



## Electromechanical wear of the contact wire–current collecting insert pair in electric transport systems

O.S. Kovtun\*<sup>0009-0000-6036-6723</sup>, A.O. Polishchuk<sup>0000-0001-7887-7169</sup>

<sup>1</sup>*Khmelnytskyi National University, Ukraine*

\*E-mail: [alkovt1982@gmail.com](mailto:alkovt1982@gmail.com)

Received: 15 February 2026; Revised 28 February 2026; Accept: 15 March 2026

### Abstract

The article considers the processes of current collection and wear in the sliding electrical contact system "contact wire - current collection insert" of a trolleybus. It is shown that the destruction of contact surfaces has a complex electromechanical nature and is caused by the simultaneous action of mechanical, electrical and thermal factors. The main mechanisms of electrical and mechanical wear of contact elements are analyzed, in particular, electroerosion, abrasive, fatigue and molecular-mechanical wear. The influence of contact pressure, current collector speed, traction current magnitude and properties of contact pair materials on the intensity of destruction of surface layers is considered. It is shown that the uneven distribution of current in the contact zone leads to local overheating of the surface and the formation of electric arcs, which accelerate the electroerosion destruction of contact elements. It is established that the formation of a thin graphite film on the surface of the contact wire can partially reduce the friction coefficient and wear intensity. The results obtained can be used to increase the durability of current-collecting elements of electric transport and optimize their operating modes.

**Keywords:** current collection; current collection insert; contact wire; electrical wear; mechanical wear; electrical erosion; sliding electrical contact; electric transport.

### Introduction

Electric transport, in particular trolleybuses, is widely used in urban transport systems due to its high energy efficiency and environmental friendliness. One of the most important elements of such systems is the contact network, through which electrical energy is transmitted from the power supply network to the rolling stock. The transmission of current from the contact wire to the electrical equipment of the vehicle occurs through pantographs equipped with current-collecting inserts that are in constant sliding contact with the contact wire (Fig. 1).

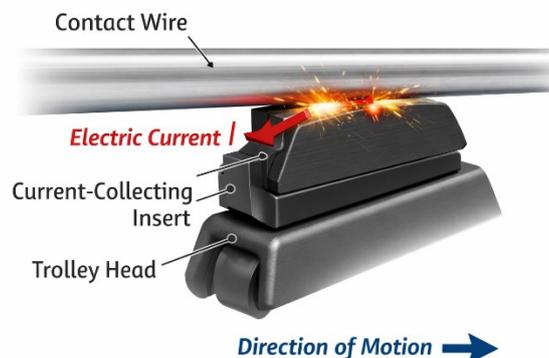


Fig. 1. Tribocontact pair "contact wire-current collector insert"



During operation, a complex interaction of mechanical, electrical and thermal processes occurs in the contact zone of the contact wire and the current collector insert. Under the action of contact pressure, electric current and friction forces, the surface layers of materials are subjected to intense plastic deformation, local heating and electrical erosion. This leads to the gradual destruction of the contact surfaces, which manifests itself in the form of wear of the contact wire and current collector elements. The intensity of wear of the contact pair largely depends on the design parameters of the contact network, the stability of the contact pressure of the current collector, the speed of the vehicle and the magnitude of the electric current. An important role is also played by the physical, mechanical and electrophysical properties of the materials of the contact elements, in particular their electrical conductivity, hardness, thermal conductivity and melting point. The study of wear processes in a sliding electrical contact allows us to determine the main mechanisms of destruction of contact surfaces and develop effective methods for increasing the durability of current collector elements. This is important for reducing the costs of maintenance of the contact network and increasing the reliability of electric transport. In this regard, the purpose of this work is to analyze the main mechanisms of electrical and mechanical wear of the contact pair "contact wire - current collector insert" and determine the factors that most affect the intensity of destruction of contact surfaces during the operation of trolleybus transport.

### **Literature review**

The problem of wear of the contact pair "contact wire - current collector insert" of electric transport is important for ensuring the reliability of current collection systems and the stability of the operation of the contact network. It is known that in a sliding electrical contact, mechanical, electrical and thermal processes simultaneously operate, which determine the intensity of destruction of the contacting surfaces [1].

