ISSN 2079-1372 Problems of Tribology, V. 30, No 3/117-2025, 13-20

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

DOI: https://doi.org/10.31891/2079-1372-2025-117-3-13-20

Analysis of frictional stresses and wear in the contact pair of a vehicle current collector

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Received: 09 June 2025: Revised 20 June 2025: Accept: 18 July 2025

Abstract

The article presents the results of numerical modeling of the operation of the trolleybus current collector pair "contact insert - wire" using the Ansys software environment. The distribution of frictional stresses (Frictional Stress) and contact pressures for two types of insert materials is analyzed: electrographite (Electrographite, parallel to plane) and copper-graphite composite Cu–40%C(f) 0.90 laminate. It was established that the real area of the contact spot is smaller than the entire surface of the gutter, which significantly affects the calculated values of the average frictional stresses and, accordingly, the wear forecast. For the electrographite insert, the average value of Frictional Stress was 0.439 MPa, for the copper-graphite insert – 0.599 MPa. The calculations showed that at a mileage of 450 km, the wear of the electrographite insert exceeds the permissible value, while for the copper-graphite one it is 2.1564 mm and is within the normal range. However, due to the higher hardness of the copper-graphite material compared to the copper wire, the wire itself can become the main element of wear, which is undesirable. It was concluded that the optimal option may be to use a material with intermediate hardness, which will provide a balance between the wear resistance of the insert and the preservation of the contact wire resource.
Keywords: contact insert, contact wire, wear resistance, frictional stress, numerical modeling, Ansys, copper–graphite composite, electrographite

Introduction

The reliability and durability of trolleybus current collection systems are largely determined by the wear resistance of the friction pair “contact insert – contact wire”. Under conditions of prolonged operational load, changes occur in the geometry of the insert surface, which leads to deterioration of electrical contact, increased resistance and increased energy losses. Traditionally, electrographite inserts are used in structures, however, in order to increase the resource, composite materials, in particular copper-graphite, are increasingly used. To optimize the choice of material, it is necessary to model the stress-strain state and analyze friction parameters in conditions close to real ones. Numerical modeling in the Ansys environment allows you to determine the stress distribution, the area of the real contact spot and predict the amount of wear based on the tribological characteristics of materials. The relevance of the study is due to the need to increase the resource of contact inserts while maintaining the operational reliability of the contact wire, which directly affects the economic efficiency of urban electric transport.

Literature review

The dynamics of research indicates a transition from empirical and bench-top approaches to combined methods, where numerical modeling is combined with experiment and data-driven resource prediction. In the work [1], a physically based model of slider wear is proposed, which takes into account the triboelectric interaction and the features of the “slider–contact wire”; the work emphasizes the different role of the hardness of the wire and the insert and the sensitivity of the model to the contact load and current regime, which directly correlates with your calculations of the average friction stresses and the width of the real contact patch. In parallel, the emphasis

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is increasing on the conditionally unsteady dynamics of the "pantograph–contact network" system, where fast interaction models show that the instability of the contact force leads to anomalous wear of both the insert and the wire; this emphasizes the importance of correctly setting the contact boundary conditions in numerical schemes, including the localization of the real contact patch. The influence of the environment and humidity on the conductive friction in carbon-copper pairs has been shown [2] in experimental studies: the water content in the carbon slider changes the friction coefficient, mass loss, contact resistance and arcing parameters, i.e. factors that in the practice of urban electric transport significantly affect the real intensity of wear and require scenario modeling. Materials science approaches [3] emphasize the microstructural parameters of composites: varying the graphite fraction and the orientation of its domains in copper-graphite composites allows you to control the current carrying capacity, flow stability and wear rate; non-monotonic dependences with wear minima have been established for a certain orientation of graphite plates and graphite content, which is consistent with the idea of selecting an "intermediate hardness" for the balance of the insert and wire resource. A separate line of work [4-7] is devoted to the force factor: increasing the normal load on the copper-graphite pair changes not only the friction level, but also the damage mechanisms (delamination, arc erosion), forming different wear transition modes; this is important for your scenarios of pressure changes from 0 to 0.5 MPa and extrapolation of wear to runs. At the level of system operational reliability, the application of AI methods for pantograph condition prediction is demonstrated [5]: building models based on neural networks allows for reducing failures through timely detection of degradation trends, which complements FEM-assessments of local stresses and wear with strategic condition-based maintenance tools. In [6], a study of tribocouples based on copper-graphite composites systematically shows the dependence of current-carrying triboproperties and wear mechanisms on contact load, highlighting the need to simultaneously limit slider wear and protect the wire - a key dilemma addressed in this study. Taken together, the results of [7] outline a framework for the approach: taking into account the real contact strip in the problem statement, parametric analysis of Frictional Stress taking into account load and current,and the selection of composites with a target microstructure/hardness as a means of balancing the life of the insert–wire pair.

