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Determination of the transition resistance of detachable electrical contacts with Camital active grease

Problem. The reliability of detachable electrical contact connections is significantly reduced due to an increase in transition electrical resistance caused by thermomechanical deformations, oxidation of contact surfaces, and a decrease in the effective contact area during operation. According to the results of operational and experimental studies, failures associated with contact degradation account for up to a third of the total number of electrical installation failures. Traditional methods, in particular the use of passive conductive lubricants, mostly only slow down oxidation processes and do not ensure active restoration of the contact condition. In this regard, it is important to develop models and technical solutions capable of describing and ensuring the stabilisation of the transition resistance of electrical contacts through controlled thermomechanical processes in the contact zone. **Goal.** To establish the regularities and interrelationships of processes in electrical contacts through experimental research and mathematical modelling of the evolution of the transition resistance of contact connections with composite grease modified with Cu–Al–Mn (Camital) with shape memory, taking into account the interaction of electrical, thermal, thermomechanical and tribological processes in normal and emergency operating modes. **Methodology.** Experimental studies were performed on models of bolted contact connections of aluminum busbars using composite grease containing 5 % and 10 % Cu–Al–Mn powder by volume, as well as on control samples without grease. Long-term measurements of contact resistance were carried out at a constant temperature and under periodic thermal loads. The theoretical study is based on a multilevel mathematical model, the numerical solution of which was carried out using implicit stable methods with parameter identification based on experimental data. **Results.** A decrease and stabilisation of contact resistance was established when using composite lubricant, most pronounced at a Cu–Al–Mn powder content of 10 % by volume. A reduced model of contact resistance evolution was proposed. **Scientific novelty.** For the first time, a generalised mathematical model of a detachable electrical contact with active composite lubricant has been developed, which takes into account the phase transformations of Cu–Al–Mn alloy particles and the mechanism of thermomechanical destruction of oxide films. The possibility of a step-like decrease in contact resistance under impulse currents is shown. **Practical value.** The results obtained can be used to improve the reliability of detachable electrical contact connections, predict changes in contact resistance during operation, and justify the choice of the composition of active electrical contact lubricants. References 37, tables 4, figures 7.

Key words: electrical contact, contact resistance, composite electrical grease, Camital, shape memory alloy, thermal, thermomechanical and tribological processes.

Проблема. Надійність розбірних електричних контактних з'єднань істотно знижується внаслідок зростання перехідного електричного опору, спричиненого термомеханічними деформаціями, окисленням контактних поверхонь та зменшенням ефективною площі контакту в процесі експлуатації. За результатами експлуатаційних і експериментальних досліджень відмови, пов'язані з деградацією контактів, становлять до третини загальної кількості пошкоджень електроустановок. Традиційні способи, зокрема застосування пасивних електропровідних мастил, здебільшого лише сповільнюють окислювальні процеси та не забезпечують активного відновлення контактного стану. У зв'язку з цим актуальним є розроблення моделей і технічних рішень, здатних описувати та забезпечувати стабілізацію перехідного опору електричних контактів за рахунок керованих термомеханічних процесів у зоні контакту. **Мета.** Встановлення закономірностей і взаємозв'язків процесів в електричних контактах шляхом експериментального дослідження та математичного моделювання еволюції перехідного опору контактних з'єднань з композитним мастилом, модифікованим порошком сплаву Cu–Al–Mn (Camital) з пам'яттю форми, з урахуванням взаємодії електричних, теплових, термомеханічних і трибологічних процесів у нормальних та аварійних режимах роботи електроустановок. **Методика.** Експериментальні дослідження виконано на моделях болтових контактних з'єднань алюмінієвих шин з використанням композитного мастила з вмістом порошку Cu–Al–Mn 5 % і 10 % за об'ємом, а також на контрольних зразках без мастила. Проводилися довготривалі вимірювання перехідного опору за сталої температури та при періодичних теплових навантаженнях. Теоретичне дослідження базується на багаторівневій математичній моделі, чисельний розв'язок якої здійснювався неявними стійкими методами з ідентифікацією параметрів за експериментальними даними. **Результати.** Встановлено зниження та стабілізацію перехідного опору при використанні композитного мастила, найбільш виражену за вмісту порошку Cu–Al–Mn 10 % за об'ємом. Запропоновано редуковану модель еволюції перехідного опору. **Наукова новизна.** Наукова новизна роботи полягає у розробленні та експериментальному обґрунтуванні нового типу композитного електротехнічного мастила для розбірних електричних контактів, що містить порошок сплаву Cu–Al–Mn з ефектом пам'яті форми, а також у встановленні фізичного механізму активної стабілізації перехідного опору контактних з'єднань за рахунок термомеханічного руйнування оксидних плівок у процесі циклічних теплових навантажень. **Практична значимість.** Отримані результати можуть бути використані для підвищення надійності розбірних електричних контактних з'єднань, прогнозування зміни перехідного опору в процесі експлуатації та обґрунтування вибору складу активних електроконтактних мастил. Бібл. 37, табл. 4, рис. 7.

