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Durability and Wear Resistance of Sliding Electric Contacts in Electric Transport

***Abstract**. This paper researches the durability and wear resistance of sliding electric contacts in urban electric transport. It proposes the use of additional impulse loading in powder metallurgy techniques to reduce wear and enhance fatigue force. The analysis highlights the importance of sustainable solutions in addressing the challenges of urban passenger transportation. Promising directions for further research include the improvement of manufacturing technology and the use of amorphous alloys.*

***Streszczenie.** W artykule zbadano trwałość i odporność na zużycie ślizgowych styków elektrycznych w miejskim transporcie elektrycznym. Proponuje się zastosowanie dodatkowego obciążenia impulsowego w technikach metalurgii proszków w celu zmniejszenia zużycia i zwiększenia siły zmęczeniowej. Analiza podkreśla znaczenie zrównoważonych rozwiązań w stawianiu czoła wyzwaniom miejskiego transportu pasażerskiego. Obiecujące kierunki dalszych badań obejmują doskonalenie technologii wytwarzania i zastosowanie stopów amorficznych. (**Trwałość i odporność na zużycie ślizgowych styków elektrycznych w transporcie elektrycznym**)*

Keywords: sliding electrical contacts, durability, wear resistance, impulse loading.
Słowa kluczowe: ślizgowe styki elektryczne, trwałość, odporność na zużycie, obciążenie impulsowe.

Introduction

Urban electric transport has a strategic importance in the socio-economic development of any country. This mode of transport retains its leading role in urban passenger transportation and is one of the most resource-intensive consumers of electricity. The steady growth of the volume of passenger traffic is accompanied by an increase in the production of urban electric transport. At the same time, it is necessary to replace the morally and physically outdated rolling stock of urban electric transport. The operated electric transport must be equipped with reliable structural elements. In addition, the repair of electric transport parts and the replacement of components and assemblies are associated with significant material costs.

An important problem is the improvement of existing designs and manufacturing technologies for sliding contacts of electric transport current-carrying units, as well as increasing their reliability, efficiency and operational durability. The solution of this problem is directly related to the development of fundamental and applied research in the field of friction and wear. It should be noted that even the use of materials with improved performance properties and taking into account the dynamics of wear of sliding contacts do not solve this problem.

The purpose of the research consists in finding ways to increase the resource during the operation of sliding electric contacts and contact wire, identifying the most significant factors of performance and increasing their durability; refinement of the technological parameters of their manufacture with the implementation of the mechanical properties of materials subjected to wear and fatigue failure of materials subjected to wear and fatigue failure.

Material of the research

The analysis of constructive and technological methods for improving the wear resistance of sliding contacts of current-carrying units of electric transport [1-8] made it possible to determine the following. The problem of identifying their rational mechanical properties is complex and unresolved to date. Sliding electric contacts are most exposed to friction and wear processes. The negative frictional effect is exacerbated by electrodynamic processes. Sliding electric contacts (SEC) are current-collecting devices of transport, electric machines, radio-electronic and radio-electric equipment. Consider the first type of SEC. It has been determined that the largest number of failures of electric transport falls on electric equipment and is most associated with SEC [1-8].

The use of methods of analysis of operational data allows us to find out the most significant factors for the loss of performance of transport current-collecting devices [1]. The most significant factors of loss of operability are shown in Fig. 1.

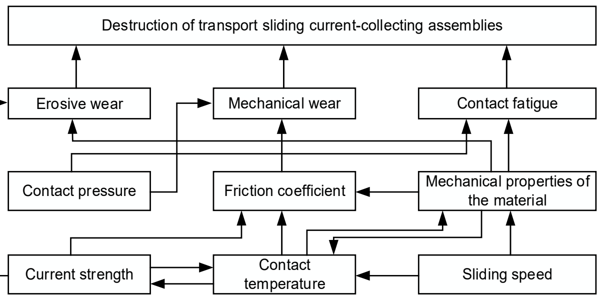

Fig 1. Most significant failure factors for sliding current-collecting assemblies

Taking into account the large range of parts of electric equipment of electric transport, the diagram includes sliding current-collecting assemblies of transport. The current-collecting assemblies of transport (urban, railway, underground) are subjected to the greatest wear, the main types of which are electrical (erosive) wear and wear associated with changes in the thermal friction conditions of the contact.