Purpose of the work

To determine the influence of the area of the actual contact spot and the physical and mechanical properties of the insert material on the stress-strain state and predicted wear of the trolleybus insert-wire pair using numerical modeling in the Ansys environment in order to optimize the choice of material to increase the resource of the current collection system.

Research objectives

1. Develop a numerical model of the local contact of the "insert – wire" pair of a trolleybus, taking into account the actual area of the contact spot.
2. Calculate the distribution of friction stresses and contact pressures for electrographite and copper-graphite insert materials.
3. Determine the dependence of the predicted insert wear value on the average values of Frictional Stress and material hardness.
4. Compare the results obtained for different insert materials and evaluate their impact on the contact wire resource.
5. Formulate recommendations for selecting an insert material that provides a balance between insert wear resistance and maintaining wire durability.

Initial data for analysis

The boundary conditions of the first iteration of the contact modeling of the current-collecting contact pair of a trolleybus "insert – wire" in Ansys were based on the entire surface of the insert groove (Fig. 1).

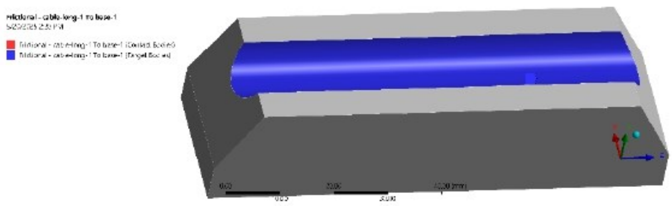

Fig. 1. Friction surface of trolleybus insert

This approach is correct and completely sufficient for determining the maximum pressure Pressure, von Misses Stress or friction (Frictional Stress), etc. However, based on the contact status map (Contact Tool > Status), it is clear that only the central dark yellow part of the trough participates in sliding (Fig. 2).

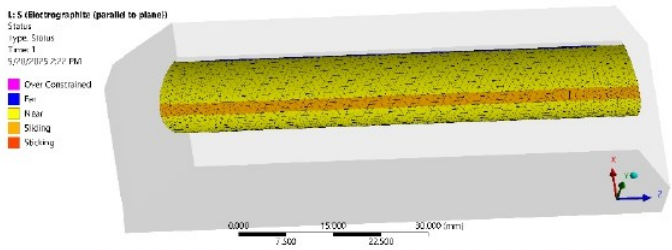

Fig. 2 Actual contact area of the insert with the wire

Since to calculate wear it is necessary to operate with the average Frictional Stress indicator, which is calculated by the integral method (depends on the number of measurement points), and therefore depends on the contact area, the boundary conditions were updated - a surface was distinguished on the surface of the gutter, the width of which corresponds to the sliding spot (Fig. 3).

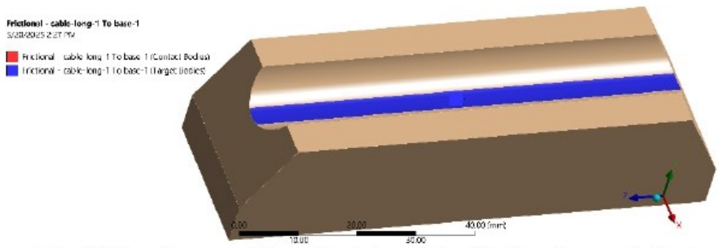

Fig. 3. Boundary conditions for determining friction stresses in the insert

Calculation results for Electrographite insert (parallel to plane)

Based on a comparison of the results of determining Frictional Stress for an insert with Electrographite (parallel to plane), we will illustrate the changes.

Full surface of the insert groove.

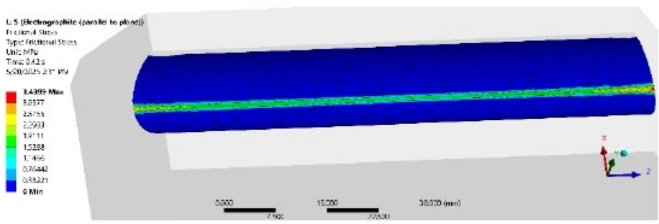

Fig. 4. Full surface of the insert groove

Full surface of the electrographite insert groove used in the numerical simulation. The geometry of the contact surface is modeled in its entirety, which makes it possible to determine the overall distribution of mechanical and frictional stresses before refining the analysis to the actual contact area.
The average value of Frictional Stress is 0.13901 MPa (Fig. 5).

