Industrial Transport of Kazakhstan
ISSN 1814-5787 (print)
ISSN 3006-0273 (online)
Vol. 22. Is. 3. Number 87 (2025). Pp. 44–57
Journal homepage: https://prom.mtgu.edu.kz
https://doi.org/10.58420/ptk/2025.87.03.004

УДК 621

NANOMATERIALS AND SYNTHESIS OF HYBRID TECHNOLOGIES IN SHAPING PARTS OF TRANSPORT ENGINEERING

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Abstract. In modern railway transport, ensuring the quality, reliability, and durability of rolling stock (RS) and track machines (TM) is critical. Effective management of manufacturing processes for parts, components, and assemblies is possible through the implementation of additive and nanotechnologies, as well as flexible manufacturing systems integrated with modern information management and transport systems. The study aims to analyze and improve engineering processes in railway transport by using traditional, additive, and nanotechnologies to enhance the quality of parts. Specific objectives include: investigating the potential of additive technologies (3D printing) to produce complex components; evaluating the effectiveness of nanotechnologies to improve strength, wear resistance, and corrosion resistance of parts and assemblies; developing and optimizing quality control methods using modern sensors and devices, including industrial computed tomography; assessing the economic impact of implementing nanostructured coatings and advanced production processes. Additive technologies allow the production of complex parts and reduce the weight of components without compromising strength. Nanotechnologies enable the formation of defect-free materials and nanoscale structures, increasing durability and service life of parts by 2–5 times. Quality control is performed via surface diagnostics and incoming material inspection. The introduction of nanostructured coatings on cutting tools, springs, and railway components improves wear resistance, strength, and reliability. Modern synthesis and material processing methods reduce production costs, extend maintenance intervals, and enhance the efficiency of railway engineering. Integration of traditional, additive, and nanotechnologies with advanced control and management systems improves the quality, reliability, and economic efficiency of railway transport component production. Technologies such as ultra-high-strength springs and nanocoatings ensure longevity, reliability, and enhanced performance of RS and TM under the conditions of JSC “Russian Railways.”

Keywords: nanotechnology, additive technologies, railway engineering, flexible manufacturing systems, nanocoatings, quality control, 3D printing

For citation: V. Perevertov, M. Abulkasimov, G. Afanasyev, Y.M. Tanzharykov (2025). Nanomaterials and synthesis of hybrid technologies in shaping parts of transport engineering // Industrial Transport of Kazakhstan. Vol. 22. No. 87. Pp. 44–57. https://doi.org/10.58420.ptk.2025.87.03.004. (In Eng.).

Conflict of interest: The authors declare that there is no conflict of interest.

НАНОМАТЕРИАЛДАР ЖӘНЕ КӨЛІК МАШИНАЛАРЫН ЖАСАУ БӨЛШЕКТЕРІН ҚАЛЫПТАСТЫРУ КЕЗІНДЕГІ ГИБРИДТІ ТЕХНОЛОГИЯЛАРДЫҢ СИНТЕЗІ

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Аннотация. Қазіргі заманғы теміржол тасымалдау саласында подвижной құрам (ПС) және жол машиналарының (ПМ) сапасы, сенімділігі және беріктігін арттыру маңызды. Дәстүрлі, аддитивтік және нанотехнологияларды қолдану, сондай-ақ заманауи ақпараттық-басқару және транспорттық жүйелермен интеграцияланған икемді өндіріс жүйелерін енгізу арқылы бөлшектер мен агрегаттарды өндіру процестерін тиімді басқаруға болады. Зерттеудің мақсаты – теміржол техникасының бөлшектерін өндіру сапасын арттыру үшін инженерлік процестерді дәстүрлі, аддитивтік және нанотехнологияларды қолданып жетілдіру. Міндеттері: күрделі бөлшектерді өндіру үшін аддитивтік технологиялардың (3D-басып шығару) мүмкіндіктерін зерттеу; нанотехнологиялардың бөлшектердің беріктігін, тозуға және коррозияға төзімділігін арттыру тиімділігін бағалау; заманауи датчиктер мен құрылғыларды, оның ішінде өндірістік компьютерлік томографияны қолдана отырып сапаны бақылау әдістерін әзірлеу және оңтайландыру; наноқабаттар мен жаңа өндіріс технологияларын енгізудің экономикалық тиімділігін бағалау. Аддитивтік технологиялар арқылы кез келген күрделілік деңгейіндегі бөлшектерді жасауға және олардың массасын азайтуға болады. Нанотехнологиялар дефектсіз материалдар мен наноөлшемді құрылымдарды қалыптастыруға мүмкіндік береді, бұл бөлшектердің беріктігі мен қызмет ету мерзімін 2–5 есе арттырады. Сапаны бақылау беттік диагностика және кіріс материалдарын тексеру арқылы жүзеге асырылады. Наноқабаттарды кескіш құралдарда, серіппелерде және теміржол бөлшектерінде қолдану олардың тозуға төзімділігін, беріктігін және сенімділігін арттырады. Дәстүрлі, аддитивтік және нанотехнологияларды заманауи бақылау және басқару жүйелерімен біріктіру теміржол бөлшектерін өндірудің сапасын, сенімділігін және экономикалық тиімділігін арттырады. Өте жоғары берікті серіппелер мен наноқабаттар технологиялары ПС және ПМ-нің ұзақ қызмет етуін, сенімділігін және жұмыс тиімділігін қамтамасыз етеді.