Electrical (erosive) wear is decisive in assessing the resource of electric transport. It occurs during sparking and arcing. It also occurs when the surfaces of the contacting elements come off in motion and in the parking lot during start-up. In this case, the rubbing elements are also subjected to impact loads. In addition, during sparking, microparticles including electrical insulation are chipped. Therefore, when forming a wear model, it is necessary to take into account these factors. To do this, we use the equation of shock-abrasive mass wear, the equation that determines the temperature in the contact zone, and material hardness and plasticity dependence on temperature.

Practical recommendations and experimental verification

The dependence for determining mass wear under the conditions of impact-abrasive wear with a fixed abrasive has the form:

$$u = (f_m + f)\frac{H \cdot A(1+\delta)}{H_m \sigma_s \delta}\gamma , \tag{1}$$

where: u – mass wear, f_m – molecular component of the friction coefficient, f – deformation component of the friction coefficient, H, H_m – hardness correspondingly of wire and current collector materials, A – work of friction force, δ – relative extension, γ – density of the pantograph insert material, σ_s – yield strength of the current collector material.

The proposed dependence corresponds to the modern theory of wear [1]. Its difference lies in taking into account the molecular component of the friction force and the plastic properties of the material (δ).

The heat flux on the contact surface is determined from the condition of the action of two heat sources: frictional and electric [1]. It is determined by dependence:

$$q = \frac{1}{A}\left[(f_m + f)N_n \upsilon + I^2\left(\rho\left(\frac{H_m}{\pi N_n}\right)^{0.5}\right) + \sigma\frac{H_m}{N_n}\right], \tag{2}$$

where: A – cross-sectional area of the wire, N_n – normal load, υ – sliding speed, I – current value, ρ – specific electrical resistance, σ – resistivity of the film on the contact.

The joint solution of the equations of wear by mass and surface temperature caused by friction makes it possible to determine the wear by mass of sliding contacts. At the same time, we assume that the work of friction forces is transformed into heat. In addition, the heat flux on the contact surface takes into account only the frictional component. The expression for wear by mass is of the form:

$$u = \frac{0.945\left(f_m + f\right)\left\{\left(f_m + f\right)N_n \upsilon + I^2\left(\rho\left(\frac{H_m}{\pi N_n}\right)^{0,5}\right) + \right.}{A_0 H_m \sigma_b \cdot \lambda_1 \delta \left(1+\delta\right)^{-1} H_\alpha^{-1}} \cdots \tag{3}$$

$$\cdots \frac{\left. +\sigma\frac{H_m}{N_n}\right\}}{\alpha_{+f}^{-1}} \cdot \left(\frac{\alpha_1 \cdot l_1}{\upsilon\pi}\right)^{0,5} \cdot \gamma .$$

This dependence has extrema in the coefficient of friction (deformation component), current value and hereditary deformation of the wire [1]. The current value is limited by the operating conditions, and it makes no sense to determine its extreme values. The value of the molecular component of the friction coefficient decreases significantly with increasing temperature [2]. The deformation component of the coefficient of friction significantly exceeds the molecular component $f >> f_m$. Therefore, value f_m^2 can be neglected. In dependence (1) the work of friction forces transforms into heat.

The optimal value of the deformation component of the friction coefficient has the form:

$$\left|f\right| = \frac{0.531 I^2\left[\rho\left(\frac{H_m}{\pi N}\right)^{0.5} + \sigma\frac{H_m}{N}\right]}{N_v} - f_{m0} exp(\alpha - \beta)\Delta T, \tag{4}$$

where: f_{m0} – molecular component of the static friction coefficient at the operating temperature, α, β – temperaturecoefficients, ΔT – temperature change.

