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IMPROVING THE RELIABILITY OF LOCOMOTIVE ELECTRICAL POWER DEVICES BY ENHANCING CONTACT JOINTS

Spivak O.M., Ivanchenko S.S., Melkonova I.V. Melkonov H.L.

ПІДВИЩЕННЯ НАДІЙНОСТІ СИЛОВИХ ПРИСТРОЇВ ЕЛЕКТРОВОЗІВ ШЛЯХОМ УДОСКОНАЛЕННЯ КОНТАКТНИХ З'ЄДНАНЬ

Співак О.М., Іванченко С.С., Мелконова І.В., Мелконов Г.Л.

In modern railway transport, the reliability of electrical power devices is a key factor in ensuring the safety and efficiency of locomotive operation.. The uninterrupted performance of systems such as traction motors, converters, and protection relays directly influences the stability of train movement and passenger safety.

Among the critical components of these systems are electrical contact joints, which are commonly used in switching devices such as contactors and circuit breakers. These joints are regularly subjected to significant electrical and mechanical stresses, including high current switching, thermal cycling, and vibration, all of which contribute to contact wear and eventual failure.

The degradation of contact surfaces leads to increased contact resistance, reduced conductivity, and a higher likelihood of arc formation, ultimately compromising the overall functionality of the power system. Therefore, improving the durability and electrical performance of contact joints is an essential objective in the development of more reliable locomotive power systems.

This study focuses on identifying effective strategies to improve contact joint reliability by analyzing contact materials, modeling key operational parameters such as contact resistance and failure probability and evaluating modern material technologies. Particular attention is given to the use of composite and nanostructured materials, which offer enhanced mechanical strength, erosion resistance, and compliance with international environmental standards.

To overcome the limitations associated with large-scale experimental testing, the research relies primarily on analytical methods supported by data from existing literature. This approach allows for the theoretical assessment of material performance and the identification of optimal solutions for practical implementation in railway systems.

Contact components used in the switching of electrical circuits have a significant impact on the performance and reliability of this equipment. This paper presents a study aimed at improving the operational reliability and mean time between failures of locomotive traction electromagnetic contactors by enhancing the stability of their contact characteristics. Due to the high cost and complexity of conducting large-scale experimental research, the emphasis is placed on analytical methods and the study of the properties of the materials used, proposing potential improvements based on available technologies and materials in accordance with international standards and current widespread innovations.

Keywords: *reliability, electrical power devices, locomotives, contact joints, electromagnetic contactors, contact resistance, international standards, innovative materials, composite materials, nanostructured materials.*

Introduction. In modern railway transport, the reliability of electrical power devices is a key factor in ensuring the safety and efficiency of locomotive operation [1]. The uninterrupted performance of systems such as traction motors, converters, and protection relays directly influences the stability of train movement and passenger safety.

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This study focuses on identifying effective strategies to improve contact joint reliability by analyzing contact materials, modeling key operational parameters such as contact resistance and failure probability and evaluating modern material technologies. Particular attention is given to the use of composite and nanostructured materials, which offer enhanced mechanical strength, erosion resistance, and compliance with international environmental standards.

To overcome the limitations associated with large-scale experimental testing, the research relies primarily on analytical methods supported by data from existing literature. This approach allows for the theoretical assessment of material performance and the identification of optimal solutions for practical implementation in railway systems.

Research results. Analysis of Contact Node Failure Causes. The operational reliability of electrical contacts in locomotive switching devices is significantly influenced by a variety of degradation mechanisms that act individually or in combination during the service life of the equipment. Understanding these failure causes is essential for the development of more durable and efficient contact materials.

The main causes of contact node failures include the following:

- Contact erosion: During switching operations, the contact surfaces are exposed to high-temperature electric arcs that lead to localized melting, pitting, and material loss. Repeated arc exposure degrades the surface integrity and reduces the effective contact area [3].
- Oxidation: Environmental exposure and elevated temperatures promote the formation of oxide layers on the contact surface. These non-conductive films increase the contact resistance and reduce current-carrying efficiency [4].
- Mechanical wear: Frequent switching cycles and mechanical vibrations lead to frictional wear of the contact surfaces. This results in surface roughness, reduced alignment, and uneven pressure distribution, ultimately degrading performance [4].
- Thermal overheating: High current densities and poor heat dissipation can cause localized overheating. This thermal stress not only accelerates oxidation and softens the contact material but may also cause microstructural degradation and deformation [5].
- Improper contact force: Both insufficient and excessive contact pressure negatively impact reliability. Low force results in unstable electrical contact and arcing, while excessive force causes mechanical deformation and accelerates wear of the contact surfaces.