Ключові слова: електричний контакт, перехідний опір, композитне електротехнічне мастило, Camital, сплав з пам'яттю форми, теплові, термомеханічні та трибологічні процеси.

Introduction. The state of contacts is determined by a number of independent and interdependent factors, the change of which in time is often random (Fig. 1). In general, the influencing factors can be divided into two conditional groups – internal and external. Internal factors, formed due to the functioning of the power supply

system itself, provide a quantitative and qualitative characteristic of processes (modes). External factors mainly reflect the characteristics of the environment: atmospheric pressure and lightning surges; humidity and air temperature; solar radiation; actions of service

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personnel, etc. To consider different levels of the power supply system, the set of factors can vary in number and composition [1–6].

Oxide films formed on the contacting surfaces of aluminum and copper have a significant electrical resistivity and reduce the effective area of the conductive contact, which leads to an increase in the transition

resistance and local overheating. The accumulation of oxide layers during operation accelerates the degradation of the contact connection, increases power losses and reduces its long-term reliability. Failure to solve this problem can lead to thermal destruction of contacts and failures of conductive assemblies.

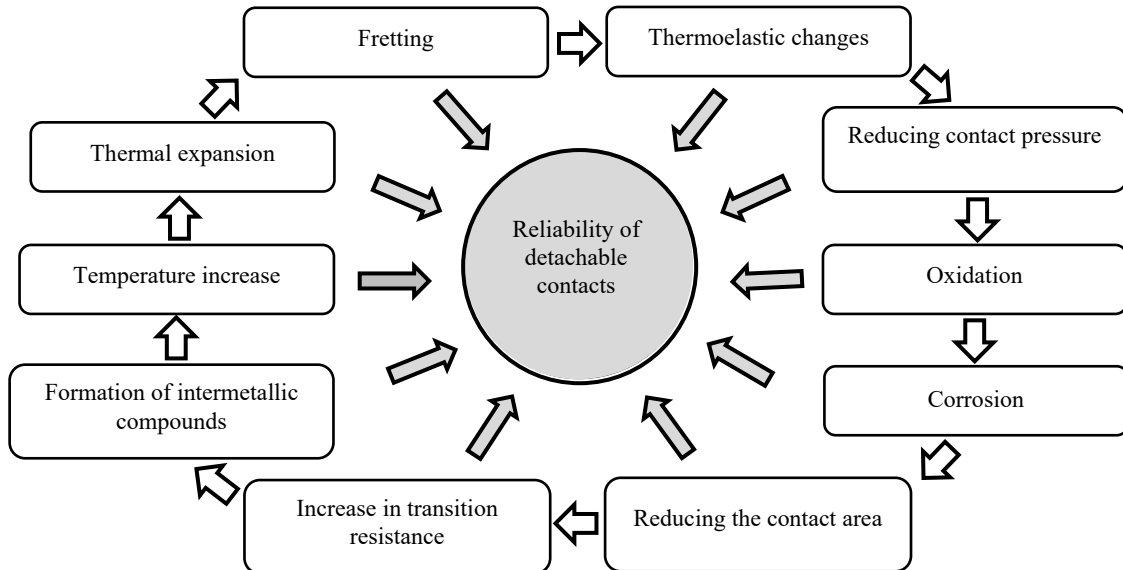


Fig. 1. Physical and chemical factors related to the reliability of electrical detachable contacts