This dependence has an extremum (min) as to the friction coefficient. The research of the extremum makes it possible to find the ratio of the physical and mechanical properties of materials corresponding to minimal wear. This dependence also makes it possible to determine the friction mode that must be implemented under given operating conditions. In the design and technological formation of parts by pressure treatment and hardening (contact-wire line, contact rail, boot) the maximum operational durability and wear resistance of hardened parts correspond to plastic deformations equal to the limiting uniform ones [5-12]. The values of these deformations are determined by dependence:

$$360 \cdot \left(130 - HB\right)^{-1} \le \varepsilon_p , \tag{5}$$

where: HB – Brinell material hardness (MPa), ε_p – strain intensity corresponding to the limiting uniform.

Coal-coke materials used for pantograph inserts are manufactured applying powder metallurgy techniques. Additional impulse loading of workpieces after primary sintering or modifying impulse loading of the powder mixture before sintering reduces the porosity of the finished part by 8-12 times. In addition, impulse loading leads to a slight decrease in hardness by 0.55 – 1% and strength. However, such additional loading results in a significant increase in the plasticity of products. Flexural strength is increased by 8 – 10% [5-12]. Giving plasticity to the materials of products operating under wear and fatigue load reduces mass wear by 30-40%. Fatigue strength increases by 3-5 times.

The results of calculating the hardening treatment parameters according to expressions (4), (5) are in good agreement with the operational data and test data on electric transport.

An increase in the durability of structural elements is provided in the process of scientific-organizational and economic substantiation of the design and technological solutions for creating parts with a given durability.

Scientific substantiation involves analyzing the operation of sliding contacts and constructing a mathematical model of their wear. Furthermore, at the final stage of structural element development, a scientific component becomes essential, entaling the formulation and development of a methodology for bench and operational tests.

The technological component is aimed at providing the necessary technological heredity, the choice of materials in the manufacturing process and methods of hardening. In this case, it is necessary to provide high mechanical and tribotechnical properties, low specific and transient electrical resistance, high electrical erosion and impact resistance.

To compare the conventional series-produced sliding contacts and ones manufactured by new technologies, it is proposed to use the following relationship:

$$\Delta u = \sqrt{I \cdot exp\left(-\frac{2H_u \rho_u \sigma_{bu} R_u f_u \sigma_{du}}{H_n \rho_n \sigma_{bn} R_n f_n \sigma_{dn}} \cdot \frac{TbC}{W}\right)}, \tag{6}$$

where: Δu – relative change in mass wear for new specimens of current-collecting units of electric transport, H_u, H_n – respectively the hardness of the material of series- produced and new sliding contacts (inserts), ρ_u, ρ_n – electrical resistivity of series-produced and new inserts, σ_{bu}, σ_{bn} – ultimate strength of series-produced and new inserts, R_u, R_n - contact resistance of series-produced and new contacts, f_u, f_n – friction coefficients of series-produced and new inserts, σ_{du}, σ_{dn} – ultimate bending strength of series-produced and new inserts, T – ambient temperature, b – surface roughness, C – a constant that depends on the shape of the insert, W – ambient humidity.

In contrast to the dependence proposed in [1], a factor is added that takes into account the plastic properties of the material of the sliding current collection assembly. This is the ratio of the bending strength of a series-produced and a new current collection assembly. In addition, for inserts containing copper, the relative humidity was placed in the denominator. This is due to the fact that with increasing humidity, the degree of implementation of selective transfer during friction increases.

Inserts made of coal-coke materials are more subject to wear. Therefore, in this case, the ambient humidity indicator remains in the numerator. Thus, to reduce the intensity of mass wear of the inserts, it is necessary to increase their physical, mechanical, electrical and tribotechnical properties, to implement the friction mode under conditions of selective transfer. In this case, the wear of the contact wire should not increase. Therefore, the wear process of the sliding contacts is controllable. Control is carried out by improving the technology of their manufacture and changing the physical and mechanical characteristics of the material. To do this, it is necessary to use new technologies and combinations of materials with desired properties. Copper should be the main component for metal-containing sliding contacts. Consider variants of the production of new inserts.