Түйін сөздер: нанотехнология, аддитивтік технология, теміржол машиностроение,икемді өндіріс жүйелері, наноқабаттар, сапаны бақылау, 3D-басып шығару

Дәйексөздер үшін: В. Перевертов, М. Абулкасимов, Г. Афанасьев, Е.М. Танжарыков (2025). Наноматериалдар және көлік машиналарын жасау бөлшектерін қалыптастыру кезіндегі гибридті технологиялардың синтезі // Қазақстан өндіріс көлігі. Том. 22. № 87. 44–57 бет. https://doi.org/10.58420.ptk.2025.87.03.004. (Ағыл тіл.).

Мүдделер қақтығысы: Авторлар осы мақалада мүдделер қақтығысы жоқ деп мәлімдейді.

НАНОМАТЕРИАЛЫ И СИНТЕЗ ГИБРИДНЫХ ТЕХНОЛОГИЙ ПРИ ФОРМООБРАЗОВАНИИ ДЕТАЛЕЙ ТРАНСПОРТНОГО МАШИНОСТРОЕНИИ

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Аннотация. В современных условиях развития железнодорожного транспорта особое значение приобретает повышение качества, надежности и долговечности подвижного состава (ПС) и путевых машин (ПМ). Эффективное управление процессами производства деталей, узлов и агрегатов возможно благодаря внедрению аддитивных и нанотехнологий, а также гибких производственных систем, интегрированных с современными информационно-управляющими и транспортными системами. Цель исследования — анализ и совершенствование технологических процессов машиностроения с применением традиционных, аддитивных и нанотехнологий для повышения качества деталей железнодорожного транспорта. Задачи исследования включают: исследование возможностей применения аддитивных технологий (3D-печати) для производства деталей любой сложности; определение эффективности нанотехнологий для улучшения прочностных, износо- и коррозионностойких характеристик деталей и агрегатов; разработка и оптимизация методов контроля качества с использованием современных датчиков и устройств, включая промышленную компьютерную томографию; оценка экономического эффекта внедрения наноструктурированных покрытий и новых технологических процессов. Использование аддитивных технологий позволяет создавать детали без ограничения сложности и уменьшать массу изделий без потери прочности. Нанотехнологии обеспечивают формирование «бездефектных» материалов и наноразмерных структур, повышающих долговечность и ресурс деталей в 2–5 раз. Контроль качества осуществляется через диагностику поверхности и входной контроль материалов. Внедрение наноструктурированных покрытий на режущие инструменты, пружины, детали ПС и ПМ повышает их износостойкость, прочность и надежность. Применение современных методов синтеза и обработки материалов позволяет снизить производственные расходы, увеличить межремонтный срок оборудования и повысить эффективность железнодорожного машиностроения. Интеграция традиционных, аддитивных и нанотехнологий с современными системами контроля и управления способствует повышению качества, надежности и экономической эффективности производства деталей железнодорожного транспорта. Технологии сверхвысокопрочных пружин и нанопокрытий обеспечивают долговечность, надежность и повышение эксплуатационных характеристик ПС и ПМ в условиях ОАО «РЖД».

Ключевые слова: нанотехнологии, аддитивные технологии, железнодорожное машиностроение, гибкие производственные системы, нанопокрытия, контроль качества, 3D-печать

Для цитирования: В. Перевертов, М. Абулкасимов, Г. Афанасьев, Е.М. Танжарыков (2025). Наноматериалы и синтез гибридных технологий при формообразовании деталей транспортного машиностроении//Помышленный транспорт Казахстана. Т. 22. No. 87. Стр. 44–57. https://doi.org/10.58420.ptk.2025.87.03.004. (На англ.).

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Introduction.

The transport system of JSC Russian Railways ensures the mobility and operational flexibility of all types of rolling stock and track machines, as well as of the system as a whole, provided that adequate reserves of throughput and hauling capacity are maintained. The growth of freight turnover is influenced by such key factors as quality, safety, and reliability of manufactured components.

The advancement of engineering technologies necessitates the adoption of modern methods for blank forming. Manufacturing processes in mechanical engineering are conventionally classified into traditional technologies (TT), additive technologies (AT), and nanotechnologies (NT) (Perevertov et al., 1987: 35–45; Perevertov, 2019: 45–53). The principal forming methods include: deposition; casting; molding; electroforming; pressure forming; machining by cutting; electrophysical and electrochemical processing; assembly of component parts; additive technologies involving the manufacture of parts from a digital model by layer-by-layer material deposition; and nanotechnologies involving the processing and modification of materials at the atomic and molecular level to produce materials and products with unique properties.

