Vol. 7, no. 3, 2023 eISSN 2541-9129
PEER-REVIEWED SCIENTIFIC AND PRACTICAL JOURNAL

Safety of Technogenic and Natural Systems

Technosphere Safety

Machine Building

Chemical Technologies, Materials Sciences, Metallurgy

www.bps-journal.ru
DOI 10.23947/2541-9129

Safety of Technogenic and Natural Systems

Peer-reviewed scientific and practical journal (published since 2017)

eISSN 2541-9129
DOI: 10.23947/2541-9129

Vol. 7, no. 3, 2023

The journal is created in order to highlight the results of research and real achievements on topical issues of Mechanical Engineering, Technosphere Safety, Modern Metallurgy and Materials Science. The journal highlights the problems of the development of fundamental research and engineering developments in a number of important areas of technical sciences. One of the main activities of the journal is integration into the international information space.

The journal publishes articles in the following fields of science:

Ground Transport and Technological Means and Complexes (Engineering Sciences)
Machines, Aggregates and Technological Processes (Engineering Sciences)
Metallurgical Science and Heat Treatment of Metals and Alloys (Engineering Sciences)
Powder Metallurgy and Composite Materials (Engineering Sciences)
Materials Science (Engineering Sciences)
Fire Safety (Engineering Sciences)
Environmental Safety (Engineering Sciences)
Occupational Safety (Engineering Sciences)

Indexing and archiving:	RISC, CyberLeninka, CrossRef, DOAJ, Index Copernicus, Internet Archive
Name of the body that registered the publication	Mass media registration certificate ЭЛ № ФС 77 – 66531 dated Jule, 21, 2016, issued by the Federal Service for Supervision of Communications, Information Technology and Mass Media
Founder and publisher	Federal State Budgetary Educational Institution of Higher Education Don State Technical University (DSTU).
Periodicity	Quarterly (4 issues per year)
Address of the founder and publisher	Gagarin Sq. 1, Rostov-on-Don, 344003, Russian Federation
E-mail	vestnik@donstu.ru
Telephone	+7 (863) 2–738–372
Website	https://bps-journal.ru
Date of publication	30.08.2023

Безопасность техногенных и природных систем

Рецензируемый научно-практический журнал (издается с 2017 года)

eISSN 2541-9129
DOI: 10.23947/2541-9129

Том 7, № 3, 2023

Создан в целях освещения результатов исследований и реальных достижений по актуальным вопросам машиностроения, техносферной безопасности, современной металлургии и материаловедения. В журнале освещаются проблемы развития фундаментальных исследований и инженерных разработок в ряде важнейших областей технических наук. Одним из главных направлений деятельности журнала является интеграция в международное информационное пространство.

Журнал включен в перечень рецензируемых научных изданий, в котором должны быть опубликованы основные научные результаты диссертаций на соискание ученой степени кандидата наук, на соискание ученой степени доктора наук (Перечень ВАК) по следующим научным специальностям:

2.5.11 – Наземные транспортно-технологические средства и комплексы (технические науки)
2.5.21 – Машины, агрегаты и технологические процессы (технические науки)
2.6.1 – Металловедение и термическая обработка металлов и сплавов (технические науки)
2.6.5 – Порошковая металлургия и композиционные материалы (технические науки)
2.6.17 – Материаловедение (технические науки)
2.10.1 – Пожарная безопасность (технические науки)
2.10.2 – Экологическая безопасность (технические науки)
2.10.3 – Безопасность труда (технические науки)

Индексация и архивация:	РИНЦ, CyberLeninka, CrossRef, DOAJ, Index Copernicus, Internet Archive
Наименование органа, зарегистрировавшего издание	Свидетельство о регистрации средства массовой информации ЭЛ № ФС 77 – 66531 от 21 июля 2016 г., выдано Федеральной службой по надзору в сфере связи, информационных технологий и массовых коммуникаций
Учредитель и издатель	Федеральное государственное бюджетное образовательное учреждение высшего образования «Донской государственный технический университет» (ДГТУ).
Периодичность	4 выпуска в год
Адрес учредителя и издателя	344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1.
E-mail	vestnik@donstu.ru
Телефон	+7 (863) 2–738–372
Сайт	https://bps-journal.ru
Дата выхода в свет	30.08.2023

Contents

Содержание

TECHNOSPHERE SAFETY
ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

UDC 614.84

Original article

https://doi.org/10.23947/2541-9129-2023-7-3-7-13

Thermal Stability of Cadmium Telluride in Infrared Detectors for Monitoring Fire Conditions

Aleksandr V. Mozzherin ✉, **Nikolay N. Paklin**

Siberian Federal University, Krasnoyarsk, Russian Federation

✉ Amozzherin@sfu-kras.ru

Abstract

Introduction. Thermal effect of fire on technical means is a common and serious problem. In this regard, it seems an urgent task to study physicochemical and thermal transformations in devices based on cadmium telluride during man-made or natural fires. For a number of materials, such studies have not been conducted, and the available results are insufficient or narrowly focused. The proposed article presents new data on the defect resistance and applicability of the material depending on the thermal effect. The work objective is to study the features of degradation under the influence of extreme temperatures to create new materials with specified properties.

Materials and Methods. Cadmium telluride (CdTe) samples used in solar panels and detectors were studied. In the practical part of the work, the thermal effect on the sample of normal and extreme temperatures was evaluated, followed by the study of the material by transmission electron microscopy methods. The experiments simulated a zone of thermal impact of a fire. The computational and theoretical work consisted in improving the mathematical model of physical and chemical transformations and the evolution of defects under thermal influence up to 1092 °C. The mathematical model took into account the heat dose characteristic of uncontrolled combustion. The Maple software package was used to solve the equations.

Results. The formation of defects in a CdTe sample at significantly different levels of thermal exposure was visualized. The lower limit was about 20 °C, the upper one was more than 600 °C. Transformations in CdTe control samples under the influence of temperatures up to 1092 °C with a step of 15 °C were worked out in detail. Point defects caused by the influence of temperature were presented as a factor of destruction of the material, and consequently, failures in the operation of the device. A system of equations was solved that takes into account a set of parameters: the frequency of vibrations of atoms in the lattice, temperature, concentrations of CdTe nodes, interstitial atoms and vacancies, migration and attachment of interstitial atoms and vacancies. The concentrations of vacancies and interstitial atoms in CdTe samples depending on thickness and temperature were graphically presented. The results of scientific research allowed us to assert that CdTe-based detectors worked relatively correctly only at a heat dose of up to 400 °C. In the ranges of 400-600 °C, the defective network of the material actively evolved, preventing destruction. However, a further increase in thermal exposure led to complete degradation of the equipment, which did not allow the use of cadmium telluride in extreme conditions, even for a short time.

Discussion and Conclusion. The proposed improved model of physical and chemical transformations in CdTe-based devices in heat-affected areas will allow a more selective approach to the use of equipment. In addition, it is necessary to improve materials and increase their resistance to extreme temperatures.

Keywords: cadmium telluride, formation of defects in a CdTe sample, density of nodes, vacancy concentration, CdTe interstitial atoms

Acknowledgements: the authors express their gratitude to colleagues from the Laboratory of Nanodisperse and Composite Materials of the Federal Research Center "Krasnoyarsk Science Center of the Siberian Branch of the Russian Academy of Sciences". In addition, the authors would like to thank the Editorial Team of the Journal and the Reviewer for attentive attitude to the article and suggestions made that helped to improve its quality.

For citation. Mozzherin AV, Paklin NN. Thermal Stability of Cadmium Telluride in Infrared Detectors for Monitoring Fire Conditions. *Safety of Technogenic and Natural Systems*. 2023;7(3):7–13. https://doi.org/10.23947/2541-9129-2023-7-3-7-13

Научная статья

Теплоустойчивость теллурида кадмия в инфракрасных детекторах для мониторинга пожарной обстановки

А.В. Мозжерин ✉, **Н.Н. Паклин**

Сибирский федеральный университет, г. Красноярск, Российская Федерация

✉ Amozzherin@sfu-kras.ru

Аннотация

Введение. Тепловое воздействие пожара на технические средства — распространенная и серьезная проблема. В этой связи представляется актуальной задачей исследование физико-химических и тепловых превращений в устройствах на основе теллурида кадмия при техногенных или природных пожарах. По ряду материалов подобные исследования не проводились, а имеющиеся результаты недостаточны или узкопрофильны. В предложенной статье представлены новые данные по дефектостойкости и применимости материала в зависимости от теплового воздействия. Цель исследования — изучение особенностей деградации под воздействием экстремальных температур для создания новых материалов с заданными свойствами.

Материалы и методы. Исследовались образцы теллурида кадмия (CdTe), используемые в солнечных панелях и детекторах. В практической части работы оценивалось тепловое воздействие на образец обычных и экстремальных температур с последующим изучением материала методами просвечивающей электронной микроскопии. Эксперименты имитировали зону теплового воздействия пожара. Расчетно-теоретическая работа заключалась в совершенствовании математической модели физико-химических превращений и эволюции дефектов при тепловом воздействии до 1092 °C. Математическая модель учитывала теплодозу, характерную для неуправляемого горения. Для решения уравнений задействовали программный пакет Maple.

Результаты исследования. Визуализировано формирование дефектов в образце CdTe при существенно разных уровнях теплового воздействия. Нижняя граница — около 20 °C, верхняя — более 600 °C. Детально проработаны превращения в контрольных образцах CdTe при воздействии температуры до 1092 °C с шагом 15 °C. Точечные дефекты, обусловленные воздействием температуры, представлены как фактор разрушения материала, а следовательно, и сбоев в работе устройства. Решена система уравнений, которая учитывает комплекс параметров: частоту колебаний атомов в решетке, температуру, концентрации узлов CdTe, междоузельных атомов и вакансий, миграцию и присоединение междоузельных атомов и вакансий. Графически представлены концентрации вакансий и междоузельных атомов в образцах CdTe в зависимости от толщины и температуры. Итоги научных изысканий позволяют утверждать, что детекторы на основе CdTe относительно корректно работают только при теплодозе до 400 °C. В диапазонах 400–600 °C дефектная сеть материала активно эволюционирует, препятствуя разрушению. Однако дальнейшее увеличение теплового воздействия приводит к полной деградации оборудования, что не позволяет использовать теллурид кадмия в экстремальных условиях даже непродолжительное время.

Обсуждение и заключение. Предложенная усовершенствованная модель физико-химических превращений в устройствах на основе CdTe в зонах теплового воздействия позволит более избирательно подходить к вопросу использования оборудования. Кроме того, необходимо совершенствовать материалы и повышать их стойкость к экстремальным температурам.

Ключевые слова: теллурид кадмия, формирование дефектов в образце CdTe, концентрация узлов, концентрация вакансий, междоузельные атомы CdTe

Благодарности: авторы выражают признательность коллегам из лаборатории нанодисперсных и композиционных материалов ФГБНУ «ФИЦ КНЦ СО РАН». Кроме того, благодарим редакционную команду журнала и рецензента за компетентную экспертизу и ценные рекомендации по улучшению статьи.

Для цитирования. Мозжерин А.В., Паклин Н.Н. Теплоустойчивость теллурида кадмия в инфракрасных детекторах для мониторинга пожарной обстановки. *Безопасность техногенных и природных систем*. 2023;7(3):7–13. https://doi.org/10.23947/2541-9129-2023-7-3-7-13

Introduction. Cadmium telluride (CdTe) is a binary chemical compound of cadmium (Cd) and tellurium (Te), a direct-band semiconductor of the A_2B_6 group. Due to its high melting point and insolubility, it is one of the most stable Cd compounds. CdTe is a strategically important material for creating thin-film solar cells, universal infrared detectors and other devices.

An important issue from the point of view of production practice is the operation of devices and equipment in various environmental conditions, their durability and fire and explosion safety[1]. It is well known that any semiconductor compound tends to degrade and change its physicochemical properties. This is due to the processes of defect formation, which occur, among other things, due to thermal exposure [1]. It is extremely important to understand these processes for the use of materials in extreme conditions while maintaining the specified properties, with minimal risk of fires, accidents and other emergencies.

It should be noted that so far scientific research in this area has not yielded exhaustive results. Studies have not been conducted on a number of materials, and the available data are insufficient or narrow-profile. The authors of the presented article offer new information concerning the resistance to defects and the applicability of the material experiencing thermal effects. The work objective is to study the features of degradation under extreme temperatures to create new materials with specified properties.

Materials and Methods. The operation of the device was studied in the event of extreme events — a natural or man-made fire. The objects of the study were three control samples of cadmium telluride. They were removed from the solar battery and subjected to constant thermal exposure from 20 °C to 1092 °C. Table 1 presents the general data of the studied materials.

Table 1

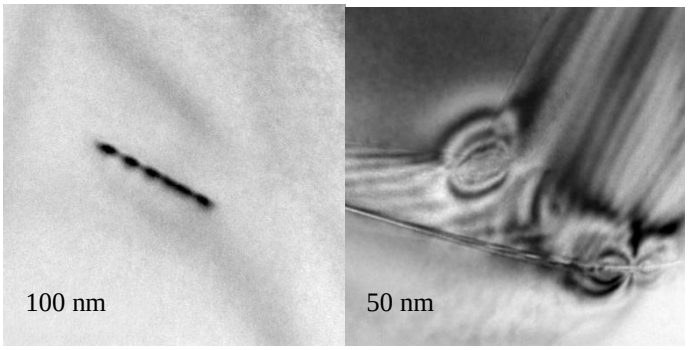
Individual properties and characteristics of cadmium telluride [2–4]

Chemical formula	CdTe
Density, g/cm^3	5.8585
Melting point, °C	1092
Solubility in water and other solvents	Insoluble
Crystal structure	Cubic, sphalerite (zinc blende)
Lattice parameter, nm	0.648
Poisson's ratio, υ	0.41
Shear modulus, GPa	9.2
Stacking fault energy, MJ/m^2	11±1.9
Fire and explosion safety	Incombustible
Toxicity	Toxic, especially dangerous in the aquatic

[1] GOST 2.1.004-91. *Occupational safety standards system. Fire safety. General requirements.* Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/9051953 (accessed: 17.04.2023).

Basic experimental study was carried out by transmission electron microscopy on a JEOL JEM-2100 device with preliminary sample preparation of samples according to basic techniques [5]. Theoretical work was based on the creation of a mathematical model of physical-chemical transformations in devices based on cadmium telluride, taking into account the heat transfer that occurs during the development of the uncontrolled combustion process. Systems of equations were solved in the Maple software package.

Results. The experimental part of the work was described in [2, 4]. The data obtained showed that the effect of thermal radiation led to the formation and active evolution of a defective network (Fig. 1), represented mainly by growth dislocations. In some cases, in the presence of cadmium or other substances in the atmosphere, precipitates appeared with the transformation of dislocations into dislocation loops or stacking faults [3, 6–7].



a) *b*)

Fig. 1. Formation of defects in the CdTe sample under thermal exposure:
a — ~ 20 °C; *b* — more than 600 °C. Scale in nanometers

Theoretical part of the study included a detailed study of transformations in CdTe control samples when exposed to temperatures up to 1092 °C in increments of 15 °C. With this type of operation of the devices, especially near the melting point, the destruction of the material occurred, which was directly related to the formation and development of point defects.

Taking into account the fixation of the temperature mode and previous experimental data, the formation of interstitial atoms and vacancies, as well as their clusters in the form of dislocation loops and pores in CdTe, was modeled. The effective values of the energy of thermal dissociation of the lattice (E_p) and the coefficient of thermal generation of point defect pairs (P) allowed us to improve the system of equations for the equilibrium distribution of defects, given in [8–9] to the following form:

$$\begin{aligned} Pc_0 + D_I \cdot C_I'' - R \cdot C_I \cdot C_V - 2A_I \cdot C_I^2 = 0, \\ Pc_0 + D_V \cdot C_V'' - R \cdot C_I \cdot C_V - 2A_V \cdot C_V^2 = 0, \end{aligned} \quad (1)$$

where $P = \nu \cdot \exp(-E_p/kT)$, ν — frequency of oscillation of atoms in the lattice, k — the Boltzmann constant, T — temperature, c_0 — concentration of CdTe nodes, C_I and C_V — effective concentrations of interstitial atoms and vacancies, D_I and D_V — diffusion coefficient (migration) of interstitial atoms and vacancies, A_I and A_V — agglomeration coefficient (joining) of interstitial atoms and vacancies, respectively, R — recombination coefficient.

Numerical values of the indicated values were used for calculations (Table 2).

Table 2

Numerical values of the parameters of the cadmium telluride crystal [3, 8–9]

c_0	D_I	D_V	A_I	A_V	R	ν	E_p	P
cm^{-3}	cm^2s^{-1}	cm^2s^{-1}	cm^3s^{-1}	cm^3s^{-1}	cm^3s^{-1}	s^{-1}	eV	cm^3s^{-1}
$1.5 \cdot 10^{22}$	$4.2 \cdot 10^{7}$	$8.3 \cdot 10^{2}$	$7.5 \cdot 10^{4}$	$1.1 \cdot 10^{4}$	$1.7 \cdot 10^{8}$	10^{13}	1.4	$2.6 \cdot 10^{-11}$

Solution to system of equations (1) is shown in Fig. 2, 3. As noted above, the upper curve corresponds to 1092 °C, the step is 15 °C.

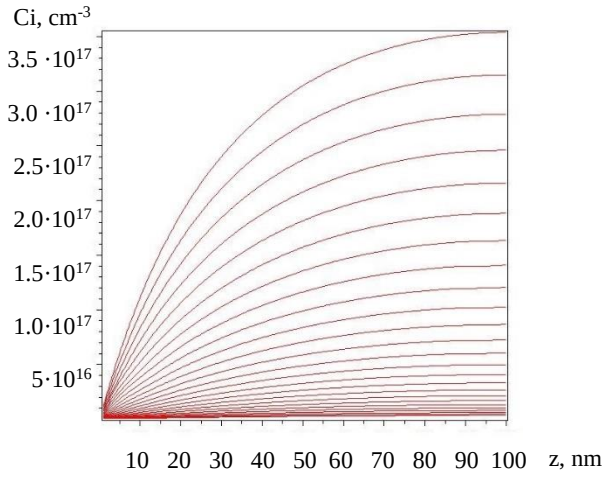


Fig. 2. Vacancy concentrations in CdTe samples depending on thickness (z) at different temperatures

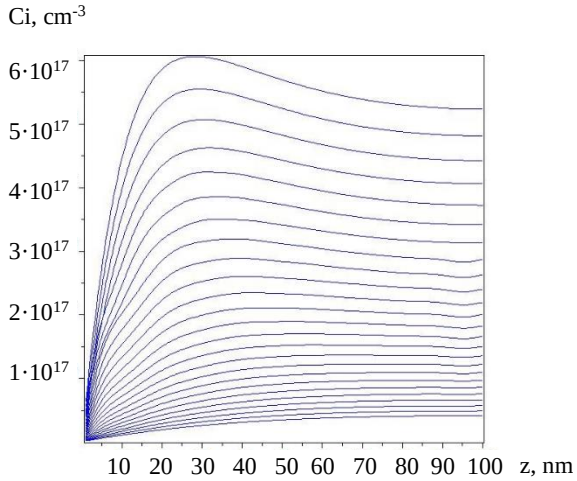


Fig. 3. Concentrations of interstitial atoms in CdTe samples depending on thickness (z) at different temperatures

The data obtained allowed us to assert that up to a temperature of 400 °C, point defects (vacancies and voids) affected the physicochemical properties weakly, with a linear increase. When the specified boundary increased, nonlinear changes were recorded. This could be explained by the reverse effect of defects (countering the destruction of the semiconductor). Active degradation was especially noticeable at temperatures above 600 °C. Under the influence of a temperature of 1000 °C, cadmium telluride began to break down.

Discussion and Conclusion. The presented study confirmed active physical-chemical transformations in cadmium telluride samples at equilibrium thermal exposure up to 1092 °C. The results of solving modified system of equations (1) allow us to assert that with increasing temperature, the destruction in cadmium telluride samples increases, and the defective network grows. These processes cause equipment failure with this material.

Devices and equipment based on cadmium telluride show high thermal stability and reliable operation up to 100 °C. However, their use is limited and becomes extremely ineffective at high temperatures. In extreme conditions, semiconductor materials such as silicon and germanium are more suitable.

References

1. Glas F. A simple calculation of energy changes upon stacking fault formation or local crystalline phase transition in semiconductors. *Journal of Applied Physics*. 2008;104(9):093520. https://doi.org/10.1063/1.3009338

2. Mozzherin AV, Paklin NN. Defektoobrazovanie v telluride kadmiya. In: *Tr. XXV Mezhdunar. nauch.-prakt. konf., posvyashchennoi pamyati general'nogo konstruktora raketno-kosmicheskikh sistem akademika M.F. Reshetneva.* Krasnoyarsk: Reshetnev Siberian State University of Science and Technology; 2021. P. 581–582.

3. Loginov YuYu, Braun PD, Dyurouz K. *Zakonomernosti obrazovaniya strukturnykh defektov v poluprovodnikakh A_2B_6*. Moscow: Logos; 2003. 304 p.

4. Loginov YuYu, Mozsherin AV, Brilikov AV. The electron microscopic study of the defect formation in the doped single crystals CdTe, ZnS and ZnSe. *Vestnik Sibirskogo gosudarstvennogo aerokosmicheskogo universiteta imeni akademika M.F. Reshetneva.* 2013;3(49):209–211. https://vestnik.sibsau.ru/en_US/vestnik/902/ (accessed: 25.07.2023).

5. Sindo D, Oikava T. *Analiticheskaya prosvechivayushchaya elektronnaya mikroskopiya.* Moscow: Tekhnosfera; 2006. 256 p. URL: https://www.technosphera.ru/lib/book/83 (accessed: 25.07.2023).

6. Loginov YY, Mozzherin AV, Paklin NN. Particularities of the interstitial atoms and vacancies clusters formation in a thin cadmium telluride foil during in situ electron irradiation in a TEM. *IOP Conference Series: Materials Science and Engineering*. 2022;1230:012013. https://doi.org/10.1088/1757-899X/1230/1/012013

7. Gorichok IV. Enthalpy of formation of schottky defects in semiconductors. *Physics of the Solid State*. 2012;54(7);1373–1376. URL: http://journals.ioffe.ru/articles/viewPDF/665 (accessed: 25.07.2023).

8. Loginov YuYu, Mozzherin AV, Paklin NN. Modeling structural defect formation in cadmium telluride during electron irradiation. *IOP Conference Series: Materials Science and Engineering*. 2019;467:012007. https://doi.org/10.1088/1757-899X/467/1/012007

9. Paklin NN, Loginov YuYu, Mozzherin AV. Equilibrium distribution of defects in cadmium telluride before exposure to external factors. *The Siberian Aerospace Journal*. 2022;23(2):315–320. https://doi.org/10.31772/2712-8970-2022-23-2-315-320

Received 28.07.2023

Revised 08.08.2023

Accepted 11.08.2023

About the Authors:

Aleksandr V. Mozzherin, Cand. Sci. (Phys.-Math.), Associate Professor of the UNESCO New Materials and Technologies Department, Siberian Federal University (79, Svobodny Ave., Krasnoyarsk Territory, Krasnoyarsk, 660041, RF), AuthorID, ORCID, Amozzherin@sfu-kras.ru

Nikolay N. Paklin, Cand. Sci. (Phys.-Math.), Associate Professor of the Theoretical Physics and Wave Phenomena Department, Siberian Federal University (79, Svobodny Ave., Krasnoyarsk Territory, Krasnoyarsk, 660041, RF), ORCID, AuthorID, Npaklin@sfu-kras.ru

Claimed contributorship:

The authors have made an equal contribution to the formulation of research objectives and goals, conducting experiments, calculations, drawing conclusions and correcting the text of the article.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 28.07.2023

Поступила после рецензирования 08.08.2023

Принята к публикации 11.08.2023

Об авторах:

Александр Владимирович Мозжерин, кандидат физико-математических наук, доцент кафедры ЮНЕСКО новых материалов и технологий Сибирского федерального университета (660041, РФ, Красноярский край, г. Красноярск, пр. Свободный, 79), AuthorID, ORCID, Amozzherin@sfu-kras.ru

Николай Николаевич Паклин, кандидат физико-математических наук, доцент кафедры теоретической физики и волновых явлений Сибирского федерального университета (660041, РФ, Красноярский край, г. Красноярск, пр. Свободный, 79), ORCID, AuthorID, Npaklin@sfu-kras.ru

Заявленный вклад соавторов:

Авторы внесли равноценный вклад в постановку задач и цели исследования, проведение экспериментов, расчеты, формулирование выводов и корректировку текста статьи.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

TECHNOSPHERE SAFETY
ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

UDC 620.193-047.42(075.8)
https://doi.org/10.23947/2541-9129-2023-7-3-14-23

Original article

Properties of Salicylidene-Aniline as a Corrosion Inhibitor in Oil and Petroleum Products Transportation Systems

Sergey G. Kuren ✉[1], **Svetlana A. Volyanik**[2], **Mariya A. Savenkova**[2], **Elvira A. Zaitseva**
[1] Don State Technical University, Rostov-on-Don, Russian Federation
[2] Rostov State Transport University, Rostov-on-Don, Russian Federation
[3] Southern Federal University, Rostov-on-Don, Russian Federation
✉ sergejgrigorevich@yandex.ru

Abstract

Introduction. Risks of accidents and fires during transportation and pumping of oil and petroleum products is a significant problem of technosphere safety. The reasons may be leaks due to corrosion damage to pipelines, tanks and oil storage tanks. In view of the possible serious financial, environmental and social consequences of such incidents, it is important to constantly seek new, more effective approaches to preventing corrosion processes. It is obvious, for example, that at present not all chemical compounds capable of suppressing or inhibiting the destruction of metals and alloys have been thoroughly studied. The presented scientific work is partly aimed at overcoming the lack of data in this area. The objective is to investigate an insufficiently studied compound salicylidene-aniline, which can be a corrosion inhibitor similar to other nitrogen-containing compounds similar in structure and composition.

Materials and Methods. The gravimetric method was used to study the inhibitory, adsorption and complexing properties of salicylidene-aniline. The experiments were carried out with St3 steel plates. The mass of metal samples without an inhibitor and with an inhibitor was recorded before and after exposure in the test media. The effect was determined by the change in the corrosion rate. When setting up experiments, the authors were guided by GOST 9.905–82 "Unified system of corrosion and ageing protection. Corrosion test methods. General requirements". The volume of the corrosive medium was determined according to GOST 9.506–87 "Unified system of corrosion and ageing protection. Corrosion inhibitors of metals in water-petroleum media. Methods of protective ability evaluation". The corrosion criteria were taken from GOST 9.908–85 "Unified system of corrosion and ageing protection. Metals and alloys. Methods for determination of corrosion and corrosion resistance indices". The calculations were based on the valuation principle, which sets the ratio of a multiplicative metrized linear order on a set of particular criteria. An integral indicator based on mathematical and methodological approaches was used for ranking.

Results. The effect of hydrochloric acid medium on steel samples St3 was studied. Four concentrations of the inhibitor were taken: 0 %, 0.01 %, 0.1 %, and 0.2 %. The mass of metal samples without an inhibitor and with an inhibitor was recorded before and after exposure in the test media. The effect was determined by the change in the corrosion rate. The mass index of corrosion was calculated. The surface quality during destruction and corrosion inhibition was determined in five stages: the elements to be evaluated were selected, the purpose of the evaluation was formulated, the elements of the technical condition of the object under study were found, the essence of determining the usefulness or value of the criterion was described, and the essence of optimization was explained. The studied properties were ranked with respect to the multiplicative metrized linear order on a set of particular criteria. For the calculations, the task was set — to determine the components of vector B in accordance with one of the evaluation stages. We are talking about the stage when the usefulness or value of the criterion is analyzed by points on the numerical axis indicating the state of the object "better — worse". We constructed an indicator z approximating a known or specified (learning) matrix of

paired relationships between objects. The resulting indicator allowed us to assess the technical condition of the surface during the course of corrosion and when it slowed down due to the addition of salicylidene-aniline. The result was obtained for samples with a surface area from $10.1 \cdot 10^{-4}$ m^2 to $11.9 \cdot 10^{-4}$ m^2. During the experiment, the mass of the metal decreased by 0.2–0.8 times with the inhibitor and almost by 3.5 times without it. The mass index of corrosion was recorded from 0.15 g/m^2·h to 0.48 g/m^2·h. At the same time, the protective ability of the inhibitor was quite high: the minimum was 77.4 %, the maximum was 94.8 %. This is a convincing indicator. It is also worth mentioning such an advantage of salicylidene-aniline as a low danger. Its hazard class is III (for comparison: the hazard class of aniline is a level higher — II).

Discussion and Conclusion. The authors propose to use salicylidene-aniline as a means to increase the safe service life of oil pipelines and tanks. The potential of this composition as an effective corrosion inhibitor, highly soluble in oil and petroleum products, has been proven. Such properties of salicylidene-aniline as slow oxidation and moderate toxicity are noted

Keywords: inhibitory properties of salicylidene-aniline, protective ability of the inhibitor, inhibitory additives, ability to complex formation, inhibitor concentration

Acknowledgements: the authors would like to thank the Editorial Board of the journal and the Reviewer for their professional analysis and suggestions made that helped to improve its quality. The authors also express special gratitude to their colleague MM Zaitseva, associate professor, Cand. Sci. (Eng.) for a significant contribution to the discussion of the results and valuable comments in the design of this work.

For citation. Kuren SG, Volyanik SA, Savenkova MA, Zaitseva EA. Properties of Salicylidene-Aniline as a Corrosion Inhibitor in Oil and Petroleum Products Transportation Systems. *Safety of Technogenic and Natural Systems*. 2023;7(3):14–23. https://doi.org/10.23947/2541-9129-2023-7-3-14-23

Научная статья

Свойства салицилиден-анилина как ингибитора коррозии в системах транспортировки нефти и нефтепродуктов

С.Г. Курень ✉[1], **С.А. Воляник**[2], **М.А. Савенкова**[2], **Э.А. Зайцева**[3]

[1] Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

[2] Ростовский государственный университет путей сообщения, г. Ростов-на-Дону, Российская Федерация

[3] Южный федеральный университет, г. Ростов-на-Дону, Российская Федерация

✉sergejgrigorevich@yandex.ru

Аннотация

Введение. Значимая проблема техносферной безопасности — риски аварий и пожаров при транспортировке и перекачке нефти и нефтепродуктов. Причинами могут быть утечки из-за коррозионных повреждений трубопроводов, цистерн, резервуаров нефтехранилищ. Ввиду возможных серьезных финансовых, экологических и социальных последствий таких происшествий важно постоянно изыскивать новые, более эффективные, подходы к предотвращению коррозионных процессов. Очевидно, например, что в настоящее время досконально изучены далеко не все химические соединения, способные подавлять или тормозить разрушение металлов и сплавов. Представленная научная работа призвана отчасти преодолеть недостаток данных в этой области. Цель — исследовать малоизученное соединение салицилиден-анилин, которое может быть ингибитором коррозии аналогично другим, сходным по строению и составу азотсодержащим составам.