To reduce the growth rate of oxide films, galvanic coatings, various methods of surface treatment, sealing and conductive greases are used [7–9]. The most common conductive and sealing greases are FOTU 571 Electrical Contact Grease, NO-OX-ID «A-Special» Electrical Contact Grease, Rheotemp™ 768G, CIATIM 221, etc. [10–17]. However, the above technical means only slow down the growth of oxide films and do not ensure their destruction. In previous studies, electrical lubricants were considered mainly as a passive means of sealing the contact space and reducing the environmental impact on the oxidation process of contact surfaces. Unlike known approaches, this work is the first to investigate a composite grease containing powder [18–23] of the Cu-Al-Mn alloy (Camital) [8, 9] with a shape memory effect, which performs the active function of thermomechanical influence on the contact surface and promotes the destruction of oxide films during operation. According to the results of the analysis of scientific publications, the authors are not aware of any works describing similar lubricant compositions or experimental studies of such a mechanism of action. The composition of this composite grease includes – electrically conductive grease and Camital intermetallic powder, which provides high electrical conductivity of the grease and destruction of oxide films. During the installation of the contact connection, the contacting surfaces are lubricated with a composite material. Tightening the bolted fastening to the nominal forces leads to deformation of the inner surface of the contact parts and particles of the shape memory alloy.

The goal of the work is to establish the regularities and interrelationships of processes in detachable electrical

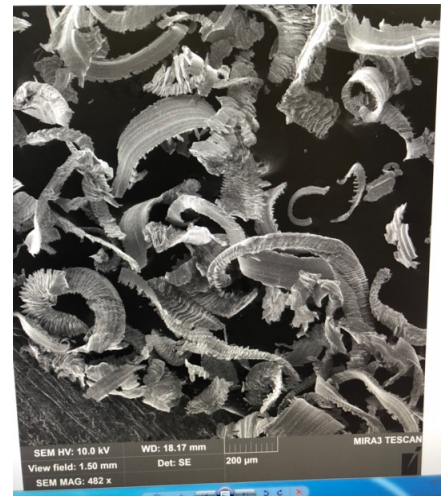
contacts by experimental research and mathematical modeling of the evolution of the transition resistance of contact connections with a composite electrical grease modified with Cu-Al-Mn alloy powder (Camital) with a shape memory effect based on the developed multi-level mathematical model, which takes into account the interaction of electrical, thermal, thermomechanical and tribological processes in normal and emergency operating modes of electrical installations.

Materials and methods. During long-term operation, films grow on the contacting surfaces, which leads to an increase in the transition resistance and a decrease in the operational life of the contact. This process is intensified by heating the contact with short-circuit currents. However, in the presence of a functional composite grease, heating the intermetallic particles with a shape memory effect leads to their restoration of the initial shape that they had before the contact was installed. Deformed, the intermetallic particles are displaced relative to the contact surface and destroy a significant part of the surface of the oxide films, which reduces the transition resistance and increases the operational life of the contact.

The study of the Camital intermetallic powder fractions was carried out on a TESCAN Mira 3 LMU scanning electron microscope (Fig. 2) designed to obtain an image of the object surface with high spatial resolution [24]. This microscope is used to study the shapes of particles and their surface morphology, analyze coatings, roughness and waviness of the surface of samples, fibers with specified properties, etc., at magnifications from 4 to 1,000,000 times with an accelerating voltage from 200 V to 30 kV.



a



b

Fig. 2. General view of the TESCAN Mira 3 LMU electron microscope (a); study of fractions of the Camital intermetallic powder (b)

Research on the influence of functional composite grease on the electrical resistance of the contact connection. To test the influence of grease on the electrical resistance of the contact connection, a series of experimental studies were conducted on models of detachable bolted contact connections – aluminum buses with dimensions of 100×50×5 mm, M12 bolted connections (bolt M12×30 mm, hexagonal nut M12, two flat washers M12) (Fig. 3). Six samples of bolted connections were used: samples No. 1 and No. 2 were coated with electrically conductive grease with fraction 1 powder (v1), samples No. 3 and No. 4 were coated with grease with fraction 2 powder (v2), control samples No. 5 and No. 6 were without grease.

