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The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).

Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).

Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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SCIENTIFIC PRINCIPLES FOR SELECTING POWDER MATERIALS FOR LASER CLADDING IN THE RESTORATION OF COMPONENTS IN THE OIL AND GAS INDUSTRY

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Abstract. Relevance. In the oil and gas industry, a significant part of the equipment is operated under conditions of intense mechanical wear, corrosion and cyclic loads, which leads to premature failure of critical parts. Restoration of these parts is an economically feasible alternative to their complete replacement, especially when using modern surface hardening technologies. **Objective.** Development of a scientifically based approach to the selection of powder materials for laser surfacing, focused on the restoration of 45 steel parts used in the oil and gas industry. **Methods.** The method is based on a comprehensive analysis of the solubility of alloying elements, their distribution coefficients between liquid

and solid phases, as well as the thermodynamic compatibility of the "coating–substrate" system. *Results.* It is shown that a decrease in the tendency to crack formation in the fusion zone is achieved by minimizing metallurgical stress concentrators that occur with an uneven distribution of alloying elements and phase components. Special attention is paid to the influence of the chemical composition of the powder material on the thermal processes during laser surfacing, including temperature distribution, heating and cooling rates, as well as the duration of the liquid phase. Numerical simulation data confirm that the nature of the laser radiation power distribution significantly affects the formation of the melt bath and residual stresses. The most effective are uneven distributions with maximum intensity in the frontal part of the spot, which reduce temperature gradients and increase the structural uniformity of the coating. *Conclusions.* A self-fluxing alloy of the PG-CP4 type containing Ni, Cr, Si and boron is considered as a promising material, which provides high compatibility with steel 45, the formation of a wear-resistant coating and a reduction in the likelihood of defect formation. The results obtained can be used in the development of technologies for the repair and restoration of parts of oil and gas equipment operating in conditions of intense wear and aggressive environments.

Keywords: laser cladding, 45 steel, oil and gas industry, component restoration, powder material, element solubility, crack formation

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МҰНАЙ-ГАЗ ӨНЕРКӘСІБІНДЕ БӨЛШЕКТЕРДІ ҚАЛПЫНА КЕЛТІРУ КЕЗІНДЕ ЛАЗЕРЛІК БАЛҚЫТУҒА АРНАЛҒАН ҰНТАҚТЫ МАТЕРИАЛДАРДЫ ТАҢДАУДЫҢ ҒЫЛЫМИ ПРИНЦИПТЕРІ

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Аннотация. *Өзектілігі.* Мұнай-газ өнеркәсібінде жабдықтың едәуір бөлігі қарқынды механикалық тозу, коррозиялық әсер ету және циклдік жүктемелер жағдайында пайдаланылады, бұл жауапты бөлшектердің мерзімінен бұрын істен шығуына әкеледі. Бұл бөлшектерді қалпына келтіру оларды толығымен ауыстырудың экономикалық тұрғыдан тиімді баламасы болып табылады, әсіресе қазіргі заманғы беттік қатайту технологияларын қолданған кезде. *Мақсаты.* Мұнай-газ өнеркәсібінде қолданылатын 45 болаттан жасалған бөлшектерді қалпына келтіруге бағытталған лазерлік балқытуға арналған ұнтақты материалдарды таңдауға ғылыми негізделген тәсілді әзірлеу. *Әдістері.* Әдістеме легирлеуші элементтердің ерігіштігін, олардың сұйық және қатты фазалар арасындағы таралу коэффициенттерін, сондай-ақ "жабу-субстрат" жүйесінің термодинамикалық үйлесімділігін кешенді талдауға негізделген. *Нәтижелері.* Балку аймағында жарықшақ пайда болу үрдісінің төмендеуіне легирлеуші элементтер мен фазалық компоненттердің біркелкі бөлінбеуінен туындайтын кернеулердің металлургиялық концентраторларын азайту арқылы қол жеткізілетіні көрсетілген. Ұнтақ материалының химиялық құрамының лазерлік балқыту кезіндегі жылу процестеріне, соның ішінде температураның таралуына, қыздыру және салқындату жылдамдығына және сұйық фазаның өмір сүру ұзақтығына әсеріне ерекше назар аударылады. Сандық модельдеу деректері лазерлік сәулелену қуатының таралу сипаты балкытылған ваннаның пайда болуына және қалдық кернеулерге айтарлықтай әсер ететіндігін растайды. Ең тиімдісі-температура градиенттерінің төмендеуін және жабынның құрылымдық біркелкілігінің жоғарылауын қамтамасыз ететін дақтың фронтальды бөлігінде максималды қарқындылығы бар біркелкі емес үлестірулер. *Қорытындылар.* Перспективалық материал ретінде құрамында Ni, Cr, Si және бор бар ПГ-СР4 типті өздігінен ағатын қорытпа қарастырылады, ол 45 болатпен жоғары үйлесімділікті, тозуға төзімді жабынды қалыптастыруды және ақаулардың пайда болу ықтималдығын төмендетуді қамтамасыз етеді. Алынған нәтижелер қарқынды тозу және агрессивті орта жағдайында жұмыс істейтін мұнай-газ жабдығының бөлшектерін жөндеу және қалпына келтіру технологияларын әзірлеу кезінде пайдаланылуы мүмкін.

