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Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

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Optimization of the composition of the composite material of contact inserts for electric vehicles based on the criterion of wear resistance

O.V. Dykha* 0000-0003-3020-9625, **O.S. Kovtun** 0009-0000-6036-6723, **V.O. Dytyniuk** 0000-0001-6377-524X, **S.F. Posonskiy** 0000-0002-4697-7699

[1]*Khmelnytskyi national University, Ukraine*
**E-mail: tribosenator@gmail.com*

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Abstract

The paper considers the problem of reusing spent graphite contact inserts of electric transport and improving their functional properties by modifying the composition of the composite material. Modern approaches to the formation of graphite and copper-graphite electrical contact composites, the influence of the granulometric composition, conductive and solid lubricating additives on the electrical and tribological characteristics are analyzed. The prospects for using secondary graphite as the main raw material are shown, provided that the structural integrity and electrically conductive contacts between particles are restored. The feasibility of using carbon black to form an additional conductive network, copper powder to reduce contact resistance, and molybdenum disulfide to stabilize friction and reduce wear is substantiated. It has been established that the properties of such composites are multifactorial and nonlinear in nature, therefore the choice of composition requires comprehensive optimization with simultaneous consideration of the electrical resistance, wear resistance of the insert, and the effect on the contact wire.
Keywords: secondary graphite, contact insert, copper powder, carbon black, molybdenum disulfide, electrical conductivity, wear resistance.

Introduction

The use of secondary graphite material for the manufacture of contact inserts is accompanied by a decrease in electrical conductivity and wear resistance, which is due to the violation of the material structure and increased porosity. In this regard, the task of optimizing the composition of the restorative composition arises by introducing functional additives and adjusting the structural parameters of the material. A feature of this task is the multi-criteria nature of assessing the effectiveness of the material, since it is necessary to simultaneously ensure high electrical conductivity and wear resistance of the contact insert and minimal wear of the contact wire. The purpose of this section is to establish the optimal composition of the composite material based on secondary graphite using methods of mathematical experimental design and construction of a quadratic regression model.

Literature review

One of the closest to the topic of reuse of current-collecting materials is the study [1], which shows the principle possibility of returning spent carbon raw materials to the production cycle. For the manufacture of traction brushes, secondary carbon and copper components with a polymer binder were used and the material was formed by hot pressing. For individual compositions, performance characteristics comparable or better than commercial analogues were obtained. This confirms the prospects of using spent graphite current-collecting elements as raw materials for new products. In [2], the electrical sliding contact between copper and copper-graphite materials was investigated. It was found that the presence of graphite contributes to a decrease in the friction coefficient and wear intensity, while the copper component improves the electrical characteristics of the contact. The important role of the tribofilm formed during friction and determining the stability of the electrical contact interaction was also shown. The results obtained are important for substantiating the simultaneous use of carbon and metal phases in composite contact materials. In the study [3], various graphite materials were compared in pairs with copper under varying sliding speeds, normal loads and electric current. It was found that the contact characteristics depend not only on the properties of the base material, but also on the nature and stability of the surface films. Polymer-bound graphite materials provided more uniform contact and more stable electrical characteristics. This confirms the importance of structural uniformity and the binder phase in the formation of composites based on secondary graphite. In [4], the influence of polarity and various combinations of electrographite, polymer-bound graphite and copper on the characteristics of a sliding electrical contact was investigated. It was shown that the direction of the current can significantly change the intensity of wear and the condition of the contact surfaces. This result indicates the need to evaluate a promising material not only by its own wear resistance, but also by its effect on the contact wire, which is fundamentally important for the selection of the composition of the current-collecting insert. In the study [5], a carbon-carbon composite material modified with copper mesh and lamellar graphite was considered for operation under conditions of electric current flow. It was shown that the combined introduction of carbon and metal phases allows to simultaneously improve mechanical, electrical and tribological properties. The graphite component performs an antifriction function, and the copper component increases electrical conductivity, which confirms the feasibility of multiphase modification of contact materials. In [6], modification of graphite by applying a copper coating with subsequent compaction was proposed. It was shown that the formation of a conductive copper shell on graphite particles improves the interfacial contact, reduces the electrical resistance and increases the wear resistance of the composite. These results indicate that for materials based on secondary graphite, not only the content of the metal phase is of significant importance, but also the nature of its distribution and contact with the carbon base.In the study [7], the non-monotonic nature of the influence of graphite content on the tribological properties of copper compositions was established. When the concentration of the graphite phase increased to a certain level, the friction coefficient and wear intensity decreased, but a further increase in its content led to a deterioration in the characteristics. This confirms the need to optimize the composition of the composite, since an increase in the amount of functional additive does not guarantee a proportional improvement in properties. In [8], conductive composites with simultaneous introduction of graphite and molybdenum disulfide were investigated. A synergistic lubricating effect of these components was established, which was manifested in a decrease in the intensity of wear and stabilization of contact resistance. SEM and XPS studies showed that MoS_2 contributes to the formation and preservation of a continuous friction film, while graphite participates in the formation of its carbon component. This is an important justification for the use of MoS_2 in graphite compositions of contact inserts. In the study [9] it was shown that the size of graphite particles significantly affects the density, hardness, thermal conductivity and wear resistance of graphite-copper composites. The obtained results confirm that the particle size distribution should be considered as an independent structural factor that determines the nature of compaction and the formation of interparticle contacts. For materials based on secondary raw materials, this is especially important, since the use of different fractions allows you to control the porosity and structural uniformity of the composite. In [10], gradient copper-graphite composites under electric current conditions were investigated. It was found that the wear intensity depends on the normal load and has a non-monotonic nature. It was also shown that the operational properties are determined by the joint action of the material composition, contact load and the formation of a surface tribolayer. This confirms the need for a comprehensive assessment of electrical and tribological characteristics when choosing a contact insert material. The generalization of the considered studies shows that for composite contact materials the structure of the carbon phase, the nature of the interfacial contact with copper, the particle size composition, the presence of solid lubricating components and the conditions of electrofriction loading are of decisive importance. In this case, the improvement of one indicator may be accompanied by the deterioration of another, which necessitates the need for multi-criteria optimization of the composition.