Studies of the characteristics of a sliding electrical contact in the "current collector - contact wire" system have shown that the stability of current collection is largely determined by the parameters of contact pressure, electric current and temperature in the contact zone. At the same time, a change in these parameters leads to an uneven distribution of current over the contact surface and an increase in contact resistance [1,7].

Experimental studies of the tribological interaction of current-collecting inserts with the contact wire have shown that the wear mechanism is complex and includes abrasive, adhesive and electroerosion processes. As a result of local overheating of the surfaces in the contact zone, electric arcs may occur, causing melting of the material and the formation of craters on the surface of the contact wire [3,10].

The speed of movement and the electrical load play an important role in the wear processes. It has been shown that with increasing current, the intensity of electrical erosion of contact surfaces increases, while an increase in contact pressure leads to an increase in the mechanical component of wear [3,4].

A number of works have investigated the influence of geometric and dynamic parameters of current collectors on the processes of destruction of contact elements. It has been established that uneven contact pressure and oscillations of the current collector can cause local overloads of the contact zones and accelerate the wear of current collection inserts [4,5].

Considerable attention in modern research is paid to predicting the service life of contact inserts. The proposed mathematical models and machine learning methods allow assessing the influence of the main operational parameters on the wear rate and predicting the moment of reaching the limit state of contact elements [6].

A review of modern research shows that the wear of the contact pair "pantograph - contact wire" is a complex electromechanical process that depends on the material of the contact surfaces, the operating mode and the parameters of the contact network [7].

An important direction for increasing the reliability of current collection systems is the improvement of contact insert materials. Studies have shown that the use of composite materials based on graphite with metal additives allows improving electrical conductivity and reducing the intensity of wear of contact surfaces [8].

Some works are devoted to increasing the wear resistance of contact elements by restoring and strengthening their surface layers. It has been shown that the use of modern technologies for restoring and modifying the surface allows to significantly increase the service life of contact units of electric transport [9].

Thus, the literature analysis shows that the wear process of the contact pair "contact wire - current collector insert" is determined by the complex interaction of mechanical, electrical and thermal factors. Despite a significant amount of research in this area, the issues of increasing the wear resistance of current collector inserts and predicting their resource remain relevant and require further research.

### **Main material**

#### **Electrical wear of sliding contact**

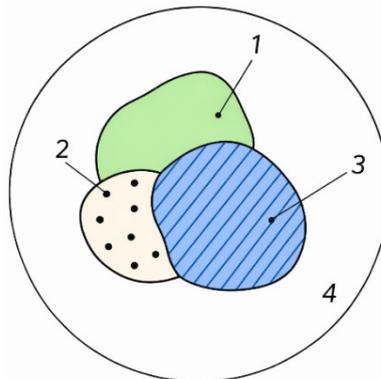
Electrical wear of a sliding contact is mainly caused by electrical erosion. Electrical erosion is the destruction of contacting materials associated with the melting and transfer of metal in a gaseous and liquid (in the form of small droplets) state from one contacting surface to another under the action of electrical discharges. Electrical erosion is especially significant in DC circuits. It can lead to the formation of growths and craters on

the contact surfaces. The higher the value of the specific heat capacity, melting point, specific heat of fusion and sublimation temperature of the contacting materials, the lower their electrical erosion. It was noted above that more thermal energy is required to melt aluminum than to melt the same mass of copper, although copper has a higher melting point. This is explained by the fact that the specific heat capacity and specific heat of fusion of aluminum are higher than those of copper.

The intensity of electrical wear of sliding contact materials depends not only on their nature, but also on the current density, contact pressure force and contact design. The surfaces of breaking and sliding contacts always have irregularities (roughness) as a result of mechanical processing, wear, plastic deformation. In addition, they are covered with a film of oxides and sulfides formed under the influence of atmospheric oxygen, ozone and sulfur-containing gases and liquids, as well as various accidental pollutants. The thickness of such a film depends on many factors and is usually  $10^{-6} \dots 10^{-5}$  mm; its specific electrical resistance is not less than  $10^3$  Ohm m. The distribution of current over the contacting surfaces is uneven, since the structure of the surfaces is inhomogeneous.