Table 1 presents the key factors affecting the reliability of contact nodes.

Table 1

Main Factors Contributing to Contact Node Failures

Factor	Description	Impact on Reliability
Contact erosion	Destruction of the contact surface due to electric arcs	Decrease in contact integrity and lifespan
Oxidation	Formation of oxides on the contact surface	Increased contact resistance
Mechanical wear	Material loss due to friction and vibration	Surface degradation and reduced durability
Thermal overheating	Localized heating from resistive losses	Microstructural damage, increased failure risk
Improper contact force	Insufficient or excessive contact pressure	Instability, arcing, mechanical damage

Limitations of Experimental Studies. Experimental research on electrical contact joints in locomotive power systems poses significant challenges, both from technical and economic perspectives. While laboratory testing provides valuable data, it is often impractical as the primary method of investigation at early design stages. Several key limitations hinder the widespread implementation of large-scale experimental studies.

First, the cost of conducting controlled tests is considerably high. This includes the procurement of specialized contact materials, high-current switching equipment, thermal monitoring tools, and arc simulation platforms. Additionally, high-power test benches with accurate force control and real-time diagnostics are required to replicate realistic switching conditions.

Second, replicating real-world operating environments such as variable mechanical loads, high humidity, contamination, and long-term thermal cycling requires the development of sophisticated and often custom-built test rigs. These setups must account for both electrical and mechanical stressors that occur simultaneously during actual locomotive operation.

Third, achieving statistically meaningful results necessitates a high number of repetitive test cycles. Since contact degradation is a stochastic process influenced by multiple variables (e.g., force, temperature, material inhomogeneity), a large sample size is required to draw reliable conclusions. This further increases time, labor, and cost.

Given these constraints, this study focuses on analytical methods as a feasible alternative during the preliminary stages of material selection and contact design. By utilizing validated theoretical models and performance data from existing literature, it becomes possible to estimate contact behavior, predict failure modes, and evaluate the long-term reliability of different material systems without the need for extensive physical testing.

This approach enables cost-effective decision-making and supports the identification of optimal solutions for improving contact joint performance using accessible and environmentally compliant materials and technologies.

Modern International Standards and Technologies. According to international standards such as IEC 60947 and IEEE C37.016, it is essential to use materials and technologies that ensure high reliability and durability of contact joints [6], [7].

Modern Materials for Contact Joints. Silver–cadmium oxide (AgCdO) and silver–tin oxide ($AgSnO_2$) are composite materials consisting of a silver matrix with dispersed cadmium or tin oxide particles [8], [9]. These materials combine the high electrical conductivity of silver with enhanced mechanical properties and erosion resistance provided by the oxide particles.

Silver–nickel alloy (AgNi) is typically considered an alloy, but under certain manufacturing conditions, it may exhibit a structure similar to a composite, where nickel forms dispersed phases within the silver matrix [10].

Composite and Nanostructured Materials. The use of composite materials with nanostructured fillers allows for enhanced contact properties [11].

Nanostructuring of $AgSnO_2$ and AgNi is a modern approach to improving their mechanical and electrical characteristics.

$AgSnO_2$ with nano-sized tin oxide particles demonstrates increased resistance to erosion and welding, along with improved electrical conductivity [9], [11].

Nanostructured AgNi exhibits improved hardness and wear resistance, contributing to the longevity of contact joints [10], [11].

Recommendations for Improving Contact Joints. Transitioning to environmentally friendly and nanostructured materials such as $AgSnO_2$ and AgNi will contribute to enhanced reliability and durability of contact joints, as well as compliance with international standards and environmental regulations [13].

Multilayer contact materials represent a promising direction for improving electrical contacts. These materials consist of multiple layers of different substances, combining their best properties [14].

The structure of multilayer contacts may include:

- Base layer: high electrical conductivity (e.g., silver or copper);
- Intermediate layers: materials that provide mechanical strength and erosion resistance (e.g., nickel or molybdenum);
- Surface layer: wear-resistant and corrosion-resistant materials (e.g., silver-based nanocomposites with metal oxides).

Nanocomposite contact materials contain nanoscale particles uniformly distributed within the matrix of the base material. This enables achieving unique properties not found in traditional materials [11].