Материалы и методы. Для исследования ингибиторных, адсорбционных и комплексообразующих свойств салицилиден-анилина использовали гравиметрический метод. Проводили опыты с пластинами из стали Ст3. Фиксировалась масса металлических образцов без ингибитора и с ингибитором до и после выдержки в испытуемых средах. Эффект определяли по изменению скорости коррозии. При постановке экспериментов ориентировались на ГОСТ 9.905–82 «Единая система защиты от коррозии и старения. Методы коррозионных

испытаний». Объем коррозионной среды определили по ГОСТу 9.506–87 «Единая система защиты от коррозии и старения. Ингибиторы коррозии металлов в водно-нефтяных средах». Критерии коррозии взяли из ГОСТа 9.908–85 «Металлы и сплавы. Методы определения показателей коррозии и коррозионной стойкости». Расчеты основывались на принципе оценивания, который задает отношение мультипликативного метризованного линейного порядка на множестве частных критериев. Для ранжирования использовали интегральный показатель, основанный на математическом и методическом подходах.

Результаты исследования. Изучено воздействие солянокислой среды на образцы стали Ст3. Брали четыре концентрации ингибитора: 0 %, 0,01 %, 0,1 %, 0,2 %. Зафиксировали массу металлических образцов без ингибитора и с ингибитором до и после выдержки в испытуемых средах. Эффект определили по изменению скорости коррозии. Рассчитали массовый показатель коррозии. Качество поверхности при разрушении и ингибировании коррозии определяли в пять этапов: выбрали оцениваемые элементы, сформулировали цель оценивания, нашли элементы технического состояния исследуемого объекта, описали суть определения полезности или ценности критерия, пояснили суть оптимизации. Исследуемые свойства ранжировали по отношению мультипликативного метризованного линейного порядка на множестве частных критериев. Для расчетов поставили задачу — определить компоненты вектора B в соответствии с одним из этапов оценки. Речь идет о стадии, когда полезность или ценность критерия анализируется по точкам на числовой оси, указывающим на состояние объекта «лучше — хуже». Построили показатель z, аппроксимирующий известную или задаваемую (обучающую) матрицу парных взаимосвязей между объектами.

Полученный в итоге показатель позволяет оценивать техническое состояние поверхности в процессе протекания коррозии и при ее замедлении за счет добавления салицилиден-анилина. Получен результат для образцов с площадью поверхности от $10{,}1 \cdot 10^{-4}$ м^2 до $11{,}9 \cdot 10^{-4}$ м^2. За время эксперимента масса металла уменьшалась в 0,2–0,8 раза с ингибитором и почти в 3,5 раза без него. Фиксировался массовый показатель коррозии от 0,15 г/м^2·ч до 0,48 г/м^2·ч. При этом защитная способность ингибитора оказалась достаточно высокой: минимальная — 77,4 %, максимальная — 94,8 %. Это убедительный показатель. Стоит также упомянуть такое преимущество салицилиден-анилина, как невысокая опасность. Класс его опасности — III (для сравнения: класс опасности анилина на уровень выше — II).

Обсуждение и заключение. Предлагается использовать салицилиден-анилин как средство, повышающее срок безопасной службы нефтепроводов и цистерн. Доказан потенциал этого состава как эффективного ингибитора коррозии, хорошо растворимого в нефти и нефтепродуктах. Отмечены такие свойства салицилиден-анилина, как медленное окисление и умеренная токсичность.

Ключевые слова: игибиторные свойства салицилиден-анилина, защитная способность ингибитора, ингибирующие добавки, способность к комплексообразованию, концентрация ингибитора

Благодарности: авторы выражают благодарность редакционной коллегии журнала и рецензенту за профессиональный анализ и рекомендации для корректировки статьи. Авторы также выражают особую благодарность коллеге Зайцевой М.М., доценту, кандидату технических наук, за значительный вклад в обсуждение результатов и ценные замечания при оформлении данной работы.

Для цитирования. Курень С.Г., Воляник С.А., Савенкова М.А. Зайцева Э.А. Свойства салицилиден-анилина как ингибитора коррозии в системах транспортировки нефти и нефтепродуктов. *Безопасность техногенных и природных систем*. 2023;7(3):14–23. https://doi.org/10.23947/2541-9129-2023-7-3-14-23

Introduction. Transportation and storage of aggressive liquids, including oil and petroleum products, generate risks of accidents with severe consequences. Special attention needs to be paid to the condition of pipes and tanks and the possibility of their damage. Oil pipelines, railway tanks and tank trucks are constantly in contact with an aggressive environment. They are made of steel, which raises the question of preventing or slowing down corrosion processes. The consequences of such destruction can be accidents and catastrophes accompanied by fires and explosions.

Corrosion inhibitors can be nitrogen-containing organic bases, primarily aliphatic and aromatic amines and their derivatives [1–3]. Azomethines are derivatives of amines. They are promising as weakly basic inhibitors (pKa bases are 1–2 orders of magnitude smaller than those of the initial amines).

Aniline (phenylamine) $C_5H_5NH_2$ is used, in particular, to increase the anti-detonation of fuel. With 1 % of aniline, the octane number of gasoline increases by 3–4 points. However, it is better not to use aniline in its pure form. During long-term storage, such an additive is oxidized, which reduces the quality of gasoline. Aniline derivatives, such as phosphates, are added to solutions of strong electrolytes to inhibit corrosion of carbon steel.

The hazard class of aniline is II (highly hazardous substance), and the hazard class of salicylidene-aniline is III (moderately hazardous). The lesser danger of salicylidene-aniline is a convincing reason for a close study of its anticorrosive properties. In addition, the known protective capabilities of heteroaromatic compounds on the example of piperidines have unequivocally confirmed their qualities as inhibitors of acid corrosion of non-alloy steel St3 [3]. At the same time, poorly soluble substances are formed in interaction with positively charged ions of the corroding metal. They are deposited in the form of ultrathin films (no more than 10 nm) and protect against further corrosion damage.

Anticorrosive protective chemicals are used as inhibitory additives — additives to aggressive media and in combination with protective coatings [2–3]. Complexing agents with anticorrosive properties: complexones (for example, sodium ethylenediaminetetraacetate (trilon B) $Na,H(OOCCH_2)_2N — (CH_2)_2 — N(CH_2COO)_2 Na,H$), various complex compounds of d-elements and mixtures based on them. The leading place in this group is occupied by phosphonates of alkaline and alkaline-earth metals [1–5].

The other group includes nitrogen- and sulfur-containing heterocycles. Nitrogen-containing compounds form less toxic products of interaction with a corrosive environment, therefore they are preferable for the development and creation of effective anticorrosive additives [3].

Quaternary ammonium salts of aliphatic and heteroaromatic nitrogenous bases, including derivatives of alcohols, aldehydes, and carboxylic acids, have proven themselves well as protective anticorrosive agents for St3 steel. They dissolve well and are stable in working environments, act in a large pH range [6].

At the same time, in view of the potential serious financial, environmental and social threats associated with corrosion of oil and petroleum products transportation systems, more effective approaches to preventing destructive processes should be continuously sought. It is obvious, for example, that not all chemical compounds capable of suppressing or inhibiting the destruction of metals and alloys have been thoroughly studied. The presented scientific work is to supplement the data in this area.

The study objective is to create compositions with high anticorrosive properties based on aniline derivatives and compounds of the azomethine class. An aniline derivative is a representative of the class of azomethines-salicylidene-aniline. We believe that this composition or compositions based on it should be used as a corrosion inhibitor of steel, which will eventually increase the safety of transportation of oil and petroleum products.

Materials and Methods. The following features of salicylidene-aniline were studied:

– inhibitory properties;

– anticorrosive activity;

– ability to complex formation;

– adsorption capabilities.

Inhibitor molecules form a contact layer on the metal surface due to the donor-acceptor bond between the electron pairs of nitrogen atoms and the free d-orbitals of the complexing agent atom (in this case, iron). Such compounds form a stronger film than many other inhibitors. As a result, micro-galvanic vapors are formed on the surface of the steel and anodic and cathodic depolarization occurs, due to which the protective properties of the inhibitor are manifested.

The gravimetric research method was used in work [1]. It is based on fixing the mass of metal samples without an inhibitor and with an inhibitor before and after the exposure in test media. The anticorrosive activity of the tested compound is estimated by the change in the corrosion rate. For each sample, the holding time in an inhibited medium is equal to the time in an environment without an anticorrosive agent [1–3].

The authors of the research used plates made of steel grade St3 according to GOST 9.905–82 "Unified system of corrosion and ageing protection. Corrosion test methods. General requirements". The volume of the corrosive medium (0.25n HCl) is 30 cm^3 in accordance with GOST 9.506–87 "Unified system of corrosion and ageing protection. Corrosion inhibitors of metals in water-petroleum media. Methods of protective ability evaluation". 0 %, 0.01 %, 0.1 % and 0.2 % salicylidene-aniline were added in the medium. Corrosion criteria was according to GOST 9.908–85 "Unified system of corrosion and ageing protection. Metals and alloys. Methods for determination of corrosion and corrosion resistance indices".

Results. The effect of hydrochloric acid medium on steel samples was considered. The results were recorded taking into account different concentrations of salicylidene-aniline and thus the anticorrosive effect was determined (Fig. 1).

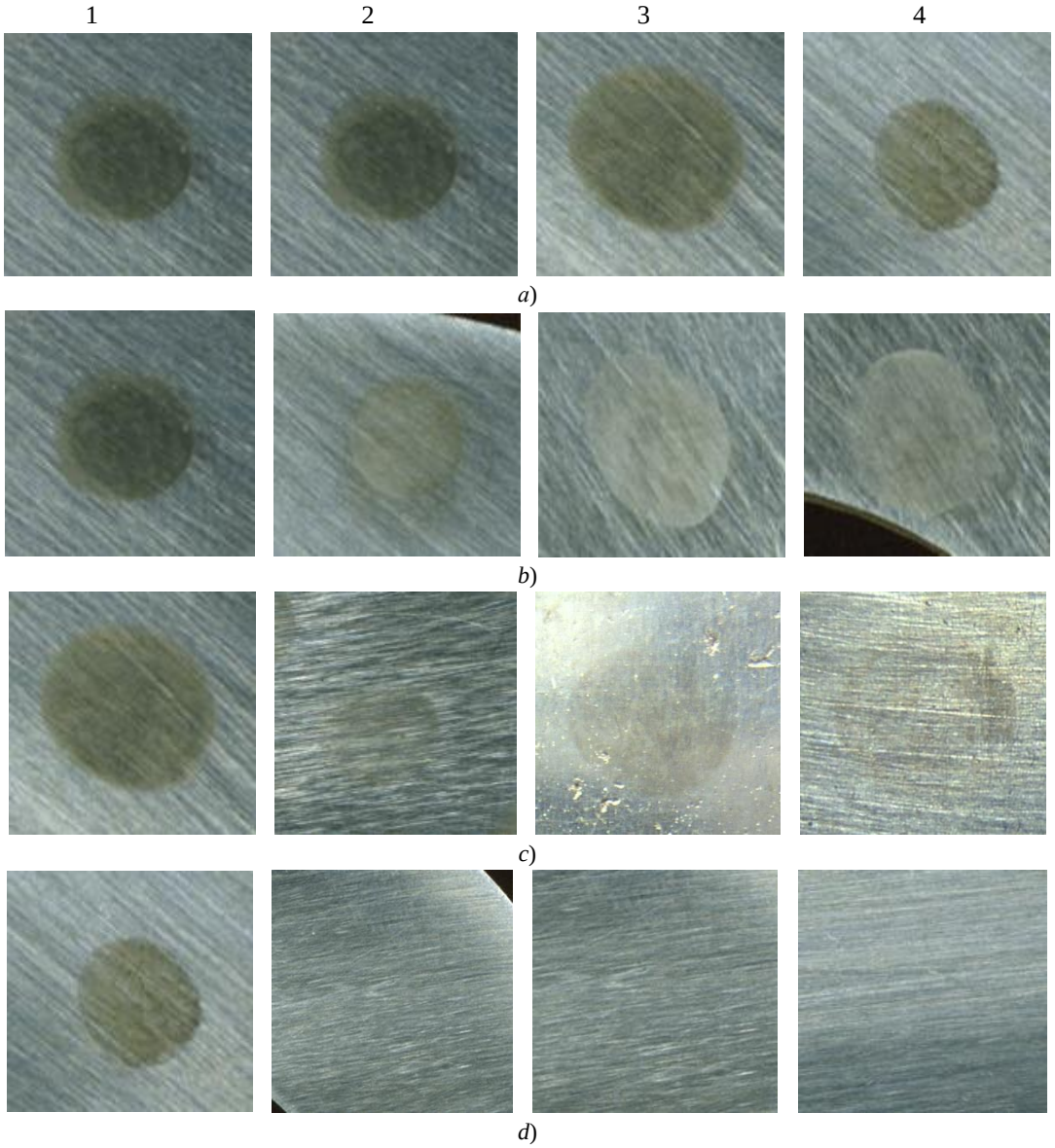


Fig. 1. Photo of corrosion damage — a type of rust stain on the surface of St3 steel samples in hydrochloric acid medium at inhibitor concentrations, %: *a* — 0; *b* — 0.01; *c* — 0.1; *d* — 0.2. Samples are numbered from top to bottom, their images after exposure are arranged vertically

Mass index of corrosion *j* was calculated by formula:

$$j = \Delta m / (S \cdot \tau), г / м^2 \cdot ч \text{ или } г / м^2 \cdot год,$$

where Δm — decrease in the mass of metal (g) during metal corrosion during time τ (hour or year) on the surface S (m^2).

The surface quality during corrosion and its inhibition (Fig. 1) was evaluated in five stages [7].

1. Based on the preliminary analysis, the problem was defined, the evaluated elements were indicated.

2. Structural analysis allowed us to formulate the main objective of the assessment and the possibilities of achieving it.

3. For the analysis of uncertainty, the search for unifying elements of the actual technical condition of the object was conducted.

4. The usefulness or value of the criterion was analyzed by the points of the numerical axis indicating the state of the object "better — worse".

5. Optimization was the search for a way to achieve the necessary technical condition.

Methods of constructing the structure of goals and the formation of a list of criteria were discussed in [8]. It was assumed that the initial array of objects was set and the study identified the best of them in terms of technical condition. Ranking was carried out according to a special integral indicator based on mathematical and methodological approaches. The main principles of selection were described in [9].

The main element of the approach under consideration was the rule (or principle) of estimating π, which set the ratio of a multiplicative metrized linear order on a set of particular criteria.

For a pair of objects a_ν and a_μ the choice was based on the following principles:

– $a_\nu > a_\mu$ — the first object was "better" than the second by the factors considered;

– $a_\nu \sim a_\mu$ — the objects were evaluated equally;

– $a_\nu < a_\mu$ — the first object was "worse" than the second by the factors considered.

Pairs of objects were characterized by comparison vectors $S_{\nu\mu}$. The principle of generalized criteria and so-called lexicographic approaches were useful for research — with a strong preference on a set of particular criteria. In this variant, the objects were equivalent ($a_\nu \sim a_\mu$), and their estimates corresponded to the established minimum values [10].

Let us consider the condition:

$$a_\nu \sim a_\mu \Leftrightarrow x_i^\nu \geq d_i,\ \ x_i^\mu \geq d_i\ , i = 1, \dots, m,$$

where d_i — the given threshold value (sufficiency level); m — the number of indicators under consideration; $x_{i\nu}$ and $x_{i\mu}$ — the estimates of the objects being compared (ν-th and μ-th).

The direct use of this principle was limited by the possibility of its application in practice, since it implied a strong preference on a set of criteria $K = \{K_1, K_2, \dots, K_m\}$ in the form:

$$K_1 \geq K_2 \geq K_3 \geq \dots \geq K_m.$$

It was more expedient to set a metrized multiplicative relation of linear order, that is, to apply a generalized criterion.

In this case,

$$a_\nu \succ a_\mu \Leftrightarrow \sum_{i=1}^{m} a_i K_i(a_\mu);\ \ a_\nu \sim a_\mu \Leftrightarrow \sum_{i=1}^{m} a_i\, K_i(a_\nu) = \sum_{i=1}^{m} a_i K_i\,(a_\mu).$$

Here a_i — the coefficients satisfying, for example, the condition

$$\sum_{i=1}^{m} a_i = 1.$$

The task was to determine the components of vector B in accordance with the 4-th stage of evaluation and to construct an indicator z, approximating an objectively known or specially specified (training) matrix of paired relationships between artificial objects (in [11] these were vehicles):

$$Q = \| q_{rk} \|_{p,p}\ .$$

Here p — the number of artificial objects under consideration, which determined the size of the matrix Q; q_{rk} — the elements of the matrix; r, k — the artificial objects on the numerical axis "better — worse".

On the *z* axis, the square of the distance between the *r-th* and *k-th* artificial objects (protection options) had the form:

$$d_{rk}(B) = (z_r - z_k)^2 = \left[\sum_{j=1}^{m} b_j\left(x_{rj} - x_{kj}\right)\right]^2,$$

$$D(B) = \| d_{rk} \|_{p,p}.$$

The matrix *D* (*B*) was evaluated using the functional

$$J(B) = \sum_{r=1}^{p-1} \sum_{k=r+1}^{p} [d_{rk}(B) - q_{rk}]^2.$$

The desired integral criterion was the function *Z*, if *J*(*B*) was minimal and the vector *B* corresponded to the set conditions. The obtained indicator was used to assess the technical condition of the surface quality as a result of corrosion and its deceleration due to the addition of salicylidene-aniline (Table 1, Fig. 1).

Table 1

Anticorrosive properties of Salicylidene-aniline for St3 steel

Sample number	*S*, 10^{-4} m^2	τ, h	$\Delta m = m_0 - m$, г	Inhibitor concentration, %	Mass corrosion index *j*, $g/m^2 \cdot h$ ($j = \Delta m / S \cdot \tau$)	Protective ability of inhibitor Z, %
1	10.22	120	3.4590	0	2.8205	–
2	10.11	120	0.7815	0.01	0.4793	77.4
3	11.9	120	0.3363	0.1	0.2542	90.2
4	11.13	120	0.1805	0.2	0.1482	94.8

As it can be seen from the table and Fig. 1, the corrosion damage of the steel surface decreased with an increase in the concentration of salicylidene-aniline.

To explain the anticorrosive activity and good adsorption ability of N-salicylidene-aniline on a steel surface, its photoinitiated structural rigidity was theoretically studied. This made it possible to find out in which tautomeric form this structure had a high energy of complexation of adsorption complexes on the surface of the protected metal [12-16].

Photochromic transition of the ketone form to the enol form was provided by proton transfer between the isomeric forms of the N-salicylidene-aniline molecule.

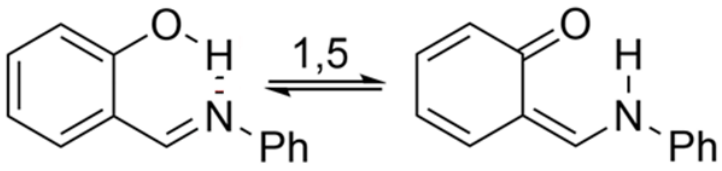
The semi-empirical method of quantum chemistry PM3 (parametric method 3) was used for a detailed determination:

– sequences of elementary stages of the main photochromic process;

– geometric characteristics of all intermediate and final photo-colored systems;

– charge distributions on atoms [17].

Salicylidene-aniline, like other anilines, is of interest because of the intramolecular hydrogen bond formed between oxygen and nitrogen atoms in a more stable cis-enol form. In fact, the forms of OH and NH are in equilibrium. Depending on the position of the hydrogen atom in this connection, O—H—N anils exhibit two tautomeric forms: enol-imine and keto-enamine (Fig. 2). The cis form is more stable. But the trans form has a better adsorption capacity. Tautomerism occurs under the influence of external factors such as radiation, temperature and pressure.



a) *b*)

Fig. 2. Keto-enol tautomerism: *a* — CA (enol); *b* — keto form

When the temperature decreases, the enol form turns into a ketone form. We proved that it was better adsorbed on the steel surface. Cis-enol is colorless. When irradiated with ultraviolet light, it turns into a red trans-ketoform. The keto isomer can be reversibly discolored thermally or photochemically under the action of visible light [18].

Discussion and Conclusion. The results of the study suggest that salicylidene-aniline actively inhibits corrosion of St3 steel. The degree of protection reaches 77.4–94.8 %.

Quantum chemical calculations using the semi-empirical PM3 method allowed us to explain the photochromism of salicylidene-aniline due to keto-enol tautomerism. Due to the monomolecular prototropic acid-base dichotomy, salicylidene-aniline has photochromism and luminescence. This distinguishes it from other azomethines.

The structure of the adsorption complex with higher stabilization energy was revealed, which explained the better adsorption capacity of the keto form of the inhibitor.

References

1. Sabanov SV, Nikulin SA, Karnavskiy EL. Determination of the priority of withdrawal to repair of equipment of anti-corrosive protection on the section of the gas pipeline in the conditions of restriction of financing. *Theory and Practice of Corrosion Protection.* 2020;25(2):7–17. https://doi.org/10.31615/j.corros.prot.2020.96.2-1

2. Tsygankova LE, Kim YaR. Novoe pokolenie ingibitorov korrozii metallov dlya neftekhimicheskoi promyshlennosti. In: *Tr. XVIII Mendeleevskogo s'ezda po obshchei i prikladnoi khimii*. Vol. 3. Moscow; 2007. P. 467.

3. Soumen Mandal, Jitendra Kumar Singh, Dong-Eun Lee, Taejoon Park. Ammonium Phosphate as Inhibitor to Mitigate the Corrosion of Steel Rebar in Chloride Contaminated Concrete Pore Solution. *Molecules*. 2020;25(17):3785. https://doi.org/10.3390/molecules25173785

4. Karthick Subbiah, Han-Seung Lee, Soumen Mandal, Taejoon Park. Conifer Cone (Pinus resinosa) as a Green Corrosion Inhibitor for Steel Rebar in Chloride-Contaminated Synthetic Concrete Pore Solutions. *ACS Applied Materials & Interfaces*. 2021;13(36):43676–43695. https://doi.org/10.1021/acsami.1c11994

5. Pakhomov VS, Shevchenko AA. *Khimicheskoe soprotivlenie materialov i zashchita ot korrozii*. Moscow: Khimiya, KolosS; 2009. 444 p.

6. Vigato PA, Tamburini S, Bertolo L. The Development of Compartmental Macrocyclic Schiff Bases and Related Polyamine derivatives. *Coordination Chemistry Reviews*. 2007;251(11–12):1311–1492. https://doi.org/10.1016/j.ccr.2006.11.016

7. Deryushev VV, Zaytseva M., Kosenko EE, Mamberger SK. Evaluation of the properties of anti-corrosion coatings of steel structures. *Safety of Technogenic and Natural Systems.* 2020;(4):24–29. https://doi.org/10.23947/2541-9129-2020-4-24-29

8. Deryushev VV, Sidelnikova EG. Generalized sufficiency indicator for the assessment of technical condition of construction and lifting-transportation machinery. *Nauchnoe obozrenie.* 2013;(9):164–167.

9. Kryanev AV, Lukin GV, Udumyan DK. *Metricheskii analiz i obrabotka dannykh*. Москва: Fizmatlit; 2012. 308 p.

10 Deryushev VV, Kosenko EE, Kosenko VV, Zaytseva MM. Technical decisions in uncertain environment at risk. *Safety of Technogenic and Natural Systems.* 2019;(2):56–61. https://doi.org/10.23947/2541-9129-2019-2-56-61

11. Kasyanov VE, Demchenko DB, Kosenko EE, Teplyakova SV. Method of machine reliability optimization using integral indicator. *Safety of Technogenic and Natural Systems.* 2020;(1):23–31. https://doi.org/10.23947/2541-9129-2020-1-23-31

12. Zaytseva MM, Megera GI, Kopylov FS, Krymskiy VS. Improving safety of equipment by reliability provision. *Safety of Technogenic and Natural Systems*. 2019;(2):33–36. https://doi.org/10.23947/2541-9129-2019-2-33-36

13. Kolesnikov VI, Migal YuF, Savenkova MA, Solodovnikova DN. Interaction of phosphorus-containing inorganic additives with iron surface: quantum-chemical analysis. *Vestnik Rostovskogo Gosudarstvennogo Universiteta Putey Soobshcheniya*. 2013;3(51):153–160.

14. Delley B. Time-dependent Density Functional Theory with DMol3. *Journal of Physics: Condensed Matter*. 2010;22(38):384208. https://doi.org/10.1088/0953-8984/22/38/384208

15. Kuren SG. *Izuchenie adsorbtsionnykh kompleksov na poverkhnosti metallov*. In: "Khimiya tverdogo tela: nanomaterialy, nanotekhnologii". Tr. X yubileinoi mezhdunar. nauch. konf. Stavropol; 2010. P. 247–249.

16. Kuren SG. *Kvantovokhimicheskoe modelirovanie adsorbtsionnykh protsessov*. Rostov-on-Don; 2012. 164 p.

17. Bravaya KB, Bochenkova AV, Granovsky AA, Savitsky AP, Nemukhin AV. Modeling photoabsorption of the asFP595 chromophore 11. *Journal of Physical Chemistry A.* 2008;112(37):8804–8810. https://doi.org/10.1021/jp804183w

18. Bagaturyants A, Vener M. *Multiscale modeling in nanophotonics. Materials and simulations*. Abingdon: Jenny Stanford Publishing; 2017. 270 p. https://doi.org/10.1201/9781315109763

Received 07.07.2023
Revised 24.07.2023
Accepted 03.08.2023

About the Authors:

Sergey G. Kuren, Cand. Sci. (Eng), Associate Professor of the Transport Systems and Logistics Operation Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, RF), AuthorID, ORCID, sergejgrigorevich@yandex.ru

Svetlana A. Volyanik, Cand. Sci. (Eng), Associate Professor, head of the Chemistry Department, Rostov State Transport University (2, Rostovskogo Strelkovogo Polka Narodnogo Opolchenya Sq., Rostov-on-Don, 344038, RF), AuthorID, ORCID, him@rgupa.ru

Mariya A. Savenkova, Cand. Sci. (Eng), Associate Professor of the Chemistry Department, Rostov State Transport University (2, Rostovskogo Strelkovogo Polka Narodnogo Opolchenya Sq., Rostov-on-Don, 344038, RF), AuthorID, ORCID, him@rgupa.ru

Elvira A. Zaitseva, Student of the Chemical Faculty, Southern Federal University (7, Zorge St., Rostov-on-Don, 344090, RF), ORCID, gems10@rambler.ru

Claimed contributorship:

SG Kuren: academic advising; formulation of the basic concept, goals and objectives of the study; conducting quantum chemical calculations and experiment; conclusions correction.

SA Volyanik: conducting an experiment; text preparation; conclusions formulation.

MA Savenkova: conducting an experiment; research results analysis, finalizing the text.

AA Zaitseva: literary and patent search; text preparation; research results analysis.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 07.07.2023
Поступила после рецензирования 24.07.2023
Принята к публикации 03.08.2023

Об авторах:

Сергей Григорьевич Курень, кандидат технических наук, доцент кафедры эксплуатации транспортных систем и логистики Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), AuthorID, ORCID, sergejgrigorevich@yandex.ru

Светлана Алексеевна Воляник, кандидат технических наук, доцент, заведующая кафедрой химии Ростовского государственного университета путей сообщения (344038, РФ, г. Ростов-на-Дону, пл. Ростовского Стрелкового Полка Народного Ополчения, 2), AuthorID, ORCID, him@rgupa.ru

Мария Андреевна Савенкова, кандидат химических наук, доцент кафедры химии Ростовского государственного университета путей сообщения (344038, РФ, г. Ростов-на-Дону, пл. Ростовского Стрелкового Полка Народного Ополчения, 2), AuthorID, ORCID, him@rgupa.ru

Эльвира Александровна Зайцева, студентка химического факультета Южного федерального университета (344090, РФ, г. Ростов-на-Дону, ул. Зорге, 7), ORCID, gems10@rambler.ru

Заявленный вклад соавторов:

С.Г. Курень — научное руководство, формулирование основной концепции, цели и задачи исследования, проведение квантовохимических расчетов и эксперимента, корректировка выводов.

С.А. Воляник — проведение эксперимента, подготовка текста, формулирование выводов.

М.А. Савенкова —проведение эксперимента, анализ результатов исследований, доработка текста.

А.А. Зайцева — литературный и патентный поиск, подготовка текста, анализ результатов исследований.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

TECHNOSPHERE SAFETY
ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

UDC 331.45
Original article
https://doi.org/10.23947/2541-9129-2023-7-3-24-33

Occupational Morbidity of Women Associated with Working Conditions in Agriculture

Valentina Yu. Kontareva
Don State Agrarian University, Persianovskii, Russian Federation
✉ valia_k@bk.ru

Abstract

Introduction. About a third of employees of medium and large agricultural enterprises work in hazardous and harmful conditions. It is worth clarifying that the situation in this area is constantly changing, information may become outdated. The presented scientific work is designed to solve this problem. New information should be considered and systematized to study current data. The work objective is to analyze recently published official statistics on the impact of working conditions on the health of agricultural sector workers and, in particular, women. In addition, the problems of the formation and development of occupational diseases of women employed in agriculture are considered.

Materials and Methods. The data of the Federal State Statistics Service, the Ministry of Health of the Russian Federation, as well as the works of foreign and Russian scientists who studied the peculiarities of work in agriculture were used as research materials. Official statistics data were summarized in the form of tables, visualized as diagrams. The illustrative material allowed us, in particular, to compare the indicators, to identify the most significant risks associated with the work of women in the agro-industrial complex.

Results. About 35 % (that is, more than a third) of the personnel of medium and large enterprises of the agro-industrial complex are women. Many of them work in harmful and dangerous conditions. From 2015 to 2021, the corresponding minimum recorded figure was 26.4 % of all women employed in agriculture, the maximum was 37 %. Generalized statistical data suggested that from 2015 to 2021 the situation was not significantly improving, a downward trend was not formed. If to speak about hard work, the proportion of women performing such functions increased from 13.8 % to 17.7 %, that is, by 2021 the situation noticeably worsened. We noted the progress with strenuous labor processes in agriculture. The proportion of women engaged in such jobs almost halved: from 3.5 % to 1.8 %. Physical overload, which functionally overstrain the organs and systems of the body, should be recognized as a particularly harmful factor for agricultural sector workers. The most problematic industry from the point of view of women's health was animal husbandry.