The growth in freight and passenger traffic volumes in Russia demands increased reliability and quality of railway services, which can be achieved through the introduction of additive and nanotechnologies in the production of RS and TM components. The use of flexible manufacturing systems (FMS) and advanced materials improves strength, wear resistance, and operational characteristics of products, reduces manufacturing waste, and lowers production costs.

The object of investigation is transport mechanical engineering under JSC Russian Railways conditions, including the production of rolling stock and track machine parts and assemblies. The subject of investigation is the application of additive and nanotechnologies, flexible manufacturing systems, and modern sensors for quality control in RS and TM component production.

The aim of the research is to investigate the possibilities of improving the quality, reliability, and durability of transport engineering parts through the integration of additive and nanotechnologies into flexible manufacturing systems of JSC Russian Railways.

The research tasks are as follows: to conduct an analysis of contemporary forming methods comprising traditional, additive, and nanotechnologies; to examine the structure and capabilities of flexible manufacturing systems (FMS) and smart manufacturing systems (SMS); to investigate the application of powder, composite, and nanomaterials and the methods for their quality control using modern sensors and instruments; to assess the impact of additive and nanotechnologies on the quality, reliability, and durability of RS and TM components; and to develop recommendations for the implementation of modern technologies to improve manufacturing efficiency and reduce production costs.

The research methods employed include: systems analysis; comparative analysis of traditional and advanced technologies; simulation of manufacturing processes using CAD/CAM/CAE tools; quality control data analysis; and experimental testing of RS and TM parts incorporating nanomaterials and additive technologies. The scientific hypothesis holds that the introduction of additive and nanotechnologies into flexible manufacturing systems will produce a significant improvement in the quality, reliability, and durability of RS and TM components through the optimization of forming processes, reduction of manufacturing waste, and precise control of material parameters.

Materials and Methods.

Smart manufacturing system (SMS) technologies are effectively applied in mechanical engineering in the form of flexible manufacturing systems (FMS), which comprise three subsystems. The blank processing subsystem encompasses forge-and-die production, foundry production, welding, plastics and powder processing, and heat treatment (Perevertov, 2023: 73; Perevertov, 1987: 35–45; Perevertov, 2017: 102–110; Perevertov, 2018: 56–63; Perevertov, 2020: 77–85; Perevertov, 2021: 90–98). The finishing processing subsystem comprises machining by cutting (MBC), including drilling, milling, and turning (Perevertov, 1987: 35–45; Perevertov, 2020: 77–85). The assembly subsystem, unified by a common transport and information management system, is integrated with product design and manufacturing technology, enabling interpenetration of subsystems and integration of traditional, additive, and nanotechnologies (Perevertov, 2023: 73; Perevertov, 2018: 56–63; Perevertov, 2022: 120–128).

The transition from conventional manufacturing models toward smart manufacturing systems (SMS) represents one of the principal technological trends in modern transport engineering. Traditional manufacturing systems are characterized by rigid technological chains, limited adaptability to changing production conditions, and dependence on manual control and post-process quality inspection. In contrast, smart manufacturing systems integrate flexible manufacturing modules, digital design environments, sensor networks, automated diagnostics, and intelligent process control into a unified cyber-physical production architecture.

For railway engineering enterprises operating under the conditions of increasing production complexity and higher reliability requirements for rolling stock (RS) and track machines (TM), the implementation of SMS technologies provides significant operational and economic advantages. These include reduction of production waste, increased manufacturing flexibility, improved process transparency, predictive maintenance capability, and enhanced product quality control throughout the entire production lifecycle. A comparative analysis of conventional and smart manufacturing systems in transport engineering is presented in Table 1.

Table 1 – Comparison of conventional manufacturing systems and smart manufacturing systems in transport engineering

Parameter	Conventional manufacturing system	Smart manufacturing system (SMS/FMS)
Production flexibility	Limited	High
Reconfiguration speed	Manual, time-consuming	Automated, software-controlled
Integration with CAD/CAM/CAE	Partial	Full digital integration
Process monitoring	Periodic/manual	Continuous real-time monitoring
Defect detection	Post-production inspection	In-process intelligent diagnostics
Resource consumption	High	Optimized
Production waste	Significant	Minimal
Adaptability to AT/NT	Limited	Fully compatible
Predictive maintenance	Not available	AI/ML-supported
Production efficiency	Medium	High

The advancement of digital technologies in design (CAD), simulation and analysis (CAE), and machining (CAM) has led to increased adoption of additive technologies for the manufacture of tools, casting molds, and RS and TM parts (Perevertov, 2019: 45–53; Perevertov, 2021: 90–98). Building upon AT, robotic technological complexes and flexible manufacturing modules for 3D printing with powder, composite, and nanomaterials have been developed. These are classified according to: materials used (liquid, granular, polymer, metal-powder, and others); the presence of laser equipment; methods of energy supply for layer consolidation (thermal action, UV or visible light irradiation, binder agent, and others); layer formation methods; and motion type.