Table 2

Comparative Characteristics of Contact Materials

Material	Electrical Conductivity, σ, S/m	Hardness, HV	Erosion Resistance	Environmental Friendliness
AgCdO	6.3×10^7	80	High	Low
$AgSnO_2$	6.1×10^7	85	High	High
AgNi	6.2×10^7	90	Medium	High

Advantages of nanocomposites include:

- Increased hardness and wear resistance due to nanoscale particles reinforcing the matrix;
- Improved electrical conductivity owing to a more uniform structure and reduced defects;
- Enhanced resistance to erosion and contact welding due to altered surface properties.

Practical Application:

$AgSnO_2$ nanocomposites involve the incorporation of nanosized SnO_2 particles into the silver matrix. This improves the distribution of oxide phases, which enhances erosion resistance and reduces contact welding [9], [11].

Applications include contactors and circuit breakers where high switching capacity and long service life are essential.

AgNi nanocomposites benefit from nano structuring that improves mechanical properties such as hardness and strength without significantly compromising electrical conductivity [10], [11].

Applications include high-frequency and high-load contacts where fast response and wear resistance are critical.

Multilayer nanocomposite contacts combine different nanocomposite layers to optimize contact properties for specific operating conditions [14].

Example structure:

- Base layer: high-conductivity material (Ag);
- Intermediate layer: AgNi nanocomposite for reinforcement;
- Surface layer: $AgSnO_2$ nanocomposite to increase erosion resistance.

Physical Vapor Deposition (PVD) enables the application of thin multilayer coatings with precise control over layer thickness and composition [15].

Advantages include high purity of coatings and the ability to form nanostructures.

Electrolytic Deposition is used for applying nanocomposite layers with controlled composition [15].

Its advantages are relative simplicity of the process and scalability for industrial production.

Mechanical Alloying is a method for producing nanocomposite materials through mechanical mixing and deformation of powder components [12].

It enables the creation of uniform nanocomposites with high particle dispersion.

Application Prospects:

- Improved reliability and durability of contact joints in locomotive electrical power devices;
- Reduced maintenance and replacement costs due to enhanced wear and erosion resistance;
- Compliance with environmental standards through the use of cadmium-free materials.

Section Conclusion:

Multilayer and nanocomposite contact materials provide a technologically advanced solution for enhancing the reliability, conductivity, and environmental safety of locomotive power contacts. Their structure allows targeted performance improvements, while modern production technologies ensure industrial scalability.

Modern environmental regulations demand that electrical equipment meet not only technical but also chemical safety standards. One of the most important is Directive 2011/65/EU (RoHS 2), which restricts the use of ten hazardous substances, including cadmium (Cd), limiting its presence to 0.01% by weight in any homogeneous material.

Silver-cadmium oxide (AgCdO), long used in electrical contact components due to its excellent arc resistance, contains cadmium and therefore falls under the restrictions of RoHS. Its use is only permitted under specific exemptions, such as exemption 8(b) listed in Annex III, which allows cadmium use in electrical contacts when no viable alternative exists.

In the context of railway applications:

- Locomotives may partially fall outside the RoHS scope if considered large-scale stationary industrial tools, as outlined in Article 2(4).
- However, electrical components marketed separately or serviceable as spare parts are generally subject to RoHS, including cadmium content limitations.

Therefore, manufacturers of locomotive electrical contacts must:

- Verify whether exemption 8(b) applies, and document its justification;
- If not applicable, ensure compliance with the cadmium threshold ($<0.01\%$) or switch to cadmium-free materials such as $AgSnO_2$ or AgNi.
- Additionally, adopting environmentally compliant materials:
- Simplifies certification for EU markets;
- Reduces legal and regulatory risks;

Table 3 presents a comparison of the RoHS compliance status for AgCdO, $AgSnO_2$, and AgNi, summarizing their cadmium content, regulatory restrictions, and environmental acceptability under Directive 2011/65/EU.

Strengthens the manufacturer's image as an environmentally responsible supplier. The application of multilayer and nanocomposite contact materials opens new opportunities for improving the characteristics of electrical contacts.