Discussion and Conclusion. The results of the work allow us to conclude about the unsatisfactory working conditions of women in agriculture. The situation can be improved by state control, mutual interest of employers and employees in the organization of workplaces and the compliance with labor protection requirements. A systematic approach should reduce the number of occupational diseases among women, improve the health indicators of agricultural workers

Keywords: women's health, occupational diseases, harmful and hazardous working conditions, physical overload

Acknowledgements: the author would like to thank the Federal State Statistics Service for open access (rosstat.gov.ru) to data on working conditions, occupational injuries and occupational diseases.

For citation. Kontareva VYu. Occupational Morbidity of Women Associated with Working Conditions in Agriculture. *Safety of Technogenic and Natural Systems*. 2023;7(3):24–33. https://doi.org/10.23947/2541-9129-2023-7-3-24-33

Научная статья

Профессиональная заболеваемость женщин, связанная с условиями труда в сельском хозяйстве

В.Ю. Контарева ✉
Донской государственный аграрный университет, п. Персиановский, Российская Федерация
✉ valia_k@bk.ru

Аннотация

Введение. Около трети сотрудниц средних и крупных сельскохозяйственных предприятий работают в опасных и вредных условиях. Стоит уточнить, что ситуация в этой сфере постоянно меняется, информация может устаревать. Указанную проблему призвана решить представленная научная работа. Для изучения актуальных данных следует рассматривать и систематизировать новые сведения. Цель исследования — анализ недавно опубликованной официальной статистики о воздействии условий труда на здоровье работников агросектора и, в частности, женщин. Кроме того, рассматриваются проблемы формирования и развития профессиональных заболеваний женщин, занятых в сельском хозяйстве.

Материалы и методы. В качестве материалов исследования использовались сведения Федеральной службы государственной статистики, Министерства здравоохранения РФ, а также труды зарубежных и российских ученых, которые изучали особенности работы в сельском хозяйстве. Данные официальной статистики обобщались в виде таблиц, визуализировались как диаграммы. Иллюстративный материал позволил, в частности, сопоставить показатели, выявить наиболее существенные риски, связанные с работой женщин в агропромышленном комплексе.

Результаты исследования. Около 35 % (то есть более трети) персонала средних и крупных предприятий агропромышленного комплекса — это женщины. Многие из них трудятся во вредных и опасных условиях. С 2015 по 2021 гг. соответствующий минимальный зафиксированный показатель — 26,4 % из всех женщин, занятых в сельском хозяйстве, максимальный — 37 %. Обобщенные статистические данные позволяют утверждать, что с 2015 по 2021 гг. ситуация существенно не улучшается, понижающий тренд не формируется. Если же говорить о тяжелых работах, то доля женщин, выполняющих такие функции, увеличилась с 13,8 до 17,7 %, то есть к 2021 году ситуация заметно ухудшилась. Отметим прогресс с напряженными трудовыми процессами в сельском хозяйстве. Доля женщин, занятых такими работами, сократилась почти вдвое: с 3,5 % до 1,8 %. Особенно вредным для работниц агросектора производственным фактором следует признать физические перегрузки, которые функционально перенапрягают органы и системы организма. Наиболее проблемная с точки зрения женского здоровья отрасль — животноводство.

Обсуждение и заключение. Результаты работы позволяют сделать вывод о неудовлетворительных условиях труда женщин в сельском хозяйстве. Ситуацию могут улучшить государственный контроль, взаимная заинтересованность работодателей и работников в организации рабочих мест и соблюдении требований охраны труда. Системный подход должен сократить число профессиональных заболеваний среди женщин, улучшить показатели по здоровью работниц агросферы.

Ключевые слова: здоровье женщин, профессиональные заболевания, вредные и опасные условия труда, физические перегрузки

Благодарности: автор выражает благодарность Федеральной службе государственной статистики за открытый доступ (rosstat.gov.ru) к данным об условиях труда, производственном травматизме и профессиональных заболеваниях.

Для цитирования. Контарева В.Ю. Профессиональная заболеваемость женщин, связанная с условиями труда в сельском хозяйстве. *Безопасность техногенных и природных систем.* 2023;7(3):24–33. https://doi.org/10.23947/2541-9129-2023-7-3-24-33

Introduction. Women's health is an important medical and social problem. Many areas depend on its solution, including the socio-demographic situation [1]. Health is determined by a number of heterogeneous factors, including:

– economy;
– ecology;
– social security (income, availability of medical services);

– nutrition;

– attitude to bad habits..

A person can spend up to 1/4 of his or her life in the workplace, so health largely depends on the production environment. The problems of occupational safety and women's health are not only actively discussed in society, but also require close attention of the authorities. It is necessary to take into account that the situation in the field is constantly changing, and the information is outdated. Using data that does not correspond to the current state of the problem will prevent its solution. The presented scientific work is designed to eliminate this drawback. The relevance involves consideration and systematization of new information. Thus, in December 2023, Russia approved the National Strategy of Action in the Interests of Women for 2023–2030. One of its priorities is to preserve women's health[1]. The Labor Code contains provisions on occupational safety and women's health[2]. Decree of the President of Russia of 04.03.1993 No. 337 "On the priorities of state policy in relation to women" declares the need for priority provision of women's rights to occupational safety, protection of their life and health, taking into account the function of motherhood[3]. It should be recognized that in some cases, the working conditions of women remain unsafe and harmful, and the state of health is unsatisfactory.

The study objective is to analyze recently published official statistics on the impact of working conditions on women's health. In addition, the problems of the formation and development of occupational diseases of workers employed in the agricultural sector are considered.

Materials and Methods. The paper considers Russian and foreign literature devoted to the problem. These materials are compared with the data of the Federal State Statistics Service and the Ministry of Health of the Russian Federation. This approach made it possible to systematize and show in dynamics the information about the number of women working in hazardous and harmful working conditions, and about the potential threat to their health. A comparative analysis was carried out, which established similar and different risks for men and women employed in the agro-industrial complex. The information was summarized, presented in the form of tables and diagrams. Processing of a significant digital array gave grounds to speak about the representativeness of the material and the validity of the proposed conclusions.

Results. A significant part of the working population of the country is involved in agriculture. Therefore, by the end of 2021, almost 900 thousand people worked in the agro-industrial complex of Russia. Here and further we will provide the analytics without taking into account small and microenterprises, since Rosstat has not published the relevant data. Of these 900 thousand, 313 thousand people (about 35 %, that is, more than a third) were women[4, 5].

A significant proportion of those employed in jobs with working conditions that did not meet the requirements of legislation remained in the country as a whole (Fig. 1) and in the agricultural sector (Fig. 2) [2].

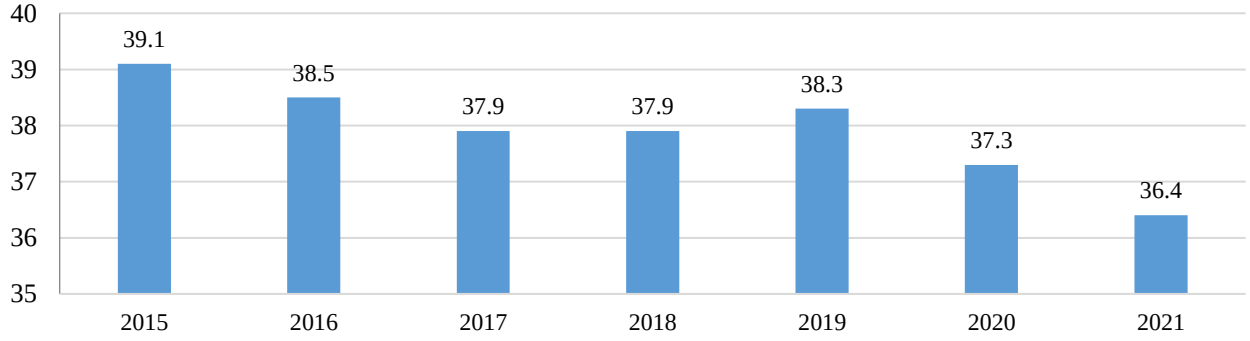


Fig. 1. The share of employees engaged in work with harmful and (or) hazardous working conditions, %

[1] *Ob utverzhdenii Nacional'noj strategii dejstvij v interesah zhenshhin na 2023–2030 gody.* Decree of the Government of the Russian Federation No. 4356-r of 29.12.2022. Consultant Plus. URL: http://www.consultant.ru/document/cons_doc_LAW_436691/0ab1d11f34aa37bd186ca7948792439bf4b2d4c1/ (accessed: 31.05.2023).

[2] *Labor Code of the Russian Federation.* No. 197-FZ of 30.12.2001. Consultant Plus. URL: http://www.consultant.ru/document/cons_doc_LAW_34683/ (accessed: 31.05.2023).

[3] *O pervoocherednyh zadachah gosudarstvennoj politiki v otnoshenii zhenshhin.* Decree of the President of the Russian Federation No. 337 of 04.03.1993. Consultant Plus. URL: http://www.consultant.ru/document/cons_doc_LAW_1591/ (accessed: 31.05.2023).

[4] *Uslovija truda. Proizvodstvennyj travmatizm.* Federal State Statistics Service. URL: https://rosstat.gov.ru/working_conditions (accessed: 31.05.2023).

[5] *Sostojanie uslovij truda rabotnikov organizacij Rossijskoj Federacii po otdel'nym vidam jekonomicheskoj dejatel'nosti.* Federal State Statistics Service. URL: https://rosstat.gov.ru/folder/11110/document/13264 (accessed: 31.05.2023).

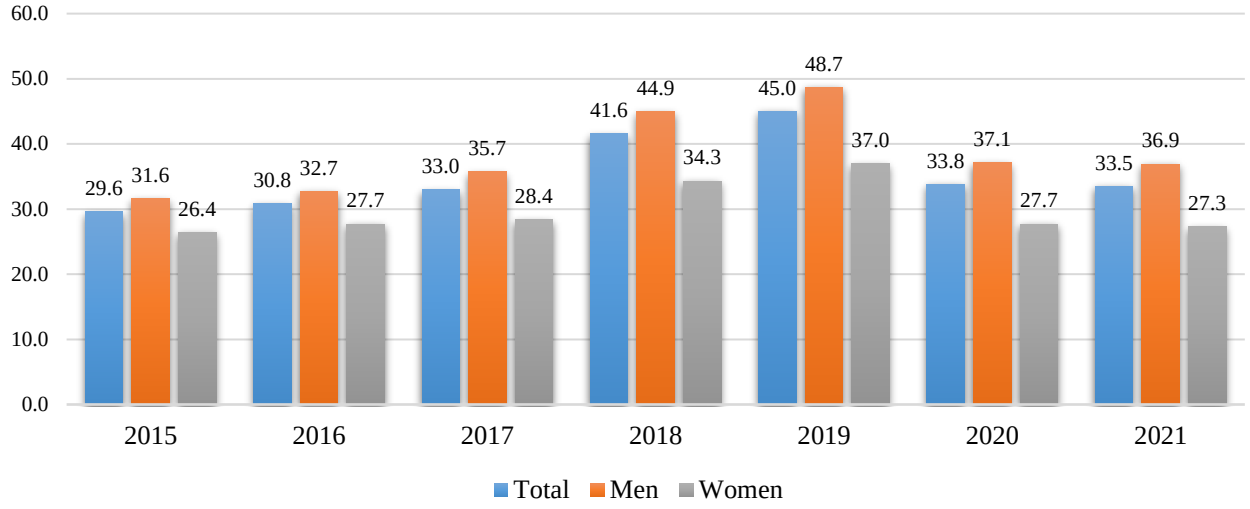


Fig. 2. The share of employees engaged in work with harmful and (or) hazardous working conditions in agriculture, %

This and the following similar figures require explanation. Each column of the chart shows the proportion of agricultural sector employees working in various unfavorable conditions. Everything counts from 100 %. In this case, for example, in 2015, out of the total number of employees (100 %), 29.6 % worked in harmful and (or) hazardous conditions. Out of 100 % of men, it was 31.6 %; out of 100 % of women it was 26.4 %.

From 2015 to 2021, 29.6–45 % of the staff had harmful or hazardous working conditions in agriculture, and the declining trend line was not fixed (see Figure 2). During these years, about a third of agricultural workers (26.4–37 %) worked in dangerous and hazardous conditions.

Hazardous and harmful working conditions in agriculture are associated with factors of the production environment (Fig. 3, Table 1), the severity (Fig. 4) and the intensity of the labor process (Fig. 5).

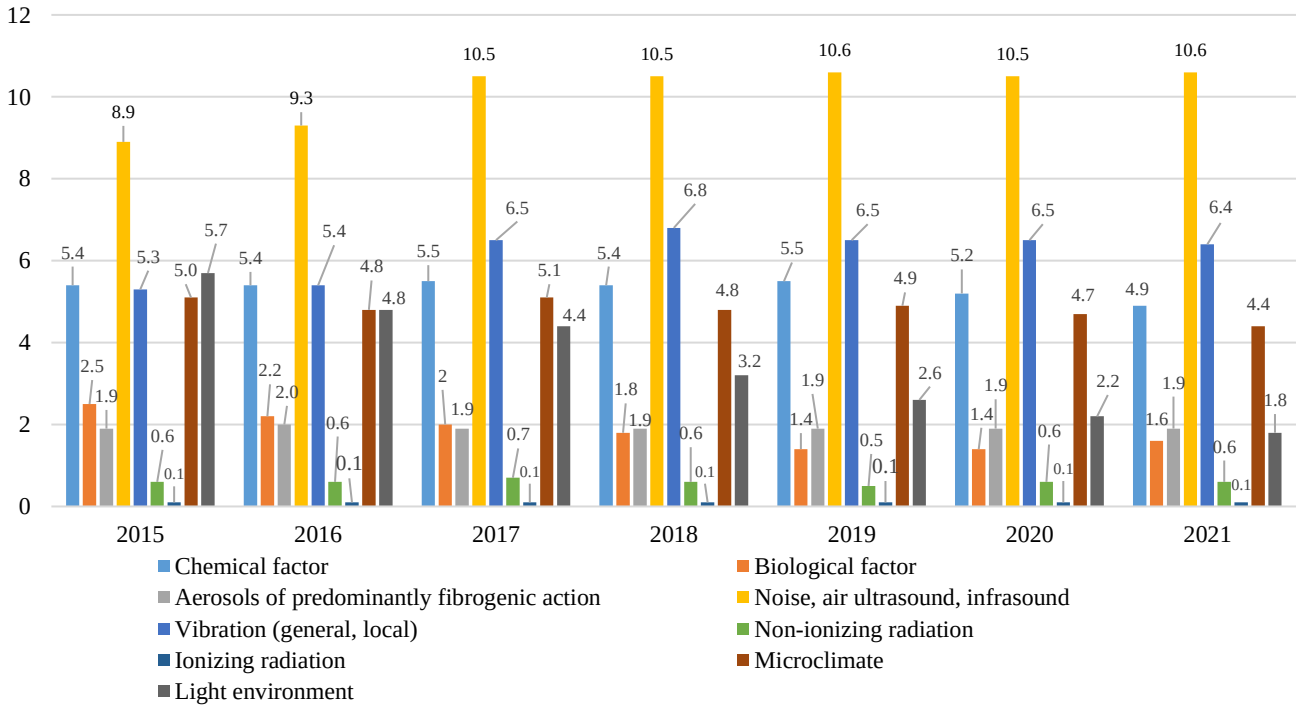


Fig. 3. The share of agricultural workers exposed to various harmful factors of the production environment, %

As you can see, acoustic factors, vibration, chemicals and microclimate influenced most often people.

Table 1

The number of agricultural sector workers exposed to adverse factors of the production environment

Year	Number of people	Are under the influence of these factors, people, %*									
		Total	1	2	3	4	5	6	7	8	9
2015	375773	99011/26.4	53411/ 4.6	12313/ 3.3	5690/ 1.5	20236/ 5.4	1901/ 0.5	2431/ 0.7	278/ 0.1	21817/ 5.8	25787/ 6.9
2016	389677	107798/27.7	17115/ 4.4	12211/ 3.1	6631/ 1.7	20397/ 5.2	1930/ 0.5	2017/ 0.5	235/ 0.1	21552/ 5.5	22320/ 5.7
2017	359596	102176/28.4	15852/ 4.4	10730/ 3.0	5129/ 1.4	21192/ 5.9	1790/ 0.5	1446/ 0.4	131/ 0.0	21319/ 5.9	18142/ 5.1
2018	342316	97298/28.4	15250/ 4.5	8577/ 2.5	5128/ 1.5	20507/ 6.0	1958/ 0.6	656/ 0.2	98/ 0.0	20308/ 5.9	11994/ 3.5
2019	342532	96567/28.2	15321/ 4.5	7138/ 2.1	5273/ 1.5	21335/ 6.2	2021/ 0.6	545/ 0.2	153/ 0.0	22669/ 6.6	9905/ 2.9
2020	325955	90312/27.7	13726/ 4.2	7123/ 2.2	5144/ 1.6	19554/ 6.0	1903/ 0.6	486/ 0.1	165/ 0.1	21129/ 6.5	7826/ 2.4
2021	312653	85227/27.3	12314/ 3.9	7014/ 2.2	4456/ 1.4	18523/ 5.9	1578/ 0.5	280/ 0.1	94/ 0.0	19132/ 6.1	5945/ 1.9
* 1 — chemical; 2 — biological; 3 — aerosols, mainly of fibrogenic action; 4 — noise, ultrasound, air, infrasound; 5 — vibration (general and local); 6 — non-ionizing radiation; 7 — ionizing radiation; 8 — microclimate; 9 — light environment.											

Therefore, the workplaces of 26.4–28.4 % of employees did not meet the standards. Unfavorable conditions were primarily noise, air ultrasound, infrasound, chemistry and microclimate. Of the factors described above, women were the least likely to experience vibration.

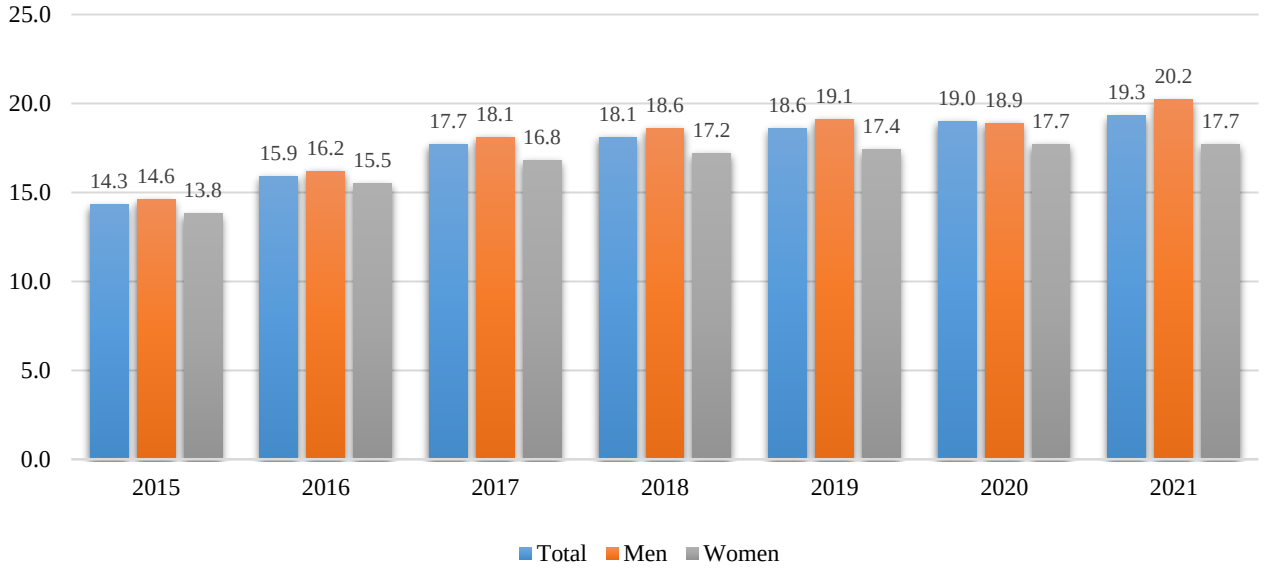


Fig. 4. The share of people employed in heavy work in agriculture, %

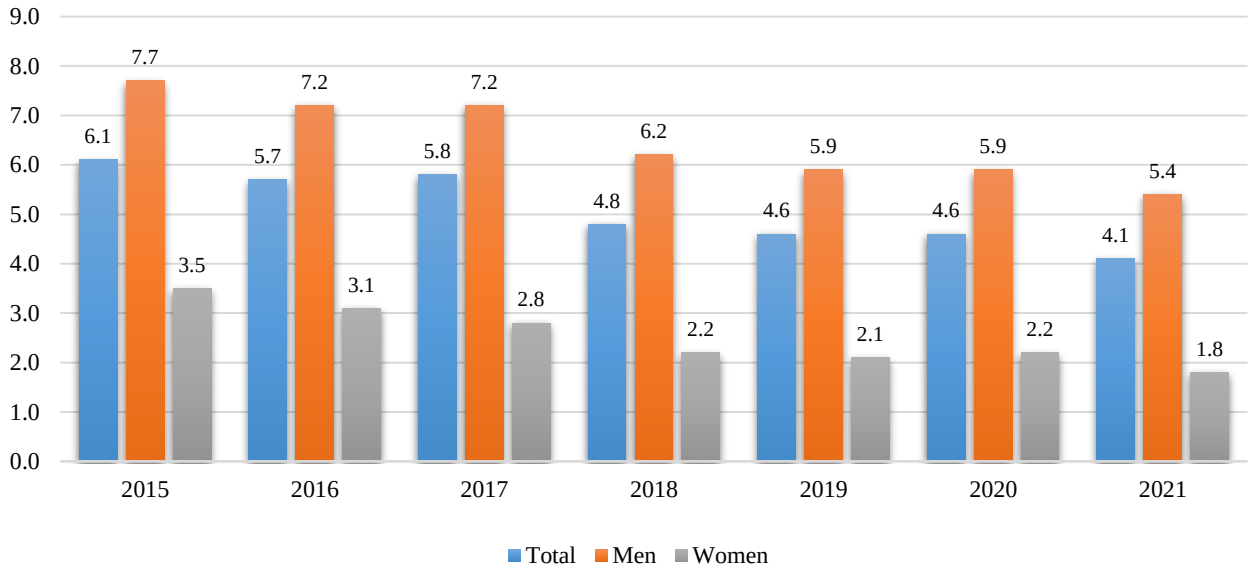


Fig. 5. The share of people employed in stressful labor processes in agriculture, %

First of all, we should note the increase in the share of those engaged in hard work. In general, this indicator increased from 14.3 % to 19.3 %. The corresponding figures for women — from 13.8 % to 17.7 %. In addition, Figures 4 and 5 show that the share of people in stressful labor processes decreased from 6.1 % to 4.1 % in general and from 3.5 % to 1.8 %, if we talk about women.

The negative phenomena described above create risks for the development of occupational and professionally caused diseases. Among the branches of the Russian economy, agriculture ranks fourth in terms of such ailments, as well as related disability[6]. Diseases caused by physical overloads, functional overstrain of organs and body systems were recorded especially a lot (about 51 %). In second place was the impact of physical factors (about 22.5 %). The third was the harmful effect of aerosols, mainly fibrogenic ones (about 13 %), and chemicals (about 8.5 %) [2].

Of the primary identified occupational pathologies of agricultural workers, diseases of the musculoskeletal system and connective tissue (radiculopathy, musculotonic syndromes, myalgia, myofibrosis of the forearms, epicondyle of humerus, etc.) were most common (64.8 %). 10.3 % were respiratory diseases (occupational bronchitis, bronchial asthma, etc.). Injuries, poisoning and other consequences of external influences, as well as diseases of the skin, nervous system, ear and mastoid process were recorded in 11.6 % [2].

Studies of domestic and foreign scientists confirm the impact of factors that form harmful and hazardous working conditions on the health of women in agriculture. In particular, hard work was considered, in which employees lifted weights of more than 10 kg every day. 2/3 of such women suffered from pain in the spine (mainly in the lower back), cervical and thoracic sections. This reduced the quality of life and provoked such health risks as overwork and premature menopause [3]. Heavy female labor was a common cause of musculoskeletal diseases of the lower back, shoulders, knees and especially wrists [4]. Severe conditions and exposure to chemicals turn into reproductive health problems [5, 6]. Lipid metabolism disorders were widespread among postmenopausal women in the agricultural sector, which indicates the risks of cardiovascular diseases [7].

[6] *Glavnyj vneshtatnyj specialist profpatolog. Planiruemye rezul'taty dejatel'nosti. Otchet glavnogo vneshtatnogo specialista profpatologa Minzdrava Rossii za 2019 god*. Ministry of Health of the Russian Federation.URL: https://minzdrav.gov.ru/vneshtatnye-spetsialisty/glavnyy-vneshtatnyy-spetsialist-38/plan-38 (accessed: 18.07.2023).

The working environment in agriculture provoked allergic respiratory diseases. The reasons were organic substances, solid particles of biological origin (organic dust) with mold and microorganisms. Such a suspension can cause allergic reactions, rhinitis, asthma, exogenous allergic alveolitis, pneumonitis [8], [9]. Vibroacoustic factors of the production environment in agriculture can contribute to hearing impairment [10].

Judging by the list of possible diseases, the situation in animal husbandry was particularly difficult. Here, women were at risk of diseases of the neuromuscular apparatus, peripheral nervous system, heart and blood vessels, digestive organs, movement, and the female genital sphere. Conditions of pig breeding enterprises can provoke chronic tonsillitis, myocardiopathy associated with focal infection. Those employed in poultry farming were diagnosed with diseases of the upper respiratory tract and skin infections. In crop production, female workers suffer from vegetative-vascular disorders, hypertension, diseases of the peripheral nervous system. Under the influence of pesticides, chronic coronary insufficiency, diseases of the heart muscle, gastrointestinal tract, liver and biliary tract developed. Severe dustiness caused nonspecific lung diseases [11].

As a result of investigations of cases of occupational pathology, the main causes of acute occupational and chronic occupational diseases were established (Fig. 6).

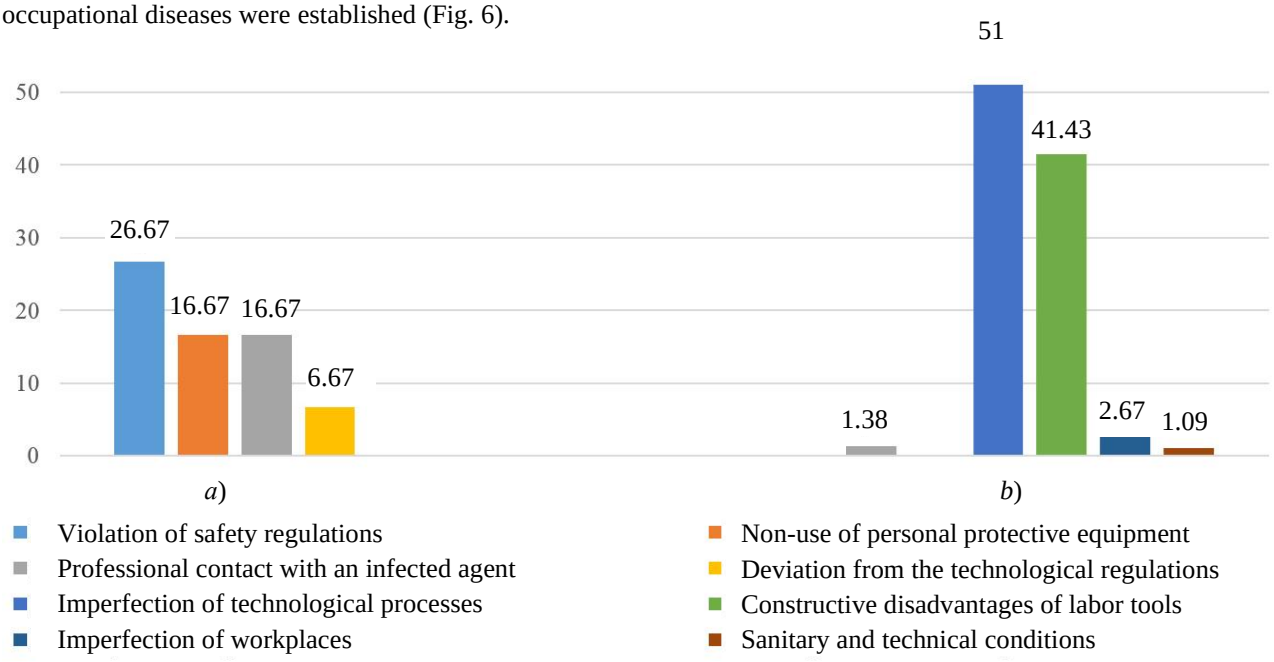


Fig. 6. Causes of occupational diseases, %: *a* — acute; *b* — chronic

Let us clarify that the diagrams in Fig. 6 reflect only the most significant, according to experts, causes of ailments. Part *(a)* does not take into account shortcomings in the use of personal and collective protective equipment, emergencies, lack of timely first aid. Part *(b)* does not take into account violations of industrial sanitation and occupational hygiene, insufficiently good working conditions, weak mechanization and automation.

Studies of working conditions and occupational diseases in agriculture indicate non-compliance with sanitary and other standards established to protect the health of workers. Let us name some violations:

– there was no regular monitoring of working environment factors, labor processes, industrial and sanitary facilities;

– the rules of workplace organization, requirements for equipment, facilities, transport were not observed;

– preliminary and periodic medical examinations of employees engaged in harmful and hazardous production conditions were not carried out [12].

The following measures will contribute to the normalization of working conditions and the prevention of occupational diseases of agricultural workers:

– compliance with legislation in the field of occupational safety and women's health;

– sufficient financing of occupational safety measures;

– regular inspections and scheduled preventive repairs, modernization of equipment — a source of harmful and hazardous factors;

– control of technical processes and technological equipment of workplaces;

– mechanization and automation of production;

– organization of work, adequate to the nature and scope of work performed, technological process;

– compliance with the work and rest regime, depending on the severity and intensity of work;

– step-by-step production control of working conditions, sanitary and epidemiological condition and ergonomics of workplaces;

– taking into account standard norms and special assessment of working conditions to provide employees with collective protection, individual protection, special clothing and footwear, as well as monitoring their use;

– special assessment of working conditions to reduce the impact of the identified negative factors of the production environment and the labor process;

– introduction of modern digital tools for training, instruction on occupational safety, first aid;

– timely medical examinations and compliance with doctors' prescriptions;

– maintenance of equipped medical offices, psychological relief departments, sports and recreational facilities in working condition;

– immunization and seasonal prevention of respiratory diseases;

– promotion of a healthy lifestyle.

Discussion and Conclusion. Many women employed in agriculture work in unsatisfactory conditions. About a third of employees are affected by negative factors. The severity and intensity of production processes contribute to the development of occupational diseases. To improve the situation, state control over the state of working conditions and occupational diseases is necessary. It is necessary to develop and implement measures for the protection of women's labor and health, including in agriculture.