Electrically conductive grease with fraction 1 powder (v1) contained 95 % (by volume) CIATIM 221 and 5 % Camital intermetallic powder. The grease with powder fraction No. 2 (v2) contained 90 % CIATIM 221 and 10 % Camital intermetallic powder. The grease was applied in a thin layer to the contact surfaces of the aluminum tires (Fig. 4). A torque wrench (Intertool XT-9003) was used to control the tightening torque of the bolted joint, which was 40 N·m.



Fig. 3. Preparation for the experiment

The experiment consisted of periodic measurement of the electrical resistance of contact connection samples (Fig. 5). The duration of the experiment was from March 11, 2024 to April 1, 2025.



Fig. 4. Application of functional composite material to contact surfaces



Fig. 5. Measuring the resistance of the contact connection

Samples of contact connections No. 1, No. 3 and No. 5 were periodically heated in an oven to a temperature of 120 °C, held at this temperature for 4 min., and natural cooling to a temperature of 21 °C. In this way, overheating of the contacts was simulated. Samples of contact connections No. 2, No. 4 and No. 6 were constantly in the room at a temperature of 21 °C with an air humidity of 45 %.

Results and discussion. The results of experimental studies are presented in Tables 1, 2 (the first and last experiments, respectively), and in Fig. 6 all experimental measurements.

Table 1

Results of contact resistance measurement on 11.03.2024 and 16.03.2024

Sample No.	Lubrication type	The resistance value of the contact connection. Measurements on 11.03.2024, $\mu\Omega$					The resistance value of the contact connection. Measurements on 16.03.2024, $\mu\Omega$				
		1	2	3	4	average value	1	2	3	4	average value
		1	v1	22,37	22,54	22,92	22,54	22,59	22,05	22,16	22,27
2	v1	21,24	22,05	21,18	21,24	21,43	20,97	21,02	20,86	21,02	20,97
3	v2	19,01	18,96	18,91	19,07	18,99	19,07	19,34	18,69	18,85	18,99
4	v2	20,15	20,1	20,48	20,59	20,33	20,1	20,15	20,1	20,21	20,14
5	without lubrication	31,75	31,8	30,72	31,15	31,36	31,64	31,69	31,75	31,75	31,71
6	without lubrication	28,66	28,5	28,66	28,77	28,65	27,36	28,06	27,41	27,36	27,55

Table 2

Results of contact resistance measurement on 04.03.2025 and 01.04.2025

Sample No.	Lubrication type	The resistance value of the contact connection. Measurements on 04.03.2025, $\mu\Omega$					The resistance value of the contact connection. Measurements on 01.04.2025, $\mu\Omega$				
		1	2	3	4	average value	1	2	3	4	average value
		1	v1	25,74	25,72	25,67	25,78	25,73	25,73	25,79	25,79
2	v1	21,98	22,02	21,78	21,84	21,91	22,03	21,99	21,82	21,85	21,92
3	v2	20,68	20,86	20,84	20,9	20,82	20,71	20,84	20,82	20,79	20,79
4	v2	20,98	21,06	20,85	20,78	20,92	21,01	20,98	20,86	20,82	20,92
5	without lubrication	39,05	39,15	39,12	39,07	39,10	39,04	39,2	39,15	39,06	39,11
6	without lubrication	28,67	29,13	29,05	29,01	28,97	28,71	29,11	29,01	29,02	28,96

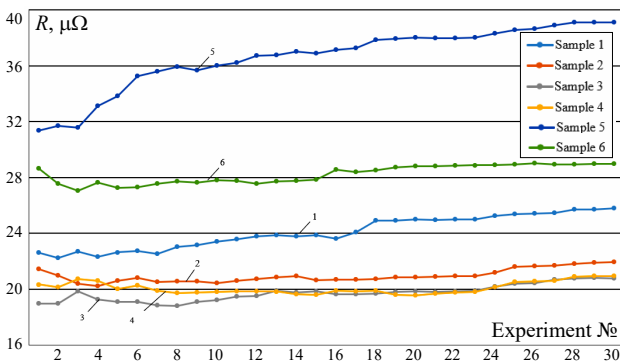


Fig. 6. Results of experimental measurements of contact connection resistance in the period from 11.03.2024 to 01.04.2025

Analysis of experimental research results. The presence of Camital intermetallic powder increases the electrical conductivity of contacts – reduces the initial resistance of contacts by 65 % (resistance of contacts No. 3 and No. 5).