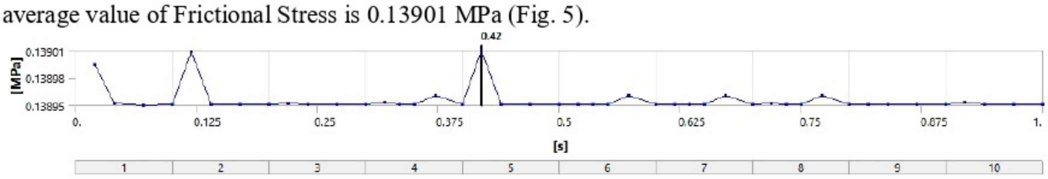

Fig. 5. Distribution of friction stresses over the entire surface of the insert

Distribution of frictional stresses (Frictional Stress) over the full surface of the electrographite insert groove obtained from numerical simulation. The highest values are concentrated in the central contact zone, indicating non-uniform loading and identifying local areas of potentially intensive wear, while the peripheral regions are characterized by significantly lower stresses.

The central part of the insert surface is highlighted: the maximum value of Frictional Stress is 3.3364 MPa (Fig. 6).

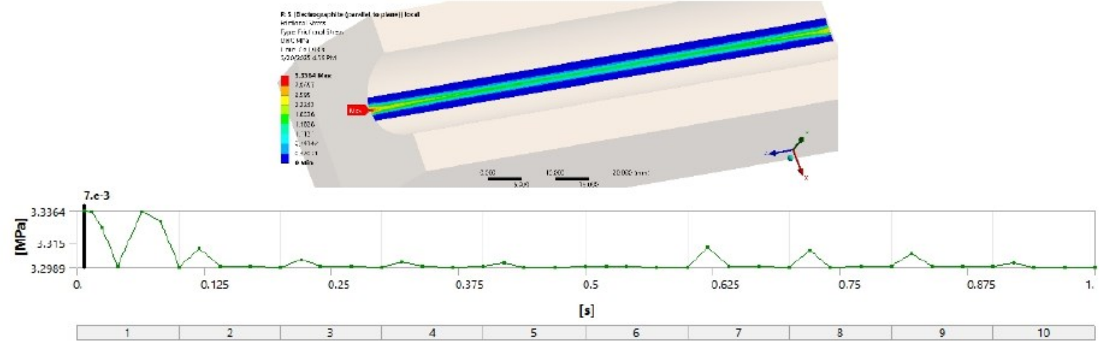

Fig. 6. Isolated part of the insert surface for friction stresses

Isolated central area of the electrographite insert surface for frictional stress analysis. The highest stress concentrations are observed within this zone, reflecting the actual contact patch during operation and indicating regions with the greatest potential wear intensity.

The average value of Frictional Stress is 0.439 MPa (Fig. 7).

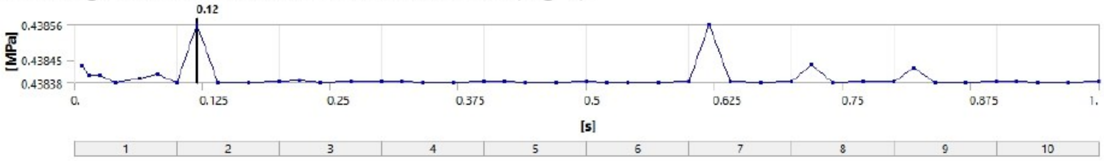

Fig. 7. Distribution of average stresses

Gap map (Fig. 8).

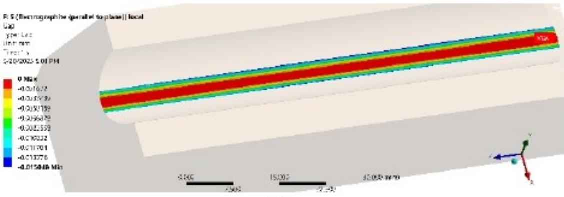

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Fig. 8. Contact gap map

Contact gap map - visualization of the distribution of the clearance (gap) in the contact zone between the insert and the wire. The color gradient indicates areas of minimal and maximal separation, which directly characterizes the quality of the contact and the potential stability of current transfer.

