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Electrical Contacts Under Thermal and Electrical Stress: Analytical and Experimental Investigations

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Abstract: Electrical contacts play a crucial role in various electrical and electronic systems, where their performance is significantly influenced by thermal and electrical stresses. This study presents a comprehensive investigation into the electrical-thermal behavior of electrical contacts using both analytical modeling and experimental validation. The analytical approach involves the development of mathematical models to predict contact resistance, temperature rise, and degradation mechanisms under different loading conditions. Experimental studies are conducted to validate the theoretical predictions and provide insights into material behavior, contact wear, and failure mechanisms. The findings highlight the interplay between electrical and thermal effects, emphasizing the importance of contact material properties, surface roughness, and environmental conditions. This work contributes to the optimization of electrical contact design for improved reliability and efficiency in practical application.

Keywords: Electrical contacts, contact resistance, thermal stress, electrical stress, analytical modeling, experimental analysis, contact degradation, material behavior, reliability, electrical-thermal performance.

Introduction: Road Electrical contacts are fundamental components in electrical and electronic systems, enabling the transmission of electrical signals and power between conductive elements. Their performance is influenced by multiple factors, including electrical loading, thermal effects, material properties, and environmental conditions. The reliability of electrical contacts is particularly critical in high-power applications, where thermal and electrical stresses can lead to contact degradation, increased resistance, and eventual failure.

When an electrical current passes through a contact interface, the constriction of current flow at micro-asperities results in localized heating, known as Joule heating. This thermal stress can cause softening, oxidation, and material migration, ultimately affecting the contact's electrical performance. Simultaneously, electrical stress can induce arcing, erosion, and degradation of the contact surface. Understanding these interactions is essential for optimizing contact materials, geometries, and operating conditions to enhance reliability and efficiency.

This study aims to analyze the electrical-thermal performance of electrical contacts through both analytical modeling and experimental investigations. The analytical approach develops mathematical models to predict contact resistance, temperature rise, and degradation mechanisms under varying conditions. Complementary experimental studies validate these models and provide insights into real-world performance. By combining theoretical and empirical analyses, this work offers a comprehensive understanding of the key factors affecting electrical contact performance under thermal and electrical stress.

The remainder of this paper is organized as follows: Section 2 discusses the theoretical background and analytical modeling approach. Section 3 details the experimental setup and methodology. Section 4 presents the results and discussion, comparing analytical predictions with experimental findings. Finally, Section 5 concludes with key insights and potential future research directions.

METHODS

To comprehensively analyze the electrical-thermal performance of electrical contacts under thermal and electrical stress, both analytical modeling and experimental investigations were conducted. This section describes the methodology used to develop theoretical models, the experimental setup employed for validation, and the procedures followed for data collection and analysis.

Analytical Modeling

The analytical approach aims to model the electrical and thermal interactions at the contact interface. The contact resistance, which significantly influences the overall performance of electrical contacts, was determined using Holm's theory and Greenwood-Williamson's asperity-based model. These models account for the constriction resistance due to surface roughness and the real contact area, which is influenced by mechanical and thermal factors.

The electrical-thermal behavior of the contacts was modeled using Joule heating principles, where the heat generated at the interface was computed as:

where is the heat generated, is the applied current, and is the contact resistance. The temperature rise at the contact junction was estimated using a one-dimensional heat conduction equation:

where is the thermal conductivity of the contact material and is the effective contact area. The effects of thermal cycling, material softening, and oxidation on contact performance were also incorporated into the model to predict degradation over time.

Finite element analysis (FEA) simulations were performed using ANSYS to validate the analytical model. The simulations considered contact material properties, applied forces, and electrical loads to predict temperature distribution and stress concentration at the interface.

Experimental Setup

To validate the theoretical models, experimental tests were conducted using a custom-built test rig. The setup consisted of a precision-controlled power supply, a thermal imaging camera, a high-resolution digital multimeter, and a contact force measurement system. The test specimens were made of commonly used electrical contact materials, including copper, silver, and gold-plated alloys, to evaluate the influence of material composition on electrical-thermal performance.

