы выборочного определения предельного (минимального) значения безотказности, основывающиеся на точечных оценках параметров распределения двухпараметрического закона Вейбулла, приводят к завышению расчетных показателей вероятности безотказной работы, т.е. занижению риска. Поэтому целью работы явилось рассмотрение подхода к оцениванию риска эксплуатации производственных объектов в ситуации случайного возникновения опасных и недиагностируемых отказов в системах.

Материалы и методы. В работе применялись методы оценивания безопасности технических устройств, основанные на теории вероятностей, а вероятность отказа машины определялась на основе известного метода теории надёжности. Данный метод заключается в расчете и построении функций распределения случайных величин (несущей способности и нагруженности), оказывающих влияние на возникновение отказа. Определился уровень повышения показателя надежности, приводящий к частым непрогнозируемым отказам технических устройств (машин) и снижению безопасности их эксплуатации.

Результаты. Выявлены и обоснованы признаки противоречивости прочностных расчетов, основанные на завышенных запасах прочности, в теории исключающие отказы деталей и машин в целом. Разработан и реализован новый подход к оцениванию риска эксплуатации производственных объектов в ситуации случайного возникновения опасных и недиагностируемых отказов системами безопасности. Разработан алгоритм определения трех параметров закона Вейбулла для совокупности по выборочным данным. Построены плотности распределения ресурса стрелы одноковшового экскаватора ЕК-14. Даны рекомендации по увеличению значения вероятности безотказной работы до 0,9989.

Обсуждение и заключения. Результаты проведенных исследований позволяют обосновать новый подход к оцениванию риска эксплуатации производственных объектов в случае возникновения опасных и недиагностируемых системами безопасности отказов базовых деталей, приводящих к негативным последствиям.

Ключевые слова: промышленная безопасность, надежность, безотказность, ремонтопригодность, долговечность, сохраняемость, отказ, машина, ресурс.

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Introduction. Key factors that determine safety of hazardous production facilities are the so-called "human factor", the availability of safety systems and the reliability of machines and mechanisms used at the facility. As it is known [1–4], reliability is a complex parameter, including reliability, maintainability, durability and persistence. This article examines the impact of the reliability of the machine, as one of the main reliability parameters, on the safety of its operation. At the same time, for the analysis of reliability indicators, traditional methods of reliability theory and some new approaches to determining the parameters of random variable distributions are used to estimate the maximum values of reliability [1]. It should be noted that the safety assessment methods used here are based on the basic concepts of probability theory, the main one of which is the concept of a random variable[1]. Therefore, this paper considers only accidental failures that lead to a decrease in safety. At the same time, it should be noted that not all machine failures are accidental. For example, failures related to systematic errors of measuring instruments and the "human factor" are not accidental[2]. In this case, the proposed approaches cannot be used for their analysis without strict mathematical justification[3].

There are four types of accidental failures that occur during the operation of machines and mechanisms used at hazardous production facilities (Table 1).

The study of the diagnosed failures within the framework of the described work is not of interest, since in this case the equipment (devices, sensors) of the industrial facility safety system perform their functions in full and a catastrophic decrease in safety is excluded. In case of dangerous and undiagnosed failures, a situation may arise when the safety system is vulnerable. At the same time, in accordance with GOST ISO 12100-2013, safety is understood as the ability of a machine to perform its function(s) throughout its service life with adequate (sufficient) risk reduction.

Table 1

Types of accidental failures of machines and mechanisms

Type of failure	Description of failure	Example of failure
Dangerous	It has a significant impact on safety up to the occurrence of an accident with possible injury to personnel	Destruction of load-bearing structures of machinery (equipment) due to fatigue failures
Safe	It does not affect the safety of operation. As a result of the occurrence, the parameters of economics, aesthetics, ergonomics and others may decrease	Manifestation of corrosion phenomena, occurrence of paintwork defects
Diagnosed	Equipment (devices, sensors) of safety security system diagnose failures of this type	Occurrence of a malfunction of the hydraulic system of the machine (equipment). Violation of load capacity limits
Undiagnosed	Equipment (devices, sensors) of safety security system do not diagnose failures of this type	Manifestation of hidden defects during expansion, for example, fatigue cracks

It follows from the definition that the key concept of safety here is risk, which is defined as the possibility of an undesired event, that is, a combination of the degree of negative consequences with the possibility of its occurrence.

Materials and Methods. Usually, a negative consequence is the infliction of injuries or other harm to health during the operation of the machine. At the same time, the consequence of an accidental dangerous failure of the machine can be economic damage. In this case, the risk is assessed by the so-called functional safety of the production facility [3–5]. Consequently, the methods of reliability theory as part of probability theory should be applied to the study of the safety

[1] GOST R 53195.3-2015. *Functional safety of building/erection safety-related systems. Part 3. Requirements for systems*. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/1200124221 (accessed 23.01.2023). (In Russ.).

[2] GOST R 51901.14-2007. *Risk management. Reliability block diagram and boolean methods*. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/1200065647 (accessed 23.01.2023). (In Russ.).

[3] GOST R 50779.27-2017 *Statistical methods. Weibull distribution. Data analysis*. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/1200146523 (accessed 23.01.2023). (In Russ.).

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of the production facility in which an accidental dangerous and undiagnosed machine failure occurs. It is the risk that is the link between the reliability of machines and the safety of hazardous production facilities, including their functional safety.

An increase in the probability of an undesired event due to the occurrence of a dangerous and undiagnosed failure leads to the need to predict and assess the risk of negative consequences, the severity of which is difficult to determine. In the work, the severity of the likely negative consequences arising from a dangerous and undiagnosed failure is assumed to be the same, and risk assessment is reduced to assessing the probability of an undesired event.

The probability of machine failure is determined by the well-known methods of reliability theory [6], which consist in constructing distribution functions of random variables that influence the occurrence of failure. When considering the power elements of the structure, the distribution functions of the load-bearing capacity and loading characteristics were constructed.

To construct the distribution function of the general population of a random variable, a representative sample of values obtained on the basis of tests is usually formed. However, in real conditions, it is often difficult to conduct tests due to financial, technological and time constraints. To save costs, a number of studies [6-10] use the approach of adjusting the parameters of sample distributions. This approach is used in the work to determine the maximum (minimum) reliability value, which makes it possible to ensure maximum safety of the object under consideration by increasing the minimum calculated reliability and minimizing the risk of an undesired event. The required reliability is achieved by adjusting the parameters of the distribution of random variables that affect the probability of a dangerous and undiagnosed failure.

From the point of view of reliability, the machine is ideally trouble-free if there is no failure within a given life. In this case, the parts of this machine will fail approximately at the same time, having worked out the specified life value T_p [10, 11].

The practice of determining the reliability of domestic machines shows that the average failure interval is T = 20–200 hours, therefore, for a time between overhauls T_p=8 000–10 000 hours, from 40 to 500 failures occur, that is, tens and hundreds of failures [12–15]. Many of them are dangerous and undiagnosed. In this case, the actual life of $T_{pф}$ is significantly less than the specified one T_p, and the probability of failure tends to one. At the same time, to ensure the required level of safety, it is necessary to reduce the risks of undesired events, i.e. the probability of failures.

It is impractical to consider the option of increasing the machine safety by reducing the probability of failure of one part, since hundreds and thousands of parts are operated simultaneously in the machine, so the risk of undesired events is growing.

When drawing up a structural diagram of reliability among all machine parts, we will single out a group of parts, which we will call the basic one. This group includes parts, the failure of one of which leads to a dangerous and undiagnosed failure of the machine. In this case, it is necessary to use the sequence of the structural scheme of the reliability of the machine. Then the risk of failure is determined by the well-known formula [15]:

$$Q = 1 - \prod_{i=1}^{m}(1 - Q_i), \quad (1)$$

where Q — risk (probability) of machine failure; Q_i — probability of failure of the i-th part, m — volume of a group of parts.

For example, if the probability of failure of one part in the base group is the same and is equal to Q_1 = 0.05, which is a completely acceptable condition for the reliability of the part in operation, and the volume of all parts in the base group of the machine is m = 200, then the probability of a dangerous and undiagnosed failure of the machine will be:

$$Q = 1 - \prod_{i=1}^{200}(1 - 0{,}05) = 0{,}997.$$

Such a risk indicator is unacceptable. That is, it can be assumed that in order to reduce the risk, it is necessary to increase the life of each part, in this case the risk will decrease. For example, if you increase the life of each part by an order of magnitude, namely, if the probability of failure is $Q_1 = 0.005$, then the probability of machine failure will remain significantly high:

$$Q = 1 - \prod_{i=1}^{200}(1 - 0{,}005) = 0{,}63.$$

The development of recommendations to increase the life of the second group of parts (all other parts and assemblies that are not included in the first group), which includes consumables and spare parts, leads only to minimizing the total costs of eliminating failures, without affecting the safety of operation in any way.

Improving reliability by reducing the dispersion of failures of parts from the base group reduces the risks associated with dangerous and undiagnosed failures. As a result, the average time to failure will increase, and failures will occur less frequently. The number of failures will decrease, but it will not be possible to completely eliminate them, the risk of undesired events will remain. The actual life, although it will approach the specified one that determines the acceptable risk, will be lower.

Then an increase in the life of parts from the base group within the specified limits does not allow achieving a high level of reliability and a different methodological approach is needed to solve this problem. The proposed new approach should provide for the appearance of calculated failures of parts from the base group only outside the specified machine life. In the future, we will talk only about the parts from the base group, which we will call critical parts.

New approach to assess reliability

The study of the reliability of machines has shown that the life of parts can be dispersed within significant limits. Let us consider this fact on the example of one part from some set of the same parts. Its life is a random value determined by the parameters of the aggregate, the true parameters of which are unknown and are estimated only by the parameters of the sample distribution. The relative scope of the sample distribution can be determined by the formula:
where Tp_{max} — the maximum life value in the sample; Tp_{min} — the minimum life value in the sample.

$$R = \frac{Tp_{max} - Tp_{min}}{Tp_{min}} \quad (2)$$

It should be noted here that for the sample, as for the aggregate, the fundamental condition is fulfilled: $Tp_{min} > 0$. Therefore, to describe statistical patterns, it is recommended to apply the probabilistic Weibull shift law (for strength and life) and the Fisher-Tippett law (for operating stresses). The distributions obtained using these laws have restrictions on the left and right, respectively. In addition, the shape of the distribution function can be used to analyze the change in the failure rate over time.

Then the relative range estimated by formula (2), reflecting the deviation of the extreme upper value of the sample distribution relative to the extreme minimum value, can range from several units to hundreds or more. Therefore, the distribution density of the parts life for the sample and the aggregate may be located differently relative to a given machine life, for example, as shown in Fig. 1.

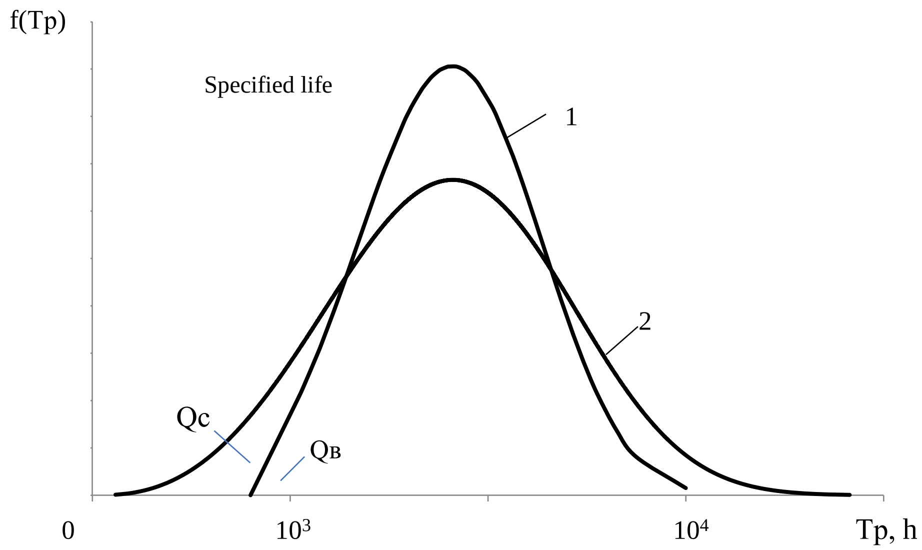

Fig. 1. Curves of the density distribution of the probability of failure for the sample (1) and the aggregate (2) for the three-parameter Weibull law

It can be concluded that the result of estimating the probability of trouble-free operation of a part is determined by the degree of adequacy of transferring the results of sample tests to the aggregate. It is obvious that the spread of point estimates of the distribution parameters of the two-parameter Weibull law obtained by the least squares method can lead to an overestimation of the calculated indicators of the probability of trouble-free operation, i.e. underestimation of risk. The main reason for this lies, as noted in [1], in the estimation of the shift parameter only based on the results of sample tests. At the same time, the volume of the aggregate is not taken into account in any way. However, we can assume that by increasing the volume of the considered aggregate, there will be a decrease in the real value of the minimum life $\mathrm{Tp}^{и}{}_{\min}$, i.e., in the aggregate, there will always be a part, the life of which is less than the specified value during random tests: $\mathrm{Tp}^{и}{}_{\min} < \mathrm{Tp}_{\min}$.

Therefore, in order to increase the reliability of the safety assessment of parts from the sample and bring it closer to the true value determined from the aggregate, it is necessary to adjust the distribution density curve for dangerous and undiagnosed failures.

To adjust the distribution parameters, it is proposed to use the following methodology.

At the first stage, according to the test results, in accordance with recommendations [4], parameters of shape $\beta_в$ and scale $\eta_в$ for a sample of volume n are determined. The minimum life value in the sample is taken as a sample parameter of shift $T_{0в} = \mathrm{Tp}_{\min}$.

At the second stage, the shift parameter for the aggregate is determined. First of all, the shift parameter requires a physical justification. For the random variable under consideration — technical life — such a physical limitation is zero life. Therefore, a probabilistic approach is proposed here. In accordance with it, the volume of population N is set, the quantile of Student's distribution $d = t_p(N - 1)$, which has degree of freedom $(N - 1)$ and confidence probability level p. Next, the shift parameter for the population is determined by the following formula:

$$T_{0c} = T_{0в}\left(1 - e^{-\frac{d}{\beta\sqrt{N-n}}}\right). \qquad (3)$$

It follows from formula (3) that as $(N - n)$, increases, i.e. as the volume of the population increases, the shift parameter decreases in the limit to zero, which corresponds to the existing physical constraint.

At the third stage, there is a correction of parameters of shape β_c and scale η_c for the aggregate in accordance with the formulas proposed in [5, 6]. The reliability of such an adjustment is proved in [5].

The algorithm for constructing a three-parameter Weibull's law for a population based on sample data is shown in Fig. 2 and represents the following scheme for calculating parameters.

1. The following numerical characteristics are estimated from the initial sample series X: average value x, standard deviation σ_x, coefficient of variation C_v, coefficient of asymmetry C_s and the minimum value $x_{\min}$.

2. Depending on C_s coefficient of variation C_v for the population is determined using the approximating expression:

$$C_V = 0.0009 \times C_S^4 - 0.0105 \times C_S^3 + 0.0277 \times C_S^2 + 0.3234 \times C_s + 0.31,$$

3. Coefficient of variation C_v determines the value of the coefficient of the distribution form of set β_c according to the formula:

$$\beta_c = 0.9889 \times C_V^{-1.093}.$$

To confirm the methodology, we will conduct a numerical experiment, the essence of which is to carry out the following sequence of actions:

– recognition of the parameters of a given set as true;

– modeling of the variation series of the aggregate of the required volume;

– formation of a true sample distributions set of volume n in the amount of m;

– determination of the most unfavorable option with the maximum value of the sample shift;

– correction of the shift and calculation of shape and scale parameters for the adjusted sample;

– comparison of the corrected parameters with the true ones.

It is obvious that in real conditions of observations (tests) during the operation of the machine, only the initial section of the left branch can be obtained. At the same time, the batch of machines should be representative and consist of at least 30 machines with an operating time of 8-10 thousand hours. Obtaining experimental data for statistical processing and constructing the entire distribution curve of the object's resource over the entire period of operation is an impossible task.