Calculation results for insert with Cu-40%C(f) 0.90 laminate

To process this calculation case, it became necessary to reduce the size of the finite elements of the mesh and increase its density: the size of the finite elements of the wire bodies and the insert was set to 1 mm; the size in the contact area was 0.5 mm.

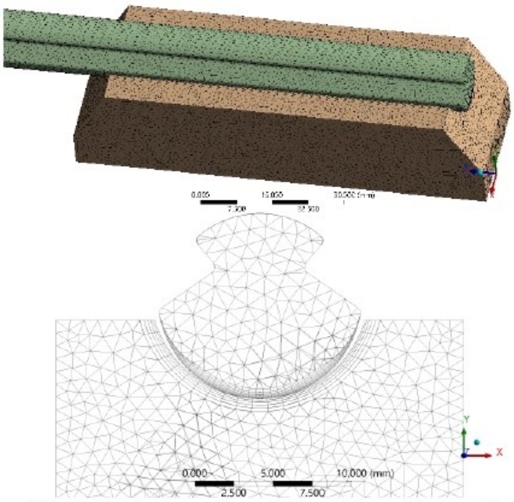

Fig. 9. Finite element mesh breakdown for Cu-C material.

The total number of elements is 1040866, and the number of nodes is 1900220.

The reason for this detailing is the higher hardness of the Cu-40%C(f) 0.90 laminate insert material and the correspondingly narrower contact spot compared to Electrographite (parallel to plane), which requires a smaller size of the end elements:

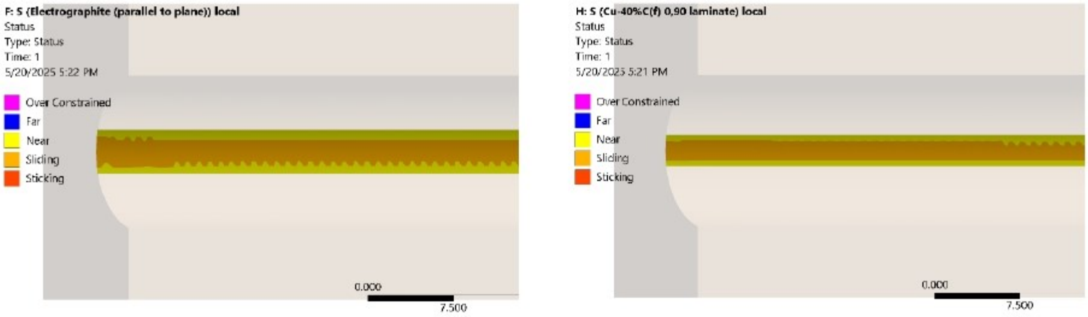

Fig. 10. Comparison of contact spots for electrographite material and copper-graphite material

The maximum value of Frictional Stress is 4.4242 MPa for the isolated central part of the insert surface (Fig. 11).

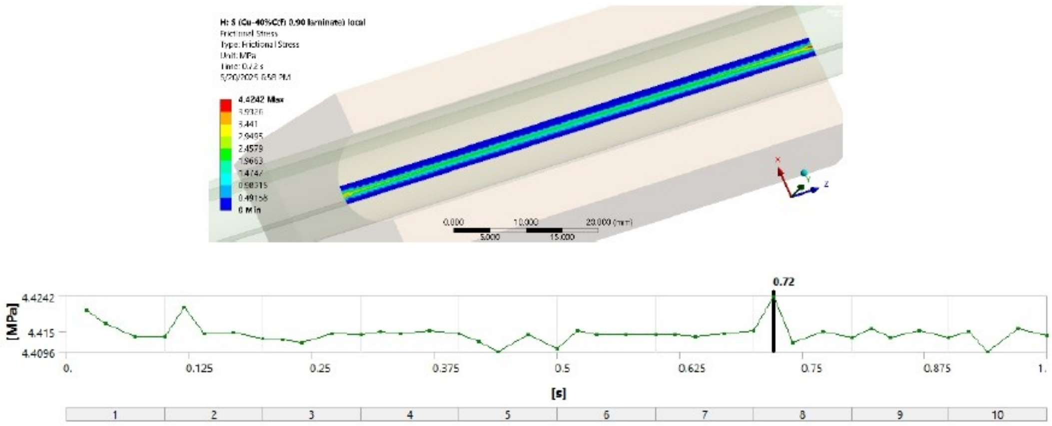

Fig. 11. Friction stress distribution for copper-graphite material

The average value of Frictional Stress is 0.599 MPa (Fig. 12).