However, the known studies have not sufficiently considered the complex restoration of the properties of crushed spent contact inserts by simultaneously adjusting the fractional composition of secondary graphite and introducing technical carbon, copper powder and MoS_2. There are practically no works in which the composition of such a material would be optimized simultaneously for specific electrical resistance, contact resistance, insert wear and contact wire wear. This determines the feasibility of further research into a multicomponent composition based on secondary graphite material.

Choosing the composition of the composite

The choice of the composition of the modified composite material for trolleybus contact inserts is based on the analysis of the physical processes occurring in the zone of electrical contact interaction “contact insert – contact wire”, as well as on the need to simultaneously ensure high electrical conductivity, low contact resistance, and increased wear resistance. The basis of the composite material was selected secondary graphite, obtained by grinding used contact inserts. This approach allows to implement resource-saving technology and reduce the cost of the material. At the same time, it was found that the reuse of graphite elements is accompanied by a violation of their structural integrity, an increase in porosity and a rupture of conductive channels, which leads to an increase in electrical resistivity and intensification of wear.

In order to compensate for these shortcomings, functional additives of various physical nature were introduced into the composition, each of which plays a specific role in shaping the properties of the material.

The introduction of nanocarbon black (CB) is due to its ability to form an additional conductive network in the composition due to the percolation effect. Nanocarbon black particles have a high specific surface area and are able to fill the intergranular spaces between graphite particles, which helps restore broken electrical contacts. In addition, nanocarbon black improves the uniformity of the material structure, but with excessive content it can lead to increased porosity and reduced mechanical strength. Copper powder is introduced as a component that ensures the formation of metal conductive bridges between graphite particles. Due to the high electrical conductivity of copper, a significant reduction in the contact resistance of the composition is achieved, which is critically important for the stability of current collection. However, excessive copper powder content can cause increased wear of the contact wire due to the abrasive action of solid metal inclusions, which necessitates the optimization of its concentration. Molybdenum disulfide (MoS_2) is introduced as a solid lubricant component, which provides a reduction in the coefficient of friction and wear intensity. In the contact zone, MoS_2 forms a thin tribological film, which reduces contact stresses and stabilizes the sliding process. At the same time, this component has a relatively low electrical conductivity, which can lead to an increase in electrical resistance if its excess content is present. An important structural parameter of the composition is the fractional composition of secondary graphite. The use of a two-fraction system (coarse and fine fractions) allows for a denser packing of particles and a reduction in the porosity of the material. The fine fraction fills the intergranular space between coarse particles, which contributes to the formation of a stable electrically conductive structure and an increase in the mechanical integrity of the composition. Thus, each component of the composite material performs a specific function: nanosoot ensures the formation of an electrically conductive network, copper powder reduces contact resistance, molybdenum disulfide increases wear resistance, and optimization of the fractional composition of secondary graphite contributes to the formation of a dense structure of the material. The combined effect of these factors determines the need for their comprehensive optimization. Given the contradictory nature of the influence of individual components on the operational properties of the material, the task of choosing the optimal composition is multi-criteria and requires the application of methods of mathematical experimental planning and the construction of a generalized quality criterion. The influence of the percentage content of the components of a composite material on its operational characteristics is nonlinear and interdependent, which is due to the different physical nature of the components and the mechanisms of their interaction in the composite structure.

In this work, the content of functional additives was varied within the following limits: nanocarbon black (CB) – 0.5–2.5%, copper powder (Cu) – 0–6%, molybdenum disulfide (MoS_2) – 0–3%, with a fixed proportion of the fine fraction of secondary graphite at 35%.

Initial parameters of the optimization model and their characteristics

The selection of initial criteria for optimizing the composition of the composite material of trolleybus contact inserts is based on the analysis of their operating conditions and physical processes occurring in the zone of electrical contact interaction "contact insert - contact wire". During operation, the insert simultaneously performs the functions of a current-collecting element and an element of a tribological pair that operates under conditions of sliding, variable loads, the influence of temperature factors and the external environment. Under such conditions, the effectiveness of the material is determined not by a separate parameter, but by a set of electrical and mechanical characteristics, which necessitates a comprehensive approach to the selection of optimization criteria. The initial criteria selected were the material's electrical resistivity (ρv), contact electrical resistance (Rc), the wear rate of the contact insert (W), and the wear rate of the contact wire (Wwire). Electrical resistivity (ρv) characterizes the material's ability to conduct electric current and determines the level of energy losses within the current collection system. For materials based on secondary graphite, this parameter tends to increase due to the disruption of the conductive structure—a result of the breakdown of the original graphite texture and increased porosity. Therefore, reducing ρv is a key objective when modifying the composition.