Table 3

Material Compliance Under RoHS Directive 2011/65/EU

Material	Contains Cadmium	RoHS Restricted	Allowed via Exemption	Environmentally Friendly
AgCdO	Yes	Yes	Yes (8b)	No
$AgSnO_2$	No	Yes	Not needed	Yes
AgNi	No	Yes	Not needed	Yes

Table 4

Calculated Contact Resistance Values for Different Materials

Contact Force F (N)	AgCdO: R_c (Ω)	$AgSnO_2$: R_c (Ω)	AgNi: R_c (Ω)
10	0,002	0,001	0,0005
20	0,001	0,0005	0,00025
30	0,000666667	0,000333333	0,000166667
40	0,0005	0,00025	0,000125
50	0,0004	0,0002	0,0001
60	0,000333333	0,000166667	8,33333E-05
70	0,000285714	0,000142857	7,14286E-05
80	0,00025	0,000125	0,0000625
90	0,000222222	0,000111111	5,55556E-05
100	0,0002	0,0001	0,00005

This approach simultaneously increases the reliability, efficiency, and environmental sustainability of locomotive power devices, representing a significant step forward in the development of modern railway transport.

Mathematical Modeling and Analysis:

Modeling of Contact Resistance. Contact resistance R_c is a critical parameter that affects the efficiency and reliability of electrical contacts. It depends on the material properties, contact force, and contact geometry. For modeling contact resistance, the following formula is used [16]:

$$R\_c=k/F$$

where:R_c — contact resistance (Ω);

F — contact force (N);

k — proportionality coefficient, which depends on the material and geometric features of the contact (Ω·N).

Selection of k Coefficients for Different Materials. For the three considered contact materials, the following k coefficients were selected based on their physical properties and literature data [4], [16]:

AgCdO: k = 0,02 Ω·N;

$AgSnO_2$: k = 0,01 Ω·N;

AgNi: k = 0,005 Ω·N.

Justification for k Selection

AgCdO has the highest k value due to its greater hardness and lower plasticity, which results in a smaller real contact area under a given contact force.

$AgSnO_2$ has an intermediate k value, as its properties allow for the formation of a larger contact area.

AgNi is characterized by the lowest k value due to its high plasticity and electrical conductivity, which provide the lowest contact resistance.

The contact resistance calculations were performed for contact forces F ranging from 10 N to 100 N, in increments of 10 N.

Example calculation for F=10N:

For AgCdO:

$$R_c = \frac{k}{F} = \frac{0{,}02}{10} = 0{,}002\ \Omega.$$

- For $AgSnO_2$:

$$R_c = \frac{0{,}01}{10} = 0{,}001\ \Omega.$$

- For AgNi:

$$R_c = \frac{0{,}005}{10} = 0{,}0005\ \Omega.$$

The results of the calculations are summarized in table 4.

Graph Construction. Based on the obtained data, a graph was constructed showing the dependence of contact resistance on contact force for different materials (Figure 1).

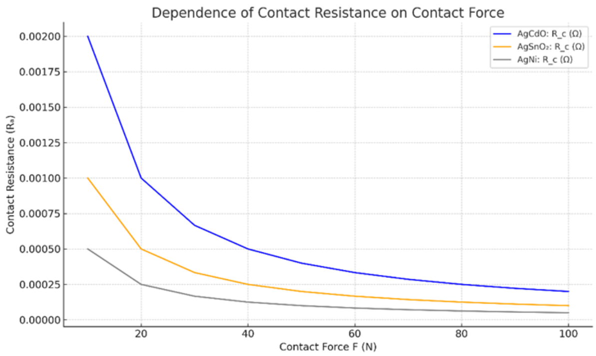

Fig. 1. Dependence of Contact Resistance on Contact Force for Different Material

Analysis of Results. The graph shows that as the contact force F increases, the contact resistance Rc decreases for all materials. This is explained by the fact that greater contact force ensures better contact between surfaces, increasing the real contact area [16].

When comparing the materials, it is evident that:

- AgNi exhibits the lowest contact resistance at any contact force, indicating its advantages for use in electrical contacts to reduce losses and increase efficiency;
- $AgSnO_2$ holds an intermediate position, demonstrating better characteristics than AgCdO;
- AgCdO shows the highest contact resistance, making it a less efficient and less environmentally friendly choice.

Reliability of Contact Joints. The reliability R(t) of a component is defined as the probability of failure-free operation over time t.

To model reliability, the exponential distribution law is used [18]:

$$R(t) = e^{-\lambda t},$$

where:R(t) — reliability at time t (hours);

λ — failure rate for the specific material (1/hour);

t — operating time (hours).