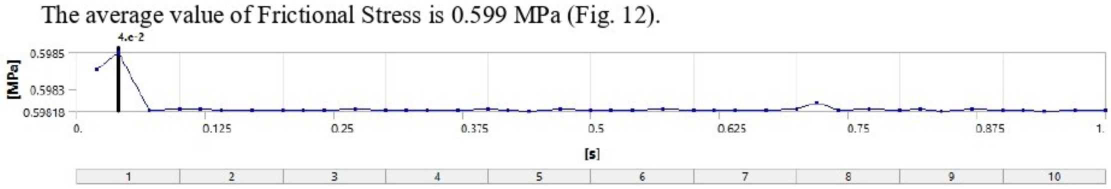

Fig. 12 Distribution of average friction stresses for copper-graphite material.

Distribution of average frictional stresses (Frictional Stress) for the copper–graphite insert obtained from numerical simulation. Elevated stress values are concentrated in the central contact zone, corresponding to the actual contact patch, while peripheral regions exhibit significantly lower stresses, indicating a non-uniform load distribution.

The Gap map is characterized by a decrease in the gap values for a given material (Fig. 13).

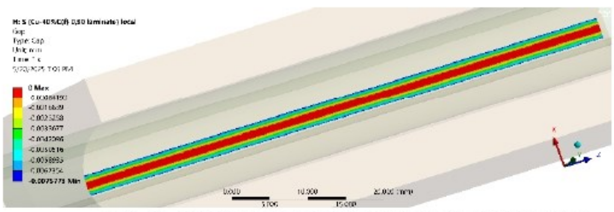

Fig. 13. Clearance map for copper-graphite insert

Calculation of insert wear

Common parameters:
- $\eta = 1 \cdot 10^{-5}$(local efficiency coefficient of energy conversion into wear)
- 1 HV ≈ 9.807 × 10^6 Pa (Hardness – Vickers)
- $s_{total} = 0.2$m (path traveled by the insert)

Electrographite insert (parallel to plane)

Considering that the Vickers hardness (Hardness – Vickers) = 4.28 – 4.72 HV, the average hardness$H = 4.5 \cdot 9.807 \cdot 10^6 = 4.41 \cdot 10^7$Pa or 44.1 MPa.
If the average value of Frictional Stress is MPa, then the amount of wear will be:$\tau_{avg} = 0.439$

$$d = \frac{\eta \cdot \tau_{avg} \cdot s_{total}}{H} = \frac{1 \cdot 10^{-5} \cdot 0.439 \cdot 10^6 \cdot 0.2}{4.41 \cdot 10^7} \approx 1.99 \cdot 10^{-5}\text{mm}$$

Total wear per 100 km or 500 thousand cycles (100,000 m / 0.2 m = 500,000 cycles): mm$1.99 \cdot 10^{-5} \cdot 500000 = 9.95$

This means that over 450 km, the wear will be:$9.95 \cdot 4.5 = 44.775$mm, which exceeds the permissible limits. Let us recall that the requirements for the VKT insert state: "the warranty period of operation of the inserts is not less than 450 km in dry weather in the absence of eccentric displacement of the wires at the joints. The depth of the maximum wear of the inserts is 10 mm." It should be noted that the parameter was measured under the condition of applying the maximum permissible pressure of the insert on the wire, equal to 0.5 MPa. In real conditions of trolleybus movement, the pressure value will fluctuate in the range of 0–0.5 MPa. Taking into account the linear dependence of the value on the applied pressure (the graph for the full surface of the insert trough below), it is easy to model the approximate amount of wear, for example: under the condition of applying a pressure of 0.25 MPa, the value will be reduced by 2 times. In addition, the contact patch on the surface of the gutter also migrates during the movement of the trolleybus (turns, inclines, etc.), which distributes wear over a larger surface, reducing local wear.$\tau_{avg}\tau_{avg}d$

The approximate wear value is approximate, since the value of the coefficient can change as the insert pressure changes on the wire, and therefore change the nature of the contact. For example, the graph of the average values of Contact > Status (model with a full surface of the insert groove) is not linear.dη