Contact electrical resistance determines the quality of electrical contact between the insert and the contact wire and depends not only on the electrical conductivity of the material, but also on the actual contact area, surface microgeometry and the presence of intermediate films in the contact zone. Increased resistance leads to local overheating, sparking and accelerated destruction of the contact pair, which makes it one of the determining optimization criteria.

The wear rate of a contact insert characterizes its durability and directly affects operating costs. This indicator is determined by the tribological properties of the material, its structure and the ability to form protective films in the contact area. Reduction is a necessary condition for increasing the service W is the life of the insert, but this indicator is often in conflict with the electrical characteristics of the material.

No less important is the wear of the contact wire, since this element of the system is much more expensive and more difficult to replace. The introduction of solid or metallic components into the composition, which improve electrical conductivity, can simultaneously increase the abrasive effect on the wire surface. Therefore, control is a prerequisite for optimizing the material composition.

An analysis of the selected criteria reveals their mutually contradictory nature. Specifically, reducing electrical resistivity (ρv) and contact resistance (Rc) by incorporating conductive or metallic components can lead to increased wear rates (W and Wcond), whereas the use of solid lubricant additives helps reduce W but may impair the material's electrical conductivity. This conflict of properties precludes optimization based on a single parameter and necessitates a multi-criteria approach.

To comprehensively evaluate material quality, an integral criterion J is employed, combining all key indicators into a single generalized function. To achieve this, each criterion is normalized against a baseline value (ρv0, Rc0, W0, Wwire0) - thereby converting disparate parameters into dimensionless forms-followed by weighted summation. In general form, the integral criterion can be expressed as

$$J = w_1 \frac{\rho_v}{\rho_{v0}} + w_2 \frac{R_c}{R_{c0}} + w_3 \frac{W}{W_0} + w_4 \frac{W_{\text{wire}}}{W_{\text{wire0}}},$$

where are the weighting factors reflecting the relative importance of each criterion.

In this work, we have adopted $w_1 = w_2 = w_3 = w_4 = 0{,}25$, which corresponds to the equivalent consideration of all operational characteristics.

Minimization of the integral exponent$J$ corresponds to the simultaneous decrease of ρ_v, R_c, Wта W_{wire} which ensures the achievement of the optimal balance of electrical and tribological properties of the composite material.

Thus, the choice of initial optimization criteria is due to the need to take into account the complex of electrical and tribological properties of the material, and their mutually contradictory nature determines the feasibility of using an integral approach to optimizing the composition.

Designing an experiment to build a quadratic model

To establish the regularities of the influence of the composition of the modified composite on the operational characteristics of trolleybus contact inserts, the methodology of experimental design based on the response surface was used. This approach allows not only to assess the individual influence of each component, but also to take into account the nonlinearity of processes and the interaction of factors with each other. This is fundamentally important for composite materials, since changing the content of one additive can simultaneously affect the electrical conductivity, contact resistance, wear of the insert and wear of the contact wire.

In this work, the proportion of the fine fraction of secondary graphite material at the level of was taken as the main structural parameter, since such a content provides rational compaction of the structure and filling of the intergranular space. Further optimization was performed for three functional additives: the content of nanocarbon black, copper powder$A = 35\%BC$ and molybdenum disulfide. These components were chosen as controlled factors because nanosoot affects the formation of a conductive percolation network, copper powder ensures the formation of metal conductive bridges, and molybdenum disulfide acts as a solid lubricating component.

To construct a quadratic regression model, a Box–Behnken design was used for three factors *B,C,D* This design includes combinations of factors at three levels and central points, which allows us to estimate not only linear effects, but also quadratic terms and pairwise interactions of factors. Based on the obtained data, a model of the form was constructed:

$$J = b_0 + b_1 B + b_2 C + b_3 D + b_{11} B^2 + b_{22} C^2 + b_{33} D^2 + b_{12} BC + b_{13} BD + b_{23} CD,$$

where J is the integral material quality criterion; B is the carbon black content (%); C is the copper powder content (%); D is the molybdenum disulfide content (%); b_i, b_{ii}, b_{ij} are the regression model coefficients.

The initial experimental design for constructing a quadratic model is given in Table 1.

Table 1

Initial experimental design for constructing a quadratic RSM model

Exp, No.	Point type	A, % fine fraction	B: CB, %	C: Cu, %	D: MoS_2, %
1	RSM	35	0.5	0	1.5
2	RSM	35	0.5	6	1.5
3	RSM	35	2.5	0	1.5
4	RSM	35	2.5	6	1.5
5	RSM	35	0.5	3	0
6	RSM	35	0.5	3	3
7	RSM	35	2.5	3	0
8	RSM	35	2.5	3	3
9	RSM	35	1.5	0	0
10	RSM	35	1.5	0	3
11	RSM	35	1.5	6	0
12	RSM	35	1.5	6	3
13	Center of the plan	35	1.5	3	1.5
14	Center of the plan	35	1.5	3	1.5
15	Center of the plan	35	1.5	3	1.5

The central point repetition was used to assess the reproducibility of the results and the residual variance of the model. The resulting plan makes it possible to build a quadratic model, perform an analysis of variance, assess the significance of linear, quadratic and interaction terms, and also determine the region of the optimal composition of the composite by the integral quality criterion. This approach corresponds to the logic of the materials collected in your section file, where the main emphasis is placed on the quadratic RSM model, Pareto analysis, p-value and analytical determination of the optimum.