Nanotechnologies encompass a set of methods for processing and modifying material properties at the nanometer scale. Unlike conventional technologies, nanotechnologies provide the ability to manipulate individual atoms and molecules, creating materials with novel physicochemical and biological properties (Perevertov, 2019: 45–53; Perevertov, 2022: 120–128). Table 2 presents a comparative classification of the three principal forming technology categories.

Table 2 – Comparative classification of part-forming technologies in transport engineering

Technology category	Main methods	Key features
Traditional technologies (TT)	Casting, forming, machining, electrochemical processing, welding, assembly	Mature processes; limited by tool geometry and material removal constraints
Additive technologies (AT)	3D printing (layer-by-layer deposition: powder, polymer, composite materials)	No geometric restrictions; waste-free; enables complex internal structures
Nanotechnologies (NT)	Nanocoatings, nanopowder synthesis, surface nanostructuring, RVS restoration technology	Atom/molecule-level control; defect-free materials; 2–5x increase in service life

Particular attention in the study was devoted to quality control of manufactured products. In AT production, the internal quality of 3D-printed items cannot be directly observed; only the external surface is accessible for inspection. It is therefore necessary to control part geometry, since it may change following forming and post-processing operations (thermal, mechanical, etc.). Incoming inspection of metal-powder compositions and verification of raw material specifications are also required. Industrial computed tomography (CT) is applied in AT to optimize synthesis parameters prior to forming, thereby reducing the scrap rate and conserving consumable material (Perevertov, 2021: 90–98).

The key elements of SMS that determine production quality are: (1) high-speed actuating elements of technological equipment; and (2) sensors — high-precision, reliable functional transducers with high stability and response speed. For quantitative measurement of the chemical composition of metals and alloys, the portable laser spectrometer LIS-01 is used. For non-contact temperature control during material processing, fast-response photon-selective fiber-optic sensors of the IRT-1 type are applied (Perevertov, 2022: 120–128; Perevertov, 2021: 90–98).

An essential feature of modern smart manufacturing systems is the extensive integration of sensor technologies and intelligent monitoring platforms into all stages of the production cycle. In railway engineering, the quality and reliability of rolling stock (RS) and track machine (TM) components depend not only on the characteristics of the applied materials and forming technologies, but also on the accuracy and stability of process monitoring systems.

The implementation of advanced sensor systems enables continuous control of technological parameters such as temperature, vibration, dimensional accuracy, chemical composition, surface integrity, and internal structural defects. In contrast to conventional inspection methods based on periodic manual measurements, intelligent monitoring technologies provide real-time data acquisition, automated diagnostics, and rapid detection of process deviations. This significantly improves manufacturing precision, reduces the probability of hidden defects, and supports predictive maintenance strategies within flexible manufacturing systems.

Particular importance is attached to non-destructive testing technologies, including industrial computed tomography (CT), laser spectroscopy, acoustic diagnostics, and fiber-optic sensing systems. These technologies ensure comprehensive quality assessment of additively manufactured and nanostructured components, where internal defects and material heterogeneity cannot be identified through conventional visual inspection methods. The principal sensor systems and monitoring technologies used in smart railway manufacturing are summarized in Table 3.

Table 3 – Sensor systems and monitoring technologies used in smart railway manufacturing

Sensor / system	Controlled parameter	Application area	Operational advantage
LIS-01 laser spectrometer	Chemical composition	Powder metallurgy, alloys	Rapid non-contact analysis
IRT-1 fiber-optic sensor	Temperature	Heat treatment, welding	High-speed thermal monitoring
Industrial CT scanner	Internal defects and porosity	Additive manufacturing	Non-destructive internal inspection
Vibration sensors	Dynamic loads	Rotating equipment	Early fault detection
Acoustic emission sensors	Crack initiation	Springs, bearings	Predictive diagnostics
AI-based monitoring platform	Process anomalies	Smart manufacturing systems	Predictive maintenance

The data presented in Table 3 demonstrate that modern sensor technologies form the core of intelligent manufacturing environments and significantly improve the reliability and efficiency of railway engineering production processes. The integration of laser spectrometers, fiber-optic thermal sensors, industrial CT systems, vibration monitoring devices, and AI-based analytical platforms enables continuous supervision of critical manufacturing parameters throughout the entire technological cycle.

Among the considered technologies, industrial computed tomography occupies a particularly important position due to its ability to perform non-destructive inspection of the internal structure of additively manufactured components. This is especially relevant for complex geometries produced by additive technologies, where hidden porosity, microcracks, or internal discontinuities may critically affect operational reliability. Early identification of such defects substantially reduces the scrap rate and improves product consistency.

Fiber-optic and laser-based sensors provide high-speed and high-precision monitoring of thermal and physicochemical parameters during welding, heat treatment, and powder-material processing. Their implementation ensures improved process stability and allows adaptive correction of manufacturing parameters in real time. Simultaneously, vibration and acoustic-emission sensors support predictive maintenance by enabling early detection of fatigue damage, crack initiation, and abnormal operating conditions in manufacturing equipment and produced components.