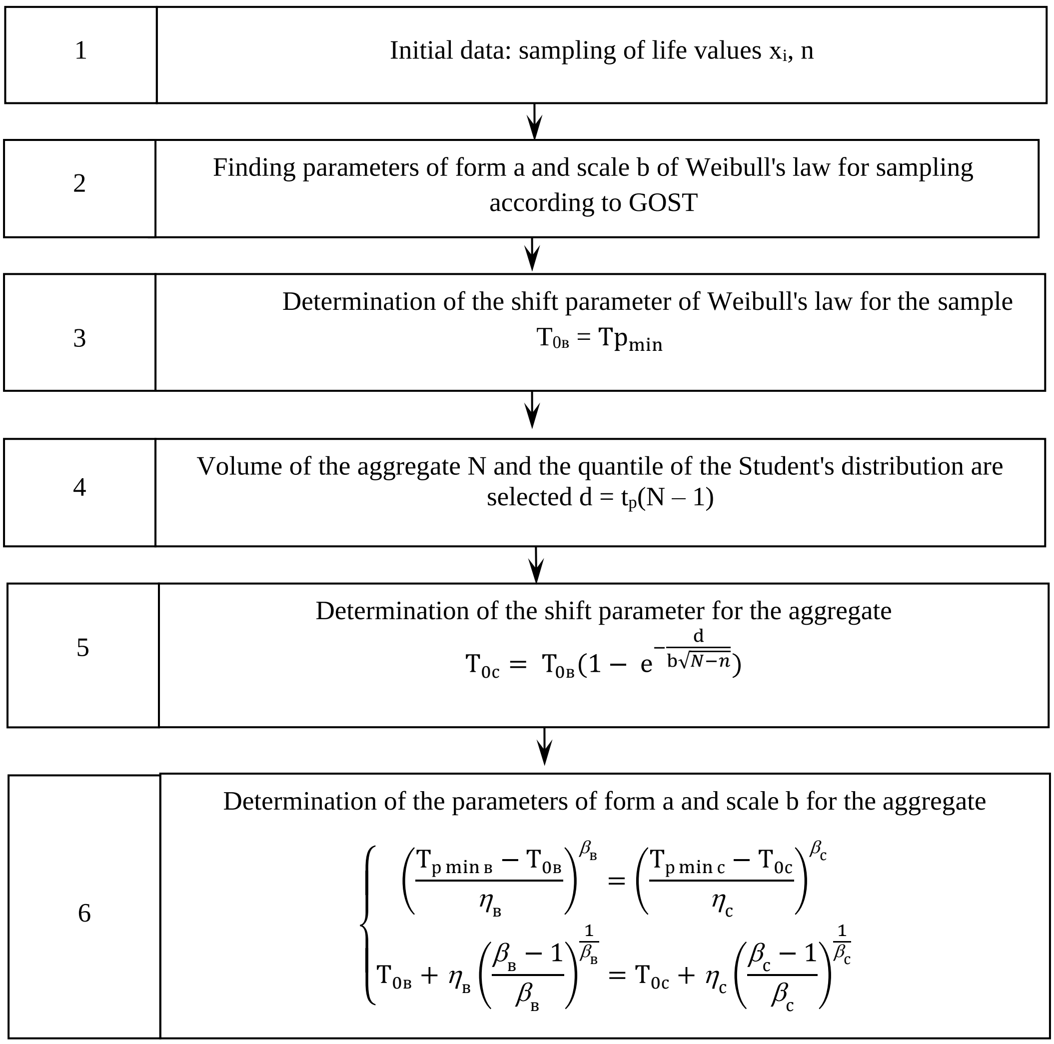

Fig. 2. Algorithm for determining the three parameters of the Weibull's law for a population based on sample data

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Therefore, a computational experiment was carried out, during which the parameters of the three-parameter distribution of the Weibull sample were determined for the sample data of the part (parts) life with volume of n=50.

Results. According to the algorithm and sequence of actions proposed above, a numerical experiment was carried out. Initially, the parameters of the true population were set, a variation series of population $N=10^4$ was modeled, samples of n=50 in the amount of m=5 were randomly extracted from it; n=100 in the amount of m=1; n=150 in the amount of m=1 and n=1000 in the amount of m=1 were selected. Next, we chose the worst sampling option corresponding to the maximum deviation of the shift value from the shift of the population. The distribution densities of the Weibull's law for the initial population and the samples obtained from it are shown in Fig. 3.

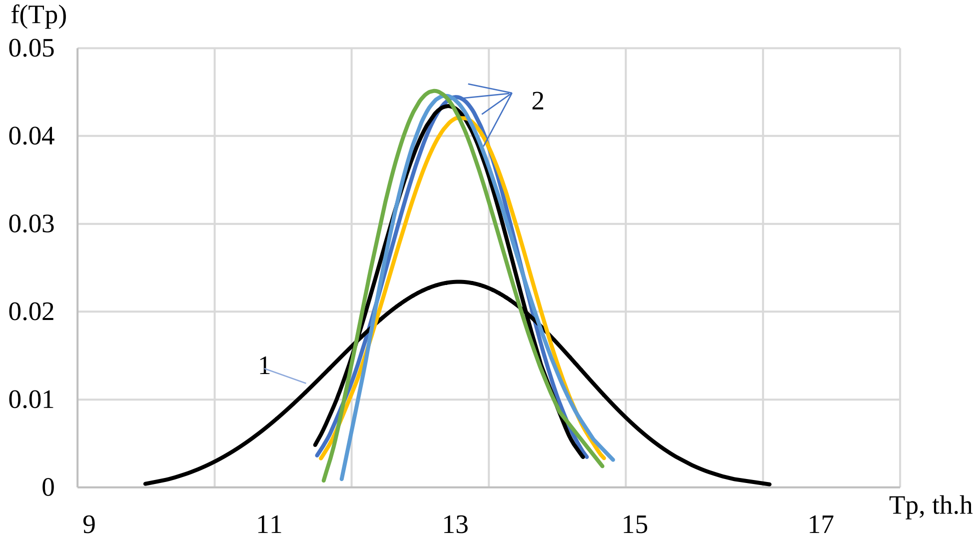

Fig. 3. Distribution densities of population (1), samples modeled from it with a volume of n=50 (2)

Based on the calculation results, we estimate the parameters by comparing the shift value of the true population and samples taken from it (Table 2).

Table 2

Parameters of samples and aggregates

Parameters	Aggregate	Samples of volume n=50					
			1	2	3	4	5
a	155 900	Initial	132 787	154 333	143 348	138 096	167 488
		Corrected	135 008.7	159 917.03	151 330.36	143 957.4	166 778.2
b	1.07	Initial	1.07	0.98	0.96	1.02	0.92
		Corrected	1.19	1.20	0.95	1.13	0.94
x min	5 509	Initial	7 344	6 007	6 813	5 962	7 491
		Corrected	8 160.36	6 675.00	7 569.74	6 625.23	7 490.71
Δ,%			10.004	10.007	9.997	10.011	0

The analysis shows that the sample parameters of the shift differ significantly from the shift of the population. The probability of falling into the real value of the shift is minimal, and an increase in the volume of samples does not guarantee that the minimum value of the population will fall into it. Therefore, in order to reduce the risks of a dangerous failure, it is necessary to adjust the parameters.

To determine the confidence level when adjusting the shift parameter of the three-parameter Weibull distribution, a parametric confidence criterion is proposed:

$$D_{\text{ВБР}} = e^{-\left(1-\frac{n}{N}\right)\cdot\Delta} \quad (4)$$

where n and N — respectively, the volumes of samples and general aggregates of a finite volume; Δ — deviation of the parameters of sample distributions from the true value of the parameters of the population.

The calculations have shown that the criterion of parametric reliability for a sample with the maximum shift value is 0.67.

To make the adjustment, we take the most unfavorable option, that is, with the maximum value of the sample shift relative to the value of the population. A graphical representation of the distribution densities of these samples is shown in Fig. 4.

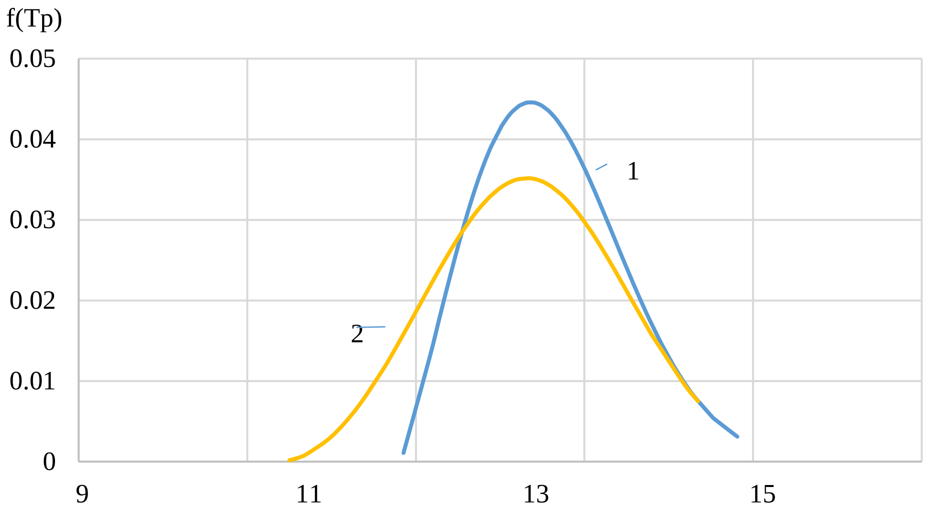

Fig. 4. Distribution densities of the initial (1) and the corrected (2) samples

Determination of the risk of uncontrolled dangerous failure of the boom part of the single-bucket excavator EK-14

As an evaluation of the proposed method for determining the parameters of the aggregate based on sample data, an example is considered for a responsible part of a single-bucket excavator —the side wall of the boom with a fatigue life before write-off T_p=20 thousand hours. The specified life is determined by the manufacturer as a life before write-off. For the boom, as the basic element of the excavator, the specified life is 20 thousand hours.

The boom of the single-bucket excavator EK-14 has a box section made of St3 rolled steel, with a side wall thickness of 10 mm. The operational experience has shown that the boom failure consists in the appearance of a fatigue crack in a dangerous section, and various kinds of repair measures did not solve the problem of crack growth. The only solution to the problem is to replace it. Therefore, sample data on the life were determined for the boom and the transition from sample data to aggregate parameters was carried out [14, 16, 17].

Numerical and full-scale experiments show that the reliability of determining the shift parameter of the aggregate according to the data of sample tests does not meet the necessary requirements. Therefore, it is necessary to adjust the data obtained according to the proposed methodology.

Further, according to the proposed sequence, a sample was obtained from the aggregate and corrected. The adjustment of the parameters of the sample distribution allowed us to approach the parameter of the population shift, but not to achieve it. Moreover, the shift parameter of the aggregate did not reach a value of 10 thousand hours, which is twice lower than the specified life, and confirms the presence of premature failures.

Therefore, for parts from the base group, it is proposed to shift (increase) the life value by changing the design parameters. For example, to increase the endurance limit of steel by replacing the steel of the serial production of the

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part with a stronger one, and (or) to reduce the effective stress by increasing the wall thickness or cross-section dimensions. In [14, 15], the life values for the side wall of the boom were calculated and compared with the variants of recommendations for the manufacture of the part. The recommendations provided for: increasing the wall thickness from 10 to 12, and then to 14 mm of the rolling sheet in the dangerous section of the part; replacement of the used grade of steel St3 (low-carbon) with low-alloy 09G2S or 15KHSND; increase in the dangerous cross section of the boom up to 20 %.

Load parameters are set deterministically. The fatigue strength of the part is limited from below by the available control of the material and the finished part, and the load is limited from above by the calculated operating modes and the presence of safety elements (safety valves, torque-limiting clutches, etc.). Therefore, in case of fatigue failure of parts for the general population, there are cases when the load parameters exceed the fatigue strength parameters due to the influence of uncontrolled random factors. The consequence of this is the need to limit the resource of the part from below, determined by the distribution of the general population, and not by the sample.

The calculations have shown that the probability of trouble-free operation is 0.9989 for the boom of a single-bucket excavator made of 15KHSND steel with a rolling sheet thickness of 12 mm, and the probability of failure, respectively, is 0.0011.

Discussion and Conclusion. To create safe machines, it is necessary that the minimum life of basic parts, justified by the proposed methodology, tends to the value of the specified machine life. The exception to this rule is only some parts with premature failures, the causes of which cannot be determined due to the lack of appropriate methods and means. In addition, planned replacements of individual parts with a low life are acceptable (increasing their life is impossible or impractical). Failures of such parts do not affect the safety of the machine.

Thus, a new approach to assessing the risk of operating production facilities in the event of dangerous and undiagnosed failures of basic parts by safety systems, leading to negative consequences, is justifie.

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Original article

Influence of the Competencies of Lifting Crane Specialists on the Probability of Emergencies

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Abstract

Introduction. The operation of lifting cranes is an integral part of the production processes. For the trouble-free operation of these mechanisms, certain knowledge, skills and abilities are required, which should also be possessed by specialists performing organizational and supervisory functions at facilities where such cranes are involved. Here there is an important problem — the lack of a reasonable connection between the level of development of professional competencies and possible emergency situations, as well as various incidents during the operation of lifting cranes. The authors of this study are trying to solve it. Their goal in this regard is to assess the probability of an emergency during the operation of lifting cranes, depending on the level of professional competence of specialists, through the use of neural networks.

Materials and Methods. The competencies of workers in the operation of lifting cranes (knowledge, skills and work responsibilities) provided for by the professional standard "Specialist in the operation of lifting structures" were used as initial data to train neural networks. Based on them, a list of possible incidents was compiled. For the purposes of training, the results of the certification of 200 conditional employees were generated. During the generation, the Monte Carlo method was used, and the data were output to Excel tables. Neural networks were trained in Python 3.10 in the PyCharm development environment. Open libraries Keras and TensorFlow, as well as auxiliary libraries for data representation and processing (Pandas, NumPy, Scikit-learn) were used for neural networks training.

Results. As a result, a tool was obtained — a neural network in the form of executable program code, which makes it possible to assess the probability of emergencies during the operation of lifting cranes by analyzing the degree of proficiency of specialists in professional competencies. It is proposed to implement artificial intelligence technologies based on neural networks in order to assess the knowledge, skills and abilities of specialists of facilities operating lifting cranes, both during the certification of employees and in the course of work.

Discussion and Conclusion. The main result of using neural networks to assess the knowledge of employees of facilities operating lifting cranes is the expected reduction in accidents, which can be ensured by timely identification of incompetent personnel at the stages of primary certification and, most importantly, during periodic tests of knowledge based on an impartial analysis and evaluation of data.

Keywords: accident, lifting crane, probability, assessment, competence, human factor, neural network.

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Научная статья

Влияние компетенций специалистов грузоподъемных кранов на вероятность возникновения аварийных ситуаций

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Аннотация

Введение. Эксплуатация грузоподъемных кранов является неотъемлемой частью производственных процессов. Для безаварийной работы этих механизмов необходимы определенные знания, умения и навыки, которыми должны обладать в том числе и специалисты, осуществляющие организационные и контролирующие функции на объектах, где задействованы такие краны. И здесь существует важная проблема — отсутствие обоснованной связи между уровнем освоения профессиональных компетенций и возможными аварийными ситуациями, а также различными инцидентами при эксплуатации грузоподъёмных кранов. Авторы данного исследования пытаются решить ее. Их цель в связи с этим — посредством применения нейронных сетей дать оценку вероятности возникновения аварийной ситуации при эксплуатации грузоподъемных кранов в зависимости от уровня профессиональных компетенций специалистов.

Материалы и методы. Для обучения нейронных сетей в качестве исходных данных использовались компетенции работников по эксплуатации грузоподъемных кранов (знания, умения и трудовые обязанности), предусмотренные профессиональным стандартом «Специалист по эксплуатации подъемных сооружений». На их основе был составлен перечень возможных инцидентов. Для целей обучения сгенерированы результаты аттестации 200 условных работников. При генерации использовался метод Монте-Карло, и данные выведены в таблицы Excel. Обучение нейронных сетей производилось на языке Python 3.10 в среде разработки PyCharm. При обучении нейронных сетей использовались открытые библиотеки Keras и TensorFlow, а также вспомогательные библиотеки представления и обработки данных (Pandas, NumPy, Scikit-learn).

Результаты исследования. В результате получен инструмент — нейронная сеть в виде исполняемого программного кода, позволяющая выполнить оценку вероятности возникновения аварийных ситуаций при эксплуатации грузоподъемных кранов посредством анализа степени владения специалистами профессиональными компетенциями. Предлагается осуществить внедрение технологий искусственного интеллекта на базе нейронных сетей с целью дать оценку знаний, умений и навыков специалистов объектов, эксплуатирующих грузоподъемные краны, как при проведении аттестации работников, так и в процессе трудовой деятельности.

Обсуждение и заключения. Основным результатом использования нейронных сетей для оценки знаний работников объектов, эксплуатирующих грузоподъемные краны, является предполагаемое снижение аварийности, что может быть обеспечено за счет своевременного выявления некомпетентного персонала на стадиях первичной аттестации и, что особенно важно, при периодических проверках знаний на основании беспристрастного анализа и оценки данных.

Ключевые слова: авария, грузоподъемный кран, вероятность, оценка, компетенция, человеческий фактор, нейронная сеть.

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Introduction. Enterprises operating lifting equipment (lifting cranes, loader cranes, lifts (towers), construction lifts, etc.), in accordance with the legislation[1] belong to hazardous production facilities (HPF), as a rule, of hazard class IV, but may also be part of objects of hazard class I, II or III. The Federal Service for Environmental, Technological and Nuclear Supervision (Rostekhnadzor) is responsible for accounting, control of activities, investigation and accounting of accidents that occurred at the HPF.

According to Rostekhnadzor[2], in 2021, about 600 thousand lifting mechanisms were operated at enterprises and organizations of the Russian Federation, of which 209,935 were lifting cranes. In 2021, there were 29 accidents during the operation of lifting structures, 27 deaths. Compared to 2020, we can observe a slight positive trend — then there were 30 accidents, 28 fatal injuries.

The largest number of accidents in 2021, as in 2015-2020, occurred during the operation of tower cranes:

– during the operation of tower cranes in 2020, 12 accidents occurred, in 2021 13 accidents occurred;

– during the operation of vehicle-mounted cranes, four accidents occurred in 2020, and four accidents also occurred in 2021;

– during the operation of overhead cranes there was one accident in 2020, in 2021 there was also one accident;

– during the operation of frame cranes there was one accident in 2020, in 2021 there were three accidents;

– during the operation of loader cranes, two accidents occurred in 2020, and two accidents also occurred in 2021.