Түйін сөздер: лазерлік балқыту, 45 болат, мұнай-газ өнеркәсібі, бөлшектерді қалпына келтіру, ұнтақ материалы, элементтердің ерігіштігі, жарықтар

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НАУЧНЫЕ ПРИНЦИПЫ ВЫБОРА ПОРОШКОВЫХ МАТЕРИАЛОВ ДЛЯ ЛАЗЕРНОЙ НАПЛАВКИ ПРИ ВОССТАНОВЛЕНИИ ДЕТАЛЕЙ В НЕФТЕГАЗОВОЙ ПРОМЫШЛЕННОСТИ

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Аннотация. *Актуальность.* В нефтегазовой промышленности значительная часть оборудования эксплуатируется в условиях интенсивного механического износа, коррозионного воздействия и циклических нагрузок, что приводит к преждевременному выходу из строя ответственных деталей. Восстановление изношенных деталей представляет собой экономически целесообразную альтернативу их полной замене, особенно при использовании современных технологий поверхностного упрочнения и нанесения защитных покрытий. *Цель.* Разработать научно обоснованный подход к выбору порошковых материалов для лазерной наплавки при восстановлении деталей из стали 45, применяемых в нефтегазовой промышленности. *Методы.* Методика исследования основана на комплексном анализе растворимости легирующих элементов, коэффициентов их распределения между жидкой и твердой фазами, а также термодинамической совместимости материалов в системе «покрытие - подложка». Дополнительно использованы методы

численного моделирования тепловых процессов, протекающих при лазерной наплавке, для оценки влияния распределения мощности лазерного излучения на формирование ванны расплава и остаточных напряжений. *Результаты.* Установлено, что снижение склонности к трещинообразованию в зоне сплавления достигается за счет минимизации металлургических факторов концентрации напряжений, обусловленных неравномерным распределением легирующих элементов и фазовых составляющих. Особое внимание уделено влиянию химического состава порошковых материалов на тепловые процессы при лазерной наплавке, включая распределение температуры, скорости нагрева и охлаждения, а также продолжительность существования жидкой фазы. Результаты численного моделирования показали, что характер распределения мощности лазерного излучения существенно влияет на формирование ванны расплава и величину остаточных напряжений. Наиболее эффективными оказались варианты неравномерного распределения интенсивности лазерного излучения с максимумом в передней части пятна нагрева, способствующие снижению температурных градиентов и повышению структурной однородности формируемого покрытия. *Выводы.* В качестве перспективного порошкового материала для лазерной наплавки рассмотрен самофлюсующийся сплав типа ПГ-СР4, содержащий никель, хром, кремний и бор. Применение данного сплава способствует обеспечению металлургической совместимости со сталью 45, формированию износостойкого покрытия и снижению вероятности возникновения дефектов в зоне наплавки. Полученные результаты могут быть использованы при разработке и совершенствовании технологий ремонта и восстановления деталей нефтегазового оборудования, эксплуатируемого в условиях интенсивного механического износа и воздействия агрессивных сред.