The integration of sensor systems with artificial intelligence and industrial IoT platforms further expands the capabilities of smart manufacturing systems. AI-based monitoring platforms can analyze large volumes of sensor data, identify hidden correlations between process variables, and generate predictive diagnostics for equipment and products. Such approaches reduce unplanned downtime, improve production planning efficiency, and create the technological basis for fully digitalized railway manufacturing enterprises operating according to Industry 4.0 principles.

The research methods employed in the study were accordingly: analysis of literature and patent sources; review of modern manufacturing technologies (casting, pressure forming, 3D printing, nanotechnologies); a systems approach to product quality and reliability evaluation; use of sensor systems and CT for part parameter control; and CAD/CAM/CAE process simulation for the optimization of forming and improvement of manufacturing efficiency.

Results and Discussion.

Part forming by AT is based on layer-by-layer material deposition using a jet or laser (concentrated energy) method from a digital model. Production of parts by AT (3D printing) offers the following advantages over traditional technologies: (1) fabrication of parts of arbitrary geometric complexity, unconstrained by the limitations inherent in traditional methods; (2) identification of new functional possibilities in the transport technological system, including application in component diagnostics; (3) reduction of part mass without loss of structural strength; and (4) use of material exclusively for part formation, eliminating production waste and reducing costs, since no excess material removal by MBC is necessary to achieve the required configuration and dimensional accuracy (Perevertov, 2022: 39; Perevertov, 2023: 75).

Nanotechnologies represent a set of methods for processing, manufacturing, and modifying the state, properties, and form of raw materials at the nanometer scale. The “raw material” consists of individual atoms (systems) rather than the micron- or macroscale material volumes conventional in traditional technology. Unlike traditional technology, nanotechnology is characterized by an “individual” approach in which external control reaches individual atoms and molecules, enabling both the formation of defect-free materials with fundamentally new physicochemical and biological properties, and the creation of new classes of devices with nanometer dimensions.

Transport engineering is a consumer of nanostructured materials (steels and cast irons, titanium and its alloys, aluminum alloys, ceramics and plastics, powder and composite materials, shape-memory materials) and nano-component parts. The economic effect is achieved from introducing wear-resistant nanocoating technology on MBC cutting tools (drills, milling cutters, etc.), dies and press molds in forging and pressure-processing machines, casting molds, as well as wear-resistant, corrosion-resistant, heat-resistant, and hydrophobic coatings on machine and mechanism parts for RS and TM, including brake system elements and suspension springs (Perevertov, 2022c: 40).

Ultra-fine nanopowder production has found application in friction units of all types of equipment. RVS (Repair and Restoration Compound) technology restores worn parts to original parameters. The cost of renovation using RVS technology is 2 to 3 times lower than with conventional methods, extending maintenance intervals by a factor of 1.5 to 2 and reducing energy and fuel consumption by 10–15 %. Nanostructuring of bearing surfaces in RS and TM increases their durability by a factor of 2 to 3 (from 150–200 to 500–600 million cycles), while tool durability increases by a factor of 5 to 6 (Perevertov, 2022c: 40; Perevertov, 2023: 76).

Copper alloy powders are used to produce anti-wear RiMET preparations containing nanoparticles active in friction zones. These nanoparticles circulate freely in the lubricating oil, using it as a carrier medium to friction zones. Under high temperature and pressure, the nanoparticles are activated and form a new surface layer on the friction pair, assuming the full load. The following processes are achieved: (1) normalization of the crystal lattice structure; (2) relief of surface fatigue; and (3) filling of scoring marks (Perevertov, 2022c: 40; Perevertov, 2023: 76).

At Russian enterprises, the following traditional and additive technologies at the nano-level are being implemented: electrical discharge nanoscale machining; electrochemical finishing and dimensional processing of working surfaces of heavily loaded parts; ion-plasma hardening of tools and machine parts with coatings of up to 2 microns thickness; surface modification using high-speed thermochemical plasma-jet interactions aimed at improving wear and corrosion resistance of alloyed steels; surface hardening to depths of up to 2 mm; ion-plasma deposition of coatings from a spectrum of materials with specified structures (nanocrystalline, amorphous, crystalline, or composite); application of polymer nanocomposites and synthesis of nanoceramic coatings; development of ultra-high-strength spring production technology and wear-resistant articles from nanostructured cermet materials; and creation of monolithic solid-carbide cutting tools with nanostructured coatings (Perevertov, 2022c: 40; Perevertov, 2023: 75).

Quality indicators (reliability, durability, service life) of transport engineering parts manufactured by these new technologies increase by a factor of 2 to 5 with nanometer precision using electrical discharge machining, electrochemical processing, milling, grinding, polishing, and finishing equipment.