References

1. Sadykov RM, Bolshakova LN. The female health: status, causes of deterioration, measures of improvement. *Problems of Social Hygiene, Public Health and History of Medicine.* 2022;30(2):247–252. https://doi.org/10.32687/0869-866X-2022-30-2-247-252

2. Bakirov AB, Shaikhlislamova ER, Gainullina MK, Masyagutova LM, Khafizova AS, Churmantayeva SKh, et al. Specific features of occupational morbidity of Bashkortostan agricultural workers under modern conditions. *Occupational medicine and human ecology*. 2015;(4):51–57.

3. Dorota Raczkiewicz, Tomasz Saran, Beata Sarecka-Hujar, Iwona Bojar Work conditions in agriculture as risk factors of spinal pain in postmenopausal women. *International Journal of Occupational Safety and Ergonomics*. 2019;25(2):250–256. https://doi.org/10.1080/10803548.2017.1364903

4. Pinzke S. Comparison of Working Conditions and Prevalence of Musculoskeletal Symptoms among Dairy Farmers in Southern Sweden over a 25-Year Period. *Front Public Health*. 2016;19:4–98. https://doi.org/10.3389/fpubh.2016.00098

5. Derya Adıbelli, Nurcan Kırca, İlknur Özkan. The problems of women working in greenhouse agriculture in rural area in Turkey: A phenomenological study from health and social perspective. *Health & Social Care in the Community*. 2022;30(1):203–211. https://doi.org/10.1111/hsc.13393

6. Pons R, Boulanger M, Tual S, Busson A, Renier M, Perrier S, et al. Agriculture exposure and time to pregnancy among women enrolled in the French prospective cohort AGRICAN. *Journal of Occupational and Environmental Medicine*. 2021;63(5):432–440. https://doi.org/10.1097/JOM.0000000000002163

7. Krakowiak J, Raczkiewicz D, Wdowiak A, Cichońska D, Bojar I, et al. Atherogenic lipid profile and health behaviours in women post-menopause working in agriculture. *Annals of Agricultural and Environmental Medicine*. 2019;26(4):585–591. https://doi.org/10.26444/aaem/105391

8. Di Stefano F, Di Giampaolo L, Verna N, Di Gioacchino M. Respiratory allergy in agriculture. *European Annals of Allergy and Clinical Immunology*. 2007;39(3):89–100.

9. Zejda JE, Dosman JA. Respiratory disorders in agriculture. *Tubercle and Lung Disease*. 1993;74(2):74–86. https://doi.org/10.1016/0962-8479(93)90031-R

10. Thaper R, Sesek R, Garnett R, Acosta-Sojo Y, Purdy GT. The Combined Impact of Hand-Arm Vibration and Noise Exposure on Hearing Sensitivity of Agricultural/Forestry Workers-A Systematic Literature Review. *International Journal of Environmental Research and Public Health*. 2023;20(5):4276. https://doi.org/10.3390/ijerph20054276

11. Spirin VF, Novikova TA, Varshamov LA. Work conditions and occupational morbidity among agricultural workers. *Russian Journal of Occupational Health and Industrial Ecology*. 2007;(11):7–12. URL: https://cyberleninka.ru/article/n/usloviya-truda-i-professionalnaya-zabolevaemost-rabotnikov-selskogo-hozyaystva/viewer (accessed: 18.06.2023).

12. Chernyshkova EM, Andriyanova EA, Yurova IYu, Chernyshkov DV, Mukhina MYu. Strategies of health preservation of agricultural workers with occupational diseases (material of focus-group research). *Saratov Journal of Medical Scientific Research*. 2017;13(1):88–92. URL: https://cyberleninka.ru/article/n/strategii-zdoroviesberezheniya-rabotnikov-selskogo-hozyaystva-s-professionalnymi-zabolevaniyami-po-materialam-fokus-gruppovogo/viewer (accessed: 18.06.2023).

Received 28.06.2023
Revised 16.07.2023
Accepted 31.07.2023

About the Author:

Valentina Yu. Kontareva, Cand. Sci. (Eng.), Associate Professor of the Life Safety, Mechanization and Automation of Technological Processes and Productions Department, Don State Agrarian University (24, Krivoshlykova str., Persianovskii, Rostov region, 346493, RF), AuthorID, ORCID, valia_k@bk.ru

Conflict of interest statement: the author does not have any conflict of interest.

The author has read and approved the final manuscript.

Поступила в редакцию 28.06.2023
Поступила после рецензирования 16.07.2023
Принята к публикации 31.07.2023

Об авторе:

Валентина Юрьевна Контарева, кандидат технических наук, доцент кафедры безопасности жизнедеятельности, механизации и автоматизации технологических процессов и производств Донского государственного аграрного университета (346493, РФ, Ростовская область, п. Персиановский, ул. Кривошлыкова д. 24), AuthorID, ORCID, valia_k@bk.ru

Конфликт интересов: автор заявляет об отсутствии конфликта интересов.

Автор прочитал и одобрил окончательный вариант рукописи.

MACHINE BUILDING
МАШИНОСТРОЕНИЕ

UDC 692.66:006.354

Original article

https://doi.org/10.23947/2541-9129-2023-7-3-34-43

Assessment of the Influence of Internal Factors on the Indicators of Passenger Elevator Units Utilization Based on the Results of Regular Monitoring

Grigorii Sh. Khazanovich ✉, **Dmitrii S. Apryshkin**

Don State Technical University, Rostov-on-Don, Russian Federation

✉ hazanovich@mail.ru

Abstract

Introduction. Ensuring high reliability and safety of operation of passenger elevator units is largely determined by the implemented maintenance conditions (MC). The frequency of performing preventive actions depends, first of all, on the level of elevator utilization. Time, power indicators and the degree of remaining life are used to evaluate it. Among the time indicators, the net machine time coefficient (NMT) and the turn-on frequency are accepted, which are random variables depending on a number of internal factors characterizing the operating conditions of the unit. The work objective is to establish the relationship between the average values of NMT, as one of the main indicators of the load of the elevator unit, and the main internal factors.

Materials and Methods. The research was carried out on the basis of processing and generalization of statistical materials of dispatching control of time indicators of a number of passenger elevator units. 11 elevators were randomly selected, differing in the number of floors, the specific number of residents using the elevator, and the speed of movement of the cab. Graphical-analytic methods were used to construct empirical dependences of NMT on the number of residents, the speed of the cab and the number of floors of the building. Along with the technical parameters of the elevator, random changes in the NMT indicators for individual periods of the day were taken into account.

Results. Empirical dependences of the NMT on the main internal factors — the density of occupation, the number of floors of the building and the speed of the cab movement were established. Mathematical models provided results adequate to experimental values. The error when comparing the calculated data with the actual data did not exceed 10 % in most cases.

Discussion and Conclusion. The value of the empirical dependencies obtained consists in the ability to assess the workload of units during the current period of operation without additional multi-day measurements. Empirical formulas can be used as basic relations in simulation modeling at any stage of the life cycle.

Keywords: passenger elevator, technical condition, workload indicators, maintenance interval, machine time coefficient

Acknowledgements: the authors express their gratitude to the staff of Liftservice OAO in Rostov-on-Don for the opportunity to use the data on regular observations of the operation of elevator units.

For citation. Khazanovich GSh, Apryshkin DS. Assessment of the Influence of Internal Factors on the Indicators of Passenger Elevator Units Utilization Based on the Results of Regular Monitoring. *Safety of Technogenic and Natural Systems.* 2023;7(3):34–43. https://doi.org/10.23947/2541-9129-2023-7-3-34-43

Научная статья

Оценка влияния внутренних факторов на показатели загруженности пассажирских лифтовых установок на основе результатов регулярного мониторинга

Г.Ш. Хазанович ✉, **Д.С. Апрышкин**
Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация
✉ hazanovich@mail.ru

Аннотация

Введение. Обеспечение высокой надежности и безопасности эксплуатации пассажирских лифтовых установок во многом определяется реализуемым режимом их технического обслуживания (ТО). Частота выполнения профилактических воздействий зависит прежде всего от уровня загруженности лифта, для оценки которого используются временны́е, силовые показатели и степень отработки ресурса. В качестве временны́х показателей приняты коэффициент чистого машинного времени (КМВ) и частота включений, которые являются случайными величинами, зависящими от ряда внутренних факторов, характеризующих условия эксплуатации установки. Целью данной работы является установление взаимосвязи средних значений КМВ, как одного из главных показателей загруженности лифтовой установки, и основных внутренних факторов.

Материалы и методы. Исследования выполнены на основе обработки и обобщения статистических материалов диспетчерского контроля временны́х показателей ряда пассажирских лифтовых установок. Случайным образом отобраны 11 лифтов в домах, отличающихся этажностью, количеством жильцов, пользующихся лифтом, и скоростью движения кабины. Для построения эмпирических зависимостей КМВ от числа жильцов, скорости кабины и этажности дома использованы графоаналитические методы. Наряду с техническими параметрами лифта учитывались случайные изменения показателей КМВ по времени суток.

Результаты исследования. Установлены эмпирические зависимости КМВ от основных внутренних факторов — плотности заселения дома, этажности здания и скорости движения кабины. Математические модели обеспечивают получение результатов, адекватных экспериментальным значениям. Ошибка при сравнении расчетных данных с фактическими не превышала в большинстве случаев 10 %.

Обсуждение и заключение. Значения полученных эмпирических зависимостей дают возможность оценивать загруженность установок в текущий период эксплуатации без проведения дополнительных многодневных замеров. Эмпирические формулы можно использовать в качестве базовых соотношений при имитационном моделирования в произвольной стадии жизненного цикла.

Ключевые слова: лифт пассажирский, техническое состояние, показатели загруженности, периодичность технического обслуживания, коэффициент машинного времени

Благодарности: авторы выражают благодарность коллективу ОАО «ЛифтСервис» г. Ростова-на-Дону за предоставленные возможности использовать данные регулярных наблюдений за работой лифтовых установок.

Для цитирования. Хазанович Г.Ш., Апрышкин Д.С. Оценка влияния внутренних факторов на показатели загруженности пассажирских лифтовых установок на основе результатов регулярного мониторинга. *Безопасность техногенных и природных систем*. 2023;7(3):34–43. https://doi.org/10.23947/2541-9129-2023-7-3-34-43

Introduction. Elevator unit utilization during operation depends on a number of internal factors, which include the number of floors of the building, occupation density of the building, the characteristics of the elevator unit, etc. The level of elevator utilization has a direct impact on the technical condition of its components throughout the entire life of the unit. One of the methods of ensuring the necessary technical condition of the elevator is its timely maintenance. A number of researchers have attempted to determine the optimal frequency of maintenance of elevators, taking into account the actual load of the system. In the work "On the control of the technical condition of elevator ropes based on artificial intelligence and computer vision technologies" AV Panfilov, AR Yusupov, AA Korotkiy, BF Ivanov considered the use of artificial intelligence and computer vision technology to control the technical condition of elevator ropes [1]. Researchers from China and the Netherlands analyzed a scientifically based choice of strategy and frequency of maintenance [2–6]. They came to the conclusion that the universal target function should be economic indicators. To justify such a decision, the statement is given that "maintenance and emergency failures are closely

related to the reliability of elevator equipment, but differ in the nature of this relationship and economic consequences. The increase in maintenance costs leads to a reduction in emergency failures and to a reduction in costs associated with liquidation and losses due to downtime." Thus, on the one hand, the costs of maintenance are increasing; on the other hand, the costs of ensuring reliability are decreasing. Therefore, some universal ratio is taken as the objective function, for example, the so-called reduced costs, which takes into account the main economic components.

Modern dispatching control systems allow for constant monitoring of the elevator condition, as well as to obtain temporary indicators of the operation of its main components: the net duration of operation and the turn-on frequency of the main drive of the elevator[1,2]. On the basis of the listed time indicators, a methodology for determining the frequency of maintenance is built. Time indicators can also be attributed to operational data, on the basis of which the authors of the article previously conducted a study of cases of failures in the operation of passenger elevators [7, 8].

Materials and Methods. To assess the influence of internal factors on indicators of passenger elevator units utilization, the results of dispatcher records of temporary data on the operation of passenger elevator units in Rostov-on-Don were used, as well as the hypothesis about the relative duration of the machine cycle, indicating that the coefficient of the machine time of the elevator unit depends on the following main factors: the number of floors of the building— N, the number of tenants in the entrance — Z, the number of tenants using the elevator — Z_0, the average speed of the cabin — $v_{ср}$, m/s, load capacity — R, people, the number of apartments in the entrance — $M_к$, the number of apartments in the entrance, the residents of which do not use the elevator — $M_{к1}$ [9].

As shown in paper[3], the average machine trip time (excluding stops for passengers entering and exiting) is proportional to the number of floors of the building. This dependence is cited by DS Apryshkin in his dissertation "Assessment of the technical condition of machines with cable traction based on simulation modeling"[3].

For the purpose of the study, the authors selected 11 elevator units in residential buildings in Rostov-on-Don (Table 1). A preliminary analysis of the results of computer records of dispatching control showed that the values of NMT differ significantly during the day and at night [9].

Table 1

Initial data of the results of computer NMT control

Elevator no.	Address of the building and type of elevator / number of entrances	N/R	$M_к$/ $M_{1к}$, app.	Z, people	$v_{расч}$, m/s	Average NMT			Average turn-on frequency in min., NMT		
						day	night	general	day	night	general
1	Orbital'naya, 68/1	9/5	171/19	303	0.63	0.252	0.065	0.197	2.61	2.606	2.609
	Belyaeva, 22/2	9	212/20								
2	Passenger	9/5	106/10	144	0.63	0.119	0.036	0.095	2.361	2.380	2.366
3	Passenger	9/5	106/10	240	0.63	0.2	0.046	0.155	2.054	2.103	2.068
	Kapustina, 14/3	9	144/12								
4	Passenger	9/5	36/4	72	0.67	0.077	0.017	0.060	3.807	4.282	3.945
5	Passenger	9/5	36/4	99	0.67	0.085	0.02	0.066	3.067	3.360	3.152
6	Passenger	9/5	36/4	111	0.67	0.055	0.015	0.043	3.162	4.320	3.500
	Kosmonavtov, 37/2	18	140/2								
7	Passenger	18/5	35/2	65	0.91	0.167	0.031	0.127	2.004	2.367	2.110
8	Service	18/8	35/2	43	0.91	0.105	0.048	0.088	2.213	2.445	2.281
	Panovoi, 30/1	24									
9	Passenger	24/5	108/0	310	1.35	0.234	0.038	0.177	2.265	2.164	2.236
10	Passenger	24/5	108/0	347	1.35	0.276	0.05	0.210	2.219	2.433	2.281
11	Service	24/13	106/0	165	1.35	0.137	0.021	0.103	2.083	1.886	2.025

[1]*Dispetcherskii kompleks «OB"»*. User's Manual. RE 3434-001-49739805-07. URL: https://lkds.ru/upload/docs/pdf/general/RE_3434-001-49739805-07_5.pdf (accessed: 11.04.2023).
[2]*Sistema liftovogo dispetcherskogo kontrolya i svyazi SLDKS-1*. User's Manual. P. 1. Product specification ESAN.484457.001RE. URL: http://www.mnppsaturn.ru/ftp/public/doc/sldks/re%20sldks-1m%201.pdf (accessed: 11.04.2023).
[3]Apryshkin DS. *Otsenka tekhnicheskogo sostoyaniya mashin s kanatnoi tyagoi na osnove imitatsionnogo modelirovaniya.* Author's abstract. Rostov-on-Don, 2023. 21 p. URL: https://www.dissercat.com/content/otsenka-tekhnicheskogo-sostoyaniya-mashin-s-kanatnoi-tyagoi-na-osnove-imitatsionnogo-modelir/read

Constant values of factors: h=3 m — interstorey distance; $N_н$=1 — the number of floors the residents of which do not use the elevator.

On the basis of the data presented, the dependencies of the machine time coefficient K_m on the number of passengers using the elevator, Z_0 are constructed (Fig. 1).

For elevators in buildings with 9 and 24 floors, NMT is statistically directly proportional to the value Z_0. The numbers of points on the graphs correspond to the data in Table 1.

The exceptions are the positions of points 4 and 6. These deviations in experimental dependencies are quite acceptable, taking into account the formation of pure machine operating time of the elevator as a stochastic process under the influence of many random factors. The graphs in Fig. 1 reflect the approximate position of the straight lines $K_{mэ}=f(Z_0)$, the exact position of the lines is obtained by the least squares method [10].

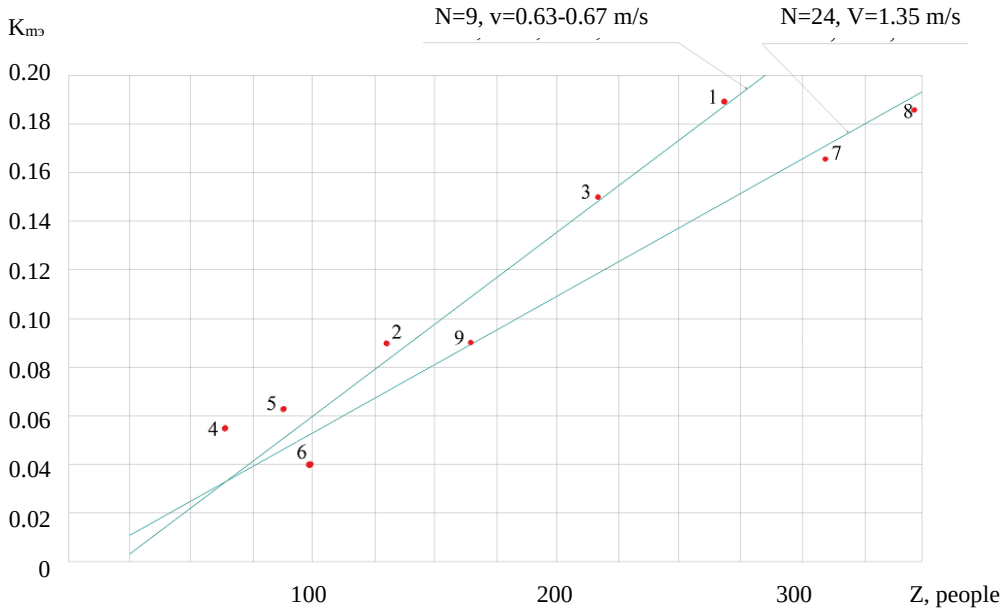


Fig. 1. Dependences of $K_{mэ}$ machine time coefficient on the number of residents using the elevator for average daily data processing

The graphs in Fig. 1 clearly show that NMT-$K_{mэ}$ linearly depends on the number of passengers using the elevator, Z_0, and with an increase in the speed of the cabin, *v*, NMT decreases.

When constructing mathematical model (1) of the average NMT value, a structure consisting of three factors was adopted: $\frac{\alpha_{m1}}{\lambda_н}$ — takes into account the angle of inclination of the straight line depending on the time period of the day; $Z_i(1-\frac{M_{k1i}}{M_{ki}})$ — the number of tenants using the elevator; $\Phi(\frac{v_{calc.i}}{v_{base}})$ — the function of NMT change from the ratio of the elevator speeds taken as the base, v_{base}, and the elevator with a specific speed, $v_{calc.i}$. Elevator N=9 with an average speed, v_{base}=0.65 m/s is taken as the base. In this case, the lines $K_{mi}=f(Z_i)$ pass through the origin:

$$K_{mi} = \frac{\alpha_{m1}}{\lambda_н} \cdot Z_i(1-\frac{M_{k1i}}{M_{ki}}) \cdot \Phi(\frac{v_{расч.i}}{v_{баз}}), \quad (1)$$

where i=1, 2, 3 etc. determines the number of a straight line with a fixed value of the average speed of the cab, $v_{calc.i}$, along which the K_{mi} values are concentrated depending on the number of residents of the house (entrance) using the elevator:

i=1 — elevators with an average speed $v_{calc.1}$=0.63–0,65 m/s;

i=2 — elevators with an average speed $v_{calc.2}$=0.91 m/s;

i=3 — elevators with an average speed $v_{calc.3}$=1.35 m/s;

$\lambda_н$ — coefficients of NMT reduction in the night period, determined based on the processing of monitoring results (Table 1): for N=9 and v_1=0.63…0.67 m/s — $\lambda_{н1}$=3.0; for N=18 and v_2=0.91 m/s — $\lambda_{н2}$=3.5; for N=24 and v_3=1.35 m/s — $\lambda_{н3}$=4.0; for day mode: N=9, v_1=0.63 and 0.67 m/s — $\lambda_{н1}$= 0.773; N=18, v_2=0.91 m/s — $\lambda_{н2}$=0.721; N=24, v_3=1.35 m/s — $\lambda_{н3}$=0.669.

α_{m1} — angular coefficient of the basic dependence $K_{m1}=\alpha_{m1}\cdot Z_0$; for the rightmost point of the basic linear dependence at Z=303 people, Z_0=269 people, K_{m1}=0.197 we get (see the first line of Table 1):

$$\alpha_{m1} = \frac{0.197}{269} = 0.00073\ (\frac{ea.NMT}{people}).$$

$\Phi(\frac{v_{calc.i}}{v_{base}})$ — linear function that takes into account the influence of the ratio of the lowest speed, $v_1=v_{base}=0.65$ m/s, to the actual speed of the elevator, $v_{calc.2}=0.91$, $v_{calc.3}=1.35$ et al.

Let us set the form of the function $\Phi(\frac{v_{calc.i}}{v_{base}})$, using the data in Table 2. The function must pass through points $\alpha_{m1}, \alpha_{m2}\ and\ \alpha_{m3}$. Table 2 provides numerical characteristics for these points.

Table 2

Numerical characteristics of points $\alpha_{m1}, \alpha_{m2}\ and\ \alpha_{m3}$

Points	1	2	3
v, m/s	0.65	0.91	1.35
$K_{m.max}$	0.197	0.192	0.186
$Z_{0.max}$	269	300	347
α_{mi}	0.00073	0.00064	0.00054

The equation of a straight line passing through two points, 1 and 3

Let us denote $\alpha_{mi} = y$; $\frac{v_i}{v} = x$. Coordinates of points 1–x_1=1; y_1=1;

3–x_3=1.35/0.65=2.08; y_3=0.00054/0.00073=0.762. Equation of a straight line:

$$\frac{x-1}{2.08-1} = \frac{y-1}{0.762-1};$$

after simple transformations, we get y=1.22–0.22x.

Then $\Phi\left(\frac{v_{calc.i}}{v_{base}}\right) = 1.22 - 0.22\ \frac{v_{calc.i}}{v_{base}}$. Equation (1) takes the form

$$K_{mi} = \frac{\alpha_{m1}}{\lambda_н} \cdot Z_i\left(1 - \frac{M_{k1i}}{M_k}\right) \cdot \left(1{,}22 - 0{,}22\,\frac{v_{расч.i}}{v_{баз}}\right). \quad (2)$$

Results. Assessment of the calculation results reliability according to formula (2), $K_{mcalc.}$, in comparison with the data of dispatcher records, $K_{m.э.}$, is given in Table 3.

Table 3

Comparison of calculation results and dispatcher records data

No.	i	$V_{расч.i}$, m/s	Z_i, people	M_{k1i}, people.	M_{ki}, people.	$K_{m.расч.}$	$K_{m.э.}$
1	1	0.65	240	106	10	0.152	0.150
3	1	0.65	99	36	4	0.062	0.063
4	2	0.91	130	35	4	0.094	0.120
5	2	0.91	143	35	4	0.081	0.080
6	3	1.35	310	108	0	0.166	0.166
7	3	1.35	165	108	0	0.089	0.090

As can be seen from expression (2), the number of floors of building N is not explicitly included in the formula. Indirectly, the influence of N is manifested through Z_0. The influence of Z_0 (50...300 people) and $v_{calc.}$ (0.6…2.0 m/s) is shown in Fig. 2. As follows from these dependencies, with an increase in the average speed of the elevator, $v_{calc.i,}$ the NMT decreases almost proportionally. With an increase in the occupancy of the house, the NMT increases proportionally.

Thus, in a wide range of influencing factors, mathematical model (2) provides results adequate to experimental values (the deviation of experimental data in comparison with the calculated ones does not exceed 10 % in most cases) and allows predicting the value of NMT when the most important factors change — the density of occupancy of a building or entrance and the speed of movement of the cabin, on which the elevator equipment utilization largely depends.

At the same time, ratio (2) takes into account the influence of only two factors on the NMT: Z_0, and $v_{ср}$. The value of N is not directly included in the formula, which limits its application and reduces visibility in practical use. This formula generalizes only the set of data from regular observations limited by Table 1.

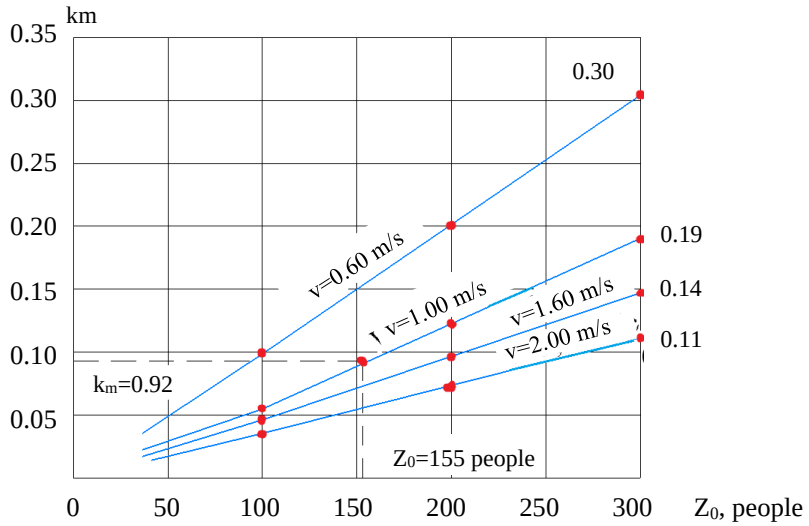


Fig. 2. Calculated dependences of NMT on the number of residents of the building (entrance), Z_0, using the elevator, and the average speed of the cab

Let us use another approach to derive the general ratio $K_m=f(N, v_{cp}, Z_0)$. Previously conducted researches[3] proved that the average value of NMT is proportional to Z_0, and the proportionality coefficients for buildings of different floors differ significantly. So, for elevators N=9 and v_{cp}=0.63 m/s the coefficient characterizing the ratio of the increment of NMT Δ_{Km} to the increment of the number of residents using the elevator Δ_{Z0}, is $\frac{\Delta_{Km}}{\Delta_{Z0}} = 0.075\ \frac{ea.K_m}{100\ people}$, for elevators N=24 and v_{cp}=1.35 m/s — $\frac{\Delta_{Km}}{\Delta_{Z0}} = 0.055\ \frac{ea.K_m}{100\ people}$.

These data indicate the dependence of the specific NMT – $\frac{\Delta_{Km}}{\Delta_{Z0}}$ (i.e., per registered tenant using the elevator) on two main factors — the number of floors of the building N and the average speed of the cabin v_{cp}.

With an increase in the number of floors, the average number of flights passed by an elevator in one cycle increases in direct proportion to the number of floors. With a constant number of cycles per unit of time to ensure the necessary capacity of the elevator, the machine cycle time will increase proportionally with the increase in the number of floors. With an increase in the average speed, the duration of the trip and the machine time are proportionally reduced.

If we denote the coefficient of influence of the listed factors N and v_{cp} on the specific NMT α_{Km}, then in the first approximation the dependence $\alpha_{Km}=f(N,v_{cp})$ has the form:

$$\alpha_{Km}=\alpha_{Km0}+\frac{K_1 \cdot N}{K_2+v}, \quad (3)$$

where $\alpha_{Km0}=0.0004\ \frac{ea.K_m}{100 people}$ — the minimum value of the specific NMT recorded as a result of processing dispatcher surveillance data.

Using experimental data and the given logical reasoning, we obtain a generalized dependence of the specific NMT on N and v_{cp}:

$$\alpha_{Km}=0{,}0004+\frac{0{,}00228N}{v_{cp}-0{,}358}. \quad (4)$$

The dimension of quantity $[\alpha_{Km}]=\frac{ea.K_m}{100\ people}$. In expression (4), the specific NMT is proportional to the number of floors of the building and inversely proportional to the average speed of the cabin. The substantiation of the structure of formula (4) was made according to recommendations [10, 11], the selection of constants K_1 and K_2 was carried out according to the methodology [12, 13].

Dependences $\alpha_{Km}=f(N, v_{cp})$ in graphical form in the ranges of variables N=(9…24), v=(0.6…2.0 m/s) are shown in Fig. 3.

Using an example for an elevator that is not included in the number of objects of regular observations, we will show the calculation of NMT using expression (4). Initial data: N=16; v_{cp}=1 m/s; Z_0=250 (2.5x100) people.

Calculation results:

$$\alpha_{Km}=0.0004+\frac{0.0228N}{v_{cp}-0.358}=0.0004+\frac{0.00228\cdot 16}{1-0.358}=0.0569\frac{ea.K_m}{100\ people}.$$

Estimated NMT of the elevator unit:

$$K_m=0.0569\cdot 2.5=0.142.$$

Formula (4) is valid for N=9…24, v_{cp}=0.6…2.0 m/s, with an arbitrary number of residents Z_0 and allows you to determine the preliminary value of the NMT when assessing the elevator mode of operation utilization.

It should be noted that strict regularities for another important indicator (the specific number of turns-on per unit of net machine time, n_{cp}) could not be established. Let us note that the relationship between K_m and n is not traced (Table 4 and Fig. 4).