Long-term exposure of contact connections No. 2, No. 4 and No. 6 at a constant temperature of 21 °C and relative humidity of 45 % does not lead to changes in the initial resistance of the contact connection during the year (conclusion taking into account the relative measurement error of 5 %).

The influence of the volume content of intermetallic powder in the functional grease on the initial resistance of the contact and the subsequent increase in resistance during periodic heating of the contacts is significant. This conclusion is confirmed by a comparison of the initial resistances of contacts No. 1 (powder content 5 %) and No. 3 (powder content 10 %) – the difference in the initial resistances is 19 %, and the final resistance is 23 %.

Periodic heating of contacts in the absence of Camital intermetallic powder in the grease leads to an increase in the resistance of the contact connection – contact No. 5 by 25 %. The presence of Camital

intermetallic powder in the grease in a volume of 10 % practically eliminates the effect of periodic temperature changes on the resistance of the contact connection.

Theoretical modeling of processes in a detachable electrical contact joint containing a composite grease with Camital alloy powder. In an aluminum-aluminum (or Cu-Cu) contact joint with grease and Cu-Al-Mn powder, 4 interrelated processes occur simultaneously:

- formation of contact electrical conductivity. The contact resistance is determined by: the real contact area; the thickness and integrity of oxide films; the number of microcontacts created by the powder;
- thermomechanical cycle. Current load → heating → phase transformation of the shape memory alloy → restoration of the particle shape → local mechanical stresses → destruction of oxides;
- «microscraper» mechanism. Sharp edges of Camital particles: concentrate stresses; perform cyclic microcutting of the oxide film; periodically «renew» the metal-metal contact;
- chemical aging. Without powder – monotonous growth of the oxide area and thickness. With powder – competition of two processes: oxide growth; its thermomechanical destruction.

The structure of the mathematical model is multilevel, the system is nonlinear, transient, with internal feedback. The general structure of the mathematical model consists of 5 interconnected subsystems:

1. Electrical – contact resistance, current, current density;
2. Thermal – heating and cooling of the contact;
3. Thermomechanical (SMA) – deformation of Cu-Al-Mn particles;
4. Tribological – destruction of the oxide film;
5. Evolution of contact resistance.

1. The total contact resistance is defined as the sum of the components [25, 26]:

$$R_c(t) = R_b + R_{ox}(t), \quad (1)$$

where $R_c(t)$ is the total contact resistance, Ω ; R_b is the volume resistance of the busbar material, Ω ; $R_{ox}(t)$ is the resistance of the oxide film, Ω .

2. Current I and current density J :

$$I(t) = U(t)/R_c(t); \quad (2)$$

$$J(t) = I(t)/A_{ef}(t), \quad (3)$$

where $I(t)$ is the current, A; $U(t)$ is the voltage, V; $A_{ef}(t)$ is the effective area of the electrical contact, m^2 .

3. Thermal subsystem (contact heating). The contact is considered as a concentrated heat capacity. The heat balance equation [27, 28]:

$$C_{th} \frac{dT}{dt} = I^2(t)R_c(t) - h_{th}(T - T_0), \quad (4)$$

where T is the contact temperature, K; T_0 is the ambient temperature, K; C_{th} is the contact heat capacity, $J \cdot K^{-1}$; h_{th} is the heat transfer coefficient, $W \cdot K^{-1}$.

4. Thermomechanical model of Cu-Al-Mn powder (SMA). Kinetics of phase transformation. The variable is introduced – austenite fraction $\xi(t)$ [29–31]:

$$\frac{d\xi}{dt} = k_\xi [H(T - A_s)(1 - \xi) - H(M_s - T)\xi], \quad (5)$$

where ξ is the austenite fraction, dimensionless; k_ξ is the kinetic coefficient, s^{-1} ; A_s , M_s are the phase transition temperatures, K; H is the Heaviside function, p.u.