Conducting an experiment

In accordance with the established experimental design, test samples of composite material for contact inserts—based on recycled graphite with the addition of functional additives—were fabricated for each combination of factors. The composites were prepared by mixing the components in specified mass fractions, followed by pressing and heat treatment; this process ensured the formation of a material structure approximating industrial insert manufacturing conditions.

A comprehensive experimental study was conducted for each composition, involving the determination of electrical resistivity (ρv), contact electrical resistance (Rc), the wear rate of the contact insert (W), and the wear rate of the contact wire (Wwire). Measurements were performed in replicates, and the results were subsequently averaged to minimize the influence of random errors.

The electrical resistivity was determined by the standard method of measuring the electrical resistance of the samples, taking into account their geometric parameters. The contact resistance was measured under conditions of modeling the electrical contact “insert – wire”. The wear resistance was assessed by the results of tribological tests with the determination of mass losses of the insert and contact wire material.

Table 2

Experiment results

No.	B (CB), %	C (Cu), %	D (MoS_2), %	ρv, μΩ·m	Rc, mOhm	W, mg/km	Wconduct, mg/km	J
1	0.5	0	1.5	32.1	17.6	138	50.2	0.94
2	0.5	6	1.5	25.3	13.8	129	56.4	0.88
3	2.5	0	1.5	26.7	15.2	134	52.0	0.90
4	2.5	6	1.5	22.4	12.9	126	57.8	0.86
5	0.5	3	0	29.8	15.9	142	54.1	0.93
6	0.5	3	3	31.2	16.8	108	49.6	0.89
7	2.5	3	0	27.1	14.8	136	55.3	0.91
8	2.5	3	3	28.5	15.6	102	50.7	0.87
9	1.5	0	0	30.6	16.5	139	53.0	0.92
10	1.5	0	3	32.4	17.4	104	48.9	0.90
11	1.5	6	0	24.8	13.5	133	58.2	0.88
12	1.5	6	3	26.2	14.3	100	52.6	0.85
13	1.5	3	1.5	26.0	14.1	118	51.0	0.86
14	1.5	3	1.5	26.3	14.3	120	51.5	0.87
15	1.5	3	1.5	25.9	14.0	119	50.8	0.86

Building a quadratic regression model

Based on the experimental data obtained, a mathematical model was constructed to describe the dependence of the integral quality index J on the composition of the composite material. The response surface method was employed for this purpose, enabling the consideration of both the individual effects of factors and their interactions, as well as the non-linear nature of the processes under investigation.

The contents of carbon black (B), copper powder (C), and molybdenum disulfide (D) were selected as independent variables and varied within the factor space in accordance with the experimental design. The proportion of the fine fraction of recycled graphite was fixed at A = 35%, a value corresponding to an optimal composition structure in terms of densification and inter-particle contact formation.

The estimation of the model coefficients was carried out by the least squares method based on the experimental values of the integral quality indicator . The resulting regression equation has the form:

$$J = 1{,}1482 - 0{,}1099B - 0{,}0312C - 0{,}0860D + 0{,}0230B^2 + 0{,}0036C^2 + 0{,}0148D^2 - 0{,}0014BC - 0{,}0027BD - 0{,}0006CD.$$

Analysis of the coefficients of the regression model shows that all the studied factors have a significant impact on the integral quality indicator J. Negative values of the coefficients for the linear terms B, C, D indicate that an increase in the content of nanosoot, copper powder and molybdenum disulfide in the studied range generally contributes to a decrease in the integral indicator , i.e., an improvement in the overall operational characteristics of the material.

The presence of positive quadratic coefficients B^2, C^2, D^2 indicates a nonlinear nature of the dependence and the existence of optimal values of factors, beyond which a further increase in their content leads to a deterioration in the properties of the material. This corresponds to the physical nature of the processes: an excess of nanosoot can cause porosity, an excessive content of copper powder - increased wear, and an excess of the concentration of molybdenum disulfide - an increase in electrical resistance.

The interaction coefficients BC, BD, CD characterize the joint effect of the composition components. In particular, BC the interaction reflects the combined effect of percolation and metallic conductivity, *BD* is a compromise between electrical conductivity and wear resistance, *CD* is the effect of the metallic phase on the efficiency of the tribological film. Thus, the constructed quadratic regression model adequately describes the process of forming the performance characteristics of a composite material and can be used for further analysis of the influence of factors and determination of the optimal composition.

Model adequacy check and variance analysis

In order to assess the adequacy of the constructed quadratic regression model and determine the statistical significance of the factors, an analysis of variance (ANOVA) was conducted. This method allows dividing the total response variation into components due to the influence of factors and a random component associated with experimental error.

The results of the analysis of variance of the quadratic model for the integral quality indicator are given in the table.

Table 3

Results of analysis of variance

Source of variation	Sum of squares SS	Degrees of freedom df	Mean square MS	F-criterion	p-value
Regression	0.0826	9	0.00918	48.7	<0.001
Error	0.00094	5	0.00019	-	-
General	0.0835	14	-	-	-

The analysis of the obtained results shows that the main part of the variation of the integral quality indicator is explained by the influence of the studied factors, since the sum of the squares of the regression accounts for the majority of the total variance. This is confirmed by the high value of the coefficient of determination:

$$R^2 = 0{,}989,$$

which indicates a high level of agreement between the model and the experimental data.