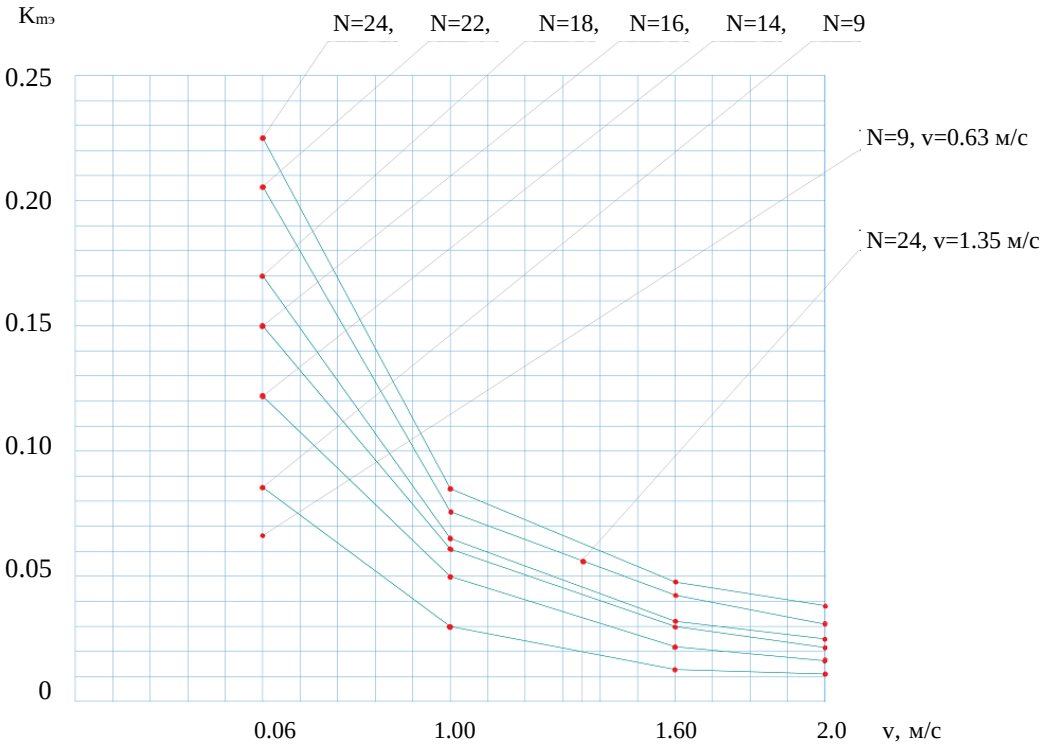


Fig. 3. Dependence of the specific NMT on the number of floors of the building and the speed of the elevator

Table 4

Average values of elevator operating modes

Elevator no.	1	2	3	4	5	6	7	8	9	10	11
NMT Coefficient	0.190	0.089	0.149	0.056	0.063	0.040	0.145	0.065	0.088	0.107	0.080
n, 1/min. NMT	2.45	2.13	1.90	3.43	2.75	2.86	1.95	1.83	3.08	2.25	1.89

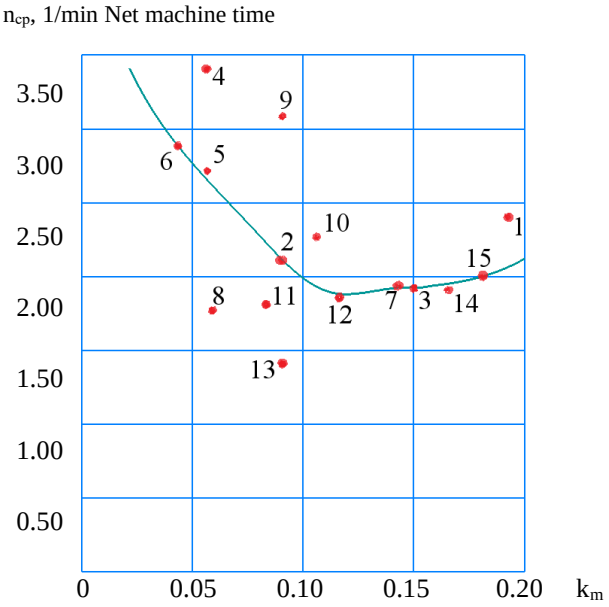


Fig. 4. Relationship of random values of $n_{cp.}$ and $K_{mcp.}$

The results of data processing of daily monitoring of the operation of elevator units with different characteristics in different types of residential multi-storey buildings, as well as of the same type or identical elevator units in one multi-entrance structure are presented in Table 4. The main indicators of the operation mode of the main drive of the elevator vary widely: NMT — five times, from 0.04 to 0.19, the number of turns-on per minute of net machine time — 1.87 times, from 1.83 to 3.43. NMT objectively characterizes the net time spent by all elements of the elevator in working condition, the values of this coefficient for most units are at a low level (0.05 ...0.2). This indicates a significant underloading of the main drive and other components. The specific number of turns-on determines the frequency of application of dynamic loads on the drive, ropes, cabin structure and other components. The characteristic value of the number of turns-on is from two to three per minute of net machine time, in terms of the hourly frequency of turns-on, this will be 120 ... 180 turns-on, which is quite acceptable for the engine, gearboxes and braking devices used.

Discussion and Conclusion. When designing and implementing maintenance systems for passenger elevator units, it is necessary first of all to determine the level of loading of their main power elements — the engine, gearbox, rope pulley, ropes, etc. [14]. Among the most important indicators of the degree of loading of the system, the NMT and the frequency of turns-on should be taken into account. The most reliable way to predict these indicators is statistical processing of dispatcher control data for the operation of elevators. The presented empirical dependences of the machine time coefficient on the number of floors of buildings, the number of residents using the elevator, and the speed of the cabin are also basic for the simulation of the time indicators of the operation of elevator units being put into operation, as well as elevators that are not equipped with a dispatch control system.

References

1. Panfilov AV, Yusupov AR, Korotkiy AA, Ivanov BF. On the Control of the Technical Condition of Elevator Ropes Based on Artificial Intelligence and Computer Vision Technology. *Advanced Engineering Research (Rostov-on-Don).* 2022;22(4):323–330. https://doi.org/10.23947/2687-1653-2022-22-4-323-330

2. Jae-Hak Lim, Dong Ho Park. Optimal Periodic Preventive Maintenance Schedules with Improvement Factors Depending on Number of Preventive Maintenances. *Asia-Pacific Journal of Operational Research*. 2007;24(1):111–124. https://doi.org/10.1142/S0217595907001139

3. Hongjiu Liu, Jiaxuan Wu. Research on Preventive Maintenance Strategy of Elevator Equipment. *Open Journal of Social Sciences.* 2018;06(01):165–174. https://doi.org/10.4236/jss.2018.61012

4. Li YH, Liu Z. Maintenance Interval Optimization Method Based on Improvement Factor for System Components. *Mechanical Engineering & Automation*. 2016;4:6–8.

5. Gia-Shie Liu. Three M-Failure Group Maintenance Models for M/M/N Unreliable Queuing Service Systems. *Computers & Industrial Engineering*. 2012;62(4):1011–1024. https://doi.org/10.1016/j.cie.2011.12.028

6. Almgren T, Patriksson M, Wojciechowsri A. Optimization Models for Improving Periodic Maintenance Schedules by Utilizing Opportunities. In: *Proceedings of the 4th Production and Operations Management World Conference.* The Netherlands, Amsterdam; 2012.

7. Khazanovich GS, Apryshkin DS. Modern condition monitoring systems of elevator units. Safety of Technogenic and Natural Systems. 2019;(2):37–40. https://doi.org/10.23947/2541-9129-2019-2-37-40

8. Shpet NA, Muravlev OP. Investigation of passenger lift failure by the operation data. *Bulletin of the Tomsk Polytechnic University.* 2013;323(4):123–126. http://earchive.tpu.ru/handle/11683/5035 (accessed: 12.06.2023).

9. Khazanovich GS, Apryshkin DS. Assessment of load of load-bearing elements of the passenger elevator based on regular monitoring results. *Safety of Technogenic and Natural Systems*. 2020;(1):32–42. https://doi.org/10.23947/2541-9129-2020-1-32-42

10. Gubanov VS. *Obobshchennyi metod naimen'shikh kvadratov*. Monograph. Saint-Petersburg: Nauka; 1997. 318 p. URL: http://pzs.dstu.dp.ua/DataMining/mls/bibl/gubanov.pdf (accessed: 12.06.2023)

11. Venttsel ES. *Teoriya veroyatnostei*. Textbook for universities. Moscow: Vysshaya shkola; 1999. 576 p.

12. Gnedenko BV. *Kurs teorii veroyatnostei*. Textbook. Moscow: Librokom; 2011. 448 p.

13. Gmurman VE. *Teoriya veroyatnostei i matematicheskaya statistika*. Textbook for universities. Moscow: Vysshaya shkola; 2003. 479 p.

14. Podberezina SG. Liftovoe khozyaistvo: organizuem sistemu planovo-predupreditel'nogo remonta. *Promyshlennaya bezopasnost'*. 2020;3:73–84. https://www.profiz.ru/pb/3_2020/lift_remont/ (accessed: 12.06.2023).

Received 03.07.2023
Revised 24.07.2023
Accepted 24.07.2023

About the Authors:

Grigorii Sh. Khazanovich, Dr. Sci. (Eng.), Professor, Chief Researcher of the Center for Scientific Competencies, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, RF), AuthorID, ORCID, hazanovich@mail.ru

Dmitrii S. Apryshkin, Senior lecturer of the Transport Systems and Logistics Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, RF), AuthorID, ORCID, aprechnik@mail.ru

Claimed contributorship:

GSh Khazanovich: formulation of the basic concept, goals and objectives of the study; revision of the text; evaluation of the reliability of the results; correction of conclusions.

DS Apryshkin: derivation of analytical relations; preparation of the text; research results analysis; drawing conclusions; carrying out calculations.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 03.07.2023
Поступила после рецензирования 24.07.2023
Принята к публикации 24.07.2023

Об авторах:

Хазанович Григорий Шнеерович, доктор технических наук, профессор, главный научный сотрудник центра научных компетенций Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), AuthorID, ORCID, hazanovich@mail.ru

Апрышкин Дмитрий Сергеевич, старший преподаватель кафедры эксплуатации транспортных систем и логистики Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), AuthorID, ORCID, aprechnik@mail.ru

Заявленный вклад соавторов:

Г.Ш. Хазанович — формирование основной концепции, цели и задачи исследования, доработка текста, оценка достоверности результатов, корректировка выводов.

Д.С. Апрышкин — вывод аналитических соотношений, подготовка текста, анализ результатов исследований, формирование выводов, проведение расчетов.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

MACHINE BUILDING
МАШИНОСТРОЕНИЕ

UDC 620.179

Original article

Variation Coefficient of Metal Yield Strength in New and Long-Used Building Structures

Nikas L. Vernezi ✉

Don State Technical University, Rostov-on-Don, Russian Federation

✉ vernezin@mail.ru

Abstract

Introduction. Non-destructive methods are most often used to assess the condition of the metal structure. Dangerous stress is determined by the value of the yield strength. This approach has weaknesses. This is, firstly, the probabilistic nature of the methodology (the minimum value of the indicator obtained during laboratory tests is entered into the regulatory and technical documentation). Secondly, the limitations on the number of samples should be overcome. Thirdly, the different duration of operation causes a significant difference in the mechanical characteristics of the metal, which to a certain extent complicates the long-term prediction of the condition of the structure. The presented work is designed to solve these problems within the framework of the study of new and long-operated facilities in the Rostov region. The scientific research objective is to analyze fatigue changes and determine possible degradation of the metal.

Materials and Methods. The mechanical characteristics of the material under study were reliably described by the Weibull distribution law through the shear parameter (the minimum possible value of the characteristic) and the shape parameter (magnitude dispersion). For scientific research, the indentation method based on a modified Rockwell hardness estimation method was used as part of the work. A conical indenter was embedded in the surface, then the reaction of the metal was analyzed. To implement the method, an analog-to-digital converter and a laptop were used. For correlation analysis, intermediate characteristics were taken: depth, maximum and minimum velocities, maximum and minimum acceleration of cone insertion. A correlation was established with the mechanical characteristics determined by standard tensile and hardness tests of the metal.

Results. Objects with zero and long-term operation were studied. The measurements were carried out in a warehouse, production site, stadium, bridge, Palace of Sports and on a power line support. From the group of new and used structures, one was selected for a detailed fixation of the values of yield strength. So, before the start of operation, the condition of three metal trusses of the warehouse was analyzed. It was established that the lowest value of the yield strength here was 240 MPa, the maximum was 345 MPa. On the power transmission line poles, which have been in operation for 43 years, the lowest recorded value of the yield strength was 235 MPa, the highest was 384 MPa. For each of the six structures, the minimum and average distribution of the metal yield strength values was given, and the coefficients of variation of this indicator were given. The recorded values were summarized in the form of a table. The average values for all new and used designs were calculated. Graphically presented data illustrate the growth of the coefficients of variation of the yield strength with increasing service life.

Discussion and Conclusion. A comparative analysis of the obtained values of the yield strength of building structures of approximately the same strength class suggests that the influence of operating time can both increase and decrease the studied indicator. At the same time, long-term operation is a factor that increases the average value of the coefficient of variation. To monitor the strength capabilities of the structure, it is advisable to use a non-destructive method, selectively monitoring the mechanical characteristics of the elements before and during operation.

Keywords: non-destructive testing, metal yield strength, metal of the structure in operation, metal degradation

Acknowledgements: the author would like to express his deep appreciation and gratitude to Aleksey Nikolaevich Beskopylny and Andrey Anatolyevich Veremeenko, who took part in the inspection of metal structures together with the author.

For citation. Vernezi NL. Variation Coefficient of Metal Yield Strength in New and Long-Used Building Structures. *Safety of Technogenic and Natural Systems.* 2023;7(3):44–54. https://doi.org/10.23947/2541-9129-2023-7-3-44-54
https://doi.org/10.23947/2541-9129-2023-7-3-44-54

Научная статья

Коэффициент вариации предела текучести металла новых и долгое время эксплуатировавшихся строительных конструкций

Н.Л. Вернези ✉

Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

✉vernezin@mail.ru

Аннотация

Введение. Для оценки состояния металла конструкции чаще всего применяют неразрушающие методы. Опасное напряжение определяется по значению предела текучести. У такого подхода есть слабые места. Это, во-первых, вероятностная природа методики (в нормативно-техническую документацию вносится минимальное значение показателя, полученное при лабораторных испытаниях). Во-вторых, следует преодолеть ограничения по числу образцов. В-третьих, разная длительность эксплуатации обусловливает значительную разницу механических характеристик металла, что в известной степени осложняет долгосрочное прогнозирование состояния конструкции. Представленная работа призвана решить эти задачи в рамках исследования новых и давно эксплуатируемых объектов в Ростовской области. Цель научных изысканий — анализ усталостных изменений и определение возможной деградации металла.

Материалы и методы. Механические характеристики исследуемого материала достоверно описываются законом распределения Вейбулла через параметр сдвига (минимально возможное значение характеристики) и параметр формы (рассеивание величины). Для научных изысканий в рамках работы задействовали метод индентирования, основанный на видоизмененном способе оценки твердости по Роквеллу. Конический индентор внедряется в поверхность, затем анализируется реакция металла. Для реализации метода воспользовались аналогово-цифровым преобразователем и ноутбуком. Для корреляционного анализа брали промежуточные характеристики: глубина, максимальная и минимальная скорости, максимальное и минимальное ускорение внедрения конуса. Устанавливалась корреляция с механическими характеристиками, определенными по стандартным испытаниям на растяжение и твердость металла.

Результаты исследования. Изучались объекты с нулевой и многолетней эксплуатацией. Замеры проводили на складе, производстве, стадионе, мосту, во Дворце спорта и на опоре линии электропередач. Из группы новых и отработавших сооружений выбрали по одному для подробной фиксации значений пределов текучести. Так, до начала эксплуатации проанализировали состояние трех металлических ферм склада. Установлено, что наименьше значение предела текучести здесь — 240 МПа, максимальное — 345 МПа. На опорах линии электропередач, бывших в эксплуатации 43 года, самое низкое зафиксированное значение предела текучести — 235 МПа, самое высокое — 384 МПа. Для каждого из шести сооружений приводится минимальное и среднее распределение значений предела текучести металла, даны коэффициенты вариации этого показателя. Зафиксированные значения обобщены в виде таблицы. Рассчитаны средние показатели по всем новым и отработавшим конструкциями. Графически представленные данные иллюстрируют рост коэффициентов вариации предела текучести с увеличением срока эксплуатации.

Обсуждение и заключение. Сравнительный анализ полученных значений предела текучести строительных конструкций приблизительно одного класса прочности позволяет предположить, что влияние времени эксплуатации может как увеличить, так и уменьшить исследуемый показатель. При этом длительная эксплуатация — фактор, увеличивающий среднее значение коэффициента вариации. Для мониторинга прочностных возможностей конструкции целесообразно задействовать неразрушающий метод, выборочно отслеживая механические характеристики элементов до и в процессе эксплуатации

Ключевые слова: неразрушающий контроль, предел текучести металла, металл эксплуатируемой конструкции, деградация металла

Благодарности: автор выражает глубокую признательность Алексею Николаевичу Бескопыльному и Андрею Анатольевичу Веремеенко за помощь в обследовании металлоконструкций.

Для цитирования. Вернези Н.Л. Коэффициент вариации предела текучести металла новых и долгое время эксплуатировавшихся строительных конструкций. *Безопасность техногенных и природных систем*. 2023;7(3):44–54. https://doi.org/10.23947/2541-9129-2023-7-3-44-54

Introduction. In diagnostics, restoration, reliability assessment or reconstruction of long-used steel structures, it becomes necessary to find out the mechanical characteristics of metal, including its fatigue indicators. For plastic materials, which include steel structures, dangerous stress is determined by the yield strength value. As it is known, it has a probabilistic nature; its minimum value obtained during laboratory tests of a limited number of samples is entered into the regulatory and technical documentation. In most cases, the metal structure condition is assessed using non-destructive testing.

Mechanical characteristics (in particular, yield strength) undergo certain changes while in service [1]. The study provides a comparative analysis of the yield strength values of the metal of one strength class in structures before operation and after decades in use. The values of the yield strength were obtained during the examination by the non-destructive indentation method.

Many sources describe metal changes during the operation of the structure. At the same time, there is no single point of view regarding the direction of such transformations. Much depends on the nature of the material and the duration of operation. Thus, in the nuclear power industry, the metal of structures almost does not change over 30-40 years of operation [2]. In [3], there is a decrease of almost 40 % in the cyclic strength of steels 20 and 45 after 15 years of storage. The authors of [4] emphasize that 40 or more years of operation of the main gas pipeline have almost no effect on the mechanical characteristics of steel. At the same time, in [5], a decrease in plasticity is recorded with a constant value of the strength limit of the gas pipeline metal after 37 years of operation. In [6], the danger of gas pipeline failures during long-term operation due to degradation processes in the metal is indicated. In [7], a decrease in impact strength after prolonged operation is described.

For 17G1C steel, in the first years of operation of the gas pipeline, there is an increase in strength with a decrease in ductility. In the period from 20 to 30 years of operation, there is a steady decrease in both strength and ductility [8]. Obviously, with significant differences in service life, we can expect a significant difference in the mechanical characteristics of the metal, which complicates the long-term prediction of the condition of the structure. The approach proposed in this article is designed to overcome this and the limitations mentioned above: the probabilistic nature of the indicator and the insufficient number of samples.

Several objects in the Rostov region with zero and long-term operation were examined. As a result, new data on the yield strength of real metal structures were collected and summarized. The objective of the presented scientific work is to analyze the changes and to assess the possible degradation of the metal.

Materials and Methods. Let us try to quantify the changes in the mechanical characteristics of the metal. To do this, we consider the same structural elements before and after long-term operation. Such monitoring is periodically carried out in relation to the metal of the main pipelines. At the same time, it is even possible to predict the residual durability of the material [9, 10]. However, it is difficult to implement such an approach for other metal structures. In this case, you can use the information obtained by the method of non-destructive testing of metal. Ensuring the correctness of such data assumes that:

– similar constructions are compared;

– the controlled elements are made of metal of the same strength class;

– the sample of processed data is quite representative.

The authors [11] claim that the strength class of steels for metal structures is determined by certain intervals of yield strength, strength and elongation. Hence, it is necessary to compare metals with mechanical characteristics that fit into these intervals. For example, for steel of strength class C-285, the yield strength is allowed in the range from 265 MPa to 285 MPa, i.e. it is determined with an error of 7.55 %.

Only non-destructive methods are suitable for the diagnosis of the existing structures. For example, acoustic emission is used for:

– finding defects in metal [12];

– monitoring of the stress state [13];

– detection of fatigue crack growth [14] in pressure vessels;

– determination of the beginning of active metal cracking [15];

– control of welded joints [16, 17].

At the same time, the issues of the optimal arrangement of devices for determining defects in structures of complex shape are solved [18].

With the help of electromagnetic control, the specified hardness of the metal is fixed [19]. In addition, methods of direct mechanical interaction with metal during indentation are used to assess:

– the residual stresses in the metal [20];

– the initial value of the yield strength [21].

Mechanical characteristics are reliably described by the three-parameter Weibull distribution law[1]:

$$F(X) = 1 - exp\,[-((X - C)/A)^B],$$

where X — value of the mechanical property; C — shear parameter that determines the minimum possible value of the characteristic; B — shape parameter by which it is possible to judge the dispersion of this property.

It is obvious that as a result of the impact of operational loads, the average, minimum values of the mechanical characteristics of the material may change. As a consequence, the standard deviation and the coefficient of variation of the values of mechanical characteristics change.

The indentation method used in the article is based on a modified Rockwell hardness estimation method. The conical indenter is shockingly (not statically) embedded into the polished test surface under the conditions:

- energy is 0.16 J;
- angle at the top is 90 °.

Then the reaction of the metal is analyzed. 10 sq. cm. of the free area of the metal [22-24] or the welded joint [25] is enough for work. To implement the method, an analog-to-digital converter (ADC) and a laptop were used. With the help of the ADC, the dependences of the speed change on the time of the introduction of the conical indenter of the mechanical part were obtained. Then the signal was programmatically processed in a laptop and the dependencies of the indenter movement and acceleration on time were obtained. Then we took the intermediate characteristics obtained from the graphs: depth, maximum and minimum speeds, maximum and minimum acceleration of the cone insertion. They became the object of correlation analysis. A correlation was established with the mechanical characteristics determined by standard tensile and hardness tests of the metal. As a result of studying metals of various strength classes, universal correlations of standard mechanical characteristics from intermediate ones were obtained and recorded. Then, when metal was indented, its standard mechanical characteristics at the point under study were almost immediately displayed on the laptop display. The instrumentation provided the total dispersion caused by the spread of properties in the metal and the measurement error. The limit values of the error of one measurement were ± 4 %. The ability to quickly obtain 10-20 values on a local section of metal eliminated this error. And with the prompt receipt of an unlimited number of measurements, a high representativeness of the sample was ensured. Before each examination, the device was calibrated:

– the yield strength was measured on samples with previously known properties obtained during standard tensile tests on the IR-200 tensile testing machine;

– then the adjustment was performed.

Results. The objective of the study was to obtain a quantitative comparative assessment of the possible degradation of metal during long-term operation. For this purpose, the values of the yield strength of steel structures with zero and long service life were fixed by the non-destructive indentation method.

Therefore, new structures were considered:

– warehouse on Lugovaya Street, 8 in Rostov-on-Don (Table 1);

– production building on 1-st Pyatiletki Street, 71 in Bataysk (Fig. 1);

– columns of the stands of the Torpedo Stadium in Taganrog (Fig. 2).

[1] GOST R 50779.27-2017 (IEC 61649.2008). *Statistical methods. Weibull distribution. Data analysis.* Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/1200146523 (accessed: 19.06.2023).

Table 1

Data from the survey of metal structures of the warehouse at Lugovaya Street, 8

Yield strength values, MPa										
Truss 12				Truss 15				Truss 18		
240	265	279	298	236	263	277	305	244	270	287
240	266	280	298	237	263	277	307	244	270	287
241	266	280	298	237	263	277	307	244	270	288
241	266	280	299	237	264	277	309	248	271	289
242	267	281	299	237	264	277	309	249	272	289
243	267	281	299	237	265	277	312	249	272	289
243	268	281	300	237	265	278	313	249	273	290
244	269	282	302	239	266	278	315	249	273	290
245	269	282	303	239	266	278	317	250	273	291
247	269	282	303	241	266	278	325	252	273	292
248	270	283	304	243	266	278	329	252	273	293
248	270	283	304	243	267	279	332	253	274	294
250	271	284	306	243	267	280	339	253	274	295
250	271	284	307	245	267	280	345	254	274	295
250	271	284	307	246	268	280	351	256	274	296
251	272	284	307	247	268	281		256	275	297
251	272	285	308	247	268	281		257	275	297
251	273	285	309	249	269	282		257	275	298
251	273	286	309	250	269	282		257	277	299
253	274	286	309	250	269	283		257	277	299
253	274	287	312	252	269	284		257	277	299
254	274	287	313	252	270	284		258	277	300
254	274	288	313	252	271	284		259	278	300
254	274	288	313	252	271	285		259	278	300
255	274	289	314	253	271	285		259	278	301
255	275	289	314	253	272	285		260	279	301
256	275	290	315	255	272	286		260	279	306
256	275	290	315	256	272	286		263	279	311
257	275	290	316	256	273	287		263	280	312
258	276	291	317	256	273	287		263	281	313
258	276	291	317	256	273	287		264	282	315
258	277	291	318	256	273	288		264	282	316
258	277	291	319	257	273	289		264	282	317
258	277	291	320	257	274	289		265	283	318
258	277	291	320	258	274	289		265	283	318
259	277	292	320	259	274	290		265	284	320
260	277	292	327	259	275	290		266	284	324
260	278	293	339	259	275	291		266	284	324
260	278	293	343	260	275	293		266	284	326
261	278	294	343	260	275	295		266	284	326
261	278	294	346	260	275	295		266	285	331
262	278	295	347	260	275	297		267	285	333
262	278	295	350	261	276	297		267	285	340
262	278	296	352	261	276	300		268	285	345
264	278	296	353	262	276	301		269	286	345
264	279	296	353	262	276	302		269	286	
264	279	297		262	276	302		270	286	

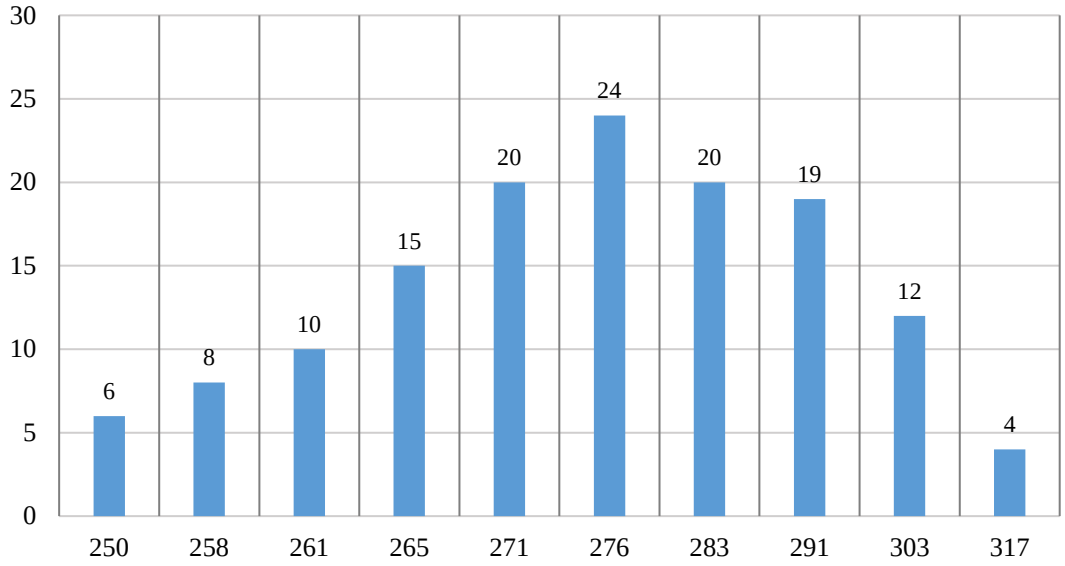


Fig. 1. Distribution of the metal structures yield strength values of the production building in Bataysk: σTmin = 246 MPa, σTcp = 277 MPa, CV = 0.054

Here and further, the sample minimum σt min, the sample average σt cp and the coefficients of variation of the yield strength CV are indicated. Ordinate is a scale of the frequency of values. The numbers above the columns are the number of measured values in a specific interval.

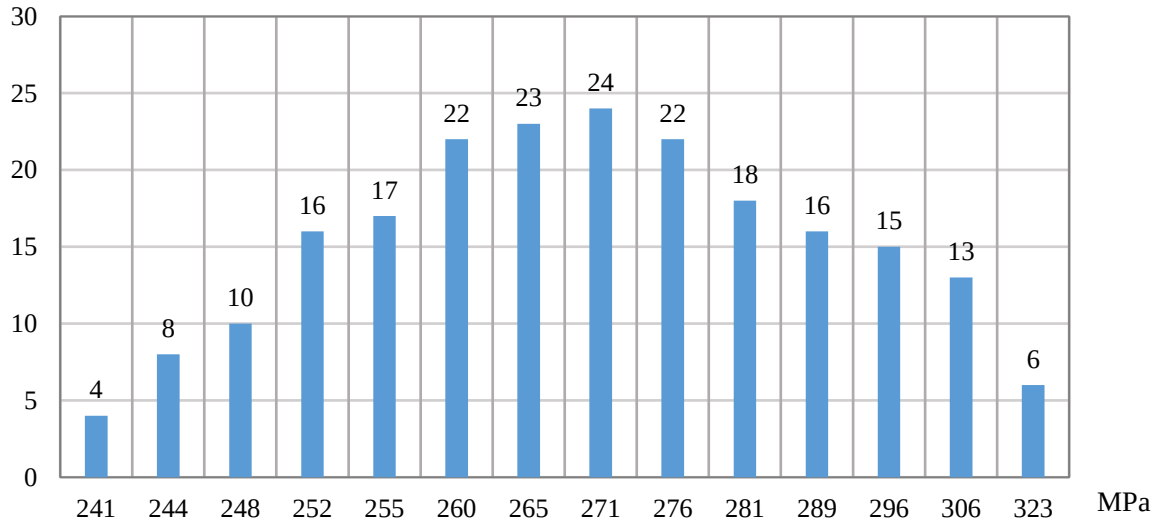


Fig. 2. Distribution of the metal yield strength values of the columns of the Torpedo Stadium in Taganrog: σTmin = 240 MPa, σTcp = 272 MPa, CV = 0.068

The metal, which had been in operation for several decades, was studied at the following objects:

– railway bridge at Likhaya station (65 years old, Fig. 3);

– the roof trusses of the Sports Palace in Rostov-on-Don (39 years old, Fig. 4);

– braces of load-bearing structures of the power transmission line poles HV line 330 "Novocherkasskaya GRES — Yuzhnaya" (43 years, Table 2).