Recoverable deformation of Camital powder particles:

$$\varepsilon(t) = \varepsilon_0 \cdot \xi(t), \quad (6)$$

where $\varepsilon(t)$ is the recoverable deformation of powder particles, p.u.; ε_0 is the initial recoverable deformation of powder particles, p.u.

Contact stresses created by a powder particle:

$$\sigma_p(t) = E_p \cdot \varepsilon(t), \quad (7)$$

where $\sigma_p(t)$ is the local contact stress created by the powder particle, Pa; E_p is the elastic modulus of the Cu-Al-Mn alloy, Pa.

5. Oxide film model. Evolution of oxide thickness [32, 33]:

$$\frac{dh}{dt} = k_{ox} - k_{br} N_p F(\sigma_p), \quad (8)$$

where h is the oxide thickness, m; k_{ox} is the oxide growth rate, $m \cdot s^{-1}$; k_{br} is the oxide film destruction coefficient, $m^2 \cdot s^{-1}$; N_p is the particle volume concentration, m^{-1} .

Oxide destruction function

$$F(\sigma_p) = \begin{cases} 0, & \text{if } \sigma_p < \sigma_{ox}; \\ \left(\frac{\sigma_p - \sigma_{ox}}{\sigma_{ox}} \right)^n, & \text{else } \sigma_p \geq \sigma_{ox}, \end{cases} \quad (9)$$

where σ_{ox} is the strength limit of the oxide film, Pa; n is the nonlinearity index of the oxide destruction mechanism, dimensionless.

6. The relationship between the oxide film and resistance.

The resistance of the oxide layer:

$$R_{ox} = \rho_{ox} h(t) / A_{ef}(t), \quad (10)$$

where ρ_{ox} is the electrical resistivity of the oxide film, $\Omega \cdot m$.

The rate of change of the effective contact area:

$$\frac{dA_{ef}}{dt} = k_A [N_p \varepsilon(t) - \alpha_A h(t)], \quad (11)$$

where k_A is the kinetic coefficient of contact area formation, $m^2 \cdot s^{-1}$; α_A is the coefficient of contact area reduction due to oxidation, $m^{-1} \cdot s^{-1}$.

Therefore, the complete system of equations has the form:

$$R_c(t) = R_b + \frac{\rho_{ox} h(t)}{A_{ef}(t)};$$

$$I(t) = U(t) / R_c(t);$$

$$C_{th} \frac{dT}{dt} = I^2(t) R_c(t) - h_{th}(T - T_0);$$

$$\frac{d\xi}{dt} = k_\xi [H(T - A_s)(1 - \xi) - H(M_s - T)\xi]; \quad (12)$$

$$\varepsilon(t) = \varepsilon_0 \cdot \xi(t);$$

$$\sigma_p(t) = E_p \cdot \varepsilon(t);$$

$$\frac{dh}{dt} = k_{ox} - k_{br} N_p F(\sigma_p);$$

$$\frac{dA_{ef}}{dt} = k_A [N_p \varepsilon(t) - \alpha_A h(t)]$$

Due to the system of differential equations is rigid due to the significant difference in the hourly scales of thermal, mechanical and chemical processes, for its numerical decoupling, the implicit stable BDF and Radau methods [34, 35] are used. Numerical modeling using the Python software environment (NumPy, SciPy, Matplotlib libraries) is carried out.

The results of numerical modeling and experimental investigations are presented in Fig. 7. The solid lines correspond to a numerical model drawn from a reduced, physically reasonable model. Each line was built with individual parameters identified for the corresponding experimental specimen.