Analyzing the above data, one can distinguish among others such a cause of accidents as the lack of proper control over production processes at facilities by responsible specialists (human factor).

Causes of accidents are:

– lack of production control over the compliance with industrial safety requirements by the management of the organization and owners of a hazardous production facility, as well as persons responsible for the maintenance of lifting structures in working condition and for the safe production of works;

– in some organizations, the facts of non-assignment of specialists responsible for this area of control are recorded, as required by regulatory legal acts[3];

– involvement of personnel who do not have the necessary qualifications in the production of works;

– absence of work production projects, work production rules, job descriptions and production instructions at the facility;

– untimely scheduled inspections, repairs and technical inspections of lifting structures.

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[1] *O promyshlennoi bezopasnosti opasnykh proizvodstvennykh ob"ektov*. Federal Law No. 116-FZ of 21.0.1997. Consultant Plus. URL: http://www.consultant.ru/document/cons_doc_LAW_15234/ (accessed 18.01.2023). (In Russ.).
[2] *Otchet o deyatel'nosti Federal'noi sluzhby po ekologicheskomu, tekhnologicheskomu i atomnomu nadzoru v 2021 godu*. Rostekhnadzor. URL: https://www.gosnadzor.ru/public/annual_reports (accessed 18.01.2023). (In Russ.).
[3] *Ob utverzhdenii federal'nykh norm i pravil v oblasti promyshlennoi bezopasnosti "Pravila bezopasnosti opasnykh proizvodstvennykh ob"ektov, na kotorykh ispol'zuyutsya pod"emnye sooruzheniya"*. Order No. 461 of the Federal Service for Environmental, Technological and Nuclear Supervision dated November 26, 2020. Electronic Fund of Legal and Regulatory and Technical Documents. URL: https://docs.cntd.ru/document/573275657 (accessed 30.03.2023). (In Russ.).

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Often, the root cause of violations committed in terms of not properly organized production control over the compliance with industrial safety requirements is the desire of owners of hazardous production facilities to reduce financial costs.

However, as statistics show, as well as numerous studies on this topic, there is a direct dependence of the occurrence of accidents on the level of qualification of managers and responsible specialists [1–3].

The probability of emergencies during the operation of lifting cranes is determined by assessing the degree of proficiency of professional competencies of personnel. In order to evaluate such knowledge, it is proposed to use artificial intelligence technologies based on neural networks during the certification of employees.

In accordance with the decree of the President of the Russian Federation[4] and the National Strategy for the Development of Artificial Intelligence for the period up to 2030, it is necessary to use artificial intelligence technologies based on neural networks to assess the residual knowledge of responsible specialists of organizations operating lifting cranes in the following cases:

– on the eve of attestation in the attestation commissions of the enterprise or the territorial attestation commission of Rostekhnadzor;

– in case of an accident or injury at the HPF, etc.

The level of competence of engineering and technical employees of the HPF operating lifting cranes, appointed by responsible specialists, is determined not only by the availability of specialized higher professional education, but also by periodic attestation in accordance with the requirements of the legislation of the Russian Federation, which is preceded by obtaining additional professional education for certain categories of specialists[5,6].

Verification of the level of knowledge and competencies based on the results of advanced training in the field of industrial safety is carried out by educational organizations through assessments developed for specific programs [4–6].

Verification of the level of knowledge and competencies during periodic examinations in the attestation commissions of Rostekhnadzor or the operating organization is carried out through testing in a unified testing system[5]. The results of the test tasks will contribute to the assessment of knowledge of legislative and regulatory documents relevant to the field of attestation[7].

There is also a need to evaluate the knowledge, skills and abilities of the HPF specialists operating lifting cranes in accordance with professional standards for specific positions[8]. At the same time, not only answers to questions, that is, theoretical knowledge, are taken into account, but also skills and abilities through practical tasks (solving thematic problems, reading drawings, making relevant documentation).

Materials and Methods. During the attestation for each type of inspections, specialists put down points. The attested person must score at least 80 % of the correct answers for admission to work. In this way, a data matrix can be formed, and statistical data in the matrix can be linked to the causes of accidents, injuries and accidents. Then it

[4]*O razvitii iskusstvennogo intellekta v Rossiiskoi Federatsii*. Decree of the President of the Russian Federation No. 490 of 10.10.2019. URL: https://www.garant.ru/products/ipo/prime/doc/72738946 / (accessed 30.03.2023). (In Russ.).

[5]O *podgotovke i ob attestatsii v oblasti promyshlennoi bezopasnosti, po voprosam bezopasnosti gidrotekhnicheskikh sooruzhenii, bezopasnosti v sfere elektroenergetiki*. Resolution of the Government of the Russian Federation No. 1365 of October 25, 2019. Information and legal base of the Russian Federation. URL: https://ipbd.ru/doc/0001201910290010/ (accessed 30.03.2023). (In Russ.).

[6]*Ob attestatsii v oblasti promyshlennoi bezopasnosti, po voprosam bezopasnosti gidrotekhnicheskikh sooruzhenii, bezopasnosti v sfere elektroenergetiki*. Resolution of the Government of the Russian Federation No. 13 of January 13, 2023. Official Internet portal of legal information. URL: http://publication.pravo.gov.ru/Document/View/0001202301170020 (accessed 30.03.2023). (In Russ.).

[7]*Ob utverzhdenii Perechnya oblastei attestatsii v oblasti promyshlennoi bezopasnosti, po voprosam bezopasnosti gidrotekhnicheskikh sooruzhenii, bezopasnosti v sfere elektroenergetiki*. Rostechnadzor Order No. 334 of September 4, 2020. Official Internet portal of legal information. URL: http://publication.pravo.gov.ru/Document/View/0001202102040015 (accessed 30.03.2023). (In Russ.).

[8]*Ob utverzhdenii professional'nogo standarta "Spetsialist po ekspluatatsii pod"emnykh sooruzhenii"*. Order of the Ministry of Labor and Social Protection of the Russian Federation No. 169n of March 20, 2018. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/542621605 (accessed 30.03.2023). (In Russ.).

becomes possible to train a neural network, which will allow, if insufficient knowledge, skills and abilities of the attested person are detected, predicting possible injuries and accidents at facilities [7–9].

The professional standard "Specialist in the operation of lifting equipment" provides 132 competencies, divided into knowledge, skills and labor functions. To train a neural network and make it easier to present data, it is necessary to assign alphanumeric indexes to them. The results of the training of conditional attested specialists were obtained by the Monte Carlo method [10–12].

The obtained values consist of 0 and 1, which corresponds to a negative and positive (more than 80 %) result of the assessment of the possession of the relevant competence. The generation is performed in such a way that the data is evenly distributed across the matrix and the neural network is trained on various combinations of positive and negative assessments of competence acquisition. During the generation, the results of the attestation of 200 conditional specialists were obtained (Fig. 1).

On the basis of Rostekhnadzor data on emergency situations on lifting cranes and the list of professional competencies, possible incidents occurring due to insufficient development of professional competencies by specialists are formulated. The probability of an incident is estimated in fractions of one and is in the range of 0.0–1.0. Each of the possible incidents was correlated with a set of competencies from the matrix. The relevant incidents and the sets of competencies affecting them are presented in Table 1.

Production of works, flowcharts, technological regulations and work permits			
Labor actions		Required skills	
Monitoring compliance with the brand system when operating bridge cranes	Preparation of the necessary documentation	Organize their own activities and the activities of lifting equipment operators and slingers, give instructions and monitor their implementation	Monitor the compliance with the requirements of industrial safety and labor protection by machinists of lifting equipment and slingers

Fig. 1. Competence matrix (fragment) (the authors' figure)

Table 1

Possible incidents and competencies affecting them (the authors' table)

Type of incident	Influencing competence	Number of competencies
Injury to unauthorized persons and workers without access to the danger zone during the operation of lifting equipment	A1, A2, B1, B7, C1, C2, C8, C9, C11, D1, D4, D7, E2, E3, E5, F1, F2, F8, F9, F14	20
Injury to workers in violation of the performance of slinging and cargo operations	A3, A4, A5, A6, B2, B3, B4, B5, B6, B7, C6, D1, D2, D4, D7, E1, E2, E3, E5, F1, F2, F6	22
Injury to personnel and damage to material assets in violation of the requirements for the laying and maintenance of crane tracks	C4, C14, D5, D6, D7, F4	6
Injury to personnel and damage to material assets in violation of the requirements for laying, maintenance and repair of crane tracks	C4, C14, D5, D6, D7, F6, H12, I4, I5, I8, J1, M11	12
Injury to personnel and damage to material assets in violation of the requirements for the storage of goods	C5, D3, F5	3

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Type of incident	Influencing competence	Number of competencies
Injury to personnel and damage to property in case of electric shock	C7, C13, E4, F7, F13, H8, K1, K14, M7, M18	10
Injury to personnel and damage to property in violation of the rules of maintenance and repair	C3, F3, F11, G1, G2, G3, G4, G5, G6, H1, H2, H3, H4, H6, H7, H8, H9, H10, H13, H14, H15, H16, H18, H19, H20, I1, I2, I3, I4, I5, I6, I7, I8, J1, J2, J3, J4, J5, J6, J8, K1, K2, K3, K4, K5, K6, K7, K8, K9, K10, K12, K14, L1, L2, L3, L4, L5, M1, M2, M3, M4, M6, M7	63
Injury to health and loss of life as a result of violation of the procedure and assistance in emergency situations	C12, F12, H5, H19, J7, K13, M5, M17	8
Injury to personnel and damage to material assets due to improper inspection and rejection of steel ropes, lifting devices, lifting mechanisms	C10, F10, H11, H17, K11, M8, M9, M10, M11, M12, M13, M14, M15, M16, M18	15

The possible incidents indicated in Table 1 are assigned alphanumeric indexes for the convenience of using data headers when training a neural network, and then the values of the probabilities of occurrence of incidents are calculated depending on the completeness of the development of competencies [13, 14] (Fig. 2).

The data obtained were used to train a neural environment in Python 3.10 in the PyCharm Community Edition development environment. The TensorFlow open library of deep machine learning, as well as the Keras open library interacting with it, were used to train the neural network. The open Pandas library is used to import data from Excel to Python. The NumPy open library was used to optimize the structure of data arrays in order to speed up neural network learning. With the help of the open library Scikit-learn, the training data was divided into train — 70 %, test — 15 % and validation — 15 %.

Injury to unauthorized persons and workers without access to the danger zone during the operation of lifting equipment	Injury to workers in violation of the performance of slinging and cargo operations	Injury to personnel and damage to material assets in violation of the requirements for the laying and maintenance of crane tracks	Injury to personnel and damage to material assets in violation of the requirements for laying, maintenance and repair of crane tracks	Injury to personnel and damage to material assets in violation of the requirements for the storage of goods	Injury to personnel and damage to property in case of electric shock	Injury to personnel and damage to property in violation of the rules of maintenance and repair	Injury to health and loss of life as a result of violation of the procedure and assistance in emergency situations	Injury to personnel and damage to material assets due to improper inspection and rejection of steel ropes, lifting devices, lifting mechanisms
EMG1	EMG2	EMG3	EMG4	EMG5	EMG6	EMG7	EMG8	EMG9
0.25	0.27	0.33	0.25	0.33	0.10	0.25	0.38	0.00
0.25	0.23	0.17	0.33	0.67	0.10	0.32	0.25	0.27

Fig. 2. Incident matrix (fragment)

During the training, the method of "training with a teacher" was used, which was an array of training data [15–17]. The training lasted 1000 epochs. A multilayer perceptron (MLP) was used as a learning model as a subclass of the Keras library's Model class. The general structure of the trained neural network is shown in Fig. 3.

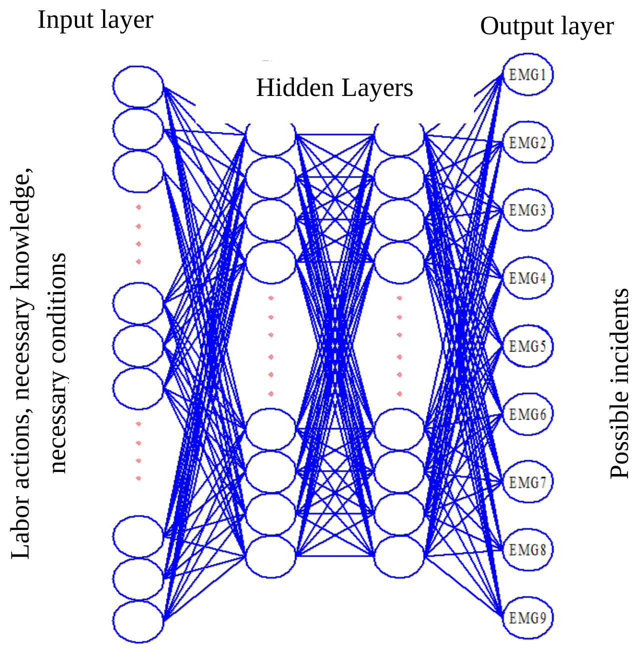

Fig. 3. The neural network diagram for assessing the probability of incidents on lifting cranes

Results. During the training, the MLP 132-25-9 neural network was obtained (25 neurons are located in hidden layers), which is a software product that makes it possible to assess the probability of incidents depending on the quality of mastering professional competencies by specialists in the field of lifting cranes.

In the process of training the neural network, various activation functions were used for the hidden layers and the output layer. The best results are obtained when using the hyperbolic tangent function (Tanh) in the hidden layer, and the Identity function in the output layer.

The mean squared error function was used as the error function. As a result, it was possible to obtain the following error values on the training, test and validation sample, respectively:

– training sample — 0.0034;

– test sample — 0.0591;

– validation sample — 0.0573.

Based on the presented values, it can be concluded that the level of errors received is quite low, which means that the neural network is trained sufficiently qualitatively for practical use [18–20] (Fig. 4).

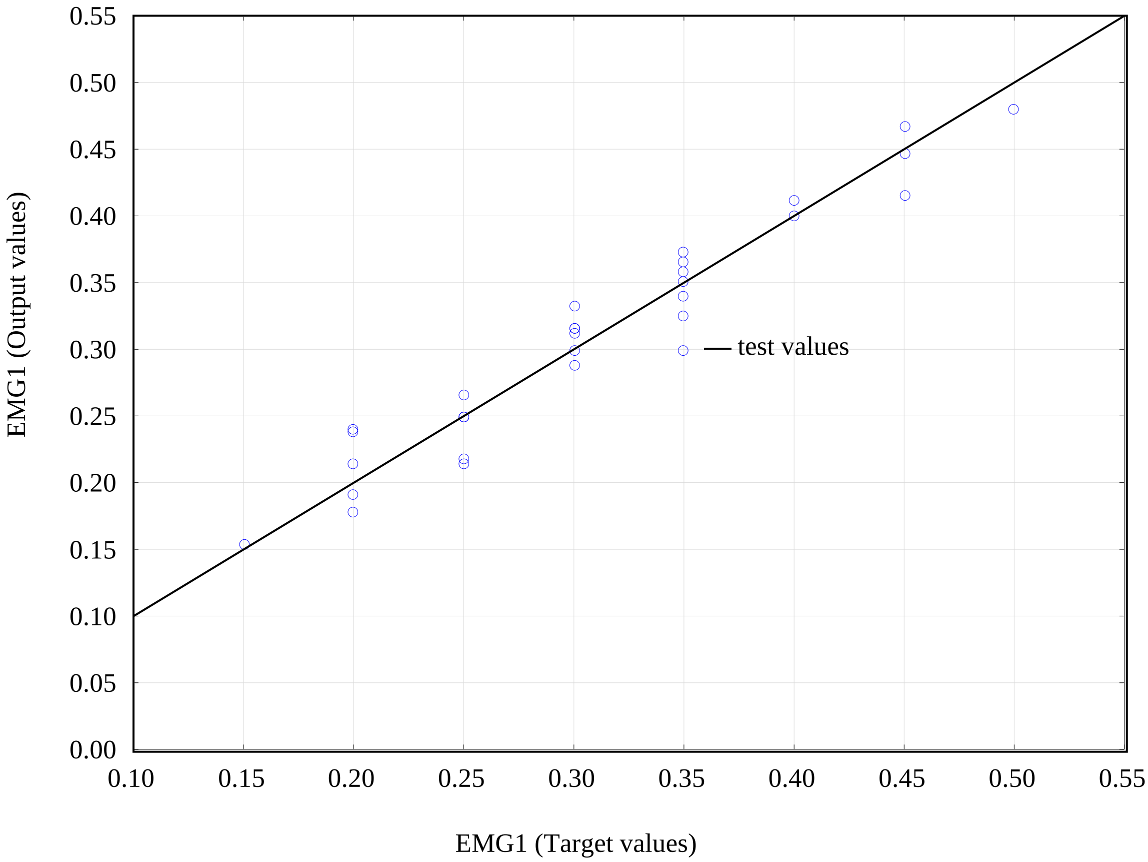

Fig. 4. Graphical representation of the results of the neural network on test data

Discussion and Conclusion. The software solution proposed by the authors, based on the use of neural networks to assess the knowledge of employees of facilities operating lifting cranes, assumes a reduction in the level of accidents, which can be ensured by timely detection of incompetence of specialists not only within the framework of attestation, but also at any stage of their professional activities based on an impartial analysis and evaluation of data. As a result of the application of the developed program, it is possible to expect informed decisions on the appointment or refusal of appointment to responsible positions related to the implementation of the evaluated labor functions. The proposed further development of this solution may be the creation of a cross-platform application that allows you to evaluate and transfer results to devices with different architectures, including mobile ones.