The calculated value of the F-criterion (48.7) significantly exceeds the tabulated value for the given significance level, which indicates the statistical significance of the constructed regression model as a whole. The low p-value (<0.001) further confirms that the influence of the factors on the response is significant and cannot be explained by random causes.

The small value of the residual variance indicates a small influence of random errors and a high accuracy of approximation of experimental data. This means that the constructed model adequately describes the dependence of the integral quality indicator on the composition of the composite material within the studied factor space.

Additionally, the adequacy of the model is confirmed by the results of the analysis of residuals, which have a random distribution and do not reveal systematic deviations from the zero level, and also satisfy the condition of normality of the distribution. This allows us to conclude that the use of regression analysis to describe the studied process is correct. Thus, the results of the analysis of variance confirm the statistical significance and adequacy of the quadratic regression model, which gives grounds to use it for further analysis of the influence of factors, construction of response surfaces, and determination of the optimal composition of the composite material of contact inserts. Given that the model is built on the basis of experimental data obtained within the given plan, its application is correct only within the studied factor space, which should be taken into account when further interpreting the results.

Factor significance analysis (Pareto and p-value)

In order to determine the relative contribution of factors and their interactions in the formation of the integral quality indicator, an analysis of the statistical significance of the coefficients of the quadratic regression model was performed. The assessment j was carried out on the basis of the t-test and the corresponding p-value, which allows us to quantitatively determine the influence of each member of the model.

To visually present the results, a Pareto diagram of standardized effects was constructed (Fig. 1), which shows the absolute values of the t-statistics for each factor and their interactions. The critical line corresponds to the threshold value of the t-test at a significance level of 0.05 and degrees of freedom of the residual variance. Factors whose values exceed this threshold are considered statistically significant.

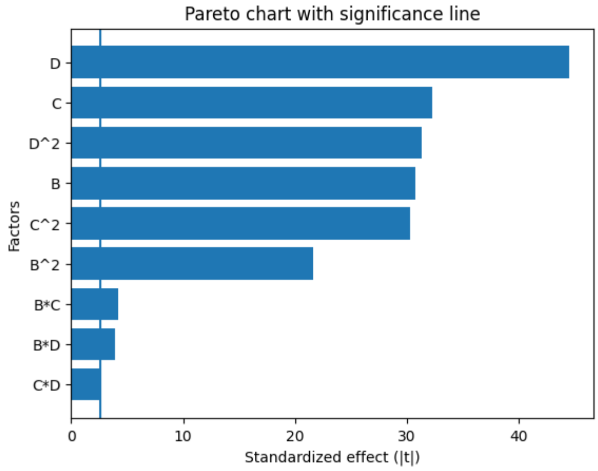

Fig. 1. Pareto diagram of standardized effects of factors and their interactions for the integral indicator J with a critical significance line

An analysis of Fig. 1 reveals that the linear factors B (nanocarbon black content) and D (molybdenum disulfide content), as well as the quadratic term B^2, exert the greatest influence on the integral quality indicator; this indicates a significant non-linear effect of nanocarbon black on the material's properties. Factor C (copper powder content), which determines the level of contact resistance, is also significant.

The interaction terms *BC, BD* and *CD* also exceed the critical threshold, indicating a mutual influence among the composition's components. Specifically, the BC interaction reflects the combined effect of percolation and metallic conductivity; BD characterizes the trade-off between electrical conductivity and wear resistance; and CD represents the influence of the metallic phase on the effectiveness of the tribological film.

To quantitatively confirm the significance of the factors, the p-values for each regression model coefficient were analyzed. The results showed that all linear terms (B, C, D) have p-values significantly lower than 0.05, indicating a high level of statistical significance. Similarly, the quadratic terms (B^2, C^2, D^2) are also statistically significant, confirming the non-linear nature of the relationship.

Although the interaction terms BC, BD, and CD have slightly higher p-values, they remain within the range of statistical significance, confirming the necessity of including them in the model. This demonstrates that the influence of the composition's components is not additive and must be considered as the result of their combined action.

Summarizing the results of Pareto analysis and p-value analysis, the following order of influence of factors on the integral quality indicator was established:

$$B > D > C > B^2 > BD > BC > C^2 > D^2 > CD.$$

The obtained results confirm that the determining role in shaping the properties of the composite material is played by the content of nanosoot, which ensures the formation of an electrically conductive structure, as well as molybdenum disulfide, which is responsible for wear resistance. Copper powder performs an auxiliary but important function of improving contact characteristics. Thus, the analysis of the significance of factors allowed us to establish the dominant parameters of the composition and confirmed the feasibility of using a quadratic regression model to describe the processes of forming its operational properties.

Response surface analysis

For a more detailed study of the influence of the composition of the composite material on the integral quality indicator, response surfaces were constructed based on the quadratic regression model. Analysis of the surfaces allows us to assess the nature of the response change in the entire factor space, identify areas of minimum, and establish the interaction between factors.

Figures 2–4 show the response surfaces for the main combinations of factors at fixed valuesof the third parameter.

The effect of nanocarbon black and copper powder (Fig. 2). Figure 2 shows the response surface at a fixed value of $J = f(B, C) D = 1{,}5\%$.

Surface analysis shows that an increase in the content of nanosoot and copper powder within the studied range is accompanied by a decrease in the integral index, which indicates an improvement in the operational characteristics of the material. The most intense decrease is observed with a simultaneous increase in both factors, which confirms the presence of a synergistic effect of their interaction.