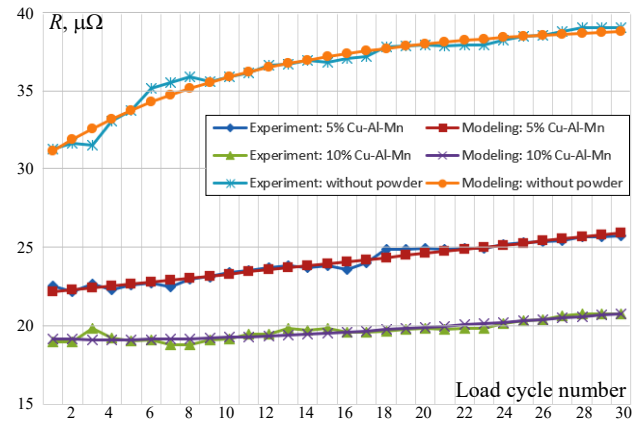


Fig. 7. Evolution of the contact resistance in a detachable contact connection of flat electrical aluminum busbars (experimental data and simulation)

Mathematical derivation of a reduced model with basic variables: $h(t)$ – oxide melt thickness; $A_{ef}(t)$ – effective contact area; $R(t)$ – transition resistance [36, 37].

Key equations:

$$\frac{dh}{dt} = k_{ox} - k_{br} N_p F(\sigma_p); \quad (13)$$

$$\frac{dA_{ef}}{dt} = k_A [N_p \varepsilon(t) - \alpha_A h(t)]; \quad (14)$$

$$R(t) = R_b + \frac{\rho_{ox} h(t)}{A_{ef}(t)}. \quad (15)$$

Averaging the thermomechanical response (key step). The temperature and phase state of the SMA particles change faster than the contact degradation:

$$\tau_T \ll \tau_h, \tau_A. \quad (16)$$

Therefore, the cycle-averaged effective strain is introduced:

$$\langle \varepsilon \rangle = \frac{1}{\Delta t} \int_0^{\Delta t} \varepsilon(T(t)) dt = \varepsilon_{eff} = \text{const}. \quad (17)$$

Similarly:

$$\langle F(\sigma_p) \rangle = F_{eff}. \quad (18)$$

Linearization of the evolution of the oxide film.

Substituting (17) into (13):

$$\frac{dh}{dt} = k_{ox} - k_{br} N_p F_{eff}. \quad (19)$$

We denote:

$$\alpha_h = k_{ox}, \beta_h = k_{br} N_p F_{eff}. \quad (20)$$

We get:

$$h(t) = h_0 + (\alpha_h - \beta_h) t. \quad (21)$$

Quasi-stationary contact area. For A_{ef} , we solve (14) with constant coefficients:

$$\frac{dA_{ef}}{dt} = k_A (N_p \varepsilon_{eff} - \alpha_A h). \quad (22)$$

Substituting (21) into (22) and integrating, we obtain:

$$A_{ef}(t) = A_0 + C(1 - e^{-\gamma t}), \quad (23)$$

where

$$\gamma \sim k_A \alpha_A, C \sim \frac{N_p \varepsilon_{eff}}{\alpha_A}. \quad (24)$$

Derivation of the reduced equation for $R(t)$.

Substituting (21), (23) into (12) and performing the Taylor series expansion with small deviations:

$$\frac{h(t)}{A_{ef}(t)} = a_0 + a_1 t - a_2 (1 - e^{-\gamma t}). \quad (25)$$

After grouping the members, we finally obtain a reduced mathematical model:

$$R(t) = R_0 + \alpha t - \beta (1 - e^{-\gamma t}), \quad (26)$$

where R_0 is the initial contact resistance of the contact connection, $\mu\Omega$; α is the rate of contact degradation due to oxidation, $\mu\Omega/\text{cycle}$; β is the integral parameter of the efficiency of thermomechanical self-cleaning of the contact by Cu-Al-Mn powder, $\mu\Omega$; γ is the intensity of the thermomechanical effect (effective frequency of thermocycles), cycle^{-1} .

Estimation of confidence intervals of parameters.

Estimation method. Parameters $\theta = (R_0, \alpha, \beta)$ were identified by the least squares method:

$$\min_{\theta} \sum_{i=1}^N [R_{\text{exp}}(t_i) - R(t_i, \theta)]^2. \quad (27)$$

The covariance matrix is estimated as:

$$C_{\theta} = \sigma^2 (J^T J)^{-1}, \quad (28)$$

where J is the Jacobi matrix.

Tables 3, 4 present the confidence intervals.