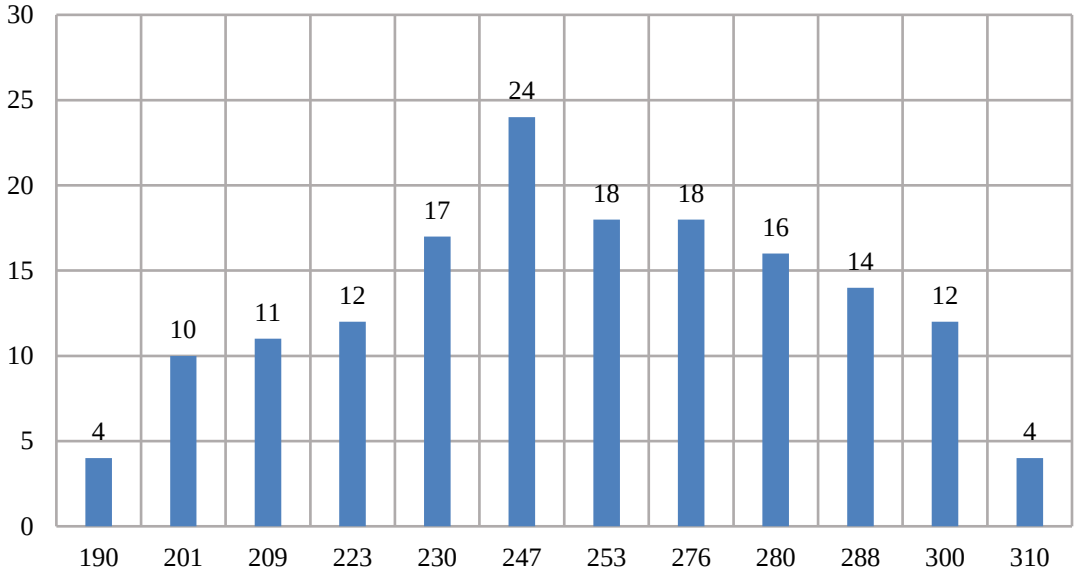


Fig. 3. Distribution of the metal structures yield strength values of the bridge at the Likhaya station: σTmin = 188, σTcp = 257, CV = 0.127

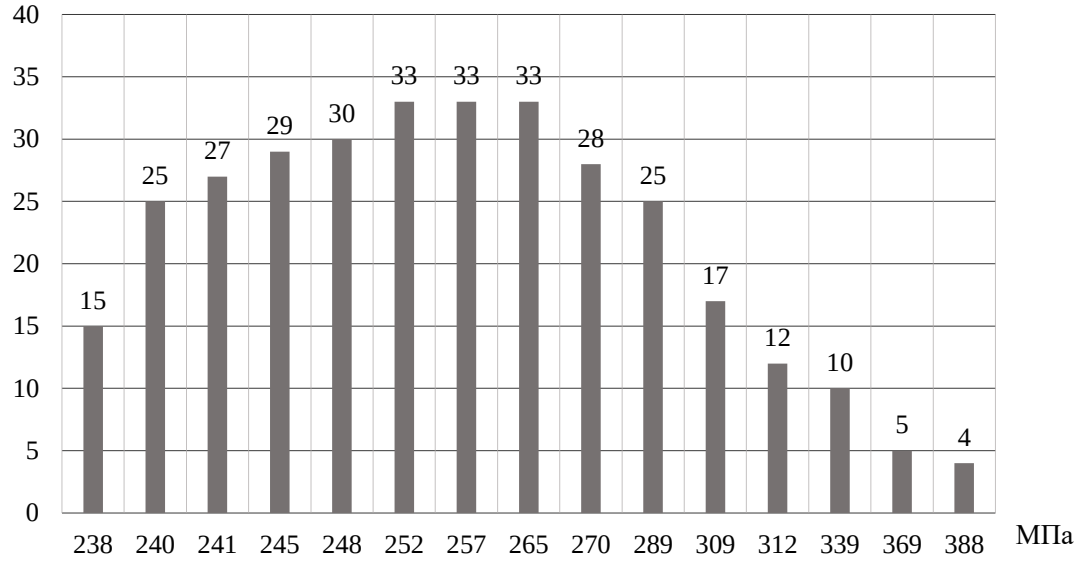


Fig 4. Distribution of the metal trusses yield strength values of the coating of the Sports Palace in Rostov-on-Don: σTmin = 238 MPa, σTcp = 263 MPa, CV = 0.11

Table 2

Examination results of power transmission line poles HV line 330

Yield strength values, MPa							
235	244	249	259	275	282	288	357
236	245	251	261	278	282	291	357
237	246	255	263	280	282	292	366
238	246	256	265	280	283	294	380
239	247	256	269	281	284	295	380
239	248	259	272	282	286	303	384

The data in Table 2 were checked for compliance with the three-parameter Weibull distribution law. It was necessary to estimate the theoretical, and not the selective minimum value of the yield strength σt min. As a result of the calculation, the theoretical value turned out to be less than the selective one by 6 MPa (229).

Let us note that the elements of the new structures were not affected by the stress-strain state, and those that were in operation for a long time were in a state of:

– compressed-bendable (upper belts of the coating trusses);

– stretched-flexed (lower belts of trusses covering);

– stretched (stretch marks).

The yield strength values obtained as a result of non-destructive testing are ranked in ascending order for better informativeness in Tables 2 and 3.

The steels of all new metal structures and HV line 330 can be attributed to the strength class C285. The metal of the bridge at the Likhaya station has an average yield strength of 8 MPa below the limit specified in [10]. The steel structures of the Sports Palace are 11 MPa higher.

The results of the comparative analysis are shown in Table 3 and Figure 5.

Table 3

Research results summary

Object	Parameters					
	Metal yield strength values, MPa				Calculation of the average coefficient of variation	
	Mean σ_T		Minimum in the sample $\sigma_{T_{min}}$	Mean $\sigma_{T_{min}}$ for objects	Standard deviation (MPa) / CV	Average value for objects
Warehouse	276	274	236	239	23.7 / 0.085	0.069
Production building	277		246		14.5 / 0.054	
Stadium	272		240		18.5 / 0.068	
Sports Palace	263	267	256	226	28.8 / 0.11	0.123
Electric power line HV line 330	280		235		39.8 / 0.142	
Railway bridge	257		188		33,5 / 0 ,127	

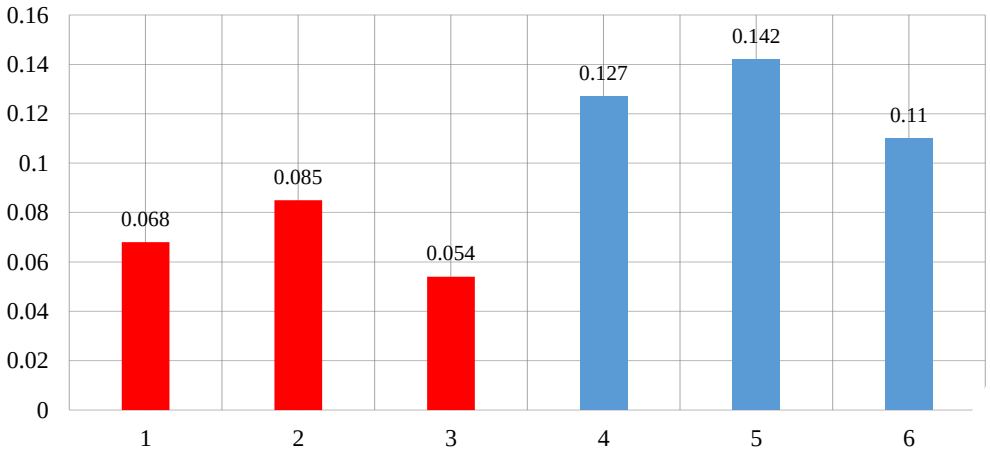


Fig. 5. Coefficients of variation of yield strength before and after long-term operation: 1 — stadium, 2 — warehouse, 3 — production building, 4 — railway bridge, 5 — electric power line HV line 330, 6 — Sports Palace

Discussion and Conclusion. Let us compare the average values of the coefficient of variation of new and long-used structures. From Table 3 it can be seen that after long-term operation, this indicator will be on average 1.78 times higher (0.123 times more than 0.069). The maximum coefficient of variation of the yield strength (0.142) was found on the power transmission line poles HV line 330 (43 years of operation). The minimum value of the yield strength (188 MPa) is for the metal of the bridge at the Likhaya station, which has been in operation for 65 years.

The possible theoretical minimum values of the yield strength decrease relative to the sample values, which can also increase the scope of the distribution and, accordingly, the coefficient of variation.

To monitor the strength capabilities (for example, for the purpose of repair or reconstruction), it is recommended to selectively monitor the mechanical characteristics of the metal structure elements by non-destructive method before and during operation.

References

1. Dotsenko ER, Myndyuk VD, Karpash MO. Otsenka izmenenii mekhanicheskikh svoistv metalla magistral'nykh truboprovodov s ispol'zovaniem metodov nerazrushayushchego kontrolya. In: *Trudy VII mezhdunar. nauch.-tekh. konf. po nadezhnosti i bezopasnosti magistral'nogo truboprovodnogo transporta.* Novopolotsk: 2011. P. 143–145. URL: https://www.psu.by/images/stories/nauka/tezis_7mntk.pdf (accessed: 12.06.2023).

2. Gorynin IV, Timofeev BT. Degradation of properties of structural materials at long time influence of operational temperatures. *Voprosy Materialovedeniya.* 2011; (1(65)):41–59.

3. Demina Yu. *Vliyanie dlitel'noi ekspluatatsii i khraneniya na mekhanicheskie svoistva i mekhanizmy razrusheniya konstruktsionnykh materialov*. Avtoref. dis. kand. tekh. nauk. Moscow; 2014. 26 p.

4. Lubenskii SA, Yamnikov SA. Vliyanie dlitel'nosti ekspluatatsii na svoistva metalla trub magistral'nykh truboprovodov. *Issues of risk analysis.* 2013;10(1):58–63.

5. Bykov IYu, Birillo IN, Kuzbozhev PA. Study of characteristics of mechanical properties of gas-distributing station pipes metal after long-term operation. *Oil and Gas Studies.* 2015;(2):86–91. https://doi.org/10.31660/0445-0108-2015-2-86-91

6. Bolshakov AM. Analiz razrusheniya i defektov v magistral'nykh gazoprovodakh i rezervuarakh Severa. *Gas Industry*. 2010;(5(646)):52–53.

7. Syromyatnikova AS. Degradation of physical and mechanical condition of gas pipeline metal during long operation at low climatic temperatures. *Tambov University Reports. Series Natural and Technical Sciences*. 2013;18(4–2):1746–1747.

8. Nikiforchin GN, Tsirul'nik OT, Zvirko OI, Gredil' MI, Voloshin VA. Degradation of the physical and mechanical properties of steels in long-run gas pipelines. *Industrial Laboratory. Diagnostics of Materials*. 2013;79(9):48–55.

9. Aneesh Bangia, Raghu V Prakash. Energy Parameter Correlation of Failure Life Data between Cyclic Ball Indentation and Low Cycle Fatigue. *Open Journal of Metal*. 2012;2(1):31–36. https://doi.org//10.4236/ojmetal.2012.21005

10. Collin M, Parenteau T, Mauvoisin G, Pilvin P. Material Parameters Identification Using Experimental Continuous Spherical Indentation for Cyclic Hardening. *Computational Materials Science*. 2009;46(2):333–338. https://doi.org//10.1016/j.commatsci.2009.03.016

11. Gorev VV, Uvarov BYu, Filippov VV, Belyi GI, Endzhievskii LV, Krylov II, et al. *Metallicheskie konstruktsii*. In 3 vol. Vol. 1. *Elementy stal'nykh konstruktsii*. Moscow: Vysshaya shkola; 1997. 527 p.

12. Pullin R, Holford KM, Lark R, Eaton MJ. Acoustic emission monitoring of bridge structures in the field and laboratory. *Journal of Acoustic Emission*. 2008;26:172–181.

13. Anastasopoulos AA, Kourousis DA, Cole PT. Acoustic emission inspection of spherical metallic pressure vessels. In: *The 2nd International Conference on Technical Inspection and NDT (TINDT2008)*. Iran, Tehran; 2008. 10 p. URL: http://www.ndt.net/article/tindt2008/papers/177.pdf (accessed: 12.06.2023).

14. Pollock, A. Probability of detection for acoustic emission. *Journal of acoustic emission*. 2007;25:231–237.

15. Polyzos D, Papacharalampopoulos A, Shiotani T, Aggelis DG. Dependence of AE Parameters on the Propagation Distance. *Journal of acoustic emission*. 2011;29:57–67.

16. Gongtian Shen, Zhanwen Wu. Study on Spectrum of Acoustic Emission Signals of Bridge Crane. *Insight — Non-Destructive Testing and Condition Monitoring*. 2010;52(3):144–148. URL: http://www.ndt.net/article/ecndt2010/reports/1_07_08.pdf (accessed: 12.06.2023).

17. Dirk Aljets, Alex Chong, Wilcox SJ, et al. Acoustic emission source location in plate-like structures using a closely arranged triangular sensor array. *Journal of acoustic emission*. 2010;28:85–98.

18. Pullin R, Baxter M, Eaton M, Holford KM, Evans S. Novel acoustic emission source location. *Journal of acoustic emission*. 2007;25:215–223.

19. Wilson JW, Liu Jun, Karimian N, Davis CL, Peyton AJ. Assessment of microstructural changes in Grade 91 power station tubes through permeability and magnetic Barkhausen noise measurements. In: *11th European Conference on Non-Destructive Testing (ECNDT 2014)*. Czech Republic, Prague; 2014. URL: https://research.manchester.ac.uk/en/publications/assessment-of-microstructural-changes-in-grade-91-power-station-t (accessed: 12.06.2023).

20. Hongping Jin, Wenyu Yang, Lin Yan. Determination of residual stresses and material properties by an energy-based method using artificial neural networks. *Proceedings of the Estonian Academy of Sciences*. 2012;61(4):296–305. https://doi.org//10.3176/proc.2012.4.04

21. Clausnera A, Richterb F. Fundamental limitations at the determination of initial yield stress using nano-indentation with spherical tips. *European Journal of Mechanics*. 2016;58:69–75. https://doi.org/10.1016/j.euromechsol.2016.01.009

22. Belenkii DM, Nedbailo AA. *Sposob opredeleniya mekhanicheskikh kharakteristik i fizicheskogo kriteriya podobiya prochnosti materiala detali.* Patent RF, No. 2279657. 2006. 12 p. URL: http://allpatents.ru/patent/2279657.html (accessed: 12.06.2023).

23. Beskopylnyi AN, Veremeenko AA, Vernezi NL. *Programma dlya EVM № 2015610650 Vektor 2015*. Certificate of the Russian Federation on state registration, No. 2014661747. 2015. URL: https://onlinepatent.ru/software/2015610650/ (accessed: 12.06.2023).

24. Vernezi NL, Veremeenko AA, Valdman DS. Research of strength characteristics of metal fixture of the wooden case of the river mooring. *Engineering journal of Don*. 2015;(3). URL: http://ivdon.ru/ru/magazine/archive/n3y2015/3231 (accessed: 12.06.2023).

25. Belen'kii DM, Vernezi NL, Cherpakov AV. Changes in the mechanical properties of butt welded joints in elastoplastic deformation. *Welding International*. 2004;18(3):213–215. https://doi.org/10.1533/wint.2004.3268

Received 26.06.2023
Revised 13.07.2023
Accepted 17.07.2023

About the Author:

Nikas L. Vernezi, Cand. Sci. (Eng.), Associate Professor of the Transport Systems and Logistics Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, RF), AuthorID, ORCID, vernezin@mail.ru

Conflict of interest statement: the author does not have any conflict of interest.

The author has read and approved the final manuscript.

Поступила в редакцию 26.06.2023
Поступила после рецензирования 13.07.2023
Принята к публикации 17.07.2023

Об авторе:

Вернези Никос Леонидович, кандидат технических наук, доцент кафедры эксплуатации транспортных систем и логистики Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), AuthorID, ORCID, vernezin@mail.ru

Конфликт интересов: автор заявляет об отсутствии конфликта интересов.

Автор прочитал и одобрил окончательный вариант рукописи.

CHEMICAL TECHNOLOGIES, MATERIALS SCIENCES, METALLURGY
ХИМИЧЕСКИЕ ТЕХНОЛОГИИ, НАУКИ О МАТЕРИАЛАХ, МЕТАЛЛУРГИЯ

UDC 621. 762.1 *Original article*
https://doi.org/10.23947/2541-9129-2023-7-3-55-65

Development of Interparticle Bonding during Sintering of Metal Powders with the Addition of Carbon

Maksim S. Egorov, Rimma V. Egorova
Don State Technical University, Rostov-on-Don, Russian Federation
✉aquavdonsk@mail.ru

Abstract

Introduction. Publications on sintered metal powder parts consider interparticle bonding in hot-deformed materials and features of low-alloy structural steels, as well as the use of carbon-containing materials. The authors of the presented article have previously investigated sintering in relation to structural changes in the material, described changes in physical and mechanical properties, reduction of oxides, recrystallization, etc. This paper shows the relationship of mechanical properties of powder steels with the parameters of intracrystalline bonding. The kinetics of its development during sintering is demonstrated for the first time. The study objective is to find out how sintering affects the interparticle bonding and structure of powder alloys with iron and carbon. The task is to study the technological modes of sintering samples from alloyed and pure iron powder to achieve the best mechanical characteristics.

Materials and Methods. The powders of the Höganäs company were sintered at a temperature of 900-1150 ºC for 0.5–2.5 hours. The protective gas medium (dissociated ammonia) made it possible to prevent oxidative and other sintering reactions. For static cold pressing, a hydraulic press 2PG-125 with a maximum force of 1250 kN was used.

Results. For the first time, the presence of intracrystalline bonding mechanisms with different intensity during sintering has been experimentally established. The dependences of the increment of the relative area of the contact surface on the duration of the isothermal exposure were constructed. With an increase in the sintering temperature to 1150 ºC and a holding time of more than 80 minutes, the contact surface area gradually increased. It was shown that the samples from the powder grades under consideration formed an intracrystalline bonding on the entire contact surface at 1150 ºC. Therefore, this technology can be recommended for practical use. The addition of graphite to the charge slows down the growth of the contact surface. At the same time, the molds from pure powder ABC100.30 and from Distaloy HP-1 powder showed differences. In the first case, with the addition of graphite to the charge, the contact surface developed more intensively than in the second one. The obtained results were recorded in the photo and visualized in the form of graphs.

Discussion and Conclusion. According to the results of mechanical tests, it is possible to estimate the proportion of the contact section of the molding with intracrystalline bonding. Its feature is the structural correspondence of the interparticle surface of the splice and the intergrain boundary. The value of this boundary is determined by comparing the relative area of the contact section with the intracrystalline bonding and the relative area of the contact surface. The possibilities of improving the quality of bonding of powder steels by increasing the temperature and time of their exposure during sintering are determined.

Keywords: metal powders, interparticle bonding, hot-deformed powder materials, intracrystalline bonding, interparticle surface, grain boundary

Acknowledgements: the authors would like to thank the engineers of the Materials Science and Technology of Metals Department YuP Pustovoit, VI Popravko for their help in preparing samples and setting up measuring equipment, as well as Dr. Sci. (Eng), Professor Zhanna Vladimirovna Eremeeva for scientific advice on the choice of experimental methods.

For citation. Egorov MS, Egorova RV. Development of Interparticle Bonding during Sintering of Metal Powders with the Addition of Carbon. *Safety of Technogenic and Natural Systems.* 2023;7(3):55–65. https://doi.org/10.23947/2541-9129-2023-7-3-55-65

Научная статья

Развитие межчастичного сращивания при спекании металлических порошков с добавлением углерода

М.С. Егоров ✉, **Р.В. Егорова**

Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

✉aquavdonsk@mail.ru

Аннотация

Введение. В публикациях о спеченных деталях из металлических порошков рассматриваются межчастичное сращивание в горячедеформированных материалах и особенности низколегированных конструкционных сталей, а также применение углеродосодержащих материалов. Авторы представленной статьи ранее исследовали спекание во взаимосвязи со структурными изменениями материала, описывали изменение физических и механических свойств, восстановление оксидов, рекристаллизацию и т. д. В данной работе показана связь механических свойств порошковых сталей с параметрами внутрикристаллитного сращивания. Кинетика его развития во время спекания демонстрируется впервые. Цель исследования — выяснить, как спекание влияет на межчастичное сращивание и структуру порошковых сплавов с железом и углеродом. Задача — изучить технологические режимы спекания образцов из легированного и чистого железного порошка для достижения наилучших механических характеристик.

Материалы и методы. Порошки фирмы «Хёганес» (Höganäs) спекали при температуре 900–1150 °С в течение 0,5–2,5 часов. Защитная газовая среда (диссоциированный аммиак) позволяла предотвратить окислительные и другие реакции спекания. Для статического холодного прессования задействовали гидравлический пресс 2ПГ-125 с максимальным усилием 1250 кН.

Результаты исследования. Впервые экспериментально установлено наличие разных по интенсивности механизмов внутрикристаллитного сращивания при спекании. Построены зависимости приращения относительной площади контактной поверхности от длительности изотермической выдержки. С ростом температуры спекания до 1150 ºС и времени выдержки более 80 мин площадь контактной поверхности постепенно увеличивается. Показано, что у образцов из рассматриваемых марок порошка при 1150 ºС формируется внутрикристаллитное сращивание на всей контактной поверхности. Следовательно, данную технологию можно рекомендовать для практического использования. Добавление в шихту графита замедляет рост контактной поверхности. При этом формовки из чистого порошка ABC100.30 и из порошка Distaloy HP-1 демонстрируют различия. В первом случае с добавлением в шихту графита контактная поверхность развивается интенсивнее, чем во втором. Полученные результаты зафиксированы на фото и визуализированы в виде графиков.

Обсуждение и заключение. По результатам механических испытаний можно оценить долю контактного сечения формовки с внутрикристаллитным сращиванием. Его признак — структурное соответствие межчастичной поверхности сращивания и межзеренной границы. Значение этой границы определяется при сопоставлении относительной площади контактного сечения с внутрикристаллитным сращиванием и относительной площадью контактной поверхности. Определены возможности повышения качества сращивания порошковых сталей за счет увеличения температуры и времени их выдержки при спекании

Ключевые слова: металлические порошки, межчастичное сращивание, порошковые горячедеформированные материалы, внутрикристаллитное сращивание, межчастичная поверхность, межзеренная граница

Благодарности: авторы выражают благодарность инженерам кафедры «Материаловедение и технологии металлов» Ю. П. Пустовойту, В. И. Поправко за помощь в подготовке образцов и настройке измерительного оборудования, а также д.т.н., профессору Жанне Владимировне Еремеевой за научные консультации по выбору методик экспериментов.

Для цитирования. Егоров М.С., Егорова Р.В. Развитие межчастичного сращивания при спекании металлических порошков с добавлением углерода. *Безопасность техногенных и природных систем.* 2023;7(3):55–65. https://doi.org/10.23947/2541-9129-2023-7-3-55-65

Introduction. Sintered parts from traditional and new compositions are widely used in industry. The latter include partially alloyed powders, nanopowders. The emergence of new initial structural materials requires additional study of the processes of formation of consolidated materials at all technological stages.

Since the beginning of the 21st century, there has been a growing interest of scientists in this topic [1–7]. For example, interparticle bonding during the formation of hot-deformed powder materials has been studied. The features of low-alloy structural steels in such processes were described. Deformation and compaction of powder materials were considered. In, the authors identified patterns of mechanical properties depending on the heat treatment modes, which also affect the quality of interparticle contacts of powder materials. Works [8–10] focus on the study of carbon-containing materials for the manufacture of powder parts from hard alloys. In addition, sintering process is simulated under various modes.

In the early works of the authors of the presented article, sintering process was investigated depending on the structural changes of the material. The removal of residual stresses after pressing, changes in physical and mechanical properties, reduction of oxides, recrystallization, etc. are described. Let us note that sintering of powder steels is a complex and not fully studied process. This work continues the study of interparticle interactions of powder steels. The relationship between their mechanical properties and the quality of intracrystalline bonding is revealed. The authors demonstrated for the first time the kinetics of the development of intracrystalline bonding for the studied materials during sintering. Various modes of sintering of samples are analyzed; the proportions of the contact section of the molding with intracrystalline bonding of powder materials are estimated.

The work objective is to find out how sintering affects interparticle bonding and structure of powder alloys with iron and carbon. The task is to study the technological modes of sintering samples from alloyed and pure iron powder to achieve maximum mechanical characteristics that ensure the formation of high-quality interparticle bonding.

Materials and Methods. During sintering, the formation of the contact surface of the powder material is considered from the standpoint of its initial state, which changes during exposure at high temperature. That is, we are talking about a sequential increment of the contact surface.

For static cold pressing, 2PG-125 hydraulic press with a maximum force of 1250 kN was used. Sintering was carried out at a temperature of 900-1150 °C for 0.5–2.5 hours. To prevent oxidative and other sintering reactions, a protective gas medium (dissociated ammonia) was provided.

Iron powders of the Swedish company Höganäs [1–3] were used in the work (Table 1).

Table 1

Types and characteristics of the powders used by the Swedish company Höganäs

Powder type	Method of production
ABC100.30	Spraying of iron melt
Distaloy HP-1	Double diffusion alloying of Astaloy 85Mo powder: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 studied

Powder type	Content of elements, mass. %								
	C	O	Mo	Ni	Cu	Mn	Si	S	P
ABC100.30	0.001	0.04	–	–	–	0.06	0.007	0.01	0.004
Distaloy HP-1	0.01	0.08	1.5	4	2	0.08	0.005	0.03	0.003

In the processes under consideration, sintering is both a final and an intermediate operation [1–4]. In the first case, the consolidation of the material ends at this stage. The sintering process, in addition to structural changes in the material, contributes to:

– removal of residual stresses after pressing;

– changes in the physical and mechanical properties of the material;

– reduction of oxides;

– recrystallization, etc.

Determining the technological parameters of sintering presses are: temperature regime, sintering duration, parameters of pretreatment of material particles by pressure, etc.

In the second case, the subsequent thermomechanical action plays an essential role in the structure formation of the material, and sintering is considered as a preparatory stage, the main purpose of which is the homogenization of the metal base.

With the development of the basic provisions of works [1, 2, 5], the essence of the intensity and efficiency of sintering was clarified. These indicators allow us to judge the change in size, the development of the structure and properties of sintered materials. According to works [5–8], a method for determining the relative area of the contact surface of a porous body has been created.

Results. When sintering charges from ABC.100.30 and Distaloy HP–1 powders, the dependences of the development of the contact surface on the initial density, temperature and sintering time were obtained (Fig. 1, 2). At the same time, they we guided by the material described in [5].

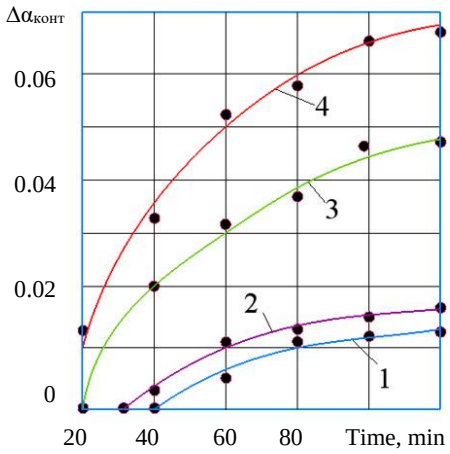


Fig. 1. Dependence of the increment of the contact surface relative area on the duration of isothermal exposure during sintering of the molding from ABC100.30 +0.5%C powder for different initial densities and temperatures: 1 — 950 °C,7.35 g/cm^3; 2 — 1150 °C, 7.35 g/cm^3; 3 — 950 °C, 6.9 g/cm^3; 4 — 1150 °C, 6.9 g/cm^3

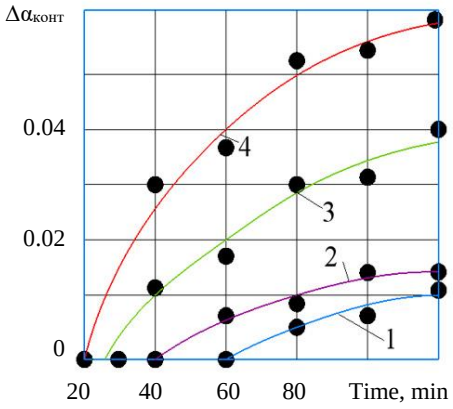


Fig. 2. Dependence of the increment of the relative contact surface area on the duration of isothermal exposure during sintering of the powder molding Distaloy HP–1+0.5%C for different initial densities and temperatures: 1 — 950 °C, 7.4 g/cm^3; 2 — 1150 °C, 7.4 g/cm^3; 3 — 950 °C, 6.6 g/cm^3; 4 — 1150 °C, 6.6 g/cm^3

With increasing temperature and sintering time, the contact surface area monotonically increased, the intensity faded as the sintering duration increased.

In molds made of ABC100.30 pure powder with the addition of graphite to the charge, the contact surface developed more intensively compared to molds made of Distaloy HP-1 powder. This could be explained. The fact was that smaller particles of copper, nickel and molybdenum were baked to the surface of the iron particles of Distaloy HP-1 powder. They formed solid solutions in Fe_γ, which complicated the course of diffusion processes (compared to pure metal). As a result, the growth of the contact surface slowed down.

The intensity of the contact surface formation depended on the initial relative density. An increase in this indicator slowed down the process, since the approach of the material structure to a non-porous state reduced the driving force of consolidation.

The addition of graphite to the charge slowed down the growth of the contact surface. This was due to a decrease in the self-diffusion coefficient of iron atoms, especially at the initial stage of sintering in contact areas with high carbon content.

Let us see how the carbon content affected the strength of sintered alloys under different sintering modes (Fig. 3, 4).

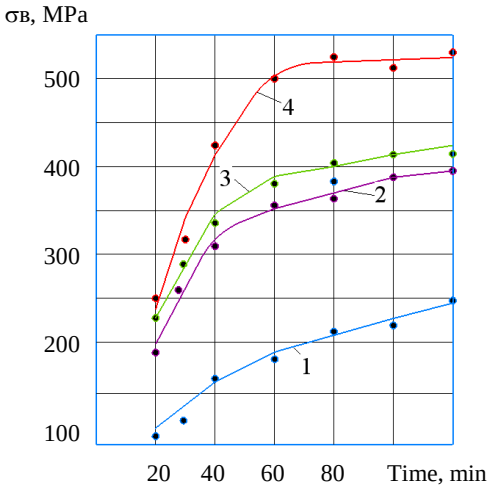


Fig. 3. Dependence of the strength limit of the sintered molding from ABC100.30+0.5% C powder on the time of isothermal exposure and the initial density: 1 — 6.9 g/cm^3, 950 °C; 2 — 6.9 g/cm^3, 1150 °C; 3 — 7.35 g/cm^3, 950 °C; 4 — 7.35 g/cm^3, 1150 °C

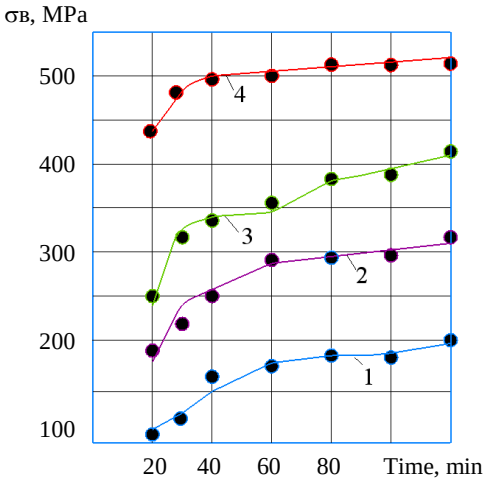


Fig. 4. Dependence of the strength limit of sintered molding from Distaloy HP–1+0.5%C powder on the time of isothermal exposure and initial density: 1 — 6.9 g/cm^3, 950 °C; 2 — 6.9 g/cm^3, 1150 °C; 3 — 7.35 g/cm^3, 950 °C; 4 — 7.35 g/cm^3, 1150 °C

The ultimate strength of the material based on ABC100.30 powder with a carbon content of 0.5 % was 610 MPa, the ultimate strength of the material based on Distaloy HP—1 powder with a carbon content of 0.5 % was 508 MPa.