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Original article

Engineering-Physical Method for Determining the Thermal Conductivity of Objects with Micrometric Thickness and a Complex Structure

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Abstract
Introduction. The application of functional coatings on products, the performance properties of which are localized in the surface layer is a trend in modern mechanical engineering and materials science. The issues considered in this regard are relevant, in particular, for thermal-barrier coatings of turbine blades of steam and gas turbine engines. It is worth mentioning the materials that experience significant thermal loads during operation. In this case, the lack of reliable methods for predicting the thermophysical properties of the coating seems to be a problem. The work objective is to create a computational and analytical methodology for determining the thermal conductivity of coatings. This approach is based on experimental data and takes into account structural parameters of the material.
Materials and Methods. The experiments were carried out with the blades of a high-speed gas turbine of a locomotive engine made of heat-resistant chromium-nickel alloy Inconel 713LC. An experimental multiphase coating of the Nb-Ti-Al intermetallic system with a thickness of about 80 microns was applied using vacuum ion-plasma technology. The two-beam scanning electron microscope Zeiss CrossBeam 340 was used in the work. The thermal conductivity of the coatings was determined by an experimental technique based on the measurement of the contact potential difference (CPD). Numerical values of this difference were obtained using a mirror galvanometer with high voltage sensitivity. A special signal amplifier and a USB oscilloscope were used to record the readings.
Results. The calculation apparatus of the thermal conductivity determination technique is based on the experimental values of Δφ CPD:
– for the base metal (Inconel 713LC) +846 mkV;
– for the coating Nb-Ti-Al — 90 mkV.
The solution to the problem of the distribution of particles in a force field with a potential difference Δφ is described by the Boltzmann distribution. Starting from the obtained result, we get:
– CPD at the boundary of the contacting metals;
– energy and thermal conductivity of the Fermi level;
– electron relaxation time.
The multidirectional influence that the dimensional differences of the particles of the second phase have on the effective thermal conductivity is considered. For this case, a dimensionless value of the effective thermal conductivity in the direction of each axis and the effective thermal conductivity of the composite are found. Porosity is taken into account according to the Maxwell—Aiken dependence and introduced into the general calculation system. The thermal conductivity of Nb-Ti-Al is established: λ_{NbTiAl} = 4,76 W/m·K. Thus, the thermal barrier coating Nb-Ti-Al fully meets its functional purpose.

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Discussion and Conclusion. The method of determining thermal conductivity described in the article is applicable only to conductive consolidated materials or composites with a continuous conductive matrix. The presented work completes the initial stage of creating a computational and analytical model for predicting the thermal conductivity of materials and coatings. The results of testing the model for materials with a complex structure showed its satisfactory accuracy. This indicates the expediency of using the two considered elements of the model. The first one is the instrumental measurement of the CPD. The second one is taking into account the features of the structural and phase state of the material. With the development of the model, it is expected to overcome its weaknesses:

– the impossibility of using non-conductive objects to determine the thermal conductivity;

– a significant decrease in the accuracy of determining thermal conductivity for materials and coatings with a gradient structure.

Keywords: thermal barrier coatings of turbine blades, prediction of thermal properties of the coating, Inconel 713LC, Nb-Ti-Al, determination of thermal conductivity, Boltzmann distribution, contact potential difference, Fermi level, Maxwell—Aiken porosity, thermal conductivity of non-conductive objects, thermal conductivity of coatings with gradient structure.

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Научная статья

Инженерно-физический метод определения теплопроводности объектов микрометрической толщины со сложной структурой

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Аннотация

Введение. Нанесение функциональных покрытий на изделия, у которых эксплуатационные свойства локализованы в поверхностном слое, — это тренд в современном машиностроении и науке о материалах. Рассматриваемые в этой связи вопросы актуальны, в частности, для термобарьерных покрытий лопаток турбин паровых и газотурбинных двигателей. Стоит отдельно упомянуть материалы, которые при эксплуатации испытывают значительные тепловые нагрузки. В таком случае представляется проблемой отсутствие надежных методов прогнозирования теплофизических свойств покрытия. Основной целью работы было создание расчетно-аналитической методики для определения теплопроводности покрытий. Данный подход базируется на экспериментальных данных и учитывает структурные параметры материала.

Материалы и методы. Эксперименты проводили с лопатками высокоскоростного газотурбинного локомотивного двигателя из жаростойкого хромоникелевого сплава Inconel 713LC. С помощью вакуумной ионно-плазменной технологии наносили экспериментальное многофазное покрытие интерметаллидной системы Nb-Ti-Al толщиной около 80 мкм. В работе использовали двулучевой сканирующий электронный микроскоп Zeiss CrossBeam 340. Теплопроводность покрытий определяли по экспериментальной методике, основанной на измерении контактной разности потенциалов (КРП). Численные значения этой разности получили с помощью зеркального гальванометра с высокой чувствительностью по напряжению. Для фиксирования показаний задействовали специальный усилитель сигнала и USB-осциллограф.

Результаты исследования. Расчетный аппарат методики определения теплопроводности базируется на экспериментальных значениях Δφ КРП:

– для основного металла (Inconel 713LC) +846 мкВ;

– для покрытия Nb-Ti-Al — 90 мкВ.

Решение задачи о распределении частиц в силовом поле с разностью потенциалов Δφ описывается распределением Больцмана. Отталкиваясь от полученного таким образом результата, узнали:

– КРП на границе соприкасающихся металлов;

– энергию и теплопроводность уровня Ферми;

– время релаксации электрона.

Рассмотрено разнонаправленное влияние, которое размерные различия частиц второй фазы оказывают на эффективную теплопроводность. Для этого случая найдено безразмерное значение эффективной теплопроводности в направлении каждой оси и эффективная теплопроводность композита. Пористость учтена по зависимости Максвелла — Эйкена и введена в общую систему расчетов. Установлена теплопроводность Nb-Ti-Al: λ_{NbTiAl} = 4,76 Вт/м·К. Таким образом, термобарьерное покрытие Nb-Ti-Al полностью отвечает своему функциональному назначению.

Обсуждение и заключения. Описанная в статье методика определения теплопроводности применима только к проводящим консолидированным материалам или композитам с непрерывной проводящей матрицей. Представленная работа завершает начальную стадию создания расчетно-аналитической модели прогнозирования теплопроводности материалов и покрытий. Итоги тестирования модели для материалов со сложной структурой показали ее удовлетворительную точность. Это свидетельствует о целесообразности использования двух рассмотренных элементов модели. Первый — инструментальное измерение КРП. Второй — учет особенностей структурно-фазового состояния материала. С развитием модели предполагается преодолеть ее слабые места:

– невозможность использования для определения теплопроводности непроводящих объектов;

– значительное снижение точности определения теплопроводности для материалов и покрытий с градиентной структурой.

Ключевые слова: термобарьерные покрытия лопаток турбин, прогнозирование теплофизических свойств покрытия, Inconel 713LC, Nb-Ti-Al, определение теплопроводности, распределение Больцмана, контактная разность потенциалов, уровень Ферми, пористость по Максвеллу — Эйкену, теплопроводность непроводящих объектов, теплопроводность покрытий с градиентной структурой.

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Introduction. The results obtained in a number of leading universities and research centers of the world on ion-plasma technology of surface modification and coating indicate the great possibilities of this method for the formation of physical, mechanical, corrosion and functional properties of materials. One of the most promising areas of research in this area is the application of protective coatings to the blades of steam turbines and gas turbine engine turbines (GTE). Such coatings are classified as wear-resistant, but in fact they are multifunctional. Thermal protection should be considered as their main function. There is also a differentiation within the thermal protection function. So, for example, the subgroup of thermal barrier coatings (TBC) includes coatings with low thermal conductivity designed to relax the thermal load on the GTE turbine blades. The characteristic features of such TBC coatings are their chemical composition based on refractory elements and a sufficiently large thickness for vacuum ion-plasma coatings — within 100 microns [1, 2].

Currently, ion-plasma technology is a well-managed process. However, the prediction and control of many physical properties remains a serious problem, since, for example, the thermal conductivity of heterophase coatings depends on many non-technological parameters: the microstructure of the matrix phase, the number and configuration of secondary phases, porosity morphology, etc. [3, 4]. That is, the issue is that the problem of forming the necessary coating structure is solved at the technological level, but the problem of determining the thermal conductivity of the formed coating has not been solved to date. The lack of solutions is due to the complexity of instrumental measurement of the properties of thin films and coatings and the lack of a calculation apparatus that takes into account the influence of structural characteristics on the thermal conductivity of coatings. In this regard, the work objective is to develop a computational and analytical methodology for determining the thermal conductivity of vacuum ion-plasma coatings based on readily available measurement methods and reference data.

Materials and Methods. The coating of Nb-Ti-Al system was applied using a vacuum ion-plasma installation "PLATITπ80" in an arc three-cathode mode with deposition on cast GTE blades made of heat-resistant Incone 713LC superalloy. In addition to the task of creating a computational and analytical methodology and using it to determine the thermal conductivity of the coating, the task was to verify the validity of the calculated values obtained. For this purpose, the developed technique was used not only to determine the thermal conductivity of the coating, which is currently not found in the scientific literature, but also to determine the thermal conductivity of the Inconel 713LC alloy substrate, which, according to reference data[1], is 11.2–4.5 W/m·K in the temperature range of 25–800 °C. Inconel family alloys, as a rule, are solid solutions with refractory elements W, Co, Mo, etc. dissolved in nickel. They are resistant to thermal fatigue and oxidation, heat resistant to temperatures of 950–1000 °C. However, during long-term operation of the gas turbine engine in the range of higher temperatures, they experience softening, for protection from which thermal barrier coatings are used. Among the requirements for TBC coatings, the main ones are the conditions that allow the thermal barrier effect to be realized — low thermal conductivity and a sufficiently large thickness [5–9]. There are no requirements for the structure and phase composition. Therefore, the experimental intermetallic coating Nb-Ti-Al include refractory components Nb and Ti with additives Al, have a multiphase composition, complex layered morphology and a total thickness of ~80 microns

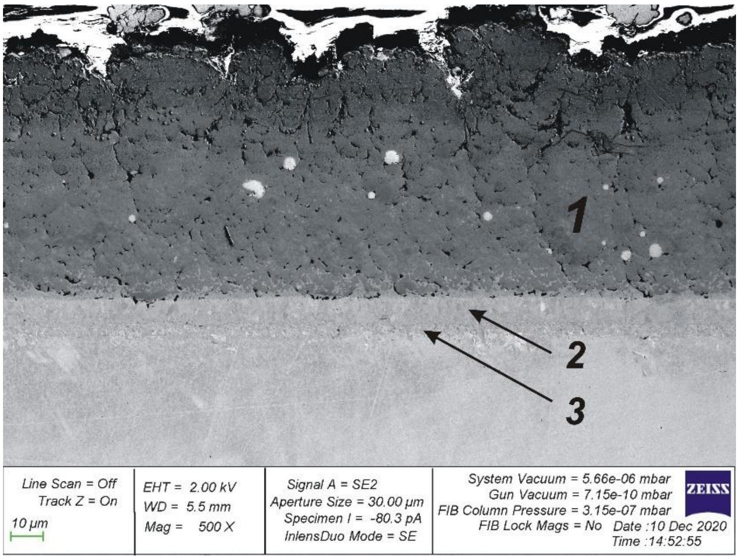
The magnitude of the contact potential difference (CPD), required to calculate the thermal conductivity by the computational and analytical method, is determined using an experimental laboratory technique using an electrocontact measurement method, in which one of the copper electrodes is heated to a temperature of +60 °C. From the point of view of the theory of physical measurements, this method is aimed at determining the extent of the potential barrier at the point of contact of the heated electrode and the object under study, on the basis of which the problem of electron equilibrium in two touching dissimilar metals is solved. The instrumental implementation of the method is carried out using a highly sensitive mirror galvanometer measuring the CPD on a microvolt scale. The measuring system also uses a USB oscilloscope and a signal amplifier to output the measured values of the CPD to print on a given time scale.

Since the developed method for calculating thermal conductivity includes characteristics of the structural-phase state of the measured object, microstructural studies are performed using a Zeiss CrossBeam 340 double-beam scanning

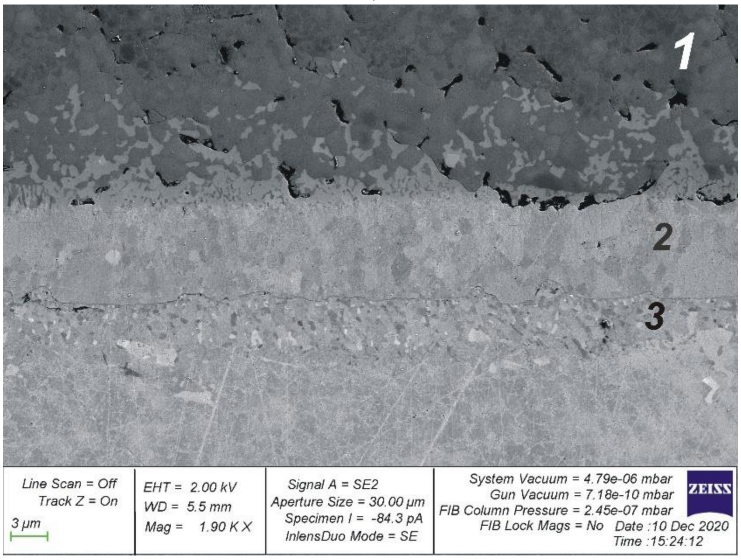
[1] *Engineering Properties of ALLOY* 713C. Brussels: Nickel Institute. URL: https://nickelinstitute.org/media/2487/alloys-713c_337.pdf (accessed 10.04.2023).

electron microscope (SEM). The elemental composition of the coating and substrate is studied on cross-sections using X-ray energy dispersion analysis (EDAX) by point sensing and scanning over the area of an arbitrary contour. Based on SEM and EDAX data, the phase composition of the coating is reconstructed.

Results. One of the distinctive features and signs of the novelty of the calculation and analytical methodology being created is taking into account the structural and phase characteristics of the object when calculating its thermal conductivity. Therefore, a coating with a complex structure consisting of several phases located along the depth of the coating with different distribution densities is purposefully chosen as the object of research. There are pores in the coating that have an uneven distribution in depth. In Fig. 1, in the NbTiAl coating structure, three layers are distinguished by section, indicated by numbers. It is clearly seen that they differ from each other in thickness, phase composition and porosity. Moreover, it should be noted that the uppermost layer of the coating (the outer one, which does not have a digital designation in Fig. 1 *a*) has a very branched porosity, openly in contact with the atmosphere. Therefore, its thermal conductivity is actually equal to atmospheric. Due to this circumstance, the outer porous layer is excluded from consideration of the thermal conductivity of the coating.



a)



b)

Fig. 1. Microstructure of NbTiAl thermal barrier coating in cross section, SEM:
a — general view of the layered architecture of the coating; *b* — fragment of the coating area adjacent to the substrate. The numerical designations refer to layers with different structural and phase composition

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The main function of thermal barrier protection is performed by layer 1. The results of detection by the EDAX method show that its elemental composition includes: 49–54 at. % Ti, 34.7–41.2 at. % Al, 6–8 at. % Nb. Moreover, according to the thickness of layer 1, the elements have a gradient distribution: Al increases to the surface by 15–20 at. % due to the facilitated diffusion of the fusible element with prolonged coating application and a temperature of 400–500 °C; Ti decreases by 5–10 at. % from the substrate to the surface, and Nb decreases by 2–6 at. %.

The reconstruction of the phase composition of layer 1 in Fig. 1, carried out on the basis of the obtained results of the elemental distribution of EDAX analysis, as well as based on the data of a few literary sources [10-15], gives reason to believe that the phase with the darkest shade in Fig. 1 is the Ti_3Al intermetallic compound – phase 2 doped with niobium. It consists of 49–54 at. % Ti, 34.7–41.2 at. % Al and 6–8 at. % Nb. The phase with the lightest shade in Fig. 1 also represents phase 2, in addition to niobium (up to 8 at. % Nb), nickel-doped (9 at. % Ni). As it can be seen from Fig. 1 *a*, the light phase — Ti_3Al (Nb,Ni) intermetallic compound — occupies a small volume fraction in layer 1 (no more than 5–7 %), which is why it does not significantly affect the thermal conductivity of the layer. Nickel is not part of the sprayed ion-plasma coating. It is detected in the lower part of the coating as a result of diffusion from the substrate during a long sputtering process, which lasted about 20 hours (taking into account the 4-hour diffusion annealing). During this time, nickel penetrates into the coating to a thickness of about 10-15 microns, displacing aluminum into the upper part of the coating.

The thermal barrier coating is operated at high temperatures (>1000 °C) and in an aggressive atmosphere, which is why it must be resistant to high-temperature gas corrosion. For this purpose, during vacuum ion-plasma spraying of TBC coatings, a dense nonporous NbTiAl sublayer (boat coat) of relatively small thickness is formed on the substrate, the main function of which is protection against the penetration of oxidants to the surface of the base metal. During the subsequent spraying of the outer thermal barrier layer, the anticorrosive sublayer is saturated with the elements of the substrate, so in Fig. 1 b in its place between the substrate and main layer 1 of the coating, two thin layers are found — 2 and 3. Layer 2 is almost entirely Ti_3Al (Nb,Ni) intermetallic. It makes a small contribution (corresponding to its small thickness) to the overall thermal conductivity of the coating, which takes into account the developed computational and analytical methodology. Layer 3 has a more complex heterophase composition, which includes, in addition to the main intermetallic phase 2 α_2, also titanium and aluminum nickelides, which complicates the calculations of thermal conductivity.