A leading trend is the spray deposition of nanomaterials to obtain nanostructured coatings applied by high-velocity thermal spray methods using source materials in the form of solutions or suspensions containing nanoscale particles. Nanotechnologies address friction and corrosion through nanoscale particles in new-generation corrosion inhibitors. Anti-friction, anti-wear, and cooling compounds for internal combustion engines reduce fuel consumption by 2–7 %, part wear by a factor of 1.5–2.5, and increase engine power by 2–4 % (Perevertov, 2023: 76). Addition of nanoparticles to conveyor belts increases their flexibility and reduces wear. Nanostructured coating application increases tool wear resistance by a factor of 2 to 2.5, enabling metalworking at higher cutting speeds. The metal removal volume increases by a factor of 2 to 2.5, and regrinding life and cutting speed increase by a factor of 1.5 to 2 (Perevertov, 2023: 76).

Precision electrochemical machine tools find application in engine manufacturing, power engineering, and tooling production for wear-resistant products made from nanostructured ceramics and cermets, including plain bearings, face seal rings, axial tools, and indexable inserts. For pump systems, tribotechnical products from nanostructured cermets operate under complex service conditions with enhanced wear resistance, extended operating temperature range, and chemical inertness, improving service life by 20–30 %. Ceramic and cermet cutting tools enable increased productivity and improved geometric accuracy (Perevertov, 2023: 76).

The technology of ultra-high-strength spring production improves reliability, durability, and relaxation resistance through hot coiling at an optimal combination of controlled parameters: heating temperature, deformation degree during coiling, and cooling-quenching scheme applied sequentially to each coil. This results in the formation of a nanoscale structure providing high strength characteristics with extended service life, elevated permissible stress levels, elimination of coil settling, and improved performance at low temperatures (Perevertov, 2022: 41). The production algorithm is shown in Figure 1.

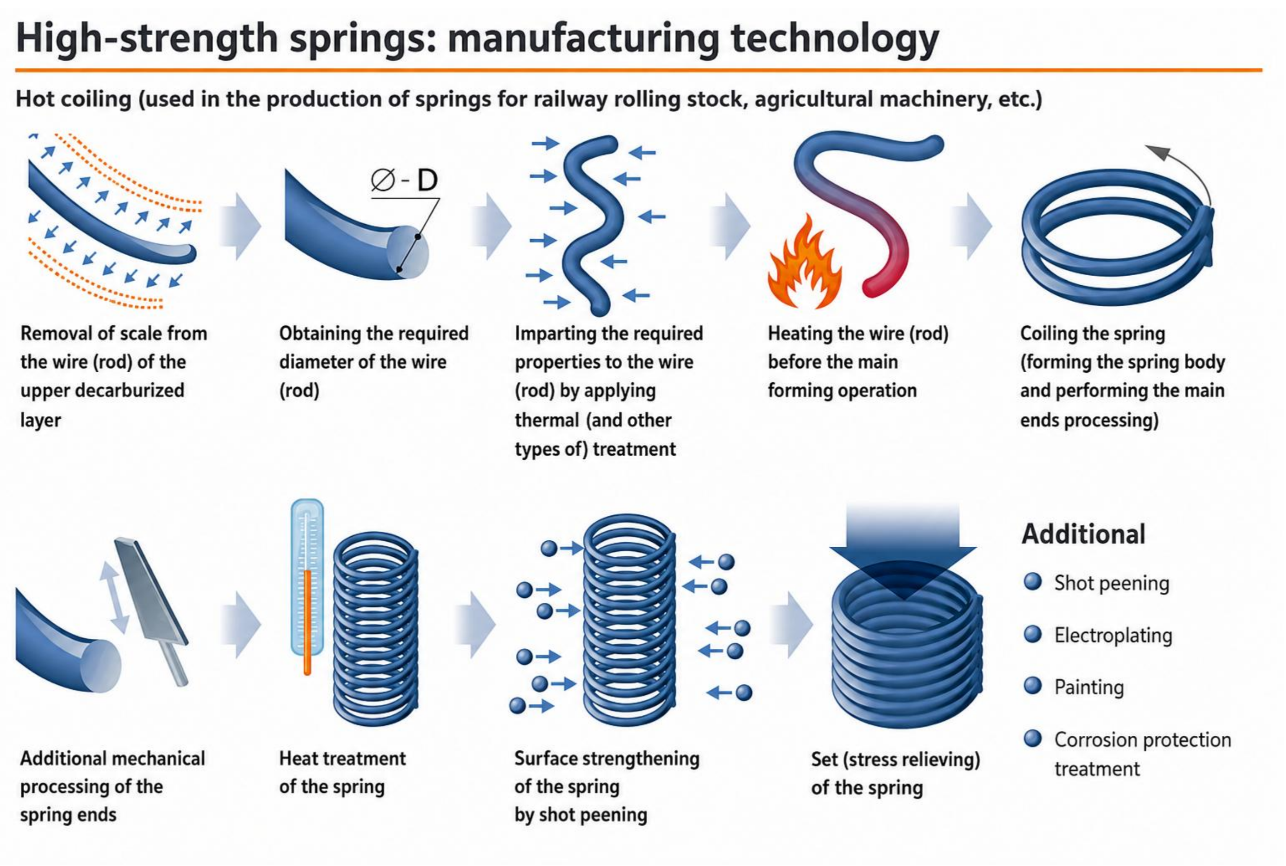

Fig. 1. Algorithm of ultra-high-strength spring production technology for rolling stock and track machines (Perevertov, 2022: 41)

The technological sequence presented in Figure 1 demonstrates the integrated approach used in the production of ultra-high-strength springs for rolling stock and track machines. The process combines controlled thermal treatment, hot coiling, surface strengthening, and residual stress stabilization operations aimed at forming a nanostructured material state with enhanced mechanical and эксплуатационные properties.