Ключевые слова: лазерная наплавка, сталь 45, нефтегазовая промышленность, восстановление деталей, порошковый материал, растворимость элементов, трещинообразование

Introduction. In the oil and gas industry, a large number of equipment operates under conditions of severe mechanical wear, corrosion and cyclic loads, which causes premature failure of important parts. Such elements include shafts, bushings, pump components, and pipeline valve parts, which are often made of 45 steels due to its favorable combination of strength and manufacturability (Steen et al., 2010; Toyserkani et al., 2004). Restoration of such parts using modern surface hardening methods is a more economical option compared to their complete replacement.

One of the most effective methods of restoration is laser cladding, which provides coatings with high adhesion, minimal heat-affected zone, and the ability to precisely control the material structure (Goldak et al., 2005; DebRoy et al., 2018). This technique allows localized addition of material with excellent metallurgical bonding and reduced thermal distortion compared to traditional welding or thermal spray methods (Qiyao Deng et al., 2024). However, the high

heating and cooling rates inherent to laser processing lead to the formation of non-equilibrium microstructures and significant residual stresses, increasing the risk of crack formation in both the clad layer and the fusion zone.

A key factor determining the quality of the restored coating is the selection of the powder material. Improper chemical composition can result in metallurgical incompatibility between the coating and the substrate, enhanced segregation effects, and defects such as porosity and intergranular cracking (Hasanov et al., 2024; Sedighi et al., 2024). These issues are particularly critical for 45 steels, which contains carbon that actively participates in phase transformations and may contribute to brittle structure formation under unfavorable cooling conditions (Zehuan Lin et al., 2024).

According to contemporary physical metallurgy concepts, the choice of alloying elements should be based on analyses of their solubility in iron and partitioning behavior between liquid and solid phases, as these parameters influence crystallization behavior, segregation tendencies, and phase formation in the fusion zone (Zapata et al., 2024). Elements with high solubility (for example Cr, Ni, Mn, Mo) promote the formation of homogeneous solid solutions, while elements with limited solubility (such as B, Ti, Nb) act as structure modifiers (Furui Jiao et al., 2025; Zhao et al., 2024).

The presence of harmful impurities (S, P, O, H), which tend to concentrate at grain boundaries and reduce ductility while encouraging crack initiation, also significantly affects performance (Bashirov et al., 2025). In the oil and gas sector, where components operate in aggressive environments, controlling chemical composition and minimizing impurities are crucial for reliable service (Sun et al., 2025).

Modern studies also show that not only the material composition but also laser processing parameters, especially the distribution of laser intensity in the focus spot, play a vital role. Optimizing these parameters enables better control of thermal cycles, reduced temperature gradients, and lower residual stress levels (Madatov et al., 2025; Mollaamin et al., 2024; Gulyaev, 1986).

Despite numerous studies in the field of laser cladding, comprehensive methodologies for selecting powder materials that fully consider the specific service conditions in the oil and gas industry remain insufficiently explored. In particular, there is a need to integrate data on chemical composition, element solubility, phase transformations, and thermal processes into a unified material selection framework (Callister, 2018; Srinivasan et al., 2020; Chen et al., 2021; Andi Huang et al., 2025).

Therefore, the objective of the present work is to develop a scientifically justified approach to the selection of powder materials for laser cladding in the restoration of 45 steel parts, aimed at enhancing wear resistance, reducing defect formation risks, and extending the service life of oil and gas equipment.

Materials and Methods. The methodology for selecting powder materials for laser cladding in the restoration of parts made of steel 45 in the oil and gas industry

is based on a comprehensive consideration of the thermodynamic compatibility of materials, the kinetics of phase transformations, and the characteristics of thermal processes occurring in the fusion zone. The proposed approach aims to minimize defect formation and ensure the required operational properties of the restored layer.

The methodology is grounded in the principles of physical metallurgy and crystallization theory, according to which the key parameters for selecting alloying elements are their solubility in iron, the distribution coefficient between liquid and solid phases, as well as the tendency to form secondary phases (Zapata et al., 2024, Furui Jiao et al., 2025). The solubility of an element in α - and γ -iron determines the possibility of forming a homogeneous solid solution, while the distribution coefficient characterizes the degree of element segregation during melt solidification (Zhao et al., 2024).

The distribution coefficient k is defined as the ratio of the concentration of an element in the solid phase to its concentration in the liquid phase at the solidification front:

$$k = C_s / C_l \quad (1)$$

where C_s is the concentration of the element in the solid phase, and C_l is its concentration in the liquid phase.