Due to the large thickness of the coating, a forced spraying mode with disabled magnetic separation was used to reduce the time of its application. This leads to the formation of a significant number of droplets in the vacuum chamber. The droplet phase in the ion flow leads to the formation of porosity in the coating. From the point of view of the thermal barrier effect, porosity does not impair the properties of the coating, since the air filling the pores is a good thermal insulator. If we talk about the thickness of the coating, then porosity is a limiting factor. If there are a lot of pores and they open, then they greatly branch the surface relief. The coating becomes unstable even to weak external influences. When assessing and calculating thermal conductivity, the volume fraction of pores and their morphology are taken into account as one of the phase components of the coating with known thermophysical characteristics inherent in the air atmosphere.

According to the depth of the coating, porosity P has a gradient distribution, since the drip phase partially heals the pores of the underlying layers during the coating process. Porosity was estimated from multimodal microstructural images of the coating with correlation settings set using the Zeiss Atlas 5 software integrated into the Zeiss CrossBeam 340 SEM. After statistical processing of the data, the following values were obtained, which were later used in calculating the integral thermal conductivity of the coating of Nb-Ti-Al system: in the upper half of the coating, the porosity P was 26 %, in the lower half — 4 %, the average value of P for the coating as a whole was at the level of 10 %.

Physical basis and thermal conductivity calculation method. As an initial stage, the method of determining thermal conductivity includes instrumental measurement of contact potential difference $\Delta\varphi$. At the same time, the temperature difference between the electrodes is fixed and is ΔT = 40 K. The measurements showed the following values:

- $\Delta\varphi_{Inconel}$ = +846 mkV — for the base metal of the blades of the Inconel 713LC alloy (substrate);
- $\Delta\varphi_{NbTiAl}$ = –90 mkV — for thermal barrier coating of the three-component Nb-Ti-Al system.

Physical significance of using the CPD value (at a fixed value of ΔT) in the process of calculating thermal conductivity is that $\Delta\varphi$ determines the electromagnetic force field in which the distribution of electrons at the boundary of two metals (in our case, this is a copper electrode with an electron concentration n_0 and the measured metal with an electron concentration n_1) is given by Boltzmann distribution (1), from which the energy value of the Fermi level E_F can be obtained [16]:

$$n_0 = n_1 \cdot \exp\left(-\frac{q_e \cdot \Delta\varphi}{kT}\right), \quad (1)$$

$$\Delta\varphi = \frac{kT}{q_e} \cdot \ln\frac{n_1}{n_0}, \quad (2)$$

$$E_F = \frac{h^2}{8m_e} \cdot \left(\frac{3n_0}{\pi}\right)^{2/3} \cdot \exp\left(\frac{2q_e}{3k} \cdot \frac{\Delta\varphi}{\Delta T}\right), \quad (3)$$

where m_e, q_e — electron mass and charge; k, h — the Boltzmann and Planck constants.

Thermal conductivity of metals and metal alloys is determined by their electronic conductivity. Therefore, in the process of calculations, the methodical transition from the energy of the Fermi level E_F to the thermal conductivity of metal systems λ is carried out indirectly — through the calculation of the electron relaxation time τ, which is determined by the expression [17]

$$\tau = \frac{2\sqrt{2}}{\pi^3} \cdot \frac{a^3 \cdot M \cdot \sqrt{m^*} \cdot k \cdot T_D}{h^2 \cdot C^2} \cdot \left(\frac{T_D}{T}\right) \cdot E_F^{3/2}, \quad (4)$$

where a — the lattice constant; m^* — effective mass of the electron, equal to 10^{-27} g; M — mass of an oscillating atom; T_D — the Debye temperature; $C = h^2 / (2m \cdot a^2)$ — the intensity constant of the interaction of an electron with lattice vibrations.

Then, according to the classical theory of thermal conductivity [17]:

$$\lambda = \frac{1}{3m} \cdot n_1 \cdot k^2 \cdot T \cdot \tau. \quad (5)$$

The calculation model consisting of expressions (1)–(5) is applicable to determine thermal conductivity of any single-phase metal alloy with a homogeneous structure, including for the Inconel 713LC nickel superalloy used by the authors as a substrate for NbTiAl thermal barrier coating. However, it is not sufficient for the coating itself. The calculation model of the thermal conductivity of a multiphase system [18, 19], in addition to the thermal conductivity of isotropic matrix λ_m, should take into account the number of phases, their shape, the dispersion of the distribution and the thermal conductivity λ_0. With respect to these parameters for such two-phase systems, to which the NbTiAl coating belongs, the following approximations can be taken [19]:

– NbTiAl coating in each of its layers (see layers 1, 2, 3 in Fig. 1) is two-phase and can be considered as a two-phase composite, for which it is customary to determine effective thermal conductivity λ, averaged over three spatial axes, that is, by values $\tilde{\lambda}_\alpha$, where α = 1, 2, 3;

– inclusions of the second phase are approximated by the shape of an ellipsoid with the ratio of semi-axes $\bar{d} = d/l$;

– the orientation of the ellipsoids is arbitrary and equally probable, which corresponds to the real structure of NbTiAl coating shown in Fig. 1, and makes it possible to exclude the influence of dimensional differences of inclusions of the second phase in different spatial directions on the effective thermal conductivity of the coating;

– porosity can also be considered as the second phase in a homogeneous isotropic metal matrix, which makes it possible to apply the approximations of sub-s 2 and 3 to it; however, unlike many intermetallic phases, porosity always reduces thermal conductivity of metals and metal alloys; in accordance with classical theory [20] for thermal conductivity of a solid with a continuous matrix and isolated pores, the universal Maxwell–Aiken equation is applicable, in which porosity P appears as a fraction of the total volume of a solid, which is taken as one:

$$\lambda_\Pi = \lambda \cdot (1 - \Pi) \cdot (1 + 0{,}5 \cdot \Pi), \quad (6)$$

Then the calculation model of thermal conductivity of a multiphase system, which includes NbTiAl ion-plasma thermal barrier coating, along with expressions (1)–(5), will be supplemented with an expression for the dimensionless effective thermal conductivity in the direction of each spatial axis:

$$\tilde{\lambda}_\alpha = \frac{1 - (\bar{\lambda} - 1) \cdot (D_\alpha + (1 + D_\alpha) \cdot C_V)}{1 + (\bar{\lambda} - 1) \cdot D_\alpha \cdot (1 - C_V)}, \quad (7)$$

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where $\tilde{\lambda}_\alpha = \lambda_\alpha / \lambda_m$, $\bar{\lambda} = \lambda_0 / \lambda_m$, $D_1 = D_2 = \frac{1}{2}\left(1 - \bar{d}^2 \ln \frac{2}{\bar{d}}\right)$, $D_3 = \bar{d}^2 \left(\ln\left(\frac{2}{\bar{d}}\right) - 1\right)$, C_V — volume fraction of inclusions, as well as an expression for the effective thermal conductivity of the composite:

$$\lambda = \frac{2\tilde{\lambda}_1 + \tilde{\lambda}_3}{3} \cdot \lambda_m . \quad (8)$$

The method of determining the thermal conductivity of multiphase metal systems, based on the measurement of CPD and expressions (1)–(8), allows us to calculate the effective thermal conductivity of both the base metal of the blades —the Inconel 713LC alloy, and the thermal barrier coating of Nb-Ti-Al system, taking into account their structural-phase state. Omitting the details of the calculations performed, due to the limited volume of the publication, we present only the final results obtained using the MathCAD application software package.

According to X-ray energy dispersion analysis (EDAX), the base metal of the substrate, Inconel 713LC alloy, had an elemental composition of Ni = 69.6 at. %, Al = 13 at. %, Mo = 2.8 at. %, Cr = 14.6 at. % and homogeneous structure of a solid solution of Cr, Al and Mo in nickel. In accordance with the calculation using expressions (1)–(8), including the above value of the CPD ((Δφ = + 846 mkV), the value of its thermal conductivity is $\lambda_{Inconel}$ = 14.34 W/m·K. The obtained value corresponds with satisfactory accuracy to the reference data given earlier, which makes up an interval of 11.2–14.5 W/m·K.for the Inconel 713LC alloy.

Compared with a single-phase base metal, the presence of multilayered and multiphase coating of Nb-Ti-Al complicates the computational part of the developed technique associated with the influence of the material structure. The coating included 4 layers. Their main phase is Ti_3Al (Nb) intermetallic compound with a different volume fraction in each layer and some variation in the composition of the components. Porosity was considered as the second phase. Only in the thinnest layer adjacent to the base metal, the second phase with a volume fraction of about 20 % was a solid solution based on Ti_3Al (Nb, Ni) intermetallic compound containing up to 9 at. % Ni. The porosity in this layer had zero value, so each layer was considered two-phase in the calculations. The influence of the structural-phase state of the coating on its thermal conductivity was taken into account using expressions (6)–(8), based on the measured value of the CPD for the coating as a whole (Δφ = – 90 mkV).

The calculation of the thermal conductivity of NbTiAl coating showed that λ_{NbTiAl} = 4.76 W/m·K. The obtained value is significantly lower than the thermal conductivity of the base metal Inconel 713LC and corresponds to the level of heat-resistant ceramics. Thus, an experimental heterophase coating formed by vacuum ion-plasma technology based on refractory metals Nb and Ti with the presence of Al can be used as a thermal barrier coating.

Conclusion. The developed computational and analytical technique allows us to predict and simulate the thermophysical properties of heterophase materials with a complex structure. Its approbation in relation to coatings of micrometric thickness opens up new opportunities in a fairly narrow field for the diagnosis of the properties of coatings and thin films.

The features of the proposed method for determining thermal conductivity through the measurement of CPR, calculation of the Fermi energy level and some other factors allow it to be applied only to conductive consolidated materials or composites with a continuous conductive matrix. The number of phases in the alloy or composite being measured is not limited, and the phases can be of a non-metallic and intermetallic nature (as in the coating of Nb-Ti-Al system). To determine the thermal conductivity of a material or coating using the developed technique, the composition, volume fraction and spatial morphology of phases are important. This makes it possible to determine the contribution of each phase to the thermal conductivity of the material, as well as to apply the technique to porous materials (subject to the continuity of their conductive matrix), identifying the pores as one of the phases of a non-metallic nature.

This work represents the completion of the initial stage of creating a computational and analytical model for predicting the thermal conductivity of materials and coatings. The above model testing results obtained for materials with a complex structure demonstrate a satisfactory level of accuracy. Thus, it is possible to assert the validity of the use of the described physical principles and algorithms in the model. First of all, this is a method of CPD instrumental measurement and consideration of the peculiarities of the structural and phase state of the material, on the basis of which the computational part of the model is constructed. The results of scientific research suggest that the model should develop, overcoming limitations and weaknesses:

– impossibility of using it to determine thermal conductivity of non-conductive objects,

– significant decrease in the accuracy of determining thermal conductivity for materials and coatings with a gradient structure.

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OV Kudryakov: academic advising, formulation of the basic concept, goals and objectives of the study, obtaining experimental data on determining the CP of materials and coatings, discussion of the results, preparation of the text, formulation of the conclusion. VN Varavka: planning and organization of experiments, conducting metallophysical studies, analysis of the results, correction of the conclusion. LP Arefieva: the idea and development of a computational and analytical model for determining thermal conductivity, calculations, analysis and discussion of the results, participation in experimental studies.

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Заявленный вклад соавторов

О.В. Кудряков — научное руководство, формирование основной концепции, цели и задачи исследования, получение экспериментальных данных по определению КРП материалов и покрытий, обсуждение результатов, подготовка текста, формулирование заключения. В.Н. Варавка — планирование и организация экспериментов, проведение металлофизических исследований, анализ результатов, корректировка заключения. Л.П. Арефьева — идея и разработка расчетно-аналитической модели определения теплопроводности, выполнение расчетов, анализ и обсуждение результатов, участие в проведении экспериментальных исследований.

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Original article

Influence of Carbon Content on the Formation of a Contact Interparticle Surface during Hot Post-Pressing

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Abstract

Introduction. The technology for producing hot-formed powder steel is one of the most energy-intensive in powder metallurgy, which includes a large number of operations. The study of the influence of technological modes on the final properties of the part is an urgent task. Developed by the scientific team under the leadership of Yu.G. Dorofeev at the end of the XX century, the technology of manufacturing hot-formed powder steels is currently one of the main ones in the production of high-density products. However, the use of new materials that improve the mechanical properties of products requires a modern approach to analyzing the quality of interparticle splicing of powder particles. The influence of the following technological factors on the formation of qualitative interparticle splicing was established: the blank density, the granulometric composition of the initial charge, the temperature and holding time of the blank during heating, the ratio of its dimensions, the deformation rate. The study objective is to analyze the effect of a graphite-containing component on the mechanical properties of hot-formed powder alloys due to the formation of high-quality interparticle splicing.

Materials and Methods. The work used domestic and foreign powders produced by PAO Severstal and the Swedish company Höganäs with the addition of carbon GC-1 (GOST 4404-78). Hot stamping was carried out on a crank press of the K2232 model with a maximum force of 1600 kN. The heating temperature of the workpieces varied between 800–1200 °C.

Results. As a result of the experiments, the influence of the sintering duration on the mechanical properties of materials was established. The reason for the change in mechanical properties are local inclusions of graphite, which did not have time to homogenize as a result of prolonged sintering. Technological modes of hot stamping for steels have been developed that affect the preservation or destruction of the pre-formed contact interparticle surface.

Discussion and Conclusion. The studies have shown that additional hot plastic deformation contributes to the formation of intracrystalline fusion on the entire contact surface. The addition of graphite to the charge improves splicing for alloyed iron powder and practically does not affect the use of alloyed and unalloyed iron powder.

Keywords: hot stamping, splicing, plastic deformation, surface microstructure

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Научная статья

Влияние содержания углерода на формирование контактной межчастичной поверхности при горячей допрессовке

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Аннотация
Введение. Технология получения горячедеформированной порошковой стали является одной из самых энергозатратных в порошковой металлургии, которая включает в себя большое количество операций. Изучение влияния технологических режимов на конечные свойства детали является актуальной задачей. Разработанная научным коллективом под руководством Ю.Г. Дорофеева в конце XX века технолог ия изготовления горячедеформированных порошковых сталей на сегодняшний день является одной из главных в производстве высокоплотных изделий. Однако применение новых материалов, улучшающих механические свойства изделий, требует современного подхода к анализу качества межчастичного сращивания порошковых частиц. Установлено влияние на процесс формирования качественного межчастичного сращивания следующих технологических факторов: плотности заготовки, гранулометрического состава исходной шихты, температуры и времени выдержки заготовки при нагреве, соотношения ее размеров, скорости деформации. Целью данного исследования является анализ влияния графитсодержащего компонента на механические свойства горячедеформированных порошковых сплавов за счет формирования качественного межчастичного сращивания.

Материалы и методы. В работе использовались отечественные и зарубежные порошки производства ПАО «Северсталь» и шведской фирмы Höganäs с добавление углерода ГК-1 (ГОСТ 4404-78). Горячая штамповка осуществлялась на кривошипном прессе модели К2232 с максимальным усилием 1600 кН. Температура нагрева заготовок варьировалась в пределах 800–1200 С.

Результаты исследования. В результате проведенных экспериментов было установлено влияние продолжительности спекания на механические свойства материалов. Причиной изменения механических свойств являются локальные включения графита, которые не успели гомогенизироваться в результате длительного спекания. Разработаны технологические режимы горячей штамповки для сталей, влияющие на сохранение или разрушение предварительно сформированной контактной межчастичной поверхности.

Обсуждение и заключения. Исследования показали, что дополнительная горячая пластическая деформация способствует формированию внутрикристаллитного сращивания на всей контактной поверхности. Добавление в шихту графита способствует улучшению сращивания для легированного железного порошка и практически не сказывается при использовании легированного и нелегированного железного порошка.

Ключевые слова: горячая штамповка, сращивание, пластическая деформация, микроструктура поверхности

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Introduction. A formation feature of powdered porous blanks is the structure formation during their processing, which has a fundamental difference from the corresponding processing of monolith materials. The features of the technological processes of structure formation in powder metallurgy are due to the intense thermomechanical effect on the processed powder steel. A large number of processes of forming and structuring of material under conditions of short-term thermomechanical action leads to the synthesis of scientific approaches of hot deformation in powder metallurgy, materials science, pressure welding, metal processing under pressure, theory of strength, plasticity [1–3].

The main objective of the authors of the article is to study the technological modes of hot deformation of products with different carbon content, as well as to study the microstructure in various zones of deformable products.

Materials and Methods. The formation of the contact surface of the powder material at the hot stamping stage is considered from the position of its initial state, which changes during the compaction process, i.e. the sequential increment of the contact surface.

Iron powders produced by the Höganäs (Sweden) and PAO Severstal (Russia) were used in the work [2, 4] (Table 1).

Table 1

Types and characteristics of the powders used

Powder brand	Manufacturer country	Powder production method
PZhRV2.200.26 TU 14-1-5365-98	RF, PAO Severstal	Atomization of the alloy by a stream of compressed air, recovery annealing
PL-N4D2M TU 14 -5402 2002	RF, PAO Severstal	Diffusion-reduction annealing of atomized powder
ABC100.30	Sweden, Höganäs	Spraying of iron melt
Astaloy 85Mo	Sweden, Höganäs	Spraying with water of an alloyed melt containing 0,85 % Mo
Distaloy HP-1	Sweden, Höganäs	Double diffusion alloying of powder Astaloy 85Mo:1.5 % Mo+4 % Ni,2 % Cu

Data on the total chemical composition are presented in Table 2.