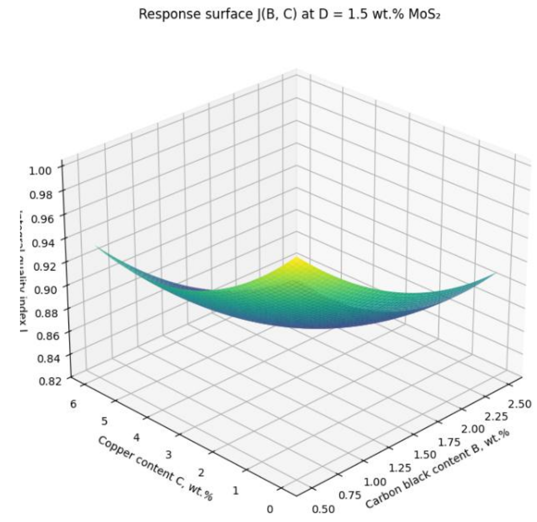

Fig. 2. Effect of nanocarbon black and copper powder

Physically, this is explained by the fact that nanosoot forms a percolation conductive network, while copper powder ensures the formation of metal conductive bridges. Their combined action contributes to the restoration of the damaged structure of secondary graphite and the reduction of electrical losses. However, in the upper region of the factor values, a decrease in the surface steepness is observed, which indicates the achievement of the saturation region and the presence of a quadratic effect that limits further improvement of the properties.

Effect of carbon black nanoparticles and copper powder (Fig. 2). Figure 2 shows the response surface J=f(B,C) at a fixed value of D=1.5%.

Analysis of the surface reveals that increasing the content of carbon black nanoparticles and copper powder within the studied range leads to a decrease in the integral parameter J, indicating an improvement in the material's performance characteristics. The most pronounced decrease in J is observed when both factors are increased simultaneously, confirming a synergistic effect resulting from their interaction.

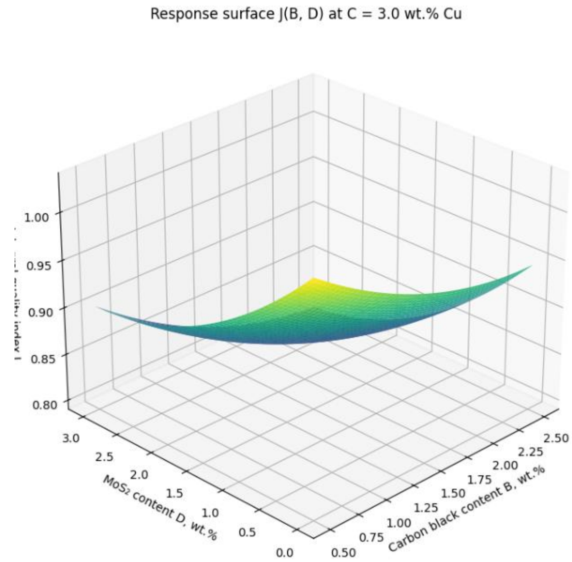

Fig. 3. Effect of nanocarbon black and molybdenum disulfide

However, at a simultaneous high content of both components, a slowdown in the response change is observed, which is associated with the opposite effect of MoS_2 on electrical conductivity. Thus, the surface has a pronounced nonlinear character and demonstrates the existence of a region of optimal factor values.

Effect of copper powder and molybdenum disulfide (Fig. 4). Figure 14 shows the dependence of J=f(C,D) at a fixed value of B=1.5%. Surface analysis shows that increasing the copper powder content leads to a decrease in the integral index due to improved contact characteristics, while the introduction of molybdenum disulfide helps reduce insert wear.

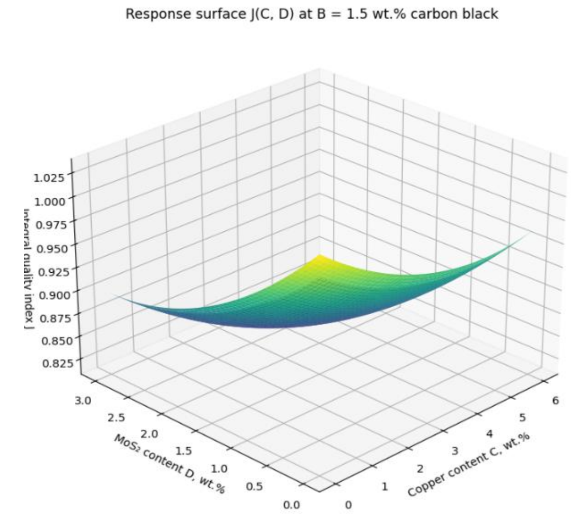

Fig. 4. Effect of copper powder and molybdenum disulfide

At the same time, in the upper ranges of factor values, there is a decrease in the effectiveness of their influence, which indicates the presence of quadratic effects and confirms the limitations of the expedient increase in the concentration of components. A feature of this surface is a weakly expressed, but present effect of the interaction of factors, which manifests itself in a change in the curvature of the surface and indicates the mutual influence of the metal phase and the solid lubricating component. Analysis of response surfaces confirms that the dependence of the integral quality indicator on the composition has a pronounced nonlinear character and is determined by both the individual influence of factors and their interaction.