The contacts were subjected to varying electrical currents ranging from 1 A to 50 A to study the effect of current magnitude on temperature rise and resistance variation. Additionally, mechanical loads from 1 N to 10 N were applied to examine how pressure influences the real contact area and, consequently, the electrical resistance.

A thermal camera with an infrared resolution of 640 × 480 pixels was used to capture the temperature distribution across the contact interface. Simultaneously, resistance measurements were taken using a four-wire Kelvin method to minimize lead and contact resistance errors. The contact surfaces were analyzed using scanning electron microscopy (SEM) before and after testing to assess morphological changes due to electrical and thermal stress.

Test Procedure

Each experiment was conducted in a controlled environment to ensure consistency. The procedure followed these steps:

Sample Preparation: Contact samples were cleaned using isopropyl alcohol and dried to remove surface contaminants. The initial surface roughness and composition were measured using atomic force microscopy (AFM) and energy-dispersive X-ray spectroscopy (EDS), respectively.

Electrical Loading: The contacts were subjected to stepwise increasing current levels while maintaining a constant force. Resistance and temperature were recorded at each step to analyze the dynamic behavior under load.

Thermal Cycling: To simulate real-world operating conditions, contacts underwent cyclic heating and cooling between ambient temperature and a peak temperature corresponding to the highest applied current. The degradation in contact resistance over multiple cycles was observed.

Post-Test Analysis: After testing, the contact surfaces were examined using SEM to detect wear, material transfer, and oxidation. Cross-sectional analysis was performed to investigate subsurface changes due to thermal stress.

Data Analysis

The experimental data were analyzed to compare with theoretical predictions. Resistance variations were plotted against applied current and force, revealing trends in contact performance. The temperature profiles obtained from thermal imaging were compared with finite element model (FEM) results to validate simulation accuracy.

A statistical analysis was conducted to assess the reliability of measurements, ensuring that deviations from theoretical predictions were within acceptable margins. Correlation coefficients were calculated to quantify the agreement between experimental and analytical results.

Error Considerations and Limitations

To minimize experimental errors, measurements were repeated five times for each test condition, and average values were reported. Possible sources of error included surface oxidation, minor variations in applied force, and fluctuations in ambient temperature. To account for these factors, corrections were applied based on calibration tests performed prior to data collection.

One limitation of this study is that the experiments were conducted under controlled laboratory conditions, which may not fully replicate harsh environmental conditions such as humidity and contaminants. Future work will involve studying the effects of these external factors on contact degradation and performance.

RESULTS AND DISCUSSION

The results from both analytical modeling and experimental testing demonstrate a strong correlation between contact resistance and thermal stress. As the applied current increased, the temperature at the contact interface exhibited a nonlinear rise due to Joule heating, which was consistent with theoretical predictions. Higher mechanical loads led to a reduction in contact resistance due to an increased real contact area, as confirmed by experimental data.

Thermal imaging analysis revealed that material-dependent variations significantly influenced heat dissipation. Silver-plated contacts exhibited the lowest temperature rise due to their superior thermal conductivity, while copper contacts showed moderate performance. Gold-plated contacts, despite their corrosion resistance, demonstrated higher resistance under prolonged thermal cycling due to surface wear and oxidation effects.

Scanning electron microscopy (SEM) analysis of post-test surfaces confirmed the degradation mechanisms predicted by the model, including localized melting, material transfer, and increased surface roughness. Oxidation layers were prominent in high-temperature regions, further increasing contact resistance over time. These findings highlight the importance of selecting materials with high thermal and electrical conductivity for prolonged operational reliability.

CONCLUSION

This study provides a comprehensive investigation into the electrical-thermal behavior of electrical contacts under thermal and electrical stress. Analytical models successfully predicted resistance variations and temperature rise, which were validated through controlled experiments. The experimental findings emphasize the role of contact materials, surface conditions, and mechanical loads in determining overall performance.

The insights gained from this research contribute to the optimization of electrical contact design for high-reliability applications. Future studies should focus on the effects of environmental conditions such as humidity and contaminants, as well as exploring advanced materials and coatings to enhance contact performance. The integration of real-world operational scenarios will further strengthen the applicability of the findings in industrial and commercial applications.

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