Table 2

Chemical composition of the powders under study

Powder brand	Content of elements, mass content, %							
	C	O	Mo	Ni	Cu	Mn	Si	S	P
PZhRV2.200.26	0.02	0.25				0.15	0.05	0.015	0.02
PL-N4D2M	0.02	0.25	0.4-0.5	3.6-4.4	1.3-1.7	0.15	0.05	0.02	0.02
ABC100.30	0.001	0.04	–	–	–	0.06	0.007	0.01	0.004
Astaloy 85Mo	<0.01	0.07	0.85	–	–	0.06	0.008	0.02	0.005

The main alloying element in the studied material is carbon introduced into the charge in the form of graphite pencil GK-1 (GOST 4404-78). Table 3 provides the chemical composition.

Table 3

Chemical and granulometric composition of graphite powder

Name of indicators	Powder
	GK-1
Moisture content, mass., %	2.0
Ash content, mass., %	5.0
Sulfur content, mass., %	1.0
Granulometric composition, microns	+100-300

The formation of the interparticle splicing surface is influenced by inclusions of the second phase, in particular, graphite particles not dissolved in austenite [2, 4, 5]. Based on the results of the chemical analysis of the material, an understanding of the process of carbon dissolution in the sample is formed, which allows us to assume that complete dissolution of carbon takes no more than 60 minutes. The mechanical properties data presented in Table 4 indicate that for samples containing 0.5% C (mass fraction) this time is insufficient, since it does not provide a high level.

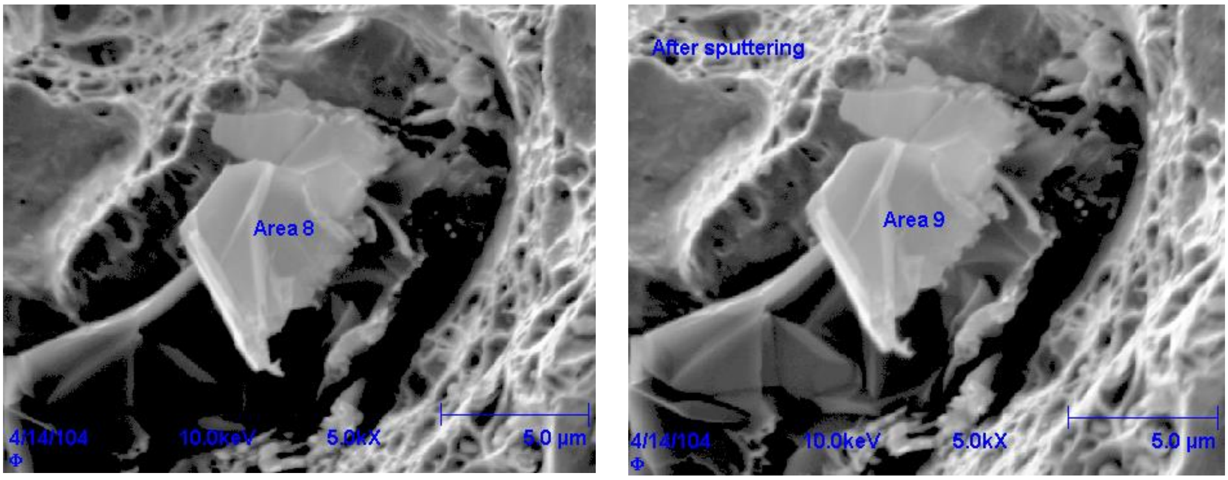
Table 4

Dependence of the mechanical properties of hot-deformable alloys on the duration of sintering

Metal base of the charge	Duration of sintering at 1000º C, hours	Mechanical properties after postcompaction		
		$\sigma_в$, MPA	Ψ, %	KCU, MJ/m^2
Astaloy 85Mo+0.5% C	0.5	610	0	0
	1	640	0	0
	1.5	690	35	0.38
ABC100.30+0.5%C	0.5	350	0	0
	1	370	0	0
	1.5	450	45	0.7

The data presented in Table 4 show that the following indicators are most sensitive to the degree of homogenization of alloys: ductility of the material and impact resistance.

The formation of sufficiently high mechanical properties of the materials under consideration with the addition of carbon occurs when choosing the correct sintering modes. The complete homogenization of carbon in the iron matrix of the base depends on this. To explain this dependence, the study of blank fractures by Auger-electron spectroscopy was carried out on a PHJ-680 spectrometer by Physical Elecrtronics [2, 5, 6]. Figure 1 shows a fractogram of the surface of a sample sintered for 60 minutes. The area of this surface, indicated by point 8, deserves attention.



a) *b)*

Fig. 1. Inclusion on the destruction surface of the blank.

Sintering at 1000 °C for 1 hour: *a* — before argon etching; *b* — after argon etching

The results of argon etching of the sample at point 8 shows that this morphological structural element is a region with a nonequilibrium carbon content (Fig. 2).

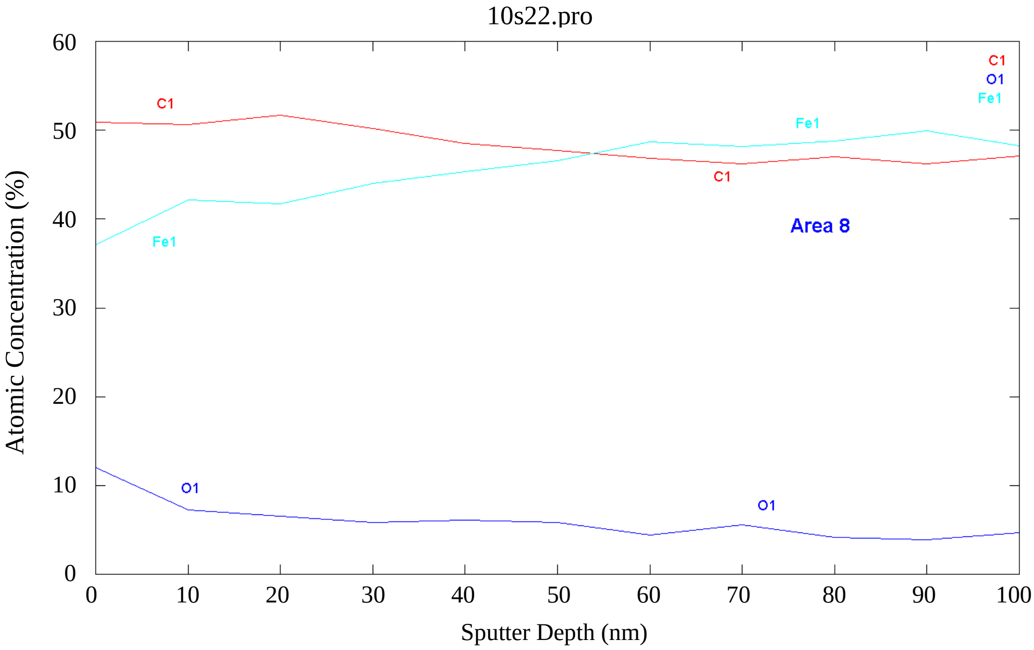


Fig. 2. Dependence of the distribution of elements at point 8 on the etching depth

The carbon content is about ~40 at % when etched into the depth of the surface of 100 nm. Consequently, the area under consideration is characterized by a three-dimensional inclusion formed as a result of diffusion during sintering of iron ions into a former graphite particle. Judging by the results of Auger-electron spectroscopy, its chemical composition corresponds to the formula of nonequilibrium carbide $Fe_{0,9}C$. A more even fracture surface of the considered zone indicates that the destruction of the sample occurred by the mechanism of chipping, characteristic of brittle fracture [1, 7, 8]. The structure, in which such an element is located, entails reduced mechanical properties of the alloys in question

Results. The research of the dependence of the mechanical properties of hot-formed steels on the carbon content in the charge were carried out. Pre-samples were sintered at a temperature of 1000 °C for 1.5 hours. Further, there was post-pressing to porosity values close to zero at a temperature of 1050 °C. This sintering mode ensures complete dissolution of carbon in the iron base of steel. The values of the ultimate strength, elongation and Vickers hardness of hot-formed steels with different carbon content are shown in Fig. 3.

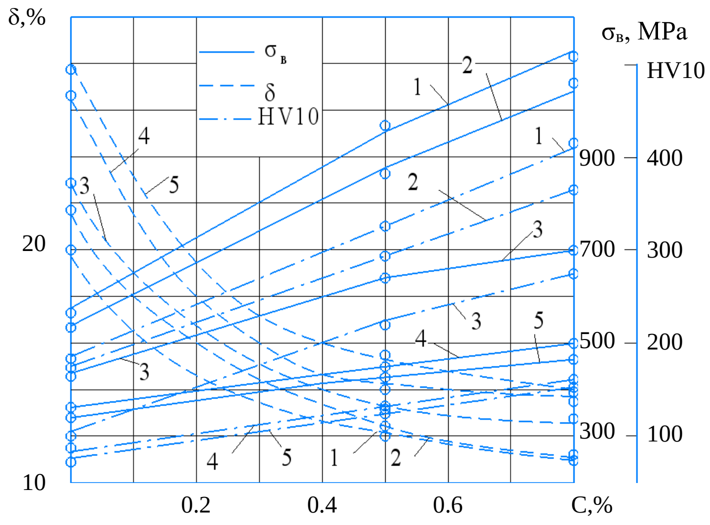


Fig. 3. Influence of carbon content on the mechanical properties of hot-formed steels based on powders:
1 — Distaloy HP-1; 2 — N4D2M; 3 — Astaloy 85Mo; 4 — PZhR2.200.26; 5 — ABC100.30

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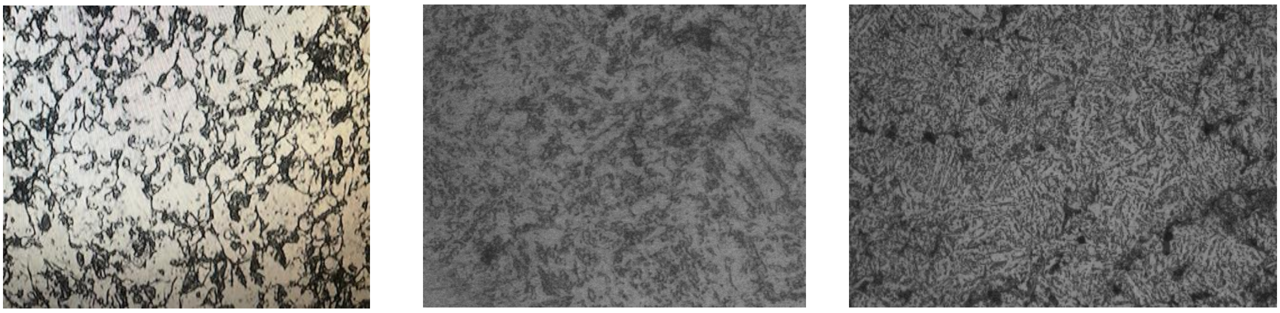
The nature of the presented dependencies is consistent with the theoretical provisions of classical and powder materials science [2, 9, 6], which is confirmed by the results of microstructural analysis (Fig. 4). With an increase in the carbon content in the steel composition, the amount of the ferritic component decreases and the amount of ferrite-cementite eutectoid mixture increases. With a carbon content of 0.8% C, the steel structure consists of finely dispersed troostite.



a) *b)* *c)*

Fig. 4. Microstructure of hot-deformed powder steel based on PZhRV2.200.26 powder with different carbon content, x250: *a* — 0.2 % C; *b* — 0.5 % C; *c* — 0.8 % C

There are no pores on the microsections, this fact indicates an almost non-porous state of the material.

The influence of carbon on the development of the contact surface is considered on the dependence of the mechanical properties of powder steel on the initial porosity (Fig. 5). Tested steels with a carbon content of 0.5% (wt.) were obtained by hot post-pressing at 1050 °C.

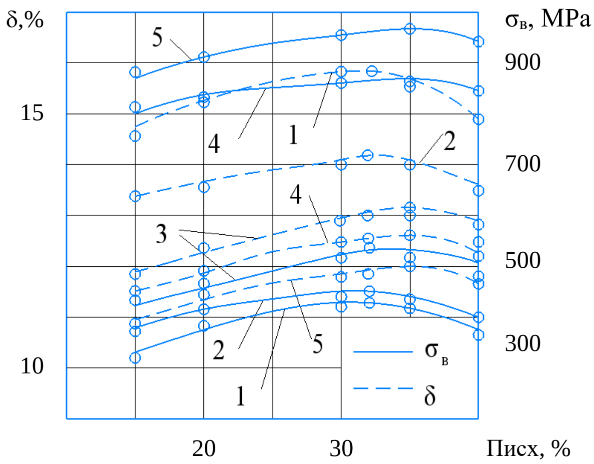


Fig. 5. Dependence of the mechanical properties of hot-deformed steels on the initial porosity:
1 — ABC100.30; 2 — PZhR2.200.26; 3 — Astaloy 85Mo; 4 — N4D2M; 5 — Distaloy HP-1

Comparing the data presented in Fig. 4 and Fig. 5, we can note the identical nature of the dependence of both strength and plastic properties on the initial porosity. For steels based on powders PZhR2.200.26 and AVS100.30, the extremum of properties is observed at the initial porosity of the workpiece of 30 %. In steels based on Astaloy 85Mo, N4D2M and Distaloy HP-1 powders, the extremum of properties shifts towards an increase in the value of the initial porosity. This circumstance can be interpreted as an increase in the quality of interparticle interaction, which is reflected in the position of the line delimiting the areas of technological modes characterized by partial or complete destruction or preservation and development of the pre-formed contact surface at the stage of hot pressing (Fig. 6) [10–12].

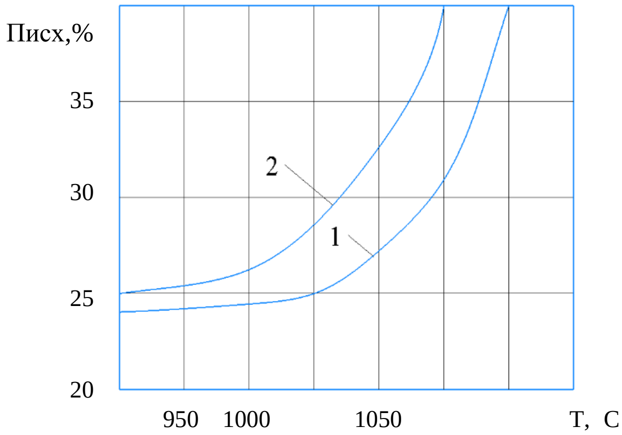


Fig. 6. Areas of technological modes of hot stamping affecting the preservation or destruction of the pre-formed contact interparticle surface for steels: 1 — PZhR2.200.26+0.5 % C; ABC100.30+0.5 % C; 2 — Astaloy 85Mo+0.5 % C; N4D2M+0.5 % C; Distaloy HP-1+0.5 % C

Table 5 provides a comparison of the results presented in Figures 5 and 6.

Table 5

Determination of the areas of technological modes of hot post-pressing for powder steels

Initial powder	Carbon content, %	Marking of the separation line
PZhR2.200.26; ABC100.30; Astaloy 85Mo; N4D2M; Distaloy HP-1	0	Line 1
PZhR2.200.26+0.5 % C; ABC100.30+0.5 % C; 2 — Astaloy 85Mo+0.5 % C; N4D2M +0.5 % C; Distaloy HP-1+0.5 % C	0.5	Line 1
Astaloy 85Mo; N4D2M; Distaloy HP-1	0.5	Line 2

The addition of carbon powder to the charge practically does not affect the application of optimal hot post-pressing modes for materials based on unalloyed iron powders. In the case of alloying iron powders with molybdenum, copper, nickel, when graphite is introduced into the charge and pre-sintering until complete homogenization of austenite, the recommended value of the initial porosity is shifted towards higher values.

It is possible to evaluate the quality of interparticle splicing of hot-deformed steels by the value of the Young's modulus. The value of the Young's modulus is taken as the criterion for additionally forged samples of the studied steels to a nonporous state (Table 6) [2, 5, 13].

Table 6

Parameters of powder steels in a nonporous state

Material		Density in the nonporous state, g/cm^3	Young's module, GPa
Metal base	Carbon content, %		
PZhRV2.200.26	0.5	7.79	201
ABC100.30		7.79	201
Astaloy 85Mo		7.83	206
N4D2M		7.81	203
Distaloy HP-1		7.85	208

Let us consider the dependence of the parameters of hot-formed steels with a carbon content of 0.5 % on the temperature of the hot post-pressing modes and the specific compaction work (W). As the parameters of the steels, we use the values of density (ρ), the Young's modulus (E) and the relative contact surface with intracrystalline splicing ($\alpha_{\text{ВКС}}$) (Table 7).