The surface structure of an electrical contact consists of four main types of contact areas (spots) (Fig. 2): contact spots with a metal contact (1), through which electric current flows without noticeable transition resistance; contact spots covered with adhesive and chemisorbed monomolecular films are quasi-metallic contacts (2), which easily pass electric current due to the tunneling effect; contact spots covered with electrically insulating relatively thick films of oxides and sulfides (3) and do not pass electric current; non-contact areas 4.

The contact parts touch only in areas 1, 2, forming a real contact surface. In areas 3, there is no contact pair. The total area of the electrical contact consists of the sum of the areas of all spots (1+2 + 3+4) and is an imaginary contact surface formed by the crushing of the roughness protrusions of the contact surfaces under the action of contact pressure (pressure). At low voltages, the electric current actually passes only through areas (spots) 1 and 2 of the real contact surface. In strong electric fields, due to the breakdown of thick films of oxides and sulfides (areas 3) and air layers (areas 4), they also become electrically conductive. In this case, part of the electrical energy is transmitted in contact through arc discharges, which cause electrical wear of the contacting surfaces and determine the efficiency and quality of current collection. Therefore, the smaller the contact pressure, the larger the area of non-contact areas, the higher the power of the electric arc and the more intense the electrical wear.



**Fig. 2. Scheme of the contact surface: 1 - metal spots (areas); 2 - quasi-metallic spots; 3 - spots of insulating thick films of oxides and sulfides; 4 - non-contact areas**

Since the electric current in the contact passes only through metallic and quasi-metallic areas, the current lines are distributed unevenly over the entire geometric surface of the contact. They are contracted to areas with metallic and quasi-metallic conductivity and are bent. As a result, the current density in these areas increases, which leads to the emergence of the resistance of the current lines to contract  $R_{con}$  (constriction resistance). In this regard, the total contact (transition) resistance  $R_c$  consists of the resistance of the conductive microcontacts and the resistance arising from the contraction of the current lines. The contact pressure force  $F$ , the state of the contacting surfaces, and the magnitude of the current  $I$  directly affect the value of  $R_{con}$  and, accordingly, the total contact resistance  $R_c$  and the heating temperature of the contacts when an electric current flows. With an increase in the contact pressure  $F$ , a decrease in the roughness of the contact surfaces and the proportion of areas covered with insulating oxide and sulfide films, the value of the contact resistance  $R_c$  can significantly decrease.

Due to the heating of the contact wire during interaction with the current-collecting elements, recrystallization and strengthening of copper occur to a certain depth (0.54-0.16 mm) within several days of operation. Later, when the contact wire wears out to the limit value, the strengthening of the surface layer in depth remains constant.

In the operating conditions of the trolleybus contact network, the electrical wear of the contact pair "contact wire - current collector insert" is largely determined by the instability of the electrical contact and the occurrence of short-term electric arcs. Such phenomena can occur when the contact is locally broken due to surface irregularities, current collector oscillations, changes in contact pressure or contamination of the contact wire surface. At the moment of microcontact rupture between the conductive sections, an electric arc is formed, which leads to local heating, melting and evaporation of the material of the contacting surfaces.

At the same time, characteristic microcraters, molten metal inflows and oxidation products are formed on the surface of the contact wire and current-collecting insert, which change the microgeometry of the surface and increase the contact resistance. This subsequently leads to an even greater current concentration on individual areas of the contact surface and intensification of electrical erosion. These processes are especially intense at high current values, unstable contact pressure and increased speeds of rolling stock.

Additionally, it should be taken into account that the electrical resistance in the contact area is largely determined by the phenomenon of current line contraction in the microcontact area. According to the classical Holm theory of electrical contacts, the contact resistance of one microcontact can be estimated by the formula:

$$R_c = \frac{\rho}{2a},$$

where  $\rho$  is the electrical resistivity of the contact material,  $a$  is the radius of the contact spot.

When an electric current flows through microcontacts, their local heating occurs, which can be estimated using the Joule–Lenz law:

$$Q = I^2 R_c t$$

where  $I$  is the current strength,  $R_c$  is the contact resistance,  $t$  is the current flow time.