It was proposed [2] to make the sliding element of urban electric transport from press powder instead of coal-coke materials. It is composed of natural graphite and pyrolytic carbon. Pyrolytic carbon is both a hardener and a binder. Niobium is introduced as a natural graphite modifier. In addition, a layer of copper is deposited on the rubbing surface of a contact made from this composite material.

The authors propose a ceramic-metal material. It is obtained through the successive pressing of cermet layers, followed by copper deposition. Prior to pressing, an electric discharge is introduced, serving as an additional impulse loading. The pressed material is then impregnated with molten copper in a vacuum furnace at a temperature of 1200°±5°C. The molten copper penetrates the pores between the grains of the cermet. The proposed ceramic-metal material is less brittle, not prone to cracking, has high wear resistance and anti-friction. The finished part made of cermet is boiled in oil with a metal-cladding component. Ceramic-metal contacts, which are operated in conditions of high humidity and in case of water ingress, practically do not wear out. This is due to the fact that the ingress of water onto the rubbing surface causes a process of selective transfer. In this case, wear is excluded.

The constructive formation of a part is associated with a rational choice of the shape of rubbing surfaces and a change or improvement in the design. With a mathematical description of mass wear process, the optimal value of the friction coefficient was obtained (4). This value, depending on the electrical properties of the materials and the oxide film, can be positive or negative. A negative value is obtained under conditions of alternating friction. This is achieved by vibrating the sliding contact. For this, according to the authors, it is necessary to introduce a piezoelectric element into the design of current-carrying elements.

The results of operational research on the wear of a standard contact wire, the hereditary deformation of which is equal to the limiting uniform one, are shown in Figs.2, 3. Figs. 4, 5 show histograms of the average wear of series-produced inserts; inserts subjected to modifying impulse loading; composite and cermet.

It has been determined (Fig. 2) that the average wear of the contact wire when interacting with serial inserts is: 2.0 ... 2.5 times [2] higher compared to modified ones; 2.0...2.2 times higher compared to the modified ones; 10…15 times higher than metal-ceramic ones. The average wear of the "hardened" contact wire during interaction: with serial inserts decreased by 1.6 ... 2.0 times; composite ones – by 5.0…5.2 times; 18...20 times in comparison with metal-ceramic ones.

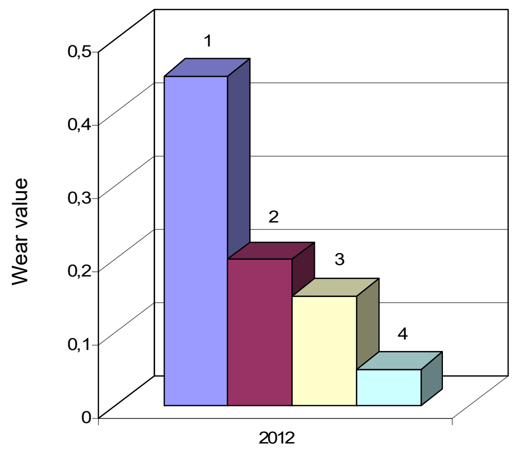

Fig. 2 The average wear of the MF100 contact wire during interaction: 1 – series-produced inserts; 2 – modified inserts; 3 – composite inserts; 4 – ceramic-metal inserts

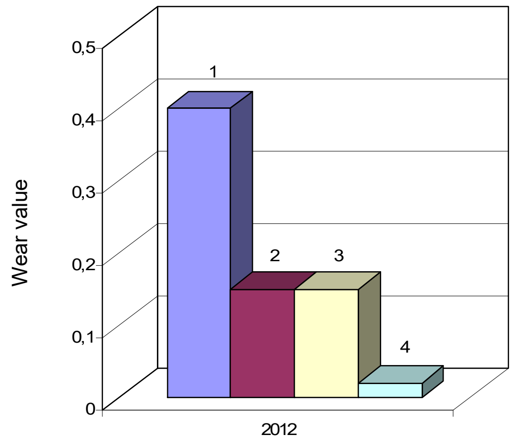

Fig. 3. The average wear of the hardened wire during interaction: 1 – serially produced inserts; 2 – modified inserts; 3 – composite inserts; 4 – ceramic-metal inserts

Regarding the wear of the inserts (Fig.4, Fig.5), the wear of inserts when interacting with contact wire MF100 compared to series-produced: modified composite ones decreased by 2.5...2.7 times; metal-ceramic ones – by 12…18 times.