When $k \approx 1$, a uniform distribution of the element in the structure is ensured, whereas for $k < 1$, the element tends to accumulate in the liquid phase, leading to segregation, which can cause chemical inhomogeneity and reduce the mechanical properties.

Based on these criteria, all alloying elements in the powder material are classified into four groups:

1. Primary alloying elements (Cr, Ni, Mn, Mo, V), which have high solubility in iron and a favorable distribution coefficient. These elements ensure the formation of a solid solution and improve the strength, wear resistance, and corrosion resistance of the restored layer (Sun et al., 2025; Madatov et al., 2025).

2. Secondary alloying elements (B, Ti, Nb, Zr), characterized by limited solubility. They act as structure modifiers, promote grain refinement, and contribute to the formation of dispersed strengthening phases. For example, boron, concentrating at grain boundaries, reduces their mobility and inhibits grain growth (Mollaamin et al., 2024).

3. Harmful impurities (S, P, O, H), which have low solubility and unfavorable distribution coefficients. Their presence leads to the formation of brittle intergranular phases, porosity, and microcracks, which is particularly hazardous in aggressive environments of the oil and gas industry (Gulyaev, 1986).

4. Low-solubility components, capable of forming stable carbides, nitrides, and borides. Their effect is evaluated in terms of their contribution to strengthening and potential increase in structural brittleness (Callister, 2018).

Additionally, the methodology takes into account the mutual solubility of alloying elements, which determines the possibility of forming stable multicomponent systems. It has been established that combinations such as Cr–Ni–Mo exhibit a high degree of compatibility and ensure the formation of a stable structure with uniform phase distribution (Srinivasan et al., 2020).

An important stage is the analysis of the influence of the chemical composition of the powder material on the technological properties of the melt, including fluidity, viscosity, and susceptibility to defect formation. Increasing the content of elements such as Si and C contributes to improved fluidity, whereas elements with high melting points (Mo, W) can increase melt viscosity and hinder the formation of a uniform layer (Chen et al., 2021).

Considering the specifics of laser cladding, particular attention is paid to the thermal conditions of the process. To describe the temperature field, the unsteady heat conduction equation is used:

$$\rho c \partial T / \partial t = \lambda \nabla^2 T + q(x, y, z, t) \quad (2)$$

where ρ - is the material density, c - is the heat capacity, λ - is the thermal conductivity coefficient, and q - is the volumetric heat source density, simulating the effect of laser radiation.

The form of the function $q(x, y, z, t)$ is determined by the law of the laser intensity distribution in the focusing spot. Within the framework of the methodology, various distribution options (Gaussian, uniform, asymmetric) are considered, which allows evaluating their influence on the geometry of the melt pool and cooling rate (Andi Huang et al. 2025).

The practical implementation of the proposed approach includes the following stages:

- Analysis of the chemical composition of the component to be restored (steel 45) and its operating conditions;
- Selection of the base alloying system considering element solubility and distribution coefficients;
- Assessment of the risk of defect formation based on the content of harmful impurities;
- Modeling of thermal processes taking into account the parameters of laser treatment;
- Prediction of the phase composition and structure of the deposited layer.

Thus, the developed methodology allows for a comprehensive and scientifically grounded selection of powder materials for laser cladding, ensuring increased reliability of restored steel 45 components, reducing the likelihood of crack formation, and extending their service life in the oil and gas industry.

Results and Discussions. The results of the conducted study are based on numerical modeling of thermal processes during laser cladding of PG-CR4-type powder material on steel 45, as well as on a comprehensive analysis of the

influence of chemical composition on the formation of structure and operational properties of the restored layer. To describe the temperature field, the unsteady heat conduction equation of the following form was used:

$$\rho * c * (dT/dt) = \lambda * (d^2T/dx^2 + d^2T/dy^2 + d^2T/dz^2) + q(x,y,z,t) \quad (3)$$

where ρ - is the material density, c - is the heat capacity, λ - is the thermal conductivity coefficient, and $q(x,y,z,t)$ is the volumetric heat source density modeling the effect of laser radiation. The computational modeling scheme and the adopted boundary conditions are shown in Figure 1, while the results of the numerical analysis of temperature fields and heating rates are presented in Figure 2 and Figure 3.