Selection of Failure Rates λ for Different Materials. Based on literature data [4], [18], the following failure rates were adopted:

$$AgCdO: \lambda = 1 \times 10^{-5} h^{-1};$$
$$AgSnO^2: \lambda = 5 \times 10^{-6}\ h^{-1};$$
$$AgNi: \lambda = 2 \times 10^{-6}\ h^{-1}.$$

Reliability Calculation. The reliability was calculated for an operating time range from 0 to 100,000 hours with a step of 10,000 hours.

Example calculation for t=10,000 hours:

- For AgCdO:

$$R(10\,000) = e^{-1\times10^{-5}\times10\,000} = e^{-0.1} \approx 0.9048.$$

- For $AgSnO_2$:

$$R(10\,000) = e^{-5\times10^{-6}\times10\,000} = e^{-0.05} \approx 0.9512.$$

- For AgNi:

$$R(10\,000) = e^{-2\times10^{-6}\times10\,000} = e^{-0.02} \approx 0.9802.$$

The results of the reliability calculations are summarized in Table 5.

Based on the obtained data, a reliability graph was plotted for contact materials (Figure 2).

Table 5

Calculated Reliability Values for Different Materials

Time t (hours)	AgCdO: R(t)	$AgSnO_2$: R(t)	AgNi: R(t)
0	1	1	1
10000	0,904837418	0,951229425	0,980198673
20000	0,818730753	0,904837418	0,960789439
30000	0,740818221	0,860707976	0,941764534
40000	0,670320046	0,818730753	0,923116346
50000	0,60653066	0,778800783	0,904837418
60000	0,548811636	0,740818221	0,886920437
70000	0,496585304	0,70468809	0,869358235
80000	0,449328964	0,670320046	0,852143789
90000	0,40656966	0,637628152	0,835270211
100000	0,367879441	0,60653066	0,818730753

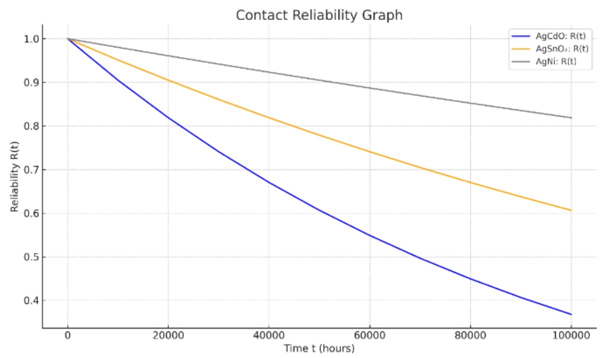

Fig. 2. Reliability of Contacts Made from Different Materials

The graph shows that:

- AgNi exhibits the highest reliability throughout the entire operational period due to its lowest failure rate λ;
- $AgSnO_2$ demonstrates better reliability than AgCdO, but is still outperformed by AgNi;
- AgCdO shows the lowest reliability because of its higher failure rate.

These results confirm the rationale for using AgNi and $AgSnO_2$ to improve the reliability of contact joints.

Practical Implementation and Prospects. Based on the conducted analysis, the following is proposed:

- Implementation of $AgSnO_2$ and AgNi as the primary contact materials in locomotive power devices to improve reliability and environmental safety;
- Application of nanostructured composites to enhance wear resistance and electrical performance of contacts;
- Utilization of modern nanostructuring technologies, such as PVD and mechanical alloying, to obtain materials with improved properties;
- Adaptation of international standards to ensure compatibility and competitiveness of the equipment in the global market.

Conclusions. The conducted study confirms that the improvement of electrical contact joints in locomotive power devices is both a technically and economically feasible approach to increasing overall system reliability. By integrating modern composite and nanostructured materials, it is possible to significantly extend the operational life of contact elements and reduce maintenance frequency, particularly under high mechanical and thermal loads typical for railway applications.

An analytical approach was effectively applied to model and compare the performance of different contact materials. This method allowed the evaluation of key parameters, such as contact resistance and long-term reliability, without the need for extensive experimental infrastructure. The calculated results show clear advantages of AgNi and $AgSnO_2$ over traditional materials like AgCdO, both in terms of lower electrical resistance and higher durability over time.

Moreover, the environmental safety of materials plays a crucial role in modern engineering. The use of cadmium-free alternatives, such as $AgSnO_2$ and AgNi, aligns with the latest international standards (e.g., IEC 60947, RoHS Directive) and supports global sustainability efforts. Their implementation reduces ecological risks and improves compatibility with future green certifications.