According to the results of mechanical tests and the value of the tensile strength of the reference samples, the relative area of the contact cross section with intracrystalline bonding (α′ICB) was determined depending on the initial

density and sintering modes of molds made of ABC.100.30+0.5%C (Fig. 5) and DistaloyHP–1+0.5%C (Fig. 6) powders.

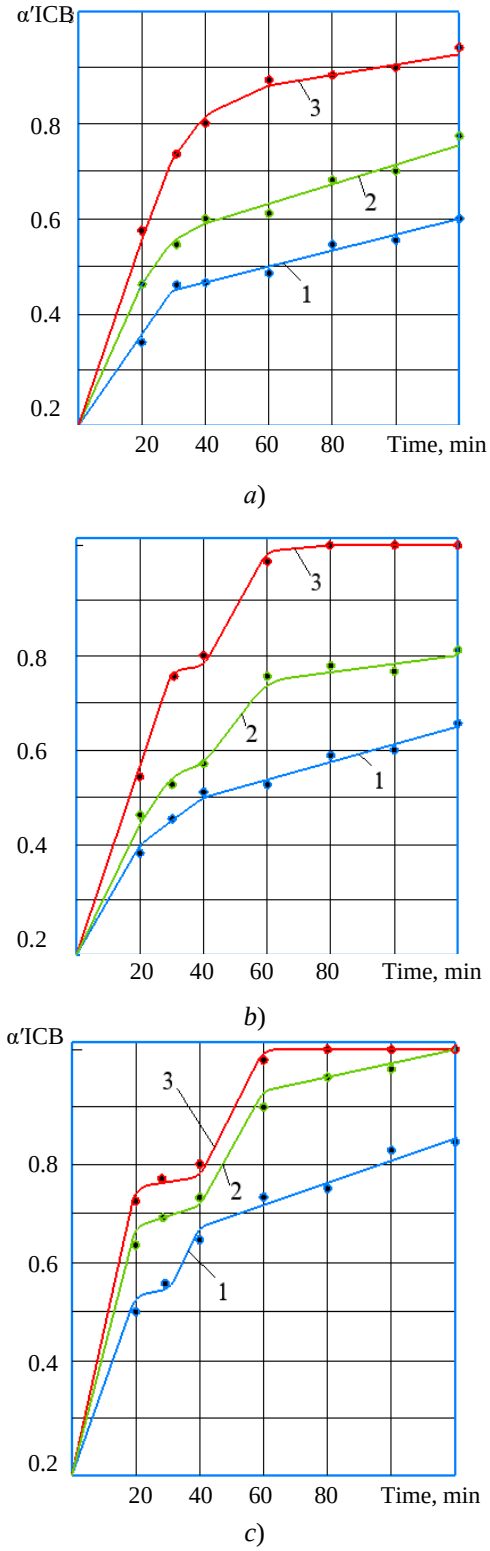


Fig. 5. Kinetics of the development of intracrystalline bonding on the contact surface, depending on the sintering modes and the initial density (ABC.100.30+0.5%C): *a* — 6.9 g/cm^3; *b* — 7.2 g/cm^3; *c* — 7.35 g/cm^3. 1 — 950 °C; 2 — 1050 °C; 3 — 1150 °C

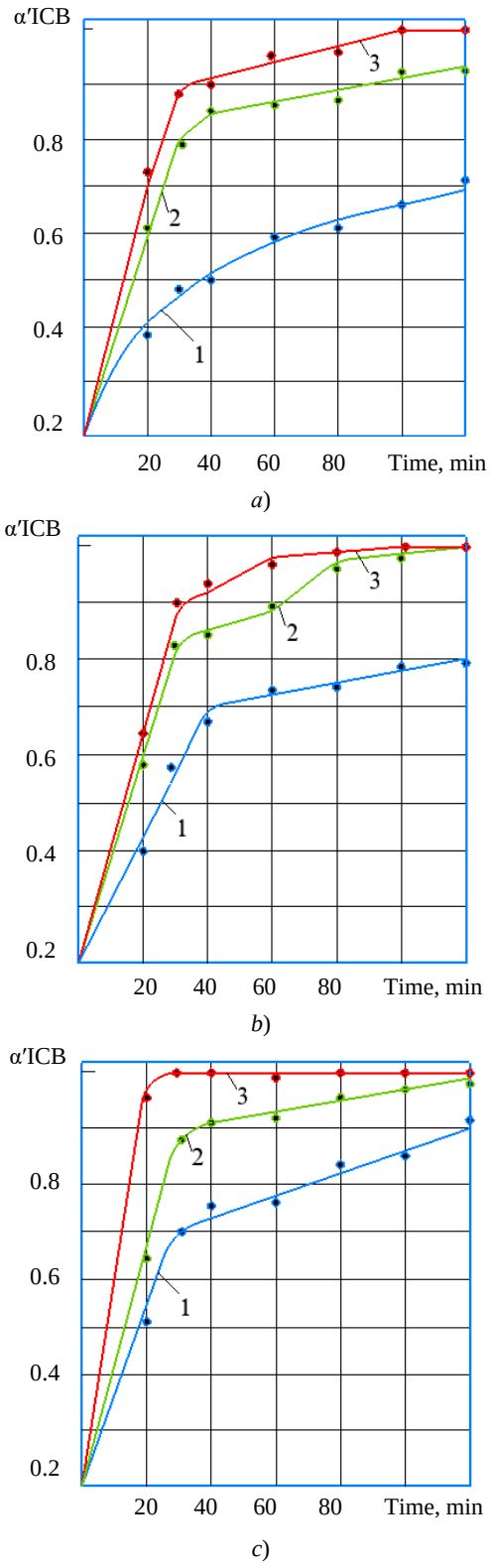


Fig. 6. Kinetics of the development of intracrystalline bonding on the contact surface depending on the sintering modes and the initial density (DistaloyHP–1+0.5%C): *a* — 6.6 g/cm^3; *b* — 7 g/cm^3; *c* — 7.4 g/cm^3.
1 — 950 °C; 2 — 1050 °C; 3 — 1150 °C

The presented dependences indicate that the introduction of graphite into the charge intensified the processes of formation of intracrystalline bonding in comparison with materials from a carbon-free charge. The results of the research coincided with the data of works [9–11].

During sintering at heating and isothermal exposure, the surface layers of iron and graphite particles continuously interacted through their contact areas (including the gas phase) [12–15]. Let us note that carbon was an active reducing agent of iron oxides, therefore, at temperatures above 500–600 °C, reduction reactions occurred at the places of contact

of iron particles with graphite. This contributed to the formation of juvenile contact with subsequent particle fusion. Favorable conditions were created for the formation of a carbon-containing gas medium due to reactions between graphite and iron particles. The reduction processes were intensified due to a significant increase in the kinetics of chemical reactions at the metal — gas interface. The growth was fixed relative to the diffusion coefficients in the contact areas of iron particles with graphite and over the entire surface of the particles. Surfaces in contact with the furnace atmosphere were also taken into account. At the same time, carbon diffused into iron particles through the formed metal contacts on the surface of the particles. Before the transformation of $\alpha \rightarrow \gamma$, the formation of a phase in the contact points of cementite was most likely. This phase had a more significant carbon diffusion coefficient at the temperatures under consideration. This was due to the insignificant dissolution of carbon in α-iron and slow diffusion in ferrite.

If the contact surface of the iron powder material developed more intensively than that of the doped powder material, then it was the latter that should be preferred when forming intracrystalline bonding.

Intracrystalline bonding is formed in two stages:

– isothermal aging of the molding in the austenitic region;

– cooling with the decomposition of austenite into a ferrite-cementite mixture.

The role of the second stage consisted in the predominant development of the interparticle bonding surface as a region of facilitated nucleation of ferrite grains and cementite plates that ensured the migration of the boundary through the surface of the physical separation of particles. This was confirmed by the results of microstructural analysis. Fig. 7–10 shows the microstructures of the material with different levels of interparticle bonding.

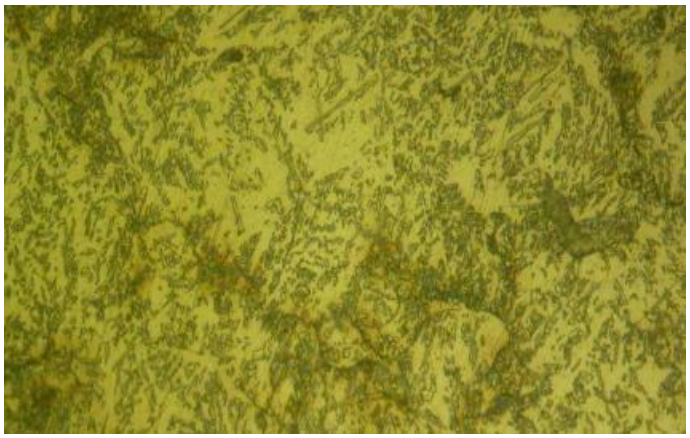


Fig. 7. Microstructure of the sample from ABC100.30+0.5%C powder after sintering at 1050 °C for 40 minutes, ×200

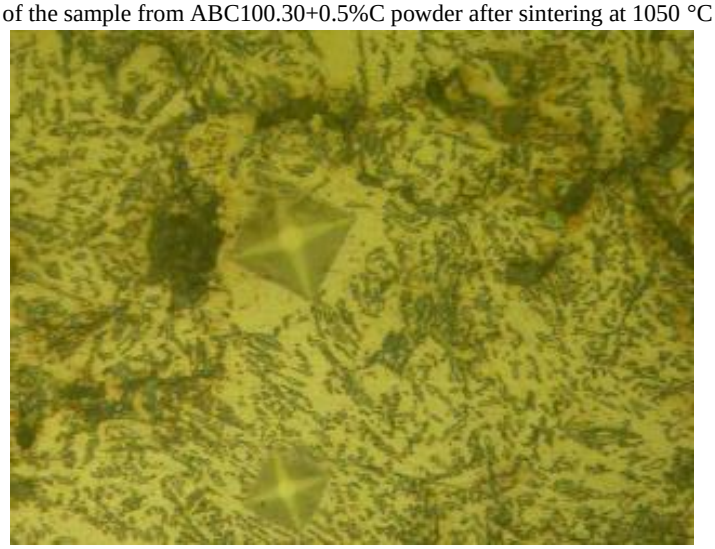


Fig. 8. Microstructure of the sample from Distaloy HP–1+0.5%C powder after sintering at 1050 °C for 20 minutes, ×200

The presented microstructures are characteristic of a low level of bonding, since the boundary of the powder particles is clearly visible.

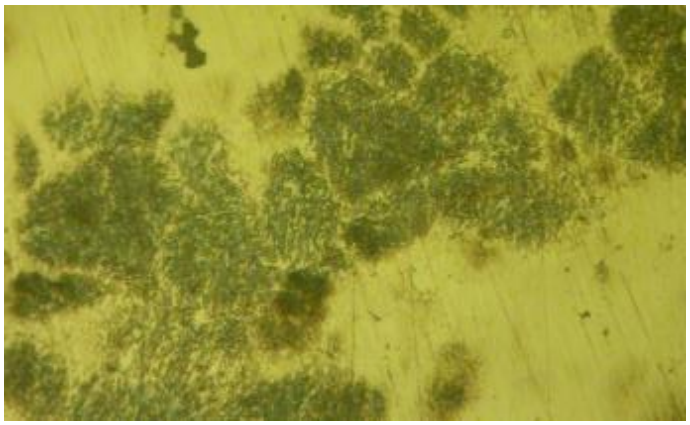


Fig. 9. Microstructure of the sample from ABC100.30+0.5%C powder after sintering at 1150 °C for 40 minutes, ×500

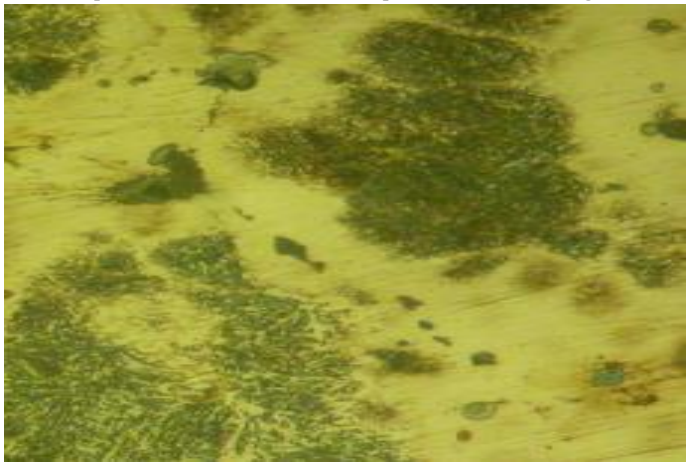


Fig. 10. Microstructure of the sample from Distaloy HP–1+0.5%C powder after sintering at 1150 °C for 40 minutes, ×500

Nonmetallic inclusions identify the former boundary of the physical separation of particles through which ferrite grains germinate. That is, the former particle interface is located inside the grain, and this is a sign of intracrystalline bonding [16].

Discussion and Conclusion. The results of the work allow us to assert that during sintering, the mechanisms of formation of intracrystalline bonding are different in intensity [5, 9, 16]. At first, the bonding is fast, then its speed decreases. Compressions with the lowest values of the initial density are characterized by the longest duration of the process of accelerated development of intracrystalline bonding, which is observed at the first stage. Moreover, with an increase in the sintering temperature, the intensity of this stage increases. The formation of intracrystalline bonding on the entire contact surface is observed in molds obtained under sintering conditions at a temperature of 1150 °C. The peculiarity of molds made of DistaloyHP–1 and ABC100.30 powders has been experimentally established. Under sintering conditions, intracrystalline bonding occurs within 60 and 80 minutes, respectively.

References

1. Dorofeev VYu, Egorov SN. *Mezhchastichnoe srashchivanie pri formirovanii poroshkovykh goryachedeformirovannykh materialov*. Moscow: Metallurgizdat; 2003. 152 p.

2. Egorov MS, Egorov SN. *Goryachedeformirovannye poroshkovye nizkolegirovannye konstruktsionnye stali.* Novocherkassk: Volgodonsk Institute of the South Russian State Technical University; 2008. 54 p.

3. Kablov YeN, Ospennikova OG, Bazyleva OA. Materials for parts of gas-turbine engines under high heat loads. *Herald of the Bauman Moscow State Technical University. Series Mechanical Engineering*. 2011;2:13–19 https://cyberleninka.ru/article/n/materialy-dlya-vysokoteplonagruzhennyh-detaley-gazoturbinnyh-dvigateley/viewer

4. Egorova RV. Microstructure analysys of surface for details of stepped form. *Metallurg*: 2009;6:65–67.

5. Grigorev AK, Rudskoi AI. *Deformatsiya i uplotnenie poroshkovykh materialov.* Moscow: Metallurgiya; 2002. 192 p.

6. Robert-Perron E, Blais C, Pelletier S. Tensile properties of sinter hardened powder metallurgy components machined in their green state. *Powder Metallurgy*. 2009;52(1):80–83. https://doi.org/10.1179/174329007X205055

7. Shtern MB, Kartuzov EV. Osobennosti vozniknoveniya i rasprostraneniya udarnykh voln v vysokoporistykh materialakh. *Powder Metallurgy*. 2016;3/4:13–22.

8. Glotka AA, Moroz AN. Comparison of the effects of carbides and nonmetallic inclusions on formation of fatigue microcracks in steels. *Metallovedenie i termicheskaya obrabotka metallov.* 2019;8(770);61–65. https://doi.org/10.30906/mitom.2019.8.61-65

9. Gurevich YuG, Antsiferov VN, Savinykh LM. Iznosostoikie kompozitsionnye materialy. VG Bamburov (Ed.). Yekaterinburg: Ural Branch of the Russian Academy of Sciences; 2005. 215 p

10. Egorov MS, Egorova RV, Kovtun MV. Influence of Carbon Content on the Formation of a Contact Interparticle Surface during Hot Post-Pressing. *Safety of Technogenic and Natural Systems*. 2023;7(2):90–101. https://doi.org/10.23947/2541-9129-2023-7-2-90-101

11. Hironobu Kondo, Hegedus M. Current trends and challenges in the global aviation industry. *Acta Metallurgica Slovaca*. 2020;26(4):141–143. https://doi.org/10.36547/ams.26.4.763

12. Gilardi R, Alzati L, Oro R, Hryha E, Nyborg L, Berg S, et al. Reactivity of Carbon Based Materials for Powder Metallurgy Parts and Hard Metal Powders Manufacturing. *Society of Powder and Powder Metallurgy*. 2016;63(7):548–554. https://doi.org/10.2497/jjspm.63.548

13. Rojek J, Nosewicz S, Mazdziarz M, Kowalczyk P, Wawrzyk K, Lumelskyj D. Modeling of a Sintering Process at Various Scales. *Procedia Engineering*. 2017;177:263–270. https://doi.org/10.1016/j.proeng.2017.02.210

14. Guo JY, Xu CX, Hu AM, Oakes KD, Sheng FY, Shi ZL, et al. Sintering dynamics and thermal stability of novel configurations of Ag clustersю *Journal of Physics and Chemistry of Solids*. 2012;73(11).1350–1357. https://doi.org/10.1016/j.jpcs.2012.06.010

15. Eremeeva ZhV, Nikitin NM, Korobov NP, Ter-Vaganyants YuS. Issledovanie protsessov termicheskoi obrabotki poroshkovykh stalei, legirovannykh nanorazmernymi dobavkami. *Nanotekhnologii: nauka i proizvodstvo.* 2016;1:63–74.

16. Egorov MS, Egorova RV, Tsordanidi GG. Formation of structural features of powder materials during cooling after heat treatment. *Safety of Technogenic and Natural Systems*. 2022;(2):69–75. https://doi.org/10.23947/2541-9129-2022-2-69-75

Received 29.06.2023
Revised 19.07.2023
Accepted 23.07.2023

About the Authors:

Maksim S. Egorov, Cand. Sci. (Eng.), Associate Professor, Head of the Materials Science and Metal Technology Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, RF), ORCID, ScopusID, ResearcherID, AuthorID, aquavdonsk@mail.ru

Rimma V. Egorova, Cand. Sci. (Eng.), Associate Professor of the Cybersecurity Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, RF), ORCID, ScopusID, AuthorID, rimmaruminskaya@gmail.com

Claimed contributorship:

MS Egorov: formulation of the basic concept, goals and objectives of the study; calculations; text preparation, conclusions formulation.

RV Egorova: academic advising; research results analysis; text revision; conclusions correction.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 29.06.2023
Поступила после рецензирования 19.07.2023
Принята к публикации 23.07.2023

Об авторах:

Максим Сергеевич Егоров, кандидат технических наук, доцент, заведующий кафедрой материаловедения и технологии металлов Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), ORCID, ScopusID, ResearcherID, AuthorID, aquavdonsk@mail.ru

Римма Викторовна Егорова, кандидат технических наук, доцент кафедры кибербезопасности Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), ORCID, ScopusID, AuthorID, rimmaruminskaya@gmail.com

Заявленный вклад соавторов:

М.С. Егоров — формирование основной концепции, цели и задачи исследования, расчеты, подготовка текста, формулирование выводов.

Р.В. Егорова — научное руководство, анализ результатов исследований, доработка текста, корректировка выводов.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

CHEMICAL TECHNOLOGIES, MATERIALS SCIENCES, METALLURGY
ХИМИЧЕСКИЕ ТЕХНОЛОГИИ, НАУКИ О МАТЕРИАЛАХ, МЕТАЛЛУРГИЯ

UDC 669.017

Original article

https://doi.org/10.23947/2541-9129-2023-7-3-66-76

Influence of the Structural-Phase Composition of the Initial Charge Material on the Qualitative Characteristics of Castings from Al-Si-Mg System Alloy

Vladimir S. Muratov, Mikhail S. Kazakov ✉

Samara State Technical University, Samara, Russian Federation

✉Kazakov.mishel@gmail.com

Introduction. The work focuses on solving quality problems of castings made of Al-Si-Mg alloy (AK9). The paper draws attention to the absence of a unified theory of alloy modification and the need to find solutions that ensure good product quality. The reasons for bad quality due to the weak justification of the choice of the manufacturer of the initial charge material — ingots are considered. Ingots from two suppliers are compared in terms of the structural-phase state. The paper shows how it causes defects in castings. The inefficiency of traditional methods of suppressing the formation of brittle plates of the iron-containing phase in the alloy of the Al-Si-Mg system due to the presence of Mn in the chemical composition of the alloy is noted. If the specified flaw is inherited from the source material, the generally accepted approach does not work. The article formulates the recommendations for solving this problem. The introduction of the proposed approach into production practice can open the way to solving an important applied task — to improve the wording of tasks for tenders. The relevance of the study is due to the widespread use of alloys of the Al-Si-Mg (AK9) system in modern mechanical engineering, including in aerospace structures. The work objective is to study the influence of the structural-phase state of the source material on the qualitative characteristics of finished castings from the Al-Si-Mg alloy system.

Materials and Methods. Eight casts were analyzed, in which ingots from two manufacturers were used. Radiography revealed a correlation between the fracture structure of castings, structure and quality indicators. Scanning electron microscopy was used to analyze the microstructure and chemical composition of the phases. When setting quality requirements, the authors proceeded from the existing industry and state standards. The conditions of heat treatment of samples were taken from the same documents. The spectrograms were visualized as graphs showing the intensity of the element peak in the Auger spectrum and the energy of the electrons resulting from the Auger effect.

Results. The results of radiography gave grounds to assert that the products provided by supplier No. 1 had significant advantages in terms of quality. If we focused on the industry standard, the exclusion of the 2nd supplier's ingots from the process ensured the production of products without casting defects at the level of 73 %. Otherwise, this figure did not exceed 57 %. The rejection indicators were discontinuities, clusters of flaws, high porosity. After melting 5–8, which involved the materials of the 2nd manufacturer, the fractures of the samples after rupture were investigated. Locations with smooth, viscous and mixed relief are highlighted. An increase of up to ×500 made it possible to establish insignificant areas with a viscous relief, which was characteristic of brittle fracture by the cleavage mechanism. The absence of inclusions and liquations was established. The microstructure of the sections from discontinuous samples was considered. It turned out that it corresponded to the modified and heat-treated state of the AK9ch alloy without signs of burnout. Individual dark needle-like phases and single pores were noted. The conditions of dispersed Si precipitations, $Al_{32}Si_{10}Fe_5Mn$ and $Al_{37}Si_5Fe_5Mn$ chipping, as well as the separation of the $Al_{36}Si_3Fe_6Mn_3$ phase in skeletal form were described. The advantages of the microstructure of ingots samples from manufacturer No. 1 were listed. It corresponded

to the modified state of the AK9ch alloy. The branches of dendrites and the sizes of silicon inclusions were smaller. Needle-like phases of $Al_xSi_yFe_zMn_q$ were not detected.

Discussion and Conclusion. Light areas in the castings fractures were formed by a brittle fracture mechanism, which is due to the presence of $Al_xSi_yFe_zMn_q$ phase plates in the alloy structure. If iron-containing phases are inherited from the source material, then traditional methods of suppressing formation do not lead to the creation of compact equiaxed polyhedra. To improve the quality of castings, it is recommended to use ingots with a pre-modified structure, without including phase plates of variable composition $Al_xSi_yFe_zMn_q$. The results obtained can be used, among other things, to justify the requirements for the material during tenders, which will enable the enterprises of the machine-building industry to improve the quality of products and reduce the cost of marriage. As a result, this will increase their competitiveness in the Russian and world markets.

Keywords: brittle plates of the iron-containing phase, Al-Si-Mg system alloy, structure-modified ingots, charge quality

Acknowledgements: the authors would like to thank the Editorial Board of the Journal and the Reviewer for attentive attitude to the article and suggestions made that helped to improve its quality.

For citation. Muratov VS, Kazakov MS. Influence of the Structural-Phase Composition of the Initial Charge Material on the Qualitative Characteristics of Castings from Al-Si-Mg System Alloy. *Safety of Technogenic and Natural Systems.* 2023;7(3):66–76. https://doi.org/10.23947/2541-9129-2023-7-3-66-76

Научная статья

Влияние структурно-фазового состояния исходного материала шихты на качественные характеристики отливок из сплава системы Al-Si-Mg

В.С. Муратов, М.С. Казаков ✉

Самарский государственный технический университет, г. Самара, Российская Федерация

✉Kazakov.mishel@gmail.com

Аннотация

Введение. Работа фокусируется на решении проблем качества отливок из сплава Al-Si-Mg (АК9). Отмечены отсутствие единой теории модифицирования сплавов и необходимость поиска решений, обеспечивающих хорошее качество продукции. Рассматриваются причины брака из-за слабого обоснования выбора производителя исходного шихтового материала — чушек. Чушки от двух поставщиков сравниваются с точки зрения структурно-фазового состояния. Показано, как оно обусловливает дефекты отливок. Отмечена неэффективность традиционных методов подавления образования хрупких пластин железосодержащей фазы в сплаве системы Al-Si-Mg за счет присутствия в химическом составе сплава Mn. Если указанный недостаток наследуется из исходного материала, общепринятый подход не срабатывает. Сформулированы рекомендации по решению этой выявленной проблемы. Внедрение предложенного подхода в производственную практику способно открыть путь к решению важной прикладной задачи — улучшить формулировки заданий для тендеров. Актуальность исследования обусловлена широким применением сплавов системы Al-Si-Mg (АК9) в современном машиностроении, в том числе в аэрокосмических конструкциях. Цель данной работы — изучить влияние структурно-фазового состояния исходного материала на качественные характеристики готовых отливок из сплава системы Al-Si-Mg.

Материалы и методы. Проанализированы восемь плавок, в которых использовались чушки двух производителей. Рентгенография позволила выявить корреляцию между строением излома отливок, структурой и качественными показателями. Для анализа микроструктуры и химического состава фаз использовали сканирующую электронную микроскопию. Устанавливая требования к качеству, исходили из действующих отраслевых и государственных стандартов. Из этих же документов брали условия термической обработки образцов. Спектрограммы визуализировали в виде графиков, демонстрирующих интенсивность пика элемента в оже-спектре и энергию электронов, возникших в результате оже-эффекта.

Результаты исследования. Результаты рентгенографии дают основания утверждать, что продукция, предоставляемая поставщиком № 1, обладает значимыми преимуществами в плане качества. Если ориентироваться на отраслевой стандарт, исключение из процесса чушек 2-го поставщика обеспечивает выпуск продукции без литейных дефектов на уровне 73 %. В противном случае этот показатель не превысил 57 %. Браковочными индикаторами были несплошности, скопления раковин, высокая пористость. После плавок 5–8, которые задействовали материалы 2-го производителя, исследовались изломы образцов после разрыва. Выделены локации с гладким, вязким и смешанным рельефом. Увеличение до ×500 позволило установить незначительные участки с вязким рельефом, что характерно для хрупкого разрушения по механизму скола. Установлено отсутствие включений и ликваций. Рассмотрена микроструктура шлифов из разрывных образцов. Выяснилось, что она соответствует модифицированному и термообработанному состоянию сплава АК9ч без признаков пережога. Отмечены отдельные темные игольчатые фазы и единичные поры. Описаны условия дисперсных выделений Si, выкрашивания $Al_{32}Si_{10}Fe_5Mn$ и $Al_{37}Si_5Fe_5Mn$, а также выделение фазы $Al_{36}Si_3Fe_6Mn_3$ в скелетообразной форме. Перечислены преимущества микроструктуры образцов чушек от производителя № 1. Она соответствует модифицированному состоянию сплава АК9ч. Ветви дендритов и размеры включений кремния меньше. Не обнаруживаются иглообразные фазы $Al_xSi_yFe_zMn_q$.

Обсуждение и заключение. Светлые участки в изломах отливок образовались по хрупкому механизму разрушения, что связано с наличием в структуре сплава пластин фазы $Al_xSi_yFe_zMn_q$. Если железосодержащие фазы наследуются из исходного материала, то традиционные методы подавления образования не приводят к созданию компактных равноосных полиэдров. Для повышения качества отливок рекомендуется использовать чушки с предварительно модифицированной структурой, без включения пластин фазы переменного состава $Al_xSi_yFe_zMn_q$. Полученные результаты можно задействовать в том числе для обоснования требований к материалу при проведении тендеров, что даст возможность предприятиям машиностроительной отрасли улучшить качество продукции и снизить затраты на брак. В итоге это повысит их конкурентоспособность на российском и мировом рынке.

Ключевые слова: хрупкие пластины железосодержащей фазы, сплав системы Al-Si-Mg, чушки с модифицированной структурой, качество шихты

Благодарности: авторы выражают благодарность редакционной коллегии журнала и рецензенту за профессиональный анализ и рекомендации для корректировки статьи.

Для цитирования. Муратов В.С., Казаков М.С. Влияние структурно-фазового состояния исходного материала шихты на качественные характеристики отливок из сплава системы Al-Si-Mg. *Безопасность техногенных и природных систем*. 2023;7(3):66–76. https://doi.org/10.23947/2541-9129-2023-7-3-66-76

Introduction. According to GOST 1583-93[1] alloys of the Al-Si-Mg (AK9) system belong to the first group (silumins). They are widely used in modern mechanical engineering. In aerospace structures, aluminum alloy castings account for 3–5 % of the mass [1].

The use of cast blanks in comparison with deformed semi-finished products can reduce the complexity of machining parts and increase the metal utilization factor several times [2]. In the aerospace industry, this alloy is used to produce parts that are complex in configuration, operating at medium loads and temperatures from minus 196 to plus 175 °C[2]. Main characteristics of the alloy:

– good casting properties;
– tightness;
– corrosion resistance;
– weldability;
– low density;
– relatively high modulus of elasticity;

[1] GOST 1583-93. *Aluminium casting alloys. Specifications*. Biblioteka GOSTov. URL: http://vsegost.com/Catalog/18/18745.shtml (accessed: 22.08.2023).

[2] OST 92-0920-85. *Metally i splavy tsvetnye. Marki, razreshennye k primeneniyu.* Tekhnicheskaya literatura. URL: https://booktech.ru/normativy/ost/ost-92-0920-85-metally-i-splavy-cvetnye-marki-razreshennye-k-primeneniyu.html (accessed: 22.08.2023).

– low temperature coefficient of linear expansion;

– wear resistance;

– affordable price [3–7].