Local heat release in the microcontact zone causes an increase in the temperature of the surface layers of the material, which can lead to their melting, the formation of microcraters and the intensification of electroerosion wear of the contact pair.

In addition, an important role in the process of electrical wear is played by the electrophysical properties of the current collector insert material, in particular electrical conductivity, thermal conductivity, melting point and the ability to form stable protective films on the surface. The use of graphite-based composite materials allows reducing the intensity of electrical erosion due to their ability to form a thin graphite film on the contact wire, which partially stabilizes the contact and reduces the local current density.

### **Mechanical wear of sliding contact**

Mechanical wear of contact wires and current-collecting elements occurs as a result of friction of surfaces that contact and slide relative to each other. The main types of mechanical wear of materials in sliding contact are oxidative, fatigue, abrasive and molecular-mechanical. Oxidative wear is associated with the destruction of thin oxide films on friction surfaces and their formation again. Fatigue wear is associated with deformation, cracking and removal of a heavily hardened (hardened) layer of rubbing surfaces. Abrasive wear is caused by the ingress of solid particles from the outside (dust, sand, etc.) between the rubbing surfaces, as well as wear products (metal oxides and particles from the destroyed heavily hardened layer). Molecular-mechanical wear is explained by the processes of seizing, tearing and tearing out of particles of contact materials. This causes deformation and heating, which causes the contact surfaces to oxidize. The lubricant significantly reduces molecular-mechanical wear.

In sliding contact, under the influence of processes caused by friction, plastic deformation and hardening of the surface layer of the contact wire occurs. As a result, the density of dislocations and the heterogeneity of their distribution increase in the surface layer of the contacting surface, which leads to the formation of microregions. During further operation, the formed microregions are crushed and disoriented. Outside their boundaries, the concentration of internal stresses increases, which lead to the formation of microcracks. Behind them, the destruction of the surface layers occurs with the separation of mechanical particles that participate in the abrasive wear of the contacting surface of the contact wire. The intensity of the formation of microregions and the subsequent destruction of the contacting surface increases with increasing speed of movement and the force of pressing the current collector on the contact wire.

Destructive processes caused by plastic deformation and hardening of the surface layer, as well as abrasive wear, largely depend on the nature of the contact wire metal. In a contact wire made of alloyed copper, the plastic deformation of the surface layer is less than in pure copper, therefore, there are fewer and further destructive processes. As a result, the resistance of the contact wire to mechanical wear increases. In alloyed copper, the tendency to set is also reduced. Since the hardness and hardening temperature of copper increase during alloying, the resistance to abrasive wear increases and the upper limit of the operating temperature increases.

The intensity of mechanical wear increases with increasing contact pressure, and decreases with improving the quality of the lubricant in the contact. Therefore, this indicator is greatly influenced by the nature of the materials of the contact pair and, first of all, their hardness. The most unfavorable in this respect are contact pairs made of the same material (for example, the contact pair "copper contact wire - copper current-collecting plate").

The dependence of the degree of wear of the contact surface of contact wires made of bronze of CuAg0.1 and CuMg0.5 grades on the speed of movement (up to 50 km/h), contact pressure (up to 300 N) and current load (up to 1000 A) was investigated. Studies have shown that at constant contact pressure (250 N) and constant current load (300 A), the maximum wear of the contact wire surface occurs at a speed of movement of about 50 km/h. At constant speed of movement (50 km/h) and constant current load (300 A), with increasing contact pressure, the wear of the contact wire surface increases. At a constant speed (50 km/h) and constant contact pressure with a force of 75 or 150 N, with increasing current load, the wear of the contact wires increases, and at a contact pressure

with a force of 300 N and with an increase in current load from 100 to 150 A, the wear of the contact wires disappears.

Studies show that when moving at high speed, with an increase in current load and contact pressure, the service life of contact wires can be extended. With an increase in traction current to a certain value, other things being equal, the intensity of contact wire wear decreases. This is explained by the "lubricating" effect of the current, which occurs as a result of the formation of a graphite film on the surface of the contact wire. When normalizing the speed of movement, it is possible to obtain a contact wire wear value of 1 mm per 100,000 pantograph passes. It also follows from these works that with an increase in current load, the electrical form of contact wire wear increases, and with an increase in contact pressure, the mechanical form of wear.