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Table 7

Parameters of hot-deformed steels from hot post-pressing modes

Material	T, ºC	W, MJ/m^3	ρ, g/cm^3	E, GPa	α_{BKC}
PZhRV2.200.26	950	60	6.5	112	0.56
		100	7.3	189	0.94
		120	7.5	193	0.96
		160	7.75	194	0.965
		180	7.79	195	0.97
	1050	60	7.25	181	0.9
		80	7.6	193	0.96
		100	7.75	195	0.97
		120	7.79	196	0.975
	1150	60	7.5	190	0.945
		80	7.74	196	0.975
		100	7.79	197	0.98
ABC100.30	950	60	6.6	166	0.82
		100	7.35	184	0.92
		120	7.55	189	0.94
		160	7.79	195	0.97
	1050	60	7.4	187	0.93
		80	7.68	194	0.965
		100	7.79	197	0.98
	1150	60	7.63	194	0.965
		80	7.79	198	0.985
Astaloy 85Mo	950	60	6.57	168	0.81
		100	7.49	191.2	0.92
		120	7.57	193.4	0.94
		160	7.81	199	0.96
		170	7.83	200	0.97
	1050	60	7.42	190.5	0.92
		80	7.69	197.5	0.96
		100	7.83	201	0.975
	1150	60	7.65	197	0.96
		80	7.83	202	0.98
N4D2M	950	60	6.53	165	0.81
		100	7.32	187	0.92
		120	7.52	190	0.93
		160	7.77	197	0.97
		180	7.81	198	0.98
	1050	60	7.28	185	0.91
		80	7.62	194	0.95
		100	7.77	198	0.97
		120	7.81	199	0.98
	1150	60	7.53	193	0.95
		80	7.76	199	0.98
		100	7.81	200	0.985
Distaloy HP-1	950	60	6.67	172	0.82
		100	7.4	190	0.91
		120	7.59	195	0.94
		160	7.85	202	0.97
	1050	60	7.47	193	0.93
		80	7.73	200	0.96
		100	7.85	203	0.975
	1150	60	7.69	200	0.96
		80	7.85	204	0.98

The experimental results presented in Table 7 show that in the entire temperature range of the study, a value of the density of the material corresponding to its nonporous state is achieved (Table 8).

Table 8

Specific compaction work (MJ/m^3) to achieve a nonporous state

T, ºC	Iron base of powder steel with a content of 0.5 % C				
	PZhRV2.200.26	ABC100.30	Astaloy 85Mo	N4D2M	Distaloy HP-1
950	180	160	170	180	160
1050	120	100	100	120	100
1150	100	80	80	100	80

Discussion and Conclusion. Despite the achievement of a nonporous state, the values of the Young's modulus show that there are the opportunities to improve the functional properties of materials, that is, during hot post-pressing, the formation of intracrystalline splicing on the entire contact surface is not achieved. Figure 7 shows a fractogram of a destroyed sample of hot-deformed steel based on PZhRV2.200.26 powder with a density of 7.81 g/cm^3. The fracture is characteristic of the viscous fracture of steel. Ridges and depressions of the pit relief are visible, which are the result of intense plastic deformation in the crack propagation center. With the predominance of the pit relief on the fractogram, areas with a flat relief characteristic of intercrystalline or transcrystalline fracture are observed. The presence of such zones on the fracture of steel indicates the incompleteness of interparticle splicing. The areas of intercrystalline cleavage directly indicate the absence of transformation of the interparticle splice surface into a large-angle intergranular surface. In the case of identification of flat fracture zones as a consequence of crack development by the mechanism of transcrystalline fracture, one can assume the hereditary nature of the structure in the fracture zone.

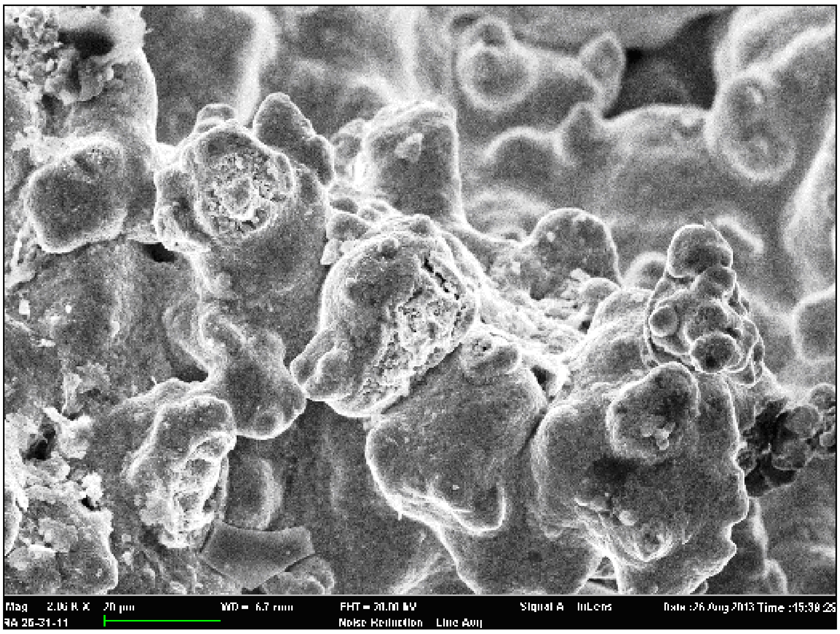

Fig. 7. Fracture surface of powder steel

The separation of the interparticle splice surface from submicropores, segregation atmosphere, dispersed inclusions of another phase leads to the preservation of these morphological elements of the structure in the zone of the former interparticle contact surface, which are factors contributing to the nucleation of the crack nucleus and its spread.

In relation to the studied steels with a content of 0.5% C, we use the technological technique proposed in [14, 15], which consists in additional hot plastic deformation with the determination of the critical degree of deformation. Let us consider the results of additional plastic deformation of a powder material based on powders PZhRV2.200.26 and N4D2M, carried out at a temperature of 1050 °C (Fig. 8). The Young's modulus is used as a criterion for the formation of intracrystalline fusion.

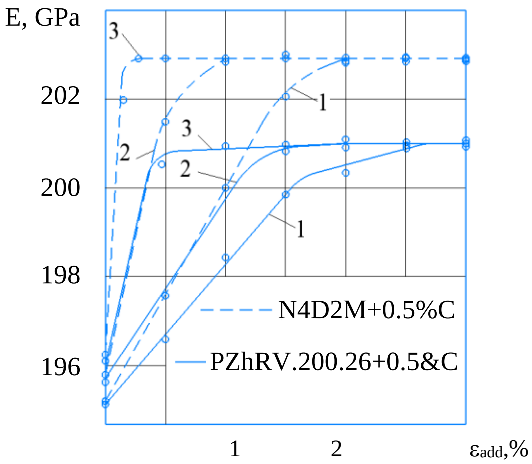

Fig. 8. Dependence of the Young's modulus on the degree of additional plastic deformation of powder steels formed at the temperature of hot post-pressing: 1 — 950 ºC, 2 — 1050 ºC, 3 — 1150 ºC

Based on the conducted studies, we present the values of the critical degree of additional plastic deformation as a function of the technological modes of hot post-pressing (Table 9). The numerator shows data for steel PZhRV2.200.26+0.5 %C, the denominator shows data for N4D2M+0.5%C.

Table 9

Critical degree of deformation at different temperatures of hot pressing

Temperature, 0 C	Initial porosity, %	Critical degree of deformation, %
950	40	2/1.5
	30	2.5/2
	20	3/2
1050	40	1.5/1
	30	1.5/1
	20	2/1.5
1150	40	0.5/0.3
	30	0.5/0.3
	20	1/0.5

Based on the conducted studies, it can be concluded that additional hot plastic deformation contributes to the formation of intracrystalline fusion on the entire contact surface. The addition of graphite to the charge improves the splicing for alloyed iron powder and practically does not affect the use of unalloyed iron powder.

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Original article

Influence of Texture Effects on the Laser-Irradiated Tool Performance

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Abstract

Introduction. Laser surface treatment of mechanical engineering products makes it possible to increase their durability. However, the laser hardening process is not good at the consistency of results, since choosing the irradiation modes and schemes of specific products, texture effects in the zones of laser exposure are not taken into account. This leads to premature wearing and even destructing the working surfaces of irradiated products. Therefore, the work objective is to study the mechanism of influence of the structure of the laser-hardened layer on the operational properties of the tool.

Materials and Methods. The materials for this study were tool steels: R6M5 and R18 (according to the EN 10027 standard tool steels: 1.3355, 1.3343). Pulsed laser irradiation was carried out at the technological device Kvant-16 with a radiation power density of 70–250 MW/m^2. Scanning probe and optical microscopy, X-ray diffraction and durometric methods for analyzing the steels structure were used. The values of steel strength in bending and impact strength were determined before and after laser treatment.

Results. It has been experimentally proven that it is necessary to strengthen the sections of the products working surfaces that are subject to maximum wear and are under the action of compressive stresses during operation. It is shown that textural effects in the laser treatment zones lead to a decrease in the friction coefficients and contribute to an increase in the wear and adhesion resistance of the steels surface layers.

Discussion and Conclusion. The results of the research carried out make it possible to rationally select the surface laser processing modes and schemes of products for various functional purposes and ensure their operability with a guarantee. The possibilities increasing the structural strength and properties of the tool due to laser alloying the surface layers of powder-coated steels and stabilizing tempering after laser irradiation are determined.

Keywords: laser irradiation, alloy steels, structure, properties, wear resistance, adhesion resistance.

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Научная статья

Влияние текстурных эффектов на работоспособность лазерно-облученного инструмента

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Аннотация

Введение. Лазерная поверхностная обработка изделий машиностроения позволяет увеличить их долговечность. Однако процесс лазерного упрочнения не отличается стабильностью получаемых результатов, так как при выборе режимов и схем облучения конкретных изделий не учитываются текстурные эффекты в зонах лазерного воздействия. Это приводит к преждевременному износу и даже разрушению рабочих поверхностей облученных изделий. Поэтому целью работы явилось исследование механизма влияния строения лазерно-закаленного слоя на эксплуатационные свойства инструмента.

Материалы и методы. Материалами для данного исследования послужили инструментальные стали Р6М5 и Р18. Импульсное лазерное облучение проводилось на технологической установке «Квант-16» с плотностью мощности излучения 70–250 МВт/м^2. Использовались сканирующая зондовая и оптическая микроскопия, рентгеноструктурный и дюрометрический методы анализа структуры сталей. Определялись значения прочности сталей на изгиб и ударную вязкость до и после лазерной обработки.

Результаты исследования. Экспериментально доказано, что упрочнять следует участки рабочих поверхностей изделий, подверженные максимальному износу и находящиеся при эксплуатации под действием сжимающих напряжений. Показано, что текстурные эффекты в зонах лазерной обработки приводят к понижению коэффициентов трения и способствуют повышению износо- и адгезионной стойкости поверхностных слоев сталей.

Обсуждение и заключения. Результаты проведенных исследований позволяют осуществлять рациональный выбор режимов и схем поверхностной лазерной обработки изделий различного функционального назначения и гарантированно обеспечивать их работоспособность. Определены возможности повышения конструкционной прочности и свойств инструмента за счет проведения лазерного легирования поверхностных слоев сталей из порошковых покрытий и проведения после лазерного облучения стабилизирующего отпуска.

Ключевые слова: лазерное облучение, легированные стали, структура, свойства, износостойкость, адгезионная стойкость.

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Introduction. Currently, machine-building enterprises pay great attention to improving the performance of tools and technological equipment, especially of high-alloy expensive steels.

The analysis of literature sources has shown that during its operation the tool experiences high contact stresses and pressures on the working surfaces [1–4]. In addition, the work of products of various functional purposes is accompanied by heating and bending stresses, as well as shock loads or vibrations.

Therefore, steels for the manufacture of tools should have high values not only of hardness, wear and heat resistance, but also strength at a sufficient level of viscosity in order to prevent premature destruction of working surfaces. Laser irradiation of tools and accessories, along with other methods of surface hardening, allows increasing their durability, but the laser treatment process does not differ in the stability of the results obtained [5–9]. This is due to the fact that the criteria for choosing modes and schemes of laser irradiation of products for various purposes are not clearly defined. In particular, the degree of influence of textural effects arising from laser treatment with surface melting on the structural strength of steels has not been considered.

To solve these problems, bending tests, impact strength, wear and adhesion resistance of irradiated samples are required.

The results of such experiments will make it possible to make a rational choice of the parameters of the surface laser treatment process.

The objective of this article is to study the effect of the structure of the laser-hardened layer on the operational properties of the tool.

Materials and Methods. The materials for this study were P6M5 and P18 instrument steels.

Pulsed laser irradiation was carried out at the Kvant-16 process installation with a radiation power density of 70–250 MW/m^2. Identification of the phase composition and the study of the structure of materials after laser treatment were carried out by metallographic, scanning probe, X-ray durometric methods.

Metallographic studies were carried out on MIM-7 and Neophot-21 microscopes. X-ray diffraction analysis was carried out on a DRON-type diffractometer. Microhardness was measured on a PMT-3 device with a load of 0.49 N. The bending strength of the samples was determined using the IM-4A machine, the impact strength of the samples without incision was determined on the KM-5T pendulum copra.

Results. Metal physical studies have established that during laser treatment of steels, a hardened layer is formed on the surface, consisting in general of a melted quenching zone from the liquid state and an underlying quenching zone from the solid (austenitic) state [10–12].

The material is melted to increase the overall depth of the hardened layer or during laser alloying of the irradiated zones. In the latter case, this is caused by the need to melt the alloying coating and a thin surface layer of steel.

Special attention was paid to the study of the features of the structure formation of steels in the zone of laser quenching from the liquid state.

It has been experimentally established that this zone has a dendritic structure (Fig. 1 *a*). Moreover, the dendrites are directed in a certain way — towards the heat sink from the irradiated surface into the depth of the hardened layer. The total thickness of the hardened layer is 80–100 microns, the average metal hardness of the surface layers is 10-10.5 GPa.

X-ray diffraction analysis showed (Fig. 1 *b*) that the following phases are present in the melting zones: α-phase (martensite), a certain amount of γ-phase (residual austenite) and blurred reflexes of incompletely dissolved carbides.

At the same time, an abnormal ratio is observed of the intensities of the diffraction lines (200) and (111) of austenite in the zones of laser quenching from the liquid state (Fig. 1 *b*, curve 2), compared with the quenching zone from the solid (austenitic) state (Fig. 1 *b*, curve 1).

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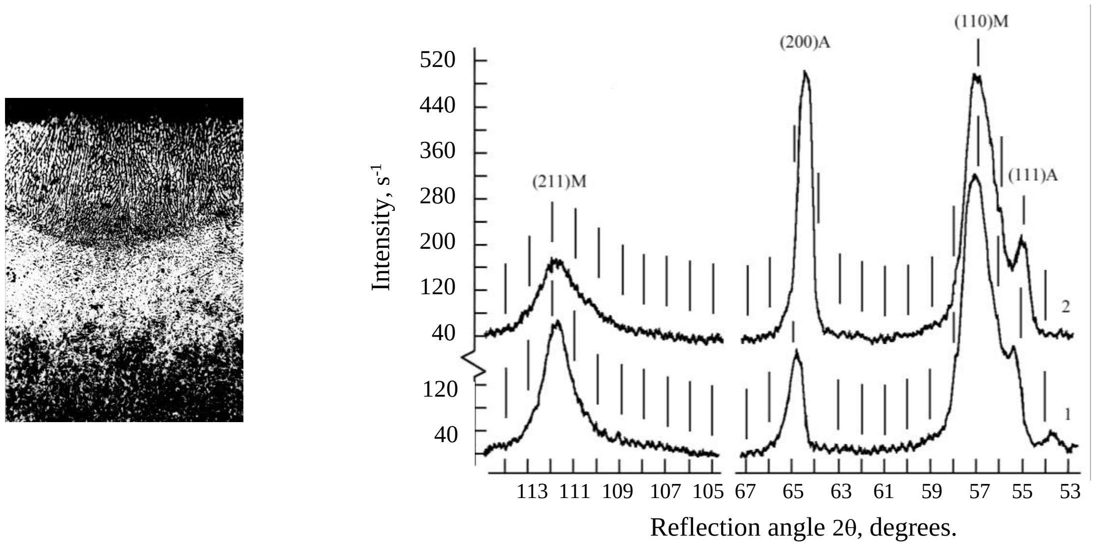

a) *b)*

Fig. 1. Location of dendrites in the zone of laser quenching from a liquid state on P6M5 steel (a), ×800 and fragments of radiographs (b) of steel after laser treatment without melting (curve 1) and with melting of the surface (curve 2)

This indicates the appearance of texture effects in the surface irradiated layers.

The formation of the austenite texture is probably due to the predominant orientation of its subgrains in the surface layer of materials, which occurs due to the directed crystallization of metal after the end of the laser pulse.

The described effect has a positive effect on the properties of products after laser treatment. In particular, the texture lowers the friction coefficients in the friction pairs, especially if the texture type is consistent with the type of stress state of the hardened products under operating conditions [13].

The paper considers some possibilities of using a texture that causes anisotropy of properties in the surface layers of steels as a factor in improving the technological characteristics of irradiated products.

For this purpose, bending and impact strength tests were carried out on samples made of P6M5 steel irradiated in different modes and according to different schemes, that is, the structural strength of laser-irradiated steels was determined.

When choosing methods of experiments, it was assumed that bending tests create a stress state in the samples close to that arising during the operation of a metalworking tool. Samples with a size of 4×6×55 mm were used.

The use of samples of non-standard cross-section is caused by the need to tighten the degree of influence of a thin hardened layer on the measured properties.

Before irradiation, the steel was subjected to standard heat treatment. To relieve internal stresses after grinding the samples to size, tempering was performed at 400 °C, as well as visual inspection for the absence of cracks or other defects. One face of the samples (6×55 mm) was subjected to laser irradiation with a radiation power density of 70–150 MW/m^2, that is, without melting and with melting of the surface of the samples. Some of the samples were subjected to laser alloying from powder coatings containing dispersed charcoal particles, followed by heating to a temperature of 550 ºC.