The properties of silumins depend on the conditions of melting and subsequent processing [8]. An effective method of improving their structure and properties is modification with multicomponent compositions. This makes it possible to influence not only silicon, which is part of the eutectic (α+Si), but also primary silicon crystals [9–10]. Let us note the need to effectively deal with such a disadvantage of Al-Si-Mg alloys as gas absorption. For this purpose, degassing fluxes and modification at low temperatures are used [11]. Currently, there is no unified theory of modification, so the search for optimal solutions continues to ensure a high level of product quality, compliance with regulatory and design documentation [11]. The presented work is intended to partially compensate for the lack of data in this area.

Control plays a leading role in improving the quality of castings. Its tasks are:

– to exclude the ingress of defective castings for machining and assembly;

– to create conditions for critical analysis and improvement of foundry technology.

The complexity of technological processes of foundries is associated with the use of a wide range of materials. The formation of the quality of castings is determined by many factors. The most critical of them are:

– the quality of the initial molding, charge and auxiliary materials;

– the level of mechanization and automation of the technological process;

– the compliance with the technological process at all stages of production;

– the organization of production and workshop management.

Within the framework of the presented work, the reasons for the growth of waste associated with an insufficiently justified choice of the manufacturer of the charge material — ingots are analyzed. The recommendations are given to eliminate this problem. A comparative analysis of the structural and phase state of the source material from two suppliers was performed. It is shown how defects in castings of the Al-Si-Mg alloy system depend on the structural and phase state of the initial charge materials.

It should be recognized that traditional methods of suppressing the formation of brittle plates of the iron-containing phase in the alloy of the Al-Si-Mg system are ineffective due to the mandatory presence of Mn in the chemical composition of the alloy. We are talking about cases when the specified defect is inherited from the source material. The recommendations for solving this identified problem are formulated. To improve the quality of castings, it is advisable to use a charge of ingots with a pre-modified structure. It should not include phase plates of variable composition AlxSiyFezMnq.

The work objective is to study the influence of the structural-phase state of the source material on the qualitative characteristics of finished castings from the Al-Si-Mg alloy system.

Materials and Methods. According to the results of eight melts, the characteristics of castings made of AK9ch alloy were analyzed. Ingots from manufacturers No. 1 and No. 2 were used as the starting material. Ingots were melted down with waste from their own production (substandard castings made of AK9ch alloy). Table 1 provides the percentage of materials. The manufacturer is selected based on the results of competitive procurement for reasons of economic feasibility. In any case, the material must comply with GOST 1583-96. The method of manufacture is permanent-mold casting.

Table 1

Percentage (by weight) of raw materials in the general melting

Melting no.	Manufacturer no. 1	Manufacturer no. 2	Waste of own production
1	40	0	60
2	35	0	65
3	25	0	75
4	20	0	80
5	20	5	75
6	10	20	70
7	5	20	75
8	0	20	80

Chemical composition of the samples was determined by the spectral method on MFS-8 device. Mechanical properties were studied on separately cast samples (GOST 1497-84[3]) after heat treatment in T6 mode (quenching — 535 ± 5 °C, cooling in water, aging — 175 ± 5 °C). To determine the mechanical properties, a strength testing machine UTS-111.2-100-22 was used. The microstructure was studied by the cuts from wedge samples, ingots and discontinuous samples etched in Keller reagent, as well as on the fractures. The Zeiss Stemi2000-C stereoscopic microscope and Carl Zeiss AxiovertA1 metallographic microscope were used. The scanning electron microscopy method was implemented using the JED-2300 AnalysisStation microscope. The chemical composition of the phases was recorded by electron microprobe analysis. The macrostructure was evaluated on the fractures of wedge samples, as well as on the templates etched in an alkaline solution, cut from wedge samples and ingots. The presence of internal defects of castings was determined using the Ruslan-225 X-ray machine.

Results. Chemical composition of the samples from each melting is presented in Table 2.

Table 2

Results of determination of chemical composition of samples

Melting no.	Content of elements, mass. %									
	Al	Si	Mg	Mn	Fe	Cu	Zn	Ti	Zr	Be
1	Base	8.71	0.22	0.28	0.44	<0.1	<0.2	0.082	<0.1	<0,1
2		9.35	0.24	0.31	0.44	0.1	<0.2	0.097	0.03	<0,1
3		8.56	0.23	0.28	0.45	0.12	<0.2	0.06	0.03	<0,1
4		9.28	0.23	0.32	0.44	0.12	<0.2	0.1	0.03	<0,1
5		8.8	0.26	0.3	0.45	0.11	<0.2	0.065	0.03	<0,1
6		8.5	0.23	0.28	0.52	0.13	<0.2	<0.05	<0.1	<0,1
7		8.8	0.26	0.3	0.45	0.11	<0.2	0.055	0.03	<0,1
8		9.28	0.23	0.32	0.44	0.12	<0.2	<0.1	<0.1	<0,1
Requirements according to GOST 1583-93										
	Base	8–10.5	0.17–0.30	0.2–0.5	≤0.9	≤0.3	0.3	∑ ≤ 0.15		<0.1

Data from Table 2 prove that chemical composition of the material of castings from all charges corresponds to GOST 1583-93.

The results of the mechanical properties test are presented in Table 3.

Table 3

Results of mechanical properties tests

Melting no.	$\sigma_{в}$, MPa	δ, %
1	280	9
2	280	6
3	270	7
4	280	3
5	340	6
6	290	6
7	340	6
8	290	7
Requirements according to GOST		
	≥ 235	≥ 3

[3] GOST 1497-84. *Metals. Methods of tension test*. Biblioteka GOSTov. URL: http://vsegost.com/Catalog/46/4616.shtml (accessed: 25.07.2023).

From the Table 3 it can be seen that according to the level of mechanical properties, the material of castings from all charges met the requirements of GOST 1583-93 for the T6 condition. Temporal tear resistance and elongation were compared.

X-ray radiography showed that for melts 1-4, in which there were no ingots from manufacturer No. 2, the yield of suitable products corresponding to OST 92-1165-2014 in terms of casting defects was 73 %. For melts 5–8, the yield of suitable products was 57 %. Rejection signs:

– irregularities in the form of shells;

– clusters of shells;

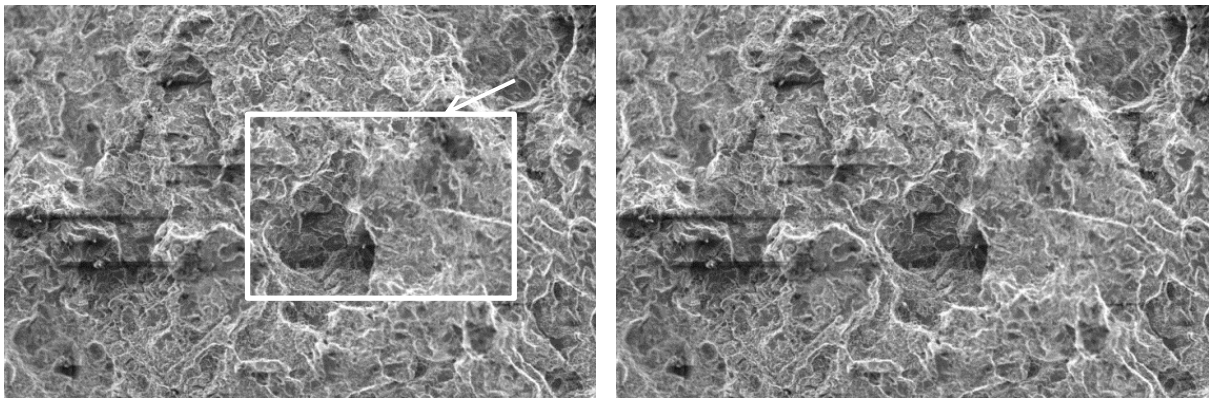
– porosity beyond the permissible level according to the X-ray standard (X-ray film obtained after X-ray inspection of the sample with a normalized porosity corresponding to a certain score[4]).

The study of the fractures of wedge samples showed that the fracture of light gray, matte, with small, light, shiny areas of various shapes and sizes was characteristic for melts 5–8 (Fig. 1).

Fig. 1. The appearance of the fracture of melts 5–8 (magnification ×6.5)

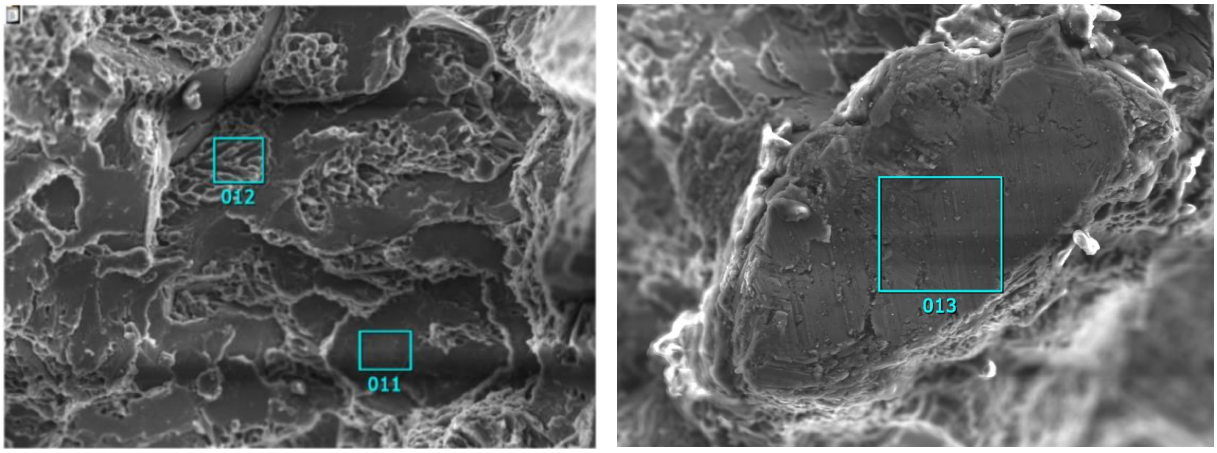
No inclusions or other defects were detected in the microstructure under the surface of the fractures, which would unambiguously cause bright, shiny areas. Porosity of 2 points according to GOST 1583-93 was observed in the macrostructure of some melts under the fracture surface. The presence of porosity did not explain the light areas in the fractures, since porosity was not observed on all wedge samples, but the appearance of all fractures was identical.

Fractures of tensile samples obtained after testing the mechanical properties of melts 5–8 were examined under an electron microscope. The bright, shiny areas (Fig. 1) corresponded to the dark area in Fig. 2 *a*. The appearance of the fracture surface at various magnifications is shown in Fig. 2.



a) *b*)

[4] OST 92-1165-75. *Castings made of aluminum alloys. Technical requirements*. Technical literature. URL: https://booktech.ru/normativy/ost/ost-92-1165-75-otlivki-iz-alyuminievyh-splavov-tehnicheskie-trebovaniya.html (accessed 21.07.2023).



c) *d*)

Fig. 2. The fracture surface of the tensile sample: *a* — general view with magnification ×50; *b* — areas with smooth relief with magnification ×150; *c* — mixed relief with magnification ×200; *d* — a large smoothed section of the fracture with magnification ×200

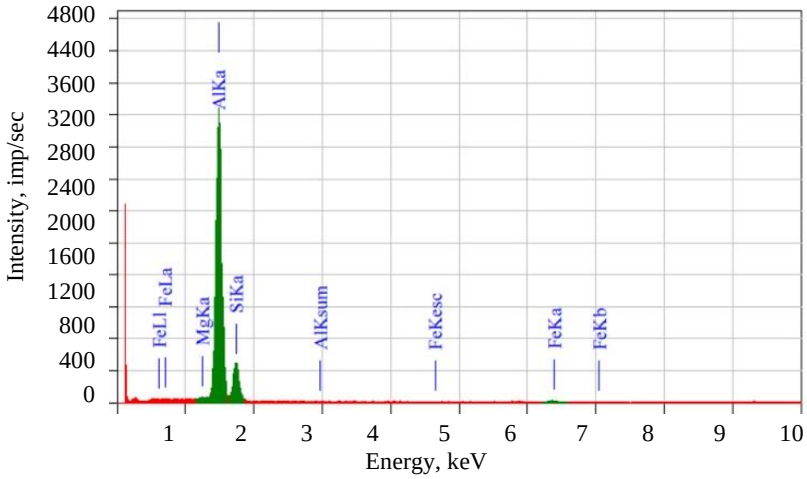
When magnified to ×500, it could be seen that the shiny areas were depressions, more often with a smoothed surface. There were minor areas with a viscous relief, which was characteristic of brittle fracture by the mechanism of chipping. The main part of the fracture surface had a viscous relief. The results of micro-X-ray spectral analysis of the fracture surface at points 11, 12, 13 (Fig. 2) are presented in Table 4. Points 11 and 13 correspond to smoothed areas, point 12 — viscous.

Table 4

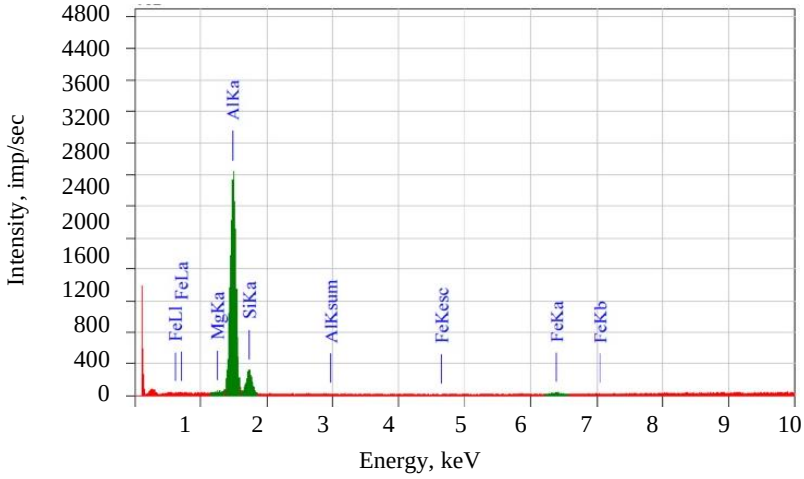
Chemical analysis of the fracture zone surface

Point no. (see Fig. 2)	Content of elements, mass. %			
	Mg	Al	Si	Fe
11	4.71	82.61	11.27	1.41
12	4.51	83.35	9.46	2.68
13	5.13	84.72	8.11	2.04

The spectrograms of the points were identical (Fig. 3). No significant differences in chemical composition were revealed between the zones with viscous and brittle smoothed relief, which indicated the absence of inclusions and liquations.



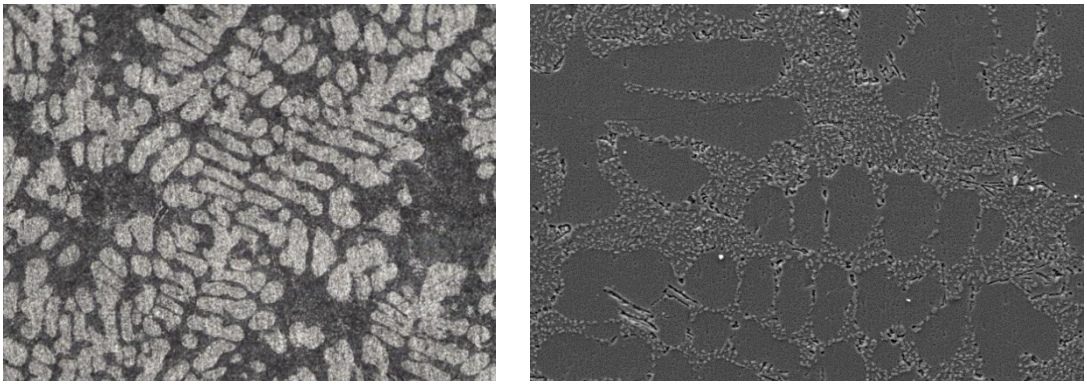
a)



b)

Fig. 3. Spectrogram of the electron microprobe analysis results of the fracture surface: *a* — point 11 from Fig. 2; *b* — point 12 from Fig. 2. Here the intensity of the peak of the element in the Auger spectrum and the energy of the electrons generated as a result of the Auger effect are shown

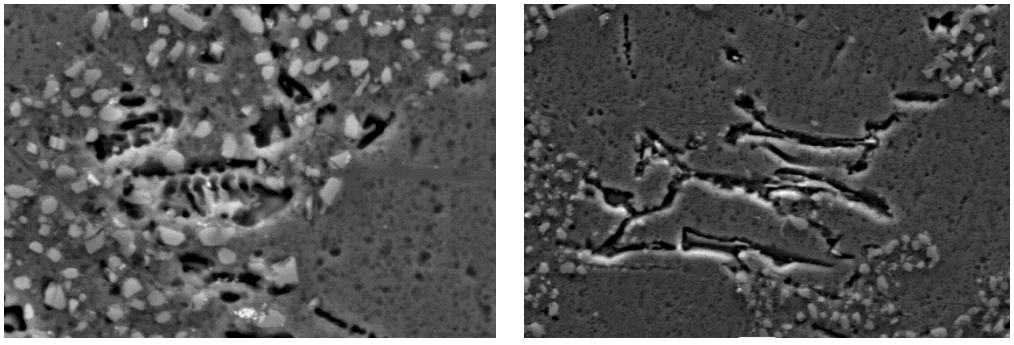
The microstructure studied on the sections made of discontinuous samples (melts 5–8) corresponded to the modified and heat-treated state of the AK9ch alloy without signs of burnout (Fig. 4 *a*). Separate dark needle-like phases and single pores were observed. The main phase components of the microstructure were clearly visible under an electron microscope (Fig. 4 *b*).



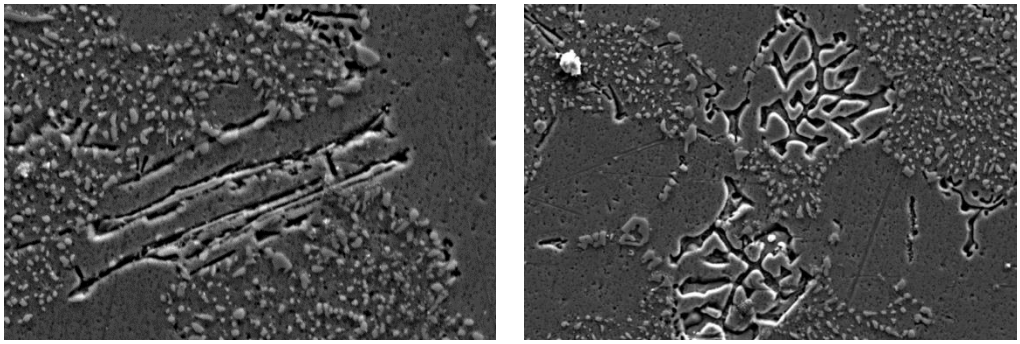
a) *b*)

Fig. 4. Appearance of the microstructure: *a* — light optical microscopy with magnification ×200; *b* — electron microscopy with magnification ×250

The data of electron microscopy and electron microprobe analysis made it possible to determine the main phases: α (light zones), α+Si (dark zones). In the α+Si phase, dispersed Si precipitations of less than 5 microns in size were observed (Fig. 5 *a*). Electron microprobe analysis showed that $Al_{32}Si_{10}Fe_5Mn$ and $Al_{37}Si_5Fe_5Mn$ (Fig. 5 *b, 5 c*) were partially crumbled during grinding and polishing (Fig. 5 *c*). The separation of $Al_{36}Si_3Fe_6Mn_3$ phase in a skeletal form was also observed (Fig. 5 *d*).



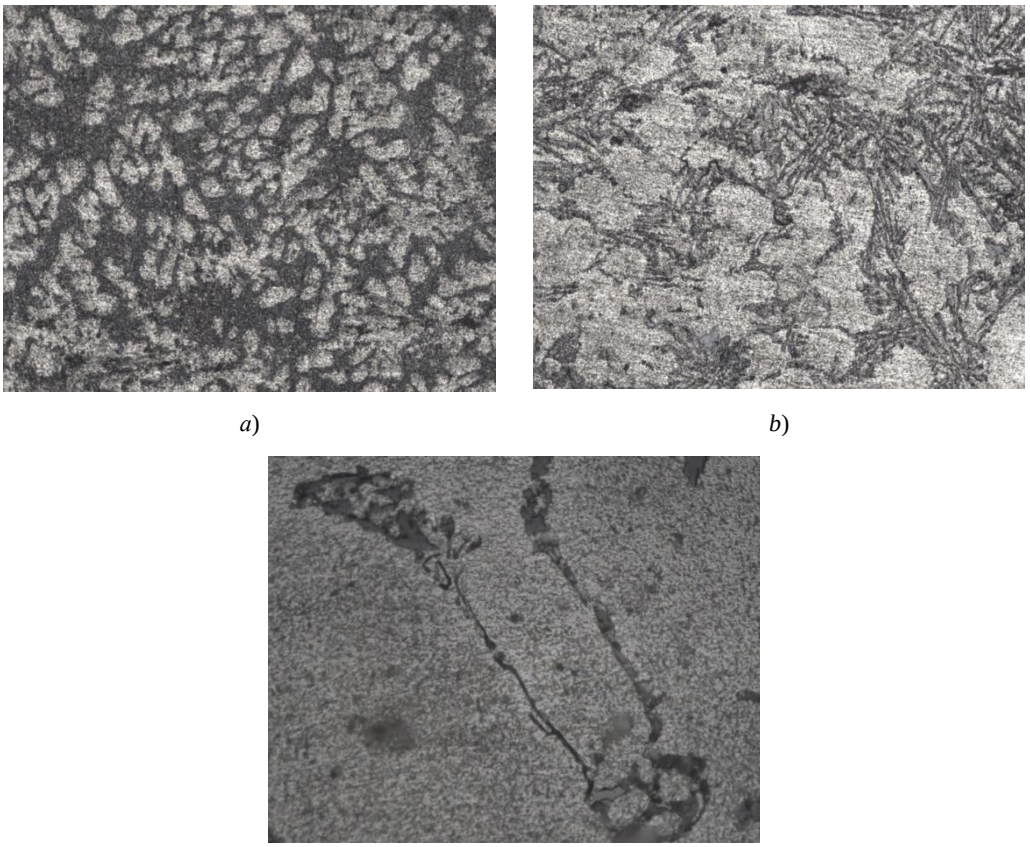
a) *b*)



c) *d*)

Fig. 5. Microstructure of melting samples (5–8): *a* — separation of silicon with magnification ×2000; *b* — phases $Al_{32}Si_{10}Fe_5Mn$ and $Al_{37}Si_5Fe_5Mn$ with magnification ×1000; *c* — chipping of brittle plates of phases $Al_{32}Si_{10}Fe_5Mn$ и and $Al_{37}Si_5Fe_5Mn$ with magnification ×750; *d* — phase $Al_{36}Si_3Fe_6Mn_3$ in skeletal form with magnification ×500

The microstructure of the ingot samples from manufacturer No. 1 corresponded to the modified state of the AK9ch alloy. The branches of the dendrites were significantly smaller than in the sample of the ingot from supplier No. 2. The sizes of silicon inclusions were up to 4 microns. They were homogeneous and had a globular appearance. The main phases were α and α+Si (Fig. 6 *a*). Needle-like phases of $Al_xSi_yFe_zMn_q$ were not found in the structure of ingot samples from manufacturer No. 1.



a) *b*)

c)

Fig. 6. The microstructure of the initial ingot: *a* — manufacturer No. 1, 70 microns with magnification ×500; *b* — manufacturer No. 2, 70 microns with magnification ×500; *c* — plate phase in the microstructure of the ingot from manufacturer No. 2, 20 microns with magnification ×1000

The microstructure of the ingot sample from supplier No. 2 corresponded to the unmodified state of the AK9ch alloy. The branches of dendrites were large. Silicon inclusions were needle-shaped and large. The main phases were α and α+Si (Fig. 6 *b*). Phases in the form of dark needle-like inclusions were observed (Fig. 6 *c*).

The analysis of the results of the study suggests that the structural-phase composition of the alloy determines the presence of shiny areas in the fracture of samples from melts 5–8. These are areas with smoothed relief — the results of

brittle destruction. The most probable cause of this phenomenon is the presence of zones with coarse needle-like precipitation, which are brittle $Al_xSi_yFe_zMn_q$ plates with a pronounced interface. During stretching or other destructive tests, these precipitations act as concentrators (breaks in the metal). Accordingly, when the crack development front goes through them, they chip off. Let us explain. Lamellar precipitates are solid and poorly retained in the base metal. In the process of grinding and polishing the samples, they crumble, leaving cavities with smooth walls. In their place are smooth areas that shine in the fracture. It can also be assumed that these phases are stable in the melt (do not dissolve in the matrix). When cooled, they will act as crystallization centers and provoke the formation of defects, since they are sharp stress concentrators.

Silicon crystallizes in the form of small spherical particles, so it can be stated that the modifier used is effective for influencing silicon, which is part of the eutectic (α+Si). At the same time, an adjustment of the technological process is required to influence the needle phases of $Al_xSi_yFe_zMn_q$. With the introduction of 0.2–0.5 % Mn, as a rule, it is possible to suppress the formation of brittle plates of $Al_xSi_yFe_zMn_q$ phase. However, in the studied melts (5–8), despite the Mn content of 0.28–0.32 %, this phase persists, since it is inherited from the source material.

Discussion and Conclusion. Based on the results of the conducted scientific research, three main conclusions can be drawn.

1. The structural-phase state of the source material is inherited in castings and in the presence of iron-containing phases in the form of brittle plates can negatively affect the quality characteristics of cast blanks.

2. The light areas in the castings' fractures are areas with smoothed relief. They were formed as a result of brittle fracture, which is due to the presence of a variable composition of $Al_xSi_yFe_zMn_q$ in the structure of brittle phase plates.

3. The presence of Mn alloy in the chemical composition does not always suppress the formation of brittle plates of the iron-containing phase. If it is inherited from the source material, this traditional approach does not work and compact equiaxed polyhedra with a weaker negative influence are not formed. To improve the quality of castings, it is recommended to use ingots with a pre-modified structure in the charge, in which there are no inclusions of plates of the phase of variable composition $Al_xSi_yFe_zMn_q$.

References

1. Polmear Ya. *Legkie splavy: ot traditsionnykh do nanokristallov*. Moscow: Tekhnosfera; 2008. 464 p. URL: https://www.technosphera.ru/lib/book/72?read=1 (accessed: 26.06.2023).

2. Zolotorevskii VS, Belov NA. Metallovedenie liteinykh alyuminievykh splavov. Moscow: MISiS; 2005. 376 p. URL: https://e.lanbook.com/book/2055 (accessed: 26.06.2023).

3. Wei Yan, Weiqing Chen, Senlin Zhang, Bing Li, Jing Li. Evolution of solidification structures and mechanical properties of high-Si Al alloys under permanent magnetic stirring. *Materials Characterization*. 2019;157:109894. https://doi.org/10.1016/j.matchar.2019.109894

4. Makhlouf MM, Guthy HV. The aluminum–silicon eutectic reaction: mechanisms and crystallography. *Journal of Light Metals*. 2001;1(4): 199–218. https://doi.org/10.1016/S1471-5317(02)00003-2

5. Haizhi Ye. An overview of the development of Al-Si alloy based material for engine applications. *Journal of Materials Engineering and Performance*. 2003;12:288–297. https://doi.org/10.1361/105994903770343132

6. Afanasev VK, Popova MV, Prudnikov AN. Effect of hydrogen on the structure and properties of eutectic silumin with 15% silicon. *Metallovedenie i termicheskaya obrabotka metallov*. 2022;(6):10–16. https://doi.org/10.30906/mitom.2022.6.10-16

7. Sathyapal Hegde, K. Narayan Prabhu. Modification of eutectic silicon in Al-Si alloys. *Journal of Materials Science*. 2008;43:3009–3027 https://doi.org/10.1007/s10853-008-2505-5

8. Kuznetsov AO, Shadayev DA, Konkevich VYu, Bochvar SG, Kunyavskaya TM. Modification of silumins: different approaches for one alloying system. *Tekhnologiya legkikh splavov*. 2014;(4):75–81.

9. Napalkov VI, Makhov SV, Pozdnyakov AV. Modifitsirovanie alyuminievykh splavov. Moscow: MISiS; 2017. 347 p. URL: https://e.lanbook.com/book/117172 (accessed: 26.06.2023).

10. Jing Zhang, Hongmei Chen, Hui Yu, Yunxue Jin. Study on dual modification of Al-17%Si alloys by structural heredity. *Metals*. 2015;5(2):1112–1126 https://doi.org/10.3390/met5021112

11. FQ Zu, Li Xiaoyun. Functions and mechanism of modification elements in eutectic solidification of Al-Si alloys. *China Foundry*. 2014;11(4):287–309 URL: https://www.researchgate.net/publication/274634943_Special_Report_CHINA_FOUNDRY_Functions_and_mechanism_of_modification_elements_in_eutectic_solidification_of_Al-Si_alloys_A_brief_review (accessed: 26.06.2023).

Received 01.07.2023
Revised 26.07.2023
Accepted 03.08.2023

About the Authors:

Vladimir S. Muratov, Dr. Sci. (Eng.), Professor of the Metallurgy, Powder Metallurgy, Nanomaterials Department, Samara State Technical University (244, Molodogvardeyskaya St., Samara, 443100, RF), ResearcherID, ScopusID, ORCID, muratov1956@mail.ru

Mikhail S. Kazakov, Postgraduate Student of the Metallurgy, Powder Metallurgy, Nanomaterials Department, Samara State Technical University (244, Molodogvardeyskaya St., Samara, 443100, RF), ResearcherID, ORCID, kazakov.mishel@gmail.com

Claimed contributorship:

VS Muratov: academic advising; research results analysis; revision of the text; conclusions correction.

MS Kazakov: formulation of the basic concept, goals and objectives of the study; testing; analysis; control; text preparation; conclusions formulation.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Об авторах:

Владимир Сергеевич Муратов, доктор технических наук, профессор кафедры металловедения, порошковой металлургии, наноматериалов Самарского государственного технического университета (443100, РФ, г. Самара, ул. Молодогвардейская, 244), ResearcherID, ScopusID, AuthorID, ORCID, muratov1956@mail.ru

Михаил Сергеевич Казаков, аспирант кафедры металловедения, порошковой металлургии, наноматериалов Самарского государственного технического университета (443100, РФ, г. Самара, ул. Молодогвардейская, 244), ResearcherID, ORCID, kazakov.mishel@gmail.com

Заявленный вклад соавторов:

В.С. Муратов — научное руководство, анализ результатов исследований, доработка текста, корректировка выводов.

М.С. Казаков — формулирование основной концепции, целей и задач исследования, проведение испытаний, анализ, контроль, подготовка текста, формулирование выводов.

Поступила в редакцию 01.07.2023
Поступила после рецензирования 26.07.2023
Принята к публикации 03.08.2023

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.