When contact wires interact with current-collecting elements as a result of heating of the contacting surfaces under the influence of high current loads, the surface layer of the contact wire can be strengthened to a depth of 0.54...1.16 mm. The weakened layer of copper (bronze) that has formed will be subject to more intense mechanical wear (abrasive and molecular-mechanical). Thus, structural changes in the metal (alloy) of the contact wire caused by electrical wear increase the intensity of its mechanical wear.

Based on the above, it can be concluded that the intensity of electromechanical wear of contact wires and current-collecting elements, in addition to their design and technical condition, mainly depends on: the uniformity of the contact suspension of the wire in the span; the amplitude of the force of pressing the moving current collector on the contact wire; the magnitude of the consumed current; the nature of the materials of the friction surfaces and the quality of the lubricant.

One of the most important and largely determining the efficiency of electric traction parameters is the cost associated with the cost of repairing worn contact wires and replacing them with new ones. These costs consist not only of the cost of new contact wires (minus the cost of the material of the worn wires) and the labor costs for their replacement, but also of losses due to delays in the traffic schedule, which are necessary for the performance of basic works.

Under conditions of sliding electrical contact of the contact wire and the current-collecting insert, mechanical wear is closely related to thermomechanical processes occurring in the surface layers of materials. Under the action of contact pressure and tangential friction forces, significant local stresses arise in the contact zone, which lead to intensive plastic deformation of the surface layer. As a result, a riveted layer with a changed microstructure, increased dislocation density and increased hardness is formed.

During long-term operation of the contact pair, cyclic loading of the surface layers of materials occurs, which leads to the development of microcracks due to contact fatigue. Further propagation of such microcracks causes the separation of small particles of material, which accumulate in the contact zone and can act as abrasive particles. In this case, the wear mechanism switches to a mixed mode, which includes elements of abrasive and fatigue wear.

An important factor affecting the intensity of mechanical wear is the microgeometry of the surface of the contact wire and the current-collecting insert. With increasing surface roughness, the number of local contacts between the protrusions of micro-irregularities increases, which leads to an increase in contact stresses and intensification of plastic deformation processes. At the same time, the probability of the formation of micro-interference between the surfaces increases, which contributes to the development of adhesive wear.

In the contact pair "copper contact wire - graphite or composite current collector insert" an important role is played by the formation on the surface of the contact wire of a thin layer of wear products containing graphite and metal oxides. Such a layer can act as a solid lubricating coating, reducing the coefficient of friction and the intensity of mechanical wear. At the same time, with excessive accumulation of wear products or ingress of solid abrasive particles from the external environment (dust, sand), this layer can turn into an abrasive medium, which accelerates the destruction of the surface of the contact wire.

In addition, it should be taken into account that mechanical wear in a sliding electrical contact is inextricably linked to electrical and thermal processes. Heating of the contact zone under the action of a current load can lead to a decrease in the strength of the surface layer of the contact wire material, which increases its susceptibility to plastic deformation and accelerates the development of mechanical wear. Thus, the real process of destruction of materials in the contact pair "contact wire - current-collecting insert" has an electromechanical nature and is determined by the complex action of mechanical, electrical and thermal factors.

## Conclusions

1. It is shown that the wear of the contact pair "contact wire – current-collecting insert" is of an electromechanical nature and is determined by the complex action of mechanical, electrical and thermal processes in the sliding contact zone.

2. It has been established that electrical wear of contact surfaces is mainly caused by electrical erosion, which occurs as a result of local electrical discharges and uneven current distribution between surface microcontacts.

3. It is shown that mechanical wear of contact elements occurs as a result of abrasive, fatigue and molecular mechanical processes and largely depends on the contact pressure, the speed of movement of the current collector and the properties of the materials of the contact pair.

4. It has been established that the use of composite graphite materials for current-collecting inserts contributes to the formation of a thin protective film on the surface of the contact wire, which reduces the friction coefficient and the intensity of wear of the contact surfaces.