It should be noted that during the tests, the laser-hardened layer was under the influence of compressive or tensile stresses, depending on its location relative to the loading element.

As a result of the tests, it was found that in the case of compressive stresses acting on the irradiated layer, the strength of the samples practically does not decrease (Table 1). In case of exposure to tensile stresses, the tendency of samples to brittle fracture increases. This is probably due to the fact that tensile bending loads initiate the nucleation and propagation of cracks in the melted surface layers of steel along the inter-dendritic layers.

Table 1

Mechanical characteristics of P6M5 steel before and after laser treatment

Processing mode	$\sigma_{изг}$×10, MPa		a×10^{-1}, MJ/m^2	
	compression	stretching	compression	stretching
Standard heat treatment (quenching and tempering)	272±7	270±7	3.2±0.2	3.1±0.2
Laser hardening without melting the surface	258±7	32±7	2.8±0.2	0.2±0.2
Laser hardening with surface melting	238±7	30±7	2.7±0.2	0.3±0.2
Laser hardening and tempering at 550 °C	257±7	31±7	2.8±0.2	0.4±0.2
Laser alloying from coal powder	291±7	33±7	2.9±0.2	0.4±0.2
Laser alloying from coal powder and tempering at 550 °C	302±7	32±7	3.0±0.2	0.2±0.2

It can be concluded that in order to stabilize the structural strength of irradiated products, it is necessary to harden the sections of their working part that are exposed to compressive loads during operation.

Of particular interest, from the point of view of improving the operational properties of laser-hardened products, are the results of experiments obtained on laser-alloyed carbon powder samples.

During metal physical studies, the microstructure features of laser alloying zones from powder coatings containing activated carbon were revealed (Fig. 2).

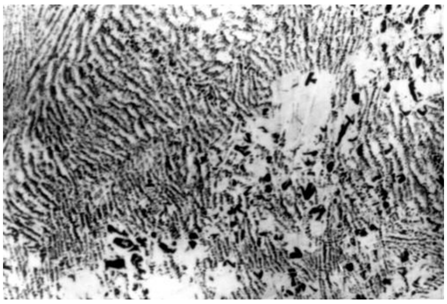

Fig. 2. Structure of the melt in liquid-hardened P6M5 steel under laser alloying from a powder containing coal particles, ×500

In particular, dispersed particles of coal are clearly visible, which are located in the irradiated metal at the boundaries of growing dendrites. Simultaneously with textural effects, the presence of graphite plates in irradiated zones lowers the friction coefficients on the working surfaces of products, acting as a solid lubricant [14]

As it can be seen from the table, under the action of compressive stresses, laser alloying and subsequent tempering at a temperature of 550 °C increase the strength of irradiated products most effectively.

An additional contribution of tempering to improving properties, in particular hardness, of the surface layers of P6M5 steel is associated with the effect of dispersion hardening in irradiated and, especially, alloyed layers of steel. To confirm the effectiveness of the process of laser hardening and alloying of the tool, taking into account textural effects in the surface layers [15, 16], there have been carried out full-scale tests on the wear resistance of cutters made of P18 steel under conditions of cutting parts made of steel 45.

Cutters made of P18 steel were subjected to volumetric quenching and tempering, as well as various surface treatment options: laser quenching with and without melting the surface, laser alloying from powder coatings containing dispersed inclusions of tungsten carbides.

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Laser irradiation was carried out along the back face of the working part of the cutter, which is exposed to compressive stresses during cutting. As shown in the article above, this eliminates the brittle destruction of the cutting edges of the tool. The experiments carried out to select the degree of overlap of the irradiated spots showed that the overlap coefficient of the irradiated zones should be at least 0.7–0.8. The depth of the hardened layer was 80-100 microns, the average metal hardness of the surface layers was 11–11.5 GPa.

The degree of wear was estimated by the size of the wear area on the back face of the cutter with the same cutting path for different surface hardening options.

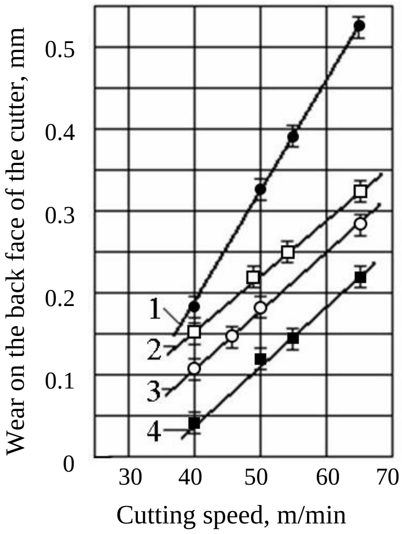
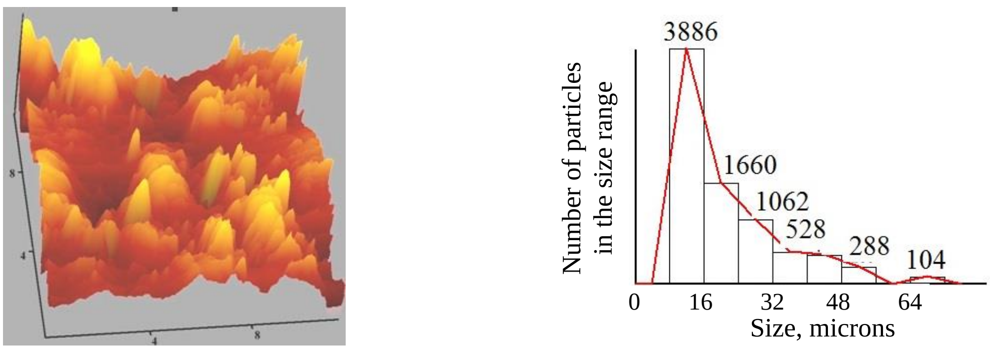


Fig. 3. Wear resistance of P18 steel cutters after volumetric heat treatment (curve 1), laser hardening without partial melting (curve 2), with surface partial melting (curve 3), laser alloying with tungsten carbides (curve 4)

As it can be seen in Fig. 3, at all cutting speeds, there is a decrease in wear by 1.5–2 times in the cutters subjected to laser hardening. Moreover, minimal wear is achieved in the case of laser alloying of the working surfaces of the cutter with tungsten carbides. At the same time, structures are formed in the surface layers of the cutters, which are a textured matrix with WC tungsten carbides fused with solid particles.

The process of laser alloying of the surface of P18 steel with tungsten carbides having a high hardness (up to 15–17 GPa) is evidenced by the WC reflexes present on the X-ray images, as well as the results of studies of coatings after laser treatment obtained on a scanning probe microscope. In Fig. 4 *a*, the carbide particles protruding above the surface of the sample are clearly distinguishable [17, 18].

Quantitative characteristics of the surface layers of steels after laser melting from coatings of WC particles were obtained in the work. To do this, a computer image processing program (CIP) was used. The results of the analysis are shown in Fig. 4 *b*.



a)

b)

Fig. 4. Scanned image of the surface of P18 steel: *a* — after laser melting of tungsten carbides; *b* — histograms of WC particle size distribution

As it can be seen in Fig. 4, inclusions of 5-10 microns are mainly present in the surface layers of steels.

The array of results of experimental determination of the wear resistance of cutters after laser alloying, processed in the program *"Statistica"*, is shown in Fig. 5. From the analysis of the figure, it can be concluded that the minimum wear of the cutters is observed after irradiation with a radiation power density of 110-130 MW/m^2. The white dots in Fig. 5 indicate the results of experimental verification of regression modeling of processes occurring in the zones of laser treatment of steels.

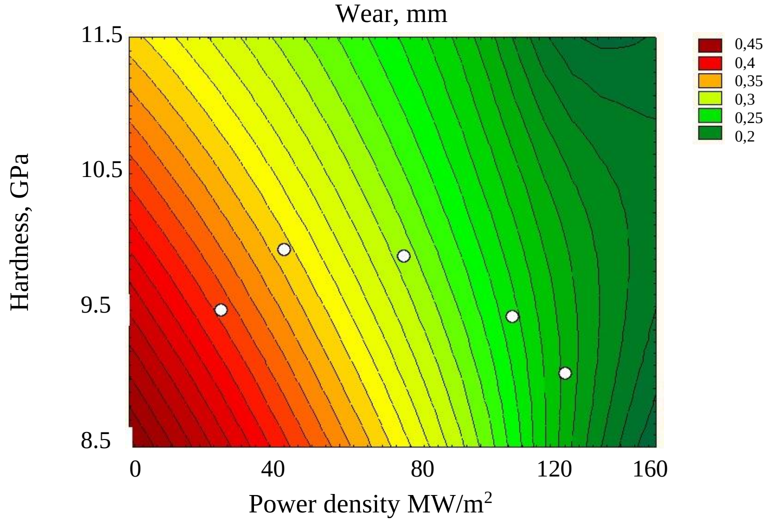


Fig. 5. Regression modeling maps of wear resistance of P18 steel cutters depending on the power density of laser radiation and the hardness of the surface layers of steel

The results obtained are of practical importance, since they allow us to reliably assign laser treatment modes to obtain the required hardness and wear resistance, that is, the operability of the irradiated products.

It should be noted that the adhesive stability of the working surfaces against "sticking" of the processed material is of no small importance for a guaranteed increase in the durability of products, especially tools. This changes the geometric dimensions of the working surfaces, leads to an increase in the loads and stresses acting in the friction pairs, causing the destruction of the surface layers of the products.

The possibilities of improving the operational properties of laser-hardened tool steel in contact with non-ferrous aluminum alloys were determined in the work.

Samples made of P6M5 steel were subjected to standard volumetric heat treatment and subsequent laser hardening with a radiation power density of 100-120 MW/m^2 to obtain a textured state of the steels on the surface. Coatings containing tungsten carbides were used during laser alloying.

Friction and adhesive stability tests were carried out on the MI-1M machine according to the "disc – pad" scheme. The counterbody was aluminum alloys with different hardness and viscosity. Alloy AD31 had a hardness of HB 2, D16 — HB 70 and AMg6 — HB 90. Damages and signs of setting on the friction surfaces were recorded using an MBS-2 microscope.

The value of the specific load applied to the friction pair and resulting in a significant increase in the coefficient of friction due to the adhesion of the aluminum alloy to the surface of the steel sample, that is, due to the adhesive process, was chosen as a criterion for assessing the tendency to set tool steel and aluminum alloy [19, 20].

As it can be seen in Fig. 6 a and b, when laser-irradiated tool steel comes into contact with aluminum alloys such as AMg6 and D16, the transfer of aluminum alloys to steel is practically absent. The friction coefficients are 0.07–0.09, in comparison with volumetrically hardened samples, for which the friction coefficients reach values of more than 0.10. Moreover, in contact with the D16 alloy, a jump-like increase in friction coefficients is observed for them, starting with specific loads in a friction pair over 6 MPa. This indicates the course of adhesive processes.

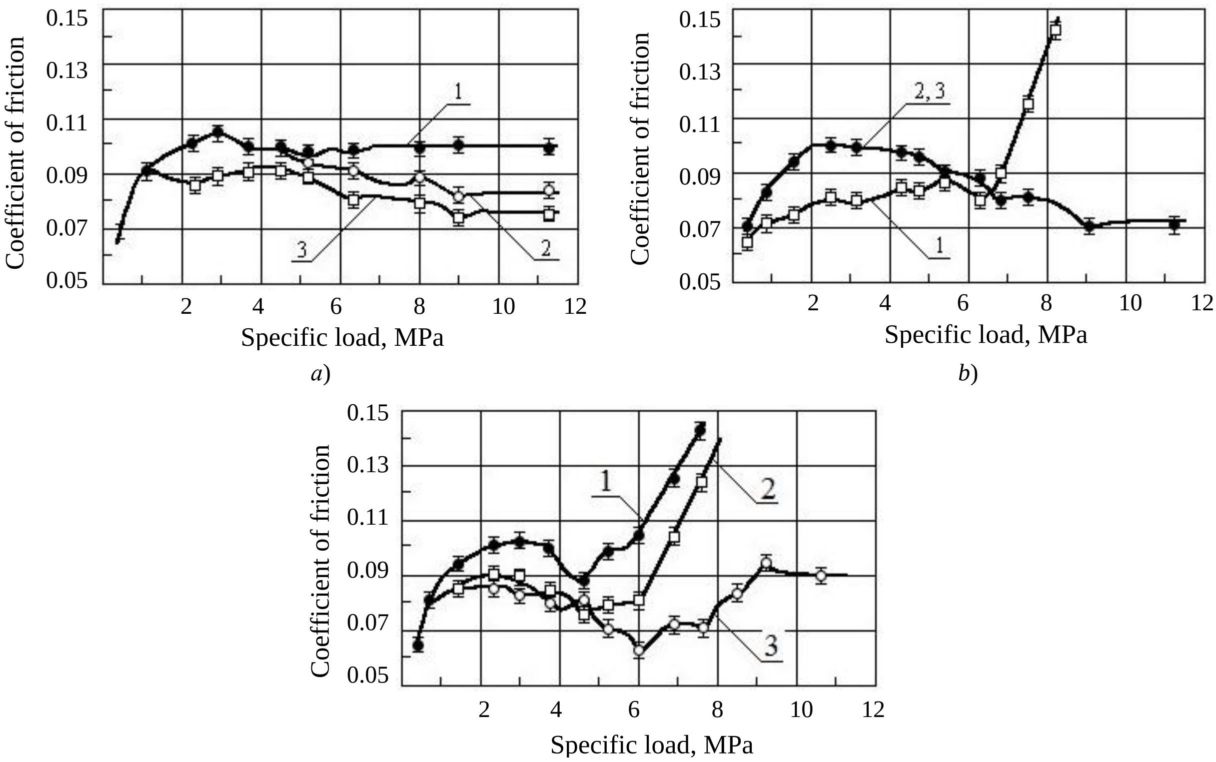


Fig. 6. Friction coefficients at contact of P18 steel with alloys AMg6 (a), D16 (b), AD31 (c) before laser treatment (curves 1), after laser hardening (curves 2), after laser alloying with tungsten carbides (curves 3)

It should be noted that in friction pairs with AD31 alloy, which has the lowest hardness, non-irradiated steel samples have a catastrophic increase in friction coefficients at specific loads of 4.5 MPa, and in laser-hardened steels at higher loads in friction pairs —6 MPa (Fig. 6 c). Only laser-alloyed samples have high adhesion resistance under these conditions [21].

The increase in adhesion resistance under laser irradiation is associated with the achievement not only of high hardness (11-11.5 GPa) of the textured surface layer, but also, as in the case of laser alloying, also with the melting of solid dispersed tungsten carbides from coatings.

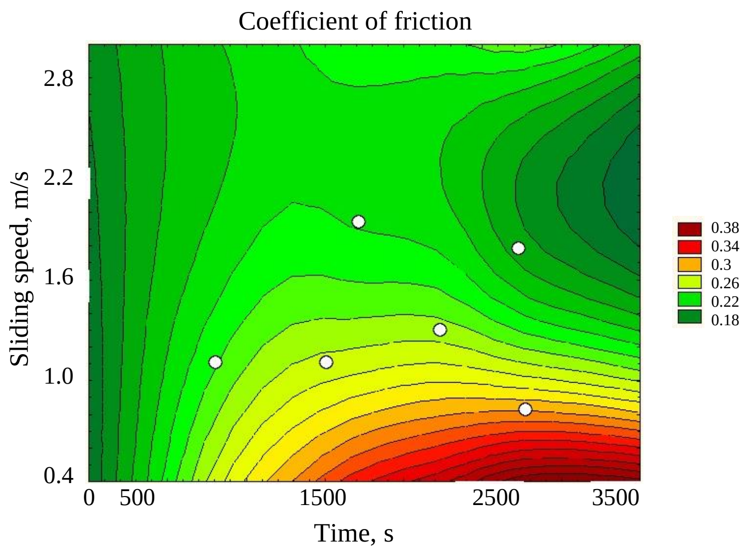


Fig. 7. Regression modeling of friction coefficient values in friction pairs "irradiated tool steel — aluminum alloy"

In order to predict and select the necessary friction coefficients that provide the specified values of wear and adhesion resistance of P18 steel in contact with aluminum alloys after laser irradiation, regression modeling of experimental results using the program *"Statistica"* was carried out (Fig. 7)

Discussion and Conclusion. It has been experimentally established that such features of the structural state of the irradiated surface layers of steels as textural effects in α-and γ-phases contribute to improving the basic properties and improving the performance of irradiated steels. This is especially significant if the texture type is consistent with the type of stress state of the hardened products under operating conditions.

It is established that it is necessary to strengthen the working surfaces of products that are in operation under the influence of compressive loads. The preferred orientation of laser treatment structures reduces the tendency of the surface layers of irradiated products to brittle destruction, reduces the friction coefficients in tribosystems compared to traditional volumetric hardening of steel by 20–30 %. At the same time, the stability of the friction coefficients during the operation of irradiated products also increases. This circumstance is important in ensuring the stationarity of processes in the friction zone, creates prerequisites for the intensification of the modes of operation of friction pairs.

The practical use of the results obtained in the work makes it possible, by purposefully selecting the schemes and parameters of the laser irradiation mode, to obtain structures on the surface that have the specified wear and adhesion resistance under external loading conditions during operation.

The possibility of increasing the structural strength and operational properties of the tool due to laser alloying from powder coatings and tempering after laser irradiation is determined.

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