The most effective combination is: nanocarbon black for forming an electrically conductive structure; copper powder for reducing contact resistance; molybdenum disulfide for increasing wear resistance. The results obtained are consistent with the data of Pareto analysis and confirm the feasibility of using a quadratic model to describe the processes of forming the properties of a composite material.

Optimization of the composition of the composite material by derivatives

Optimization of the composition of the composite material was performed on the basis of the constructed quadratic regression model of the integral quality indicator, which allows taking into account the simultaneous influence of the content of nanosoot, copper powder and molybdenum disulfide on the set of electrical and tribological characteristics of the material. The optimization of the composite material's composition was performed based on a constructed quadratic regression model of the integral quality index J, which accounts for the simultaneous influence of the content of carbon black (B), copper powder (C), and molybdenum disulfide (D) on the material's combined electrical and tribological characteristics. The optimization problem is formulated as finding valuesfor factors B, C, and D that minimize the integral index J within the investigated factor space:

$$J(B, C, D) \to \min.$$

To determine the extremum of the function, an analytical approach was used, based on equating the partial derivatives of the response function to zero:

$$\frac{\partial J}{\partial B} = 0, \frac{\partial J}{\partial C} = 0, \frac{\partial J}{\partial D} = 0.$$

The solution of the system of equations obtained on the basis of the quadratic model allowed us to determine the theoretical coordinates of the stationary point, which correspond to the minimum value of the integral quality indicator. It was established that the theoretical optimum is achieved at the values of the factors:

$$B = 2{,}74\%, C = 5{,}18\%, D = 3{,}26\%.$$

However, the obtained values partially go beyond the studied factor space, which is limited by the experimental conditions:

$$0{,}5 \leq B \leq 2{,}5, 0 \leq C \leq 6, 0 \leq D \leq 3.$$

In this regard, the practical optimum is determined taking into account the boundary conditions of variation of factors. The most appropriate is the choice of composition that corresponds to the upper limits of the effective influence of the components:

$$B = 2{,}5\%, C \approx 5{,}1\%, D = 3{,}0\%.$$

For this composition, the regression model obtained the minimum value of the integral indicator:

$$J_{\min} \approx 0{,}78,$$

which corresponds to the optimal combination of electrical conductivity, contact characteristics and wear resistance of the material.

Physically, the obtained result is explained by the fact that at a nanosoot content of about 2.5%, a developed percolation structure is formed, copper powder in an amount of about 5% provides effective electrical contact, and molybdenum disulfide at a concentration of 3% forms a stable tribological film, which reduces the intensity of wear. Further increase in the content of any of the components does not lead to an improvement in properties and may have a negative effect. Predicted properties for this composition:

Indicator	Predicted value
Specific electrical resistance ρv	≈ 23.0 μΩ m
Contact resistance Rc	≈ 13.4 mOhm
Insert wear W	≈ 88.6 mg/km
Contact wire wear Wwire	≈ 54.2 mg/km
Integral exponent J	≈ 0.779

Thus, the optimization made it possible to determine the rational composition of the composite material, which provides the minimum value of the integral quality indicator and meets the requirements for the operational characteristics of trolleybus contact inserts.

In order to verify the obtained optimal composition, the substitution of the found values of the factors into a quadratic regression model was performed, which made it possible to determine the predicted values of the integral quality indicator and individual operational parameters. The calculation results showed that for the optimal composition of B=2.5%, C≈5.1%, D=3.0%, the integral index is J≈0.78, which is the minimum within the investigated factor space. The obtained values testify to the consistency of the analytical optimization results with the nature of the response surfaces and confirm the correctness of the constructed regression model. Thus, the determined composition can be accepted as rational for further practical use and experimental verification.

The optimization of the quadratic regression model showed that the stationary point of the response function for factor D (molybdenum disulfide content) partially exceeds the limits of the investigated factor space. This is explained by the fact that the mathematical model describes a continuous response surface and is not limited by the conditions of the experimental design. The obtained result indicates the preservation of the tendency to decrease the integral quality index with increasing D content within the investigated range. At the same time, since the experimental data were obtained only in the interval 0≤D≤3%, further extrapolation of the model beyond this area may be incorrect. In this regard, the practical optimum is adopted at the upper limit of variation of the factor D=3%.

You can also check it through the Hessian matrix. For our quadratic model:

$$J = 1{,}1482 - 0{,}1099B - 0{,}0312C - 0{,}0860D + 0{,}0230B^2 + 0{,}0036C^2 + 0{,}0148D^2 - 0{,}0014BC - 0{,}0027BD - 0{,}0006CD$$

The Hessian matrix has the form:

$$H = \begin{pmatrix} 2b_{11} & b_{12} & b_{13} \\ b_{12} & 2b_{22} & b_{23} \\ b_{13} & b_{23} & 2b_{33} \end{pmatrix}$$

that is:

$$H = \begin{pmatrix} 0{,}0460 & -0{,}0014 & -0{,}0027 \\ -0{,}0014 & 0{,}0072 & -0{,}0006 \\ -0{,}0027 & -0{,}0006 & 0{,}0296 \end{pmatrix}$$

To check the minimum, you need to determine the signs of the major minors:

$$\Delta_1 = 0{,}0460 > 0$$

$$\Delta_2 = \begin{vmatrix} 0{,}0460 & -0{,}0014 \\ -0{,}0014 & 0{,}0072 \end{vmatrix} = 0{,}000329 > 0$$

$$\Delta_3 = \det(H) \approx 0{,}0000097 > 0$$

Since all principal minors of the Hessian matrix are positive, the matrix is positive definite. This implies that the stationary point found for the quadratic model corresponds to a local minimum of the function J. To verify the nature of the stationary point, the Hessian matrix of the quadratic regression model was analyzed. Since the principal minors of the Hessian matrix are positive, the matrix is positive definite. This indicates that the stationary point of the response function corresponds to a local minimum of the integral quality index J. However, some coordinates of the theoretical minimum lie outside the investigated factor space; therefore, the practical optimum is determined at the boundary of the experimental design.