Analysis of the obtained dependencies shows that the maximum temperature in the laser-affected zone reaches 1600–1700 °C, which exceeds the melting temperatures of both steel 45 and the deposited material. This indicates the formation of a stable melt pool and ensures a reliable metallurgical bond between the coating and the substrate. At the same time, it was established that the heating rate reaches values on the order of 5×10^4 °C/s, while the cooling rate varies in the range of $8 \times 10^3 - 2 \times 10^4$ °C/s depending on the processing regime and the energy distribution law, which is confirmed by the data presented in Figure 2b and Figure 3b.

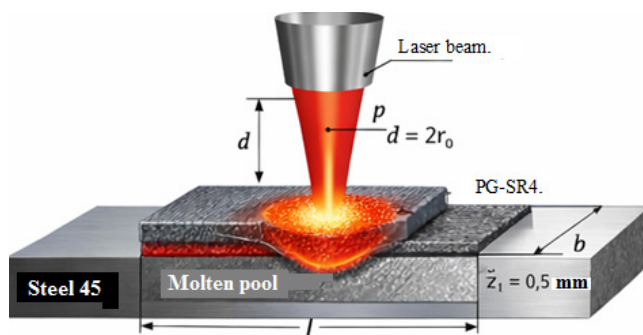


Figure 1. Computational scheme for modeling thermal processes in laser cladding.

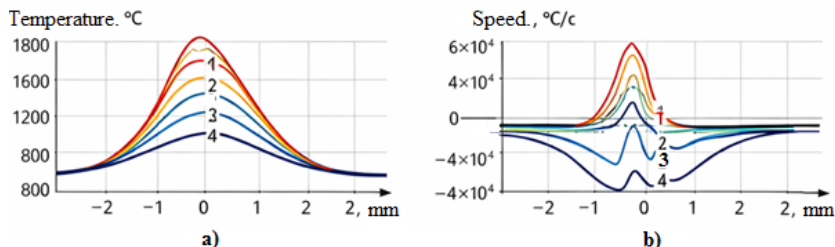


Figure 2. Temperature distribution (a) and heating and cooling rates (b) for Gaussian and uniform distributions: 1 – $z = 0$ mm, 2 – 0,25 mm, 3 – 0,45 mm, 4 – 0,85 mm.

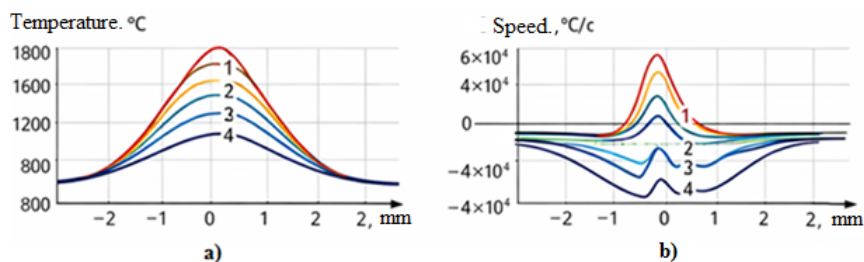


Figure 3. Temperature distribution (a) and heating and cooling rates (b) for a non-uniform offset distribution: 1 – $z = 0$ mm, 2 – 0,25 mm, 3 – 0,45 mm, 4 – 0,85 mm.

Particular attention in this work is paid to the influence of the spatial distribution of laser beam intensity on thermal processes. A comparative analysis of the simulation results shown in Figure 3 indicates that Gaussian and uniform distributions exhibit high temperature gradients, which contribute to the formation of significant residual stresses. At the same time, in the case of a non-uniform distribution with a maximum intensity at the front part of the spot, a more favorable thermal regime is formed, characterized by an increased lifetime of the liquid phase and a reduced cooling rate. This leads to a decrease in temperature gradients and, consequently, a lower probability of crack formation in the fusion zone.

The geometry of the molten pool, shown in Figure 4, demonstrates the significant influence of the thermal regime on the formation of the deposited layer's structure. It was established that in all considered regimes, the penetration depth of the substrate exceeds the thickness of the deposited coating, ensuring the formation of a strong metallurgical bond. Increasing the laser beam scanning speed from 0,2 to 0,5 m/min is accompanied by a decrease in penetration depth, which allows targeted control of the degree of mixing between the coating material and the substrate. The most rational shape of the molten pool is achieved with a frontal intensity distribution, where the melting isotherm is elongated along the direction of source movement, providing more uniform cooling of the material.