From a technological standpoint, multilayer nanocomposites and advanced deposition methods (e.g., PVD, mechanical alloying) provide engineers with powerful tools for tailoring contact surface properties to specific operating environments. These innovations enable the creation of high-performance contacts with optimized mechanical strength, thermal resistance, and conductivity.

In summary, the transition to innovative materials and manufacturing methods for contact joints:

• Increases reliability and service life of locomotive electrical systems;

• Reduces operational costs by minimizing failures and replacements;

• Ensures compliance with environmental and technical regulations;

Enhances the overall efficiency and competitiveness of railway transport technologies.

The proposed materials and design strategies represent a strategic step forward in the modernization of railway equipment and open new avenues for future research and industrial adoption.

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Співак О.М, Іванченко С.С., Мелконова І.В, Мелконов Г.Л. Підвищення надійності силових пристроїв електровозів шляхом удосконалення контактних з'єднань

У сучасному залізничному транспорті надійність електричних силових пристроїв є ключовим фактором забезпечення безпеки та ефективності експлуатації локомотивів. Безперебійна робота таких систем, як тягові двигуни, перетворювачі та захисні реле, безпосередньо впливає на стабільність руху поїздів та безпеку пасажирів.

Серед критично важливих компонентів цих систем є електричні контактні з'єднання, які зазвичай використовуються в комутаційних пристроях, таких як контактори та автоматичні вимикачі. Ці з'єднання регулярно піддаються значним електричним та механічним напруженням, включаючи комутацію високого струму, термоциклування та вібрацію, що сприяє зносу контактів та їх подальшому виходу з ладу.

Деградація контактних поверхонь призводить до збільшення контактного опору, зниження провідності та підвищеної ймовірності утворення дуги, що зрештою ставить під загрозу загальну функціональність енергосистеми. Тому підвищення довговічності та електричних характеристик контактних з'єднань є важливим завданням у розробці більш надійних енергосистем локомотивів.

Це дослідження зосереджено на визначенні ефективних стратегій підвищення надійності контактних з'єднань шляхом аналізу контактних матеріалів, моделювання ключових експлуатаційних параметрів, таких як контактний опір та ймовірність виходу з ладу, та оцінки сучасних технологій матеріалів. Особлива увага приділяється використанню композитних та наноструктурованих матеріалів, які забезпечують підвищену механічну міцність, стійкість до ерозії та відповідають міжнародним екологічним стандартам.

Надійність електричного обладнання на залізничному транспорті є критично важливою для забезпечення його працездатності та безпеки експлуатації. Контактні елементи, що використовуються для комутації електричних ланцюгів, мають суттєвий вплив на загальну ефективність та надійність роботи цих приладів. У даній статті представлено дослідження, спрямоване на підвищення експлуатаційної надійності та середнього часу відмов локомотивних тягових електромагнітних контакторів шляхом покращення стабільності їхніх контактних характеристик. У зв'язку з високою вартістю та складністю проведення широкомасштабних експериментальних досліджень основна увага зосереджена на аналітичних методах та вивченні властивостей використовуваних матеріалів. Запропоновано можливі шляхи удосконалення на *основі доступних технологій і матеріалів відповідно до міжнародних стандартів та сучасних інновацій.*

Ключові слова: *надійність, електричні силові прилади, локомотиви, контактні з'єднання, електромагнітні контактори, контактний опір, міжнародні стандарти, інноваційні матеріали, композиційні матеріали, наноструктуровані матеріали.*

Співак Олександр Миколайович – к.т.н., доц., доцент, кафедра електромеханіки та рухомого складу залізниць, Національний транспортний університет, Навчально-науковий Київський інститут залізничного транспорту (м.Київ), alexspi @ukr.net

Іванченко Сергій Сергійович – аспірант, кафедри електромеханіки та рухомого складу залізниць, Національний транспортний університет, Навчально-науковий Київський інститут залізничного транспорту (м. Київ),

Мелконова Інна Вікторівна – кт.н., доц., завідувачка кафедрою електричної інженерії, Східноукраїнський національний університет мені Володимира Даля (м. Київ), melkonova@snu.edu.ua

Мелконов Григорій Леонідович – кт.н., доц., завідувач кафедрою механізації сільського господарства, Східноукраїнський національний університет мені Володимира Даля (м. Київ), g.melkonov78@snu.edu.ua

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