Relative wear of inserts when interacting with a "hardened" contact wire compared to series-produced: series-produced inserts increased by 1.2 ... 1.4 times; modified, composite and ceramic-metal ones practically did not change.

However, it should be noted that the degree of increase in the price of a modified insert due to additional costs for increasing durability and reliability is ten times lower than for the production of composite and modified inserts. In addition, organizational issues related to the production of modified inserts are easily solved within the framework of one enterprise.

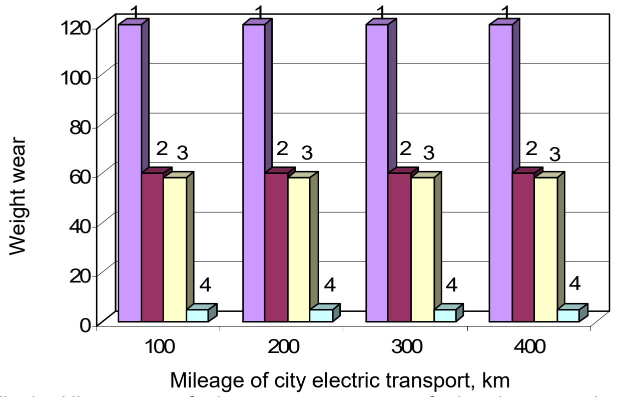

Fig.4. Histogram of the average wear of the inserts when interacting with the contact wire: 1 – serially produced inserts; 2 – modified inserts; 3 – composite inserts; 4 – ceramic-metal inserts

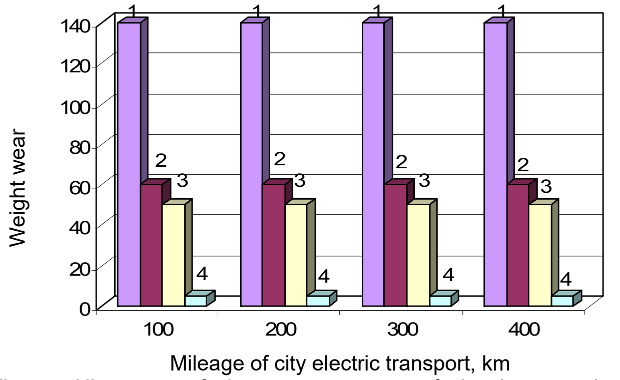

Fig. 5. Histogram of the average wear of the inserts when interacting with the hardened contact wire: 1 – serially produced inserts; 2 – modified inserts; 3 – composite inserts; 4 – ceramic-metal inserts

Approbation. The proposed method for increasing durability was carried out by electropulse loading on a 28-loop electro-hydraulic press PEG-KhAI-500. Alternative options for pulsed loading are: pulsed magnetic field, gas detonation, gunpowder explosion. Improving the technology of manufacturing the contact wire of pantograph inserts is no less effective than the use of new composite materials. I.e. by improving the manufacturing technology of sliding contacts, it is possible to control the process of their wear.

The average specific wear of sliding contacts manufactured using the new technology, as shown by bench tests, decreased by 2.0-2.2 times compared to series-produced ones. The specific wear of the contact wire made according to the new technology with these inserts is lower by 30.7 - 33.8% compared to serial ones. A slight change in technology costs 2-3 times cheaper than the use of new composite materials. In conclusion, it should be noted that a promising direction in this area consists in the use of amorphous alloys.

Conclusion

The most significant factors for the loss of efficiency of sliding current-collecting units of transport have been identified. Dependences for the calculation of mass wear and the values of limiting uniform deformations in the design and technological formation of parts obtained by plastic deformation have been determined. Reduced mass wear and fatigue strength of parts produced by powder metallurgy method has been carried out by additional impulse loading. Operational tests have shown that inserts made of metal-ceramic materials impregnated with copper have the highest wear resistance when the mass wear of the contact wire is constant.

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