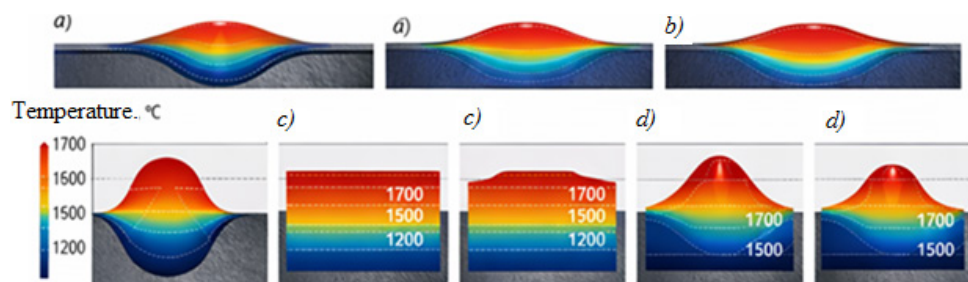


Figure 4. Temperature distribution in the longitudinal section for different laser beam intensity profiles.

Figure 4 illustrates the temperature field distribution and the geometry of the molten pool in the longitudinal section (X–Z) for different laser beam intensity distribution laws. Subfigures (a–d) correspond to the following types of energy exposure: (a) — Gaussian distribution; (b) — uniform (rectangular) distribution; (c) — non-uniform with maximum intensity at the rear part of the spot; (d) — non-uniform with maximum intensity at the front part of the spot.

The analysis shows that with a Gaussian distribution (Fig. 4a), a symmetrical molten pool is formed, with the maximum temperature localized in the central zone. In this case, significant temperature gradients are observed both in depth and along the scanning direction, which contributes to the development of elevated residual stresses. In the case of a uniform distribution (Fig. 4b), the temperature field becomes smoother; however, the symmetry of the pool and comparatively high temperature gradients remain.

With a non-uniform distribution having a maximum intensity at the rear part of the spot (Fig. 4c), the region of maximum heating shifts opposite to the direction of the beam movement, resulting in accelerated cooling of the front part of the molten pool. This, in turn, can lead to the formation of hardened structures and an increased tendency of the material to crack formation.

The most favorable thermal regime is realized with a distribution having a maximum intensity at the front part of the spot (Fig. 4d). In this case, the melting isotherms are oriented along the source movement direction, the lifetime of the liquid phase is increased, and smoother cooling is ensured. This contributes to a reduction in temperature gradients and residual stresses, the formation of a more uniform structure, and a lower probability of crack formation.

The figure is presented in two parts to allow a comprehensive analysis of both the molten pool geometry and the temperature field. The upper part reflects the pool shape and the location of the melting isotherms, enabling the assessment of penetration depth and thermal-affected zone parameters. The lower part contains quantitative data on temperature distribution along the length and depth, providing a more precise evaluation of temperature gradients and cooling conditions. This combined presentation enhances informativeness and establishes a relationship between the thermal parameters of the process and the features of the deposited layer structure formation.

Thus, the analysis results of Figure 4 confirm that varying the laser beam intensity distribution law is an effective tool for controlling molten pool geometry, temperature gradients, and cooling kinetics, which ultimately determines the quality of laser cladding in the restoration of steel 45 parts.

An important parameter determining the quality of the formed layer is the lifetime of the liquid phase, which can be estimated from the temperature dependencies as the time interval during which the temperature exceeds the melting temperature, i.e.:

$$t_{liq} \approx \Delta t (T > T_{melt}) \quad (4)$$

It was found that for a uniform energy distribution, the melt lifetime is approximately 0,05–0,07 s, whereas with a frontal distribution, it increases to 0,12–0,14 s. Increasing this parameter contributes to the homogenization of the chemical composition in the fusion zone, reduces liquation processes, and decreases the likelihood of defect formation.

The analysis results of the powder material's chemical composition, summarized in Table 1, show that the PG-SR4 alloy predominantly contains elements with high solubility in iron, such as Ni, Cr, and Si, as well as boron, which acts as a structure modifier. Nickel contributes to increased plasticity, chromium ensures higher hardness and corrosion resistance, silicon improves the melt's fluidity, and boron promotes grain refinement. The distribution coefficients of these elements are close to unity, ensuring their uniform distribution during solidification and preventing the development of segregation processes.