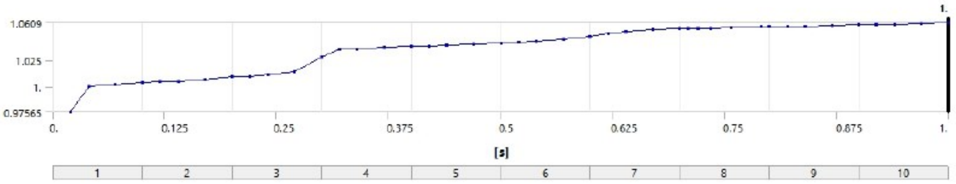

Fig. 14. Dependence for wear for full contact of the insert and wire

Conclusions on Electrographite (parallel to plane): provided the pressure of the insert on the wire is reduced and the real laboratory value of the coefficient is included in the calculation, it can theoretically be applied in inserts.η

Insert with Cu–40%C(f) laminate

Since the hardness is 120 - 135 HV, the average value$H = 127.5 \cdot 9.807 \cdot 10^6 = 1.25 \cdot 10^9$Pa or 1250 MPa. Assuming an average value of Frictional Stress$\tau_{avg} = 0.599$ MPa, the wear value will be:

$$d = \frac{\eta \cdot \tau_{avg} \cdot s_{total}}{H} = \frac{1 \cdot 10^{-5} \cdot 0.599 \cdot 10^6 \cdot 0.2}{1.25 \cdot 10^9} \approx 9.58 \cdot 10^{-7}\text{mm}$$

Total wear per 100 km or 500 thousand cycles: $9.58 \cdot 10^{-7} \cdot 500000 = 0.4792$mm

Over 450 km, the wear will be 2.1564 mm, which is quite within the normal range, but the hardness value of the wire materialCooper C10100(electrolytic tough-pitch hc copper) is lower than the composite insert material: Hardness - Vickers 80 - 115 HV. Thus, the wire will wear out first, which is not recommended.

It should be noted that the value did not change dramatically when going from Electrographite (parallel to plane) to Cu–40%C(f) laminate. In this case, it can be assumed that an intermediate hardness material will provide a value in the range between the measured 0.439 and 0.599 MPa.$\tau_{avg}\tau_{avg}$

Conclusions

The numerical simulation made it possible to specify the parameters of the local contact in the pair "insert - wire" of the trolleybus and to assess the influence of the area of the actual contact spot on the magnitude of the average friction stresses and the wear forecast. It was established that the use of electrographite inserts provides a lower level of wear of the contact wire, but their own resource under intensive operating conditions is limited. Copper-graphite inserts demonstrate higher wear resistance, but increase the risk of intensive wear of the copper wire due to a significant difference in hardness. To achieve optimal operational characteristics, it is advisable to select a material with intermediate hardness, which will balance the wear resistance of the insert and the durability of the contact wire. The results obtained can be used in the development of new insert materials and optimization of the designs of current collection systems of urban electric transport.

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Ковтун О.С., Голенко К.Е., Ганзюк А.Л., Диха М.О., Дитинюк В.О. Аналіз напружень тертя та зносу у контактній парі струмознімача транспортного засобу

У статті наведено результати чисельного моделювання роботи струмознімальної пари тролейбуса «контактна вставка – дріт» з використанням програмного середовища Ansys. Проаналізовано розподіл напружень тертя (Frictional Stress) та контактних тисків для двох типів матеріалів вставок: електрографітового (Electrographite, parallel to plane) та мідно-графітового композиту Cu–40%C(f) 0,90 laminate. Встановлено, що реальна площа плями контакту є меншою за всю поверхню жолоба, що суттєво впливає на розрахункові значення середніх напружень тертя та, відповідно, на прогноз зносу. Для електрографітової вставки середнє значення Frictional Stress становило 0.439 МПа, для мідно-графітової – 0.599 МПа. Проведені розрахунки показали, що при пробігу 450 км знос електрографітової вставки перевищує допустиме значення, тоді як для мідно-графітової він становить 2.1564 мм і знаходиться в межах норми. Проте через вищу твердість мідно-графітового матеріалу порівняно з мідним дротом основним елементом зносу може стати саме дріт, що є небажаним. Зроблено висновок, що оптимальним може бути використання матеріалу з проміжною твердістю, який забезпечить баланс між зносостійкістю вставки та збереженням ресурсу контактного дроту.

Ключьові слова: контактна вставка, контактний дріт, зносостійкість, напруження тертя, чисельне моделювання, Ansys, мідно-графітовий композит, електрографіт