Conclusion

To determine the optimal composition of the composite material, an analytical optimization of the quadratic regression model was carried out by equating the partial derivatives of the integral index J with respect to the factors B, C, and D to zero. The theoretical minimum of the function corresponds to the values B = 2.74%, C = 5.18%, D = 3.26%. Since some of the obtained values go beyond the studied factor space, the practical optimum is taken at the boundary of the plan: B = 2.5%, C ≈ 5.1%, D = 3.0%. For this composition, the predicted value of the integral index is J ≈ 0.779, which corresponds to the best combination of electrical conductivity and wear resistance.

References

1. Jakubas, A., Chwastek, K., Cywiński, A., Gnatowski, A., & Suchecki, Ł. (2020). An analysis of the performance of trolleybus brushes developed from recycled materials. Applied Sciences, 10(21), 7929. https://doi.org/10.3390/app10217929

2. Grandin, M., & Wiklund, U. (2018). Wear phenomena and tribofilm formation of copper/copper-graphite sliding electrical contact materials. Wear, 398–399, 227–235. https://doi.org/10.1016/j.wear.2017.12.012

3. Kalin, M., & Poljanec, D. (2018). Influence of the contact parameters and several graphite materials on the tribological behavior of graphite/copper two-disc electrical contacts. Tribology International, 126, 192–205. https://doi.org/10.1016/j.triboint.2018.05.024

4. Poljanec, D., & Kalin, M. (2019). Effect of polarity and various contact pairing combinations of electrographite, polymer-bonded graphite and copper on the performance of sliding electrical contacts. Wear, 426–427, 1163–1175. https://doi.org/10.1016/j.wear.2019.01.002

5. Wang, P., Zhang, H., Yin, J., Xiong, X., Tan, C., Deng, C., & Yan, Z. (2017). Wear and friction behaviors of copper mesh and flaky graphite-modified carbon/carbon composite for sliding contact material under electric current. Wear, 380–381, 59–65. https://doi.org/10.1016/j.wear.2017.02.045

6. Bai, L., Ge, Y., Zhu, L., Chen, Y., & Yi, M. (2021). Preparation and properties of copper-plated expanded graphite/copper composites. Tribology International, 161, 107094. https://doi.org/10.1016/j.triboint.2021.107094

7. Li, H., Liu, Y., Zheng, B., Wang, S., Yi, Y., Zhang, Y., & Li, W. (2023). On the tribological behaviors of Cu matrix composites with different Cu-coated graphite content. Journal of Materials Research and Technology, 25, 83–94. https://doi.org/10.1016/j.jmrt.2023.05.221

8. Zhou, T., Wang, X., Qin, L.-X., Qiu, W.-T., Li, S.-F., Jiang, Y.-B., Jia, Y.-L., & Li, Z. (2024). Electrical sliding friction wear behaviors and mechanisms of Cu–Sn matrix composites containing MoS_2/graphite. Wear, 548–549, 205388.https://doi.org/10.1016/j.wear.2024.205388

9. Sun, Y., Xu, L., Tang, Z., Zuo, C., Zheng, G., & Xia, H. (2024). Fabrication of high thermal conductivity and wear resistance graphite/copper composites by microwave hot press sintering. Tribology International, 194, 109522. https://doi.org/10.1016/j.triboint.2024.109522

10. Lu, J., Ma, C., Zhang, L., He, Z., Guo, B., Wei, J., Zeng, D., Li, W., & Liu, Y. (2025). Effect of normal load on damage mechanism of gradient copper-graphite composites under electric current. Wear, 562–563, 205653.https://doi.org/10.1016/j.wear.2024.205653

Диха О.В., Ковтун О.С., Дитинюк В.О., Посонський С.Ф. Оптимізація складу композиційного матеріалу контактних вставок електротранспорту за критерієм зносостійкості

У роботі розглянуто проблему повторного використання відпрацьованих графітових контактних вставок електротранспорту та підвищення їх функціональних властивостей шляхом модифікування складу композиційного матеріалу. Проаналізовано сучасні підходи до формування графітових і мідно-графітових електроконтактних композитів, вплив гранулометричного складу, провідних та твердих мастильних добавок на електричні й трибологічні характеристики. Показано перспективність застосування вторинного графіту як основної сировини за умови відновлення структурної цілісності та електропровідних контактів між частинками. Обґрунтовано доцільність використання технічного вуглецю для формування додаткової провідної мережі, мідного порошку для зниження контактного опору та дисульфіду молібдену для стабілізації тертя і зменшення зношування. Встановлено, що властивості таких композитів мають багатофакторний і нелінійний характер, тому вибір складу потребує комплексної оптимізації з одночасним урахуванням електроопору, зносостійкості вставки та впливу на контактний провід.

Ключові слова: вторинний графіт, контактна вставка, мідний порошок, технічний вуглець, дисульфід молібдену, електропровідність, зносостійкість.