## References

1. Wu, G., Wu, J., Wei, W., Zhou, Y., Yang, Z., & Gao, G. (2018). Characteristics of the sliding electric contact of pantograph/contact wire systems in electric railways. *Energies*, 11(1), 17. <https://doi.org/10.3390/en11010017>
2. Pieniak, D., Walczak, M., & Niewczas, A. (2025). Tests of operational wear of trolleybus traction wires. *Applied Sciences*, 15(23), 12716. <https://doi.org/10.3390/app152312716>
3. Ding, T., Xuan, W., He, Q., Wu, H., & Xiong, W. (2011). Study on friction and wear properties of pantograph strip–copper contact wire for high-speed train. *Tribology International*, 44(4), 437–444. <https://doi.org/10.1016/j.triboint.2010.12.005>
4. Zhang, W., Zhou, N., & Mei, G. (2016). Dynamic performance and wear behavior of pantograph contact strips in high-speed railway systems. *Wear*, 366–367, 220–229. <https://doi.org/10.1016/j.wear.2016.06.018>
5. Song, D., Jiang, Y., & Zhang, W. (2017). Effects of contact strip wear on service performance of pantograph system. *Journal of Southwest Jiaotong University*, 52(3). <https://doi.org/10.3969/j.issn.0258-2724.2017.03.003>
6. Kuźnar, M., Burek, J., & Zając, J. (2021). A method of predicting wear and damage of pantograph sliding strips using artificial neural networks. *Materials*, 14(24), 7612. <https://doi.org/10.3390/ma14247612>
7. Wu, G., Gao, G., Yang, Z., & Zhou, Y. (2022). Pantograph–catenary electrical contact system of high-speed railways: A review. *Railway Engineering Science*, 30, 1–15. <https://doi.org/10.1007/s40534-022-00281-2>
8. Zhi, X., Zhou, N., Wei, H., Cheng, Y., Zhang, W., & Chen, G. (2025). Study on wear performance and mechanism of pantograph contact strip under different environmental conditions. *Friction*. <https://doi.org/10.26599/FRICT.2025.9441101>
9. Kovtun, OS, Dytyniuk, VO, Staryi, AL, & Fasolia, VO (2024). Restoration and wear resistance of electric transport sliding contacts. *Problems of Tribology*, 29(2/112), 58–66. <https://doi.org/10.31891/2079-1372-2024-112-2-58-66>
10. Yang, H., Chen, G., & Gao, G. (2015). Experimental research on friction and wear properties of pantograph contact strips. *Journal of Shanghai Jiaotong University (Science)*, 20(1), 79–84. <https://doi.org/10.1007/s12204-015-1603-4>

**Ковтун О.С., Поліщук А.О.** Електромеханічне зношування пари «контактний провід – струмознімальна вставка» електротранспорту

У статті розглянуто процеси струмознімання та зношування в системі ковзного електричного контакту «контактний провід – струмознімальна вставка» тролейбуса. Показано, що руйнування контактних поверхонь має складний електромеханічний характер і зумовлюється одночасною дією механічних, електричних та теплових факторів. Проаналізовано основні механізми електричного та механічного зношування контактних елементів, зокрема електроерозію, абразивне, втомне та молекулярно-механічне зношування. Розглянуто вплив контактного натискання, швидкості руху струмоприймача, величини тягового струму та властивостей матеріалів контактної пари на інтенсивність руйнування поверхневих шарів. Показано, що нерівномірність розподілу струму у зоні контакту призводить до локального перегріву поверхні та утворення електричних дуг, які прискорюють електроерозійне руйнування контактних елементів. Встановлено, що формування на поверхні контактного дроту тонкої графітової плівки може частково знижувати коефіцієнт тертя та інтенсивність зношування. Отримані результати можуть бути використані для підвищення довговічності струмознімальних елементів електричного транспорту та оптимізації режимів їх експлуатації.

**Ключові слова:** струмознімання; струмознімальна вставка; контактний провід; електричне зношування; механічне зношування; електрична ерозія; ковзний електричний контакт; електротранспорт.