Table 3
Confidence intervals CI (95 %). Contact with 10 % Cu-Al-Mn

Parameter	Estimation	95 % CI
$R_0, \mu\Omega$	19,24	[18,9; 19,6]
$\alpha, \mu\Omega/\text{cycle}$	0,099	[0,085; 0,113]
$\beta, \mu\Omega$	1,5	[1,30; 1,70]

Table 4
Confidence intervals CI (95 %). Contact with 5 % Cu-Al-Mn

Parameter	Estimation	95 % CI
$R_0, \mu\Omega$	22,1	[21,7; 22,5]
$\alpha, \mu\Omega/\text{cycle}$	0,135	[0,120; 0,150]
$\beta, \mu\Omega$	0,15	[0,05; 0,25]

Conclusion: the parameter β is statistically significant only at 10 % powder content, which is consistent with the physics of the process.

The previous theoretical analysis concerned the processes of heating and cooling of the contact connection by electric load currents in accordance with the power consumption schedule. Let us consider a model for processes with the appearance of short-circuit currents – pulsed thermal mode.

In the short-circuit mode, the current has a pulsed nature:

$$I(t) = I_k e^{-t/\tau_1}, \quad (29)$$

where I_k is the initial (peak) value of the short-circuit pulsed current; τ_1 is the time constant of the short-circuit pulsed current decay.

Thermal equation:

$$C_{th} \frac{dT}{dt} = I_k^2 R_c e^{-2t/\tau_1} - h_{th}(T - T_0). \quad (30)$$

The solution gives the peak temperature T_{max} .

Pulsed destruction of oxide. In (13) we introduce the pulsed component:

$$\frac{dh}{dt} = k_{ox} - k_{br} N_p F(\sigma_p) \delta(t - t_k), \quad (31)$$

where t_k is the short circuit moment.

Integrating (31), we obtain:

$$\Delta h_k = -k_{br} N_p F(\sigma_p(T_{\text{max}})). \quad (32)$$

Hopping resistance model. After a short circuit pulse:

$$R(t_k^+) = R(t_k^-) - \Delta R_k, \Delta R_k > 0; \quad (33)$$

$$\Delta R_k = K_R N_p \varepsilon(T_{\text{max}}), \quad (34)$$

where K_R is the effective coefficient of electrocontact conversion of thermomechanical action into resistance change, $\Omega \cdot \text{m}^3$; t_k^- , t_k^+ are the time points before and after the short circuit.

Analysis of the structure of the mathematical model and the physical mechanisms embedded in it shows that under pulsed thermal loads characteristic of short circuit currents, in a contact connection with an electrical grease modified with Cu-Al-Mn powder, a short-term decrease in the transition resistance is possible due to thermomechanical activation of alloy particles.

Conclusions.

1. The work uses a multi-level physically based mathematical model of processes in a detachable electrical contact connection with electrical grease modified with Cu-Al-Mn alloy powder with shape memory effect.

2. The model takes into account the interrelationship of electrical, thermal, thermomechanical and tribological processes and describes the evolution of the transition resistance of the contact connection under conditions of cyclic electrical loading and emergency modes.

3. It is shown that the introduction of Cu-Al-Mn powder fundamentally changes the mechanism of electrical contact degradation: instead of a monotonic increase in the transition resistance, a mode of competition between oxidation processes and thermomechanical destruction of oxide films is realized.

4. Numerical simulations performed using the implicit stable BDF and Radau methods provided a correct solution to the rigid system of differential equations and demonstrated good agreement with experimental data.

5. It has been experimentally established that at a concentration of Cu-Al-Mn powder of 10 % by volume, the maximum effect of reducing and stabilizing the transition resistance is achieved – up to 45-48 % compared to a traditional contact connection without powder.

6. The parameters of the reduced model have a clear physical meaning, and their identification allows to quantitatively assess the effectiveness of thermomechanical self-cleaning of contacts and predict the long-term reliability of electrical connections.

7. The obtained mathematical model allows to describe the potential impact of short-circuit pulsed currents on the state of the electrical contact, which may be the subject of further experimental research.

8. The results obtained confirm the possibility of creating a new class of «active electrical contact greases» capable of thermocyclic self-healing of the contact surface and slowing down the electrochemical aging of contact connections.

9. The results obtained can serve as a scientific basis for conducting full-scale standard tests as the next stage of research.

Conflict of interest. The authors declare no conflict of interest.

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