Additional analysis of the mutual solubility of the elements confirms the high metallurgical compatibility of the “PG-SR4 – steel 45” system, which prevents the formation of brittle intermetallic compounds and reduces the likelihood of intergranular failure. The absence of significant amounts of harmful impurities, such as sulfur and phosphorus, further decreases the risk of porosity and crack formation, which is especially important for the operation of restored parts under the conditions of the oil and gas industry.

Table 1. Main alloying elements of PG-SR4 and their functions.

Element	Content, %	Functional Role in the Alloy
Ni	77–78	Increases plasticity, toughness, and crack resistance
Cr	13–14	Enhances hardness and corrosion resistance
Si	2–3	Improves melt fluidity
B	1,5–2	Refines grain and increases structural strength
Fe	3–5	Ensures compatibility with the substrate (steel 45)

Summarizing the obtained results, it should be noted that the formation of the service properties of the deposited layer is determined by the complex interaction of the material's chemical composition and the process's thermal conditions. This relationship can be expressed as:

$$P=f(C,T(x,y,z,t),dT/dt) \quad (5)$$

where P — coating properties, C — chemical composition, T — temperature field, dT/dt — rate of temperature change. It has been established that even with an optimal material composition, an unfavorable thermal regime can lead to crack formation, whereas optimization of the laser energy distribution allows for a significant improvement in coating quality.

Thus, the results of numerical modeling and the conducted analysis confirm that the key factor in improving the quality of laser cladding during the restoration of steel 45 parts is a comprehensive approach, which includes selecting a chemically compatible powder material and optimizing the thermal processing regimes. The use of a non-uniform laser intensity distribution with a maximum at the front part of the spot reduces temperature gradients, increases the liquid phase lifetime, and minimizes the likelihood of crack formation, thereby ensuring the formation of a deposited layer with high operational properties.

Conclusion. As a result of this study, a scientifically grounded approach has been developed for selecting powder materials for laser cladding in the restoration of steel 45 parts used in the oil and gas industry. The proposed methodology is based on a comprehensive analysis of the solubility of alloying elements, their distribution coefficients between liquid and solid phases, as well as the thermodynamic compatibility of the “coating–substrate” system, allowing for the prediction of the structure formation and service properties of the deposited layer.

It has been shown that the use of the classical non-stationary heat transfer model adequately describes the temperature fields and thermal cycles during laser cladding, as well as allows the evaluation of key process parameters, including maximum temperature, heating, and cooling rates. It was established that forming a stable molten pool at temperatures of 1600–1700 °C ensures a reliable metallurgical bond between the coating and steel 45.

Particular importance is attached to the liquid phase lifetime parameter, which significantly affects the crystallization processes and microstructure formation. Increasing this parameter by using an asymmetric laser intensity distribution with a maximum at the front part of the spot leads to reduced temperature gradients, decreased liquation, and consequently a lower likelihood of crack formation.

It was determined that optimizing the laser energy distribution law is no less important than selecting the chemical composition of the powder material. The use of a frontally shifted intensity distribution increases the liquid phase lifetime and promotes the formation of a more uniform structure of the deposited layer.

Chemical composition analysis showed that the self-fluxing alloy PG-SR4, containing Ni, Cr, Si, and boron, possesses high metallurgical compatibility with steel 45. The high solubility of the main alloying elements and their favorable distribution coefficients ensure the formation of a homogeneous structure without pronounced segregation, while the presence of boron contributes to grain refinement and improved mechanical properties of the coating.

The functional dependence established in this work of coating properties on chemical composition and thermal process parameters confirms the necessity of a comprehensive approach to selecting technological regimes for laser cladding. It has been demonstrated that only the combined optimization of powder composition and thermal conditions ensures high operational performance of restored parts.

Thus, the proposed approach reduces the likelihood of crack formation, increases wear resistance, and extends the service life of steel 45 parts operating

under oil and gas industry conditions. The results of this study can be applied in the development of repair and restoration technologies for critical equipment components, as well as in optimizing laser cladding parameters to enhance reliability and service life.

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