Particular importance is attached to the optimization of thermal and deformation parameters during hot coiling. The controlled combination of heating temperature, deformation degree, and cooling-quenching regime enables the formation of a refined nanoscale microstructure characterized by increased dislocation density and improved phase distribution. As a result, the produced springs exhibit substantially higher fatigue strength, relaxation resistance, and dimensional stability under cyclic loading conditions.

The surface strengthening stage performed by shot peening plays a critical role in improving operational durability. The introduction of compressive residual stresses into the surface layer suppresses crack initiation and slows fatigue crack propagation, thereby extending service life under dynamic loading conditions typical for railway suspension systems. In addition, the subsequent stress-relief operation stabilizes the internal structure of the spring and minimizes the probability of residual deformation or coil settling during long-term operation.

Additional technological operations, including electroplating, painting, and corrosion-protection treatment, further improve environmental resistance and operational reliability under aggressive climatic and эксплуатационные conditions. This is particularly important for railway transport systems operating under variable humidity, temperature fluctuations, and elevated mechanical vibration levels.

The implementation of nanostructured spring manufacturing technologies provides substantial operational advantages compared with conventional spring production methods. According to experimental and industrial data, the fatigue durability of springs manufactured using optimized hot-coiling and nanostructuring technologies increases by a factor of 2–3, while permissible stress levels increase significantly without loss of elasticity. Moreover, improved low-temperature performance enhances operational reliability in northern and continental climatic regions, which is critically important for railway systems of Russia and Kazakhstan.

From the standpoint of smart manufacturing systems, the production algorithm shown in Figure 1 can be integrated with automated thermal monitoring sensors, AI-based process control systems, and digital quality-control platforms. Such integration enables adaptive regulation of technological parameters in real time, ensuring stable product quality, reduced defect probability, and improved repeatability of mechanical characteristics across serial production batches.

Table 4 summarizes the key quantitative performance improvements achieved through the application of nanotechnologies and additive technologies across the principal application areas in transport engineering.

Table 4 – Performance improvements from nanotechnology and AT applications in transport engineering

Application area	Effect of nanotechnology / AT	Quantitative improvement
Cutting tools (drills, milling cutters)	Nanostructured wear-resistant coatings	Tool life ×1.5–2; metal removal rate ×2–2.5
Sliding/rolling bearings	Nanostructuring of contact surfaces	Durability ×2–3 (150–200 → 500–600 million cycles)
Springs (RS and TM suspension)	Ultra-high-strength spring technology with nanoscale structure	Extended service life; higher permissible stress; no coil settling
Diesel engine / pump friction units	Nanopowder anti-friction compounds (RiMET)	Fuel saving 10–15 %; wear ÷1.5–2.5; power +2–4 %
Al/Mg/Ti surfaces	Micro-arc oxidation (MAO) nanostructured ceramic coatings	Wear-resistant, corrosion-protective, or thermostable surface as required
Conveyor belts	Nanoparticle additives to belt material	Increased flexibility; reduced wear
AT-produced components	Industrial computed tomography (CT) quality control	Reduced scrap rate; optimized forming parameters

The quantitative indicators presented in Table 4 demonstrate that the application of additive and nanotechnologies produces substantial improvements in the operational characteristics of transport engineering components across multiple functional areas. The most significant effects are observed in wear resistance, fatigue durability, energy efficiency, and maintenance interval extension, which directly influence the reliability and economic efficiency of railway transport systems.

Nanostructured wear-resistant coatings applied to cutting tools considerably increase tool durability and machining productivity. The increase in allowable cutting speeds and metal removal rates enables reduction of manufacturing cycle duration while simultaneously improving dimensional accuracy and surface quality. This is especially important for high-precision machining of rolling stock and track machine components operating under elevated mechanical loads.

The nanostructuring of sliding and rolling bearing contact surfaces provides a particularly important improvement in fatigue durability. The increase in operational life from 150–200 million to 500–600 million loading cycles significantly reduces maintenance frequency and lowers the probability of unexpected equipment failures. Such improvements are achieved through refinement of the microstructure, reduction of friction coefficients, and suppression of crack initiation processes within the surface layer.

Ultra-high-strength spring technologies incorporating nanoscale structural modification demonstrate major advantages for railway suspension systems. Increased permissible stress levels, elimination of coil settling, and improved low-temperature performance substantially enhance operational stability of rolling stock under dynamic loading conditions. These characteristics are especially important for freight trains operating under heavy axle loads and severe climatic conditions.

The application of nanopowder anti-friction compounds in diesel engines and pump friction units produces combined technical and economic benefits. Reduced friction losses lower fuel consumption by 10–15 %, while simultaneous reduction of wear intensity extends equipment service life and decreases repair costs. The observed increase in engine power output additionally improves traction efficiency and overall transport system productivity.

Micro-arc oxidation (MAO) nanostructured ceramic coatings applied to aluminum, magnesium, and titanium alloys significantly enhance corrosion resistance, thermal stability, and wear protection. These coatings are particularly valuable for lightweight transport engineering structures where the combination of low mass and high durability is critically important. Depending on processing parameters, multifunctional protective layers with tailored operational properties can be obtained.

The implementation of industrial computed tomography for quality control of additively manufactured components represents another important technological advancement. Non-destructive inspection of internal structures enables identification of hidden defects, porosity, and material discontinuities that cannot be detected through conventional external inspection methods. This substantially reduces the scrap rate, improves repeatability of manufacturing processes, and supports optimization of additive manufacturing parameters.

Overall, the results summarized in Table 4 confirm that additive and nanotechnologies provide not only local improvements in individual component characteristics, but also a systemic increase in the reliability, efficiency, and sustainability of transport engineering production. The integration of these technologies into smart manufacturing systems creates the technological basis for the transition toward digitally controlled, resource-efficient, and highly adaptive railway engineering enterprises operating according to Industry 4.0 principles.

New design solutions for rolling stock and track maintenance require braking systems for RS, TM, and car bogies with independently rotating wheels. The developed disc brake scheme for RS wheelsets incorporating nanomaterials will improve reliability and safety. Cutting tools made from boron nitride nanopowder provide increased wear resistance and enhanced tool productivity, reducing component processing costs by up to 60 %. Multifunctional nanoceramic coatings on aluminum and magnesium surfaces, applied by micro-arc oxidation (MAO), form nanostructured ceramic-like layers on aluminum, magnesium, titanium, zirconium, and other metal surfaces. Depending on processing conditions, wear-resistant, corrosion-protective, electrically insulating, thermally resistant, or combined surfaces can be obtained (Perevertov, 2022: 41).

Conclusion.

The present study addressed the analysis and evaluation of traditional, additive, and nanotechnology applications in railway engineering under JSC Russian Railways conditions, with the aim of improving the quality, reliability, and durability of rolling stock and track machines. A comprehensive set of research methods was applied, including literature and patent analysis, review of modern manufacturing technologies, a systems approach to product quality evaluation, and investigation of sensor systems and quality control technologies.

The research objectives were realized as follows. A detailed analysis was conducted of forming process technologies encompassing traditional technologies (casting, machining, pressure forming), additive technologies (3D printing, robotic complexes), and nanotechnologies (nanopowders, nanocoatings, surface modification). Integration capabilities of smart manufacturing systems, including flexible manufacturing modules, information management systems, and monitoring systems, were investigated. Particular attention was devoted to quality control in AT and NT production, including industrial computed tomography for internal product structure assessment and dimensional accuracy assurance.

The following key results were obtained:

– Improved manufacturing process efficiency. Additive technologies enable production of parts of arbitrary complexity without massive blanks, reducing manufacturing waste and lowering material processing costs.

– Enhanced part quality and reliability. Nanomaterials and nanocoatings provide increased strength, wear resistance, thermal stability, and corrosion resistance of components, including brake system elements, bearings, and springs. Part durability increases by a factor of 2 to 5 compared to traditional technologies.

– Integration of flexible and intelligent management systems. Sensor systems enable real-time monitoring of manufacturing process parameters, ensuring compliance with quality standards and reducing the scrap rate.

– Economic benefit. Nanostructuring and RVS technologies reduce repair and equipment operation costs, extend maintenance intervals, and reduce electrical energy and fuel consumption by 10–15 %.

The conclusions confirm that the integration of traditional, additive, and nanotechnologies into railway engineering substantially improves the quality and reliability of manufactured products and opens new possibilities for optimizing manufacturing processes. The use of nanomaterials and flexible technological systems provides unique product properties not achievable by conventional methods and significantly expands the potential for product parameter diagnostics and control.

Prospects for further work include: implementation of AT and NT in the serial production of RS and TM components; development of new design solutions and innovative materials including nanocomposites and nanocoatings; application of computer simulation and artificial intelligence for manufacturing process optimization, part wear prediction, and forming accuracy improvement; and expansion of RVS technology and nanostructured material applications for extending equipment service life and increasing economic efficiency of railway transport operation.

The practical significance of the study lies in the fact that the results obtained can be implemented at railway engineering enterprises to improve RS and TM reliability and durability, reduce operating costs, and enhance service quality. The developed ultra-high-strength spring production algorithms, nanocoating deposition methods, and nanomaterial applications provide the basis for creating products competitive with foreign equivalents, contributing to domestic import substitution and innovative modernization of the industry.

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