Theory and Practice of Science and Technology
2025, VOL. 6, NO. 10, 165-168
DOI: 10.47297/taposatWSP2633-456933.20250610

A Review on Conductive-Wear-Resistant Integrated Research of Graphene/Copper Composite Coatings for Electrical Contacts

Yitong Tang

Beijing Institute of Petrochemical Technology, Beijing, 102617, China

ABSTRACT

Modern power systems rely on critical switching components, with the core being power contacts. Contact performance determines the efficiency, lifespan, and safety of power equipment, where conductivity and wear resistance are crucial but often trade off against each other. Current pure copper and copper alloy contacts, while offering good conductivity, suffer from poor wear resistance, which can damage power equipment. Therefore, exploring new contact materials that synergistically enhance both conductivity and wear resistance is of great significance. This article mostly adopts literature research and inductive summarization methods, and innovatively combines them on this basis to obtain more practical results. Starting from graphene and copper composite materials, this study explores their wear resistance and conductivity, aiming to achieving the integration of conductivity and wear resistance, and making the application research of graphene more diversified.

KEYWORDS

Power system; Security; Conductivity; Wear resistance; Graphene.

1 Significance of the Research Topic and Overview of its Current Status Worldwide

1.1 Topic Significance

The safe and stable operation of modern power systems highly relies on the reliability of key on-off components such as switches, relays, and circuit breakers, and the core of their performance lies in the power contacts. Contact points are responsible for frequently connecting and disconnecting currents, and their performance directly determines the efficiency, service life, and operational safety of power equipment. Among the numerous performance indicators of contacts, excellent conductivity ensures efficient transmission of electrical energy and reduces Joule heat loss, while excellent wear resistance ensures stable contact resistance and resistance to mechanical wear and arc erosion during long-term service of contacts. However, in practice, it has been found that the conductivity and wear resistance of contact materials often exhibit a contradictory relationship. The widely used pure copper and copper alloy contacts currently have excellent conductivity close to silver, but their inherent defects of low hardness and poor wear resistance make them prone to adhesive wear, material transfer, and arc erosion under frequent operation and harsh working conditions, ultimately leading to a sharp increase in contact resistance, overheating and melting of contacts, and even failure, becoming a bottleneck problem restricting the development of highly reliable and long-life power equipment. Therefore, exploring new contact materials and structural designs that can synergistically enhance conductivity and wear resistance has significant engineering application value and theoretical significance.

1.2 Problem Statement

Resolving the contradiction between the conductivity and wear resistance of copper based contacts, and achieving the integrated and coordinated improvement of their performance, is a key scientific problem that urgently needs to be broken through in this field. To address this issue, researchers have attempted various technological approaches. On the one hand, by introducing second phase reinforcements (such as ceramic particles, carbon materials) to enhance the hardness and wear resistance of the copper matrix, this method often significantly damages the overall conductivity of the material due to the introduction of insulating phases or excessive interfacial resistance. Related studies have shown that adding ceramic particles to copper matrix can increase hardness, but it leads to a significant decrease in conductivity; When adding conductive reinforcements such as carbon nanotubes, if the interface bonding is poor or the dispersion is uneven, its conductive advantages are difficult to fully utilize. On the other hand, optimizing contact surface treatment processes (such as electroplating, thermal spraying, magnetron sputtering, etc.) to prepare functional coatings to improve surface performance. However, coatings prepared by such processes generally face challenges such as insufficient bonding strength with the substrate, difficult control of internal stress in the coating, poor self uniformity, and poor long-term service stability, all of which significantly affect the wear resistance life of the coating. In recent years, introducing two-dimensional graphene materials with intrinsic ultra-high conductivity, super strong mechanical properties, and excellent thermal stability into copper matrix to form composite materials has been regarded as one of the most promising directions to break through the above bottlenecks. The core idea is to utilize the unique physical and chemical properties of graphene to simultaneously optimize the carrier transport path and strengthen the matrix at the microscale, achieving a synergistic gain in conductivity and wear resistance. Experiments have shown that the introduction of graphene can effectively reduce the friction coefficient and wear rate of copper based composites, while maintaining a high level of electrical conductivity [1]. However, the effective dispersion of graphene in copper based composite materials, the interface bonding state with the substrate, and the orientation and arrangement inside the coating are key structural factors that still constrain the practical application of this material system. How to precisely control them to achieve the construction of conductive networks and maximize the enhancement effect remains a core challenge.

2 Research Objectives, Research Content

2.1 Research Objectives

This project focuses on the optimization of power contact performance, aiming to break through the inherent contradiction between high conductivity and strong wear resistance. It systematically explores the interface bonding, current transport, and friction and wear behavior regulation mechanism of graphene in copper based composite materials, clarifies its multi-scale collaborative strengthening principle, and proposes an innovative design strategy for copper based composite coatings based on precise control of graphene spatial orientation. The goal is to achieve synergistic improvement of conductivity wear integration performance and breakthroughs in engineering applications.

(1) How to achieve synergistic improvement of conductivity and wear resistance performance: By clarifying the conductive network construction mechanism and wear resistance enhancement mechanism of graphene/copper composite materials, the regulation law of microstructure on macroscopic performance is clarified [1], providing theoretical basis for the design of high reliability power contacts.

(2) The key role of graphene: graphene synergistically optimizes performance in copper based composite materials through a dual mechanism. In terms of conductivity, its high intrinsic carrier mobility can compensate for the grain boundary scattering loss of copper. When graphene sheets and copper sheets are alternately arranged, efficient electron transport channels can be constructed, significantly improving the conductivity of composite materials [2].In terms of wear resistance, graphene layers hinder dislocation movement through pinning effect, enhancing the matrix's resistance to plastic deformation; At the same time, a continuous transfer film is formed at the friction interface, converting sliding friction into interlayer shear of graphene, significantly reducing the friction coefficient (by up to 30%) and adhesive wear risk [3]. The key to achieving the above performance lies in regulating the spatial distribution of graphene: horizontal orientation prioritizes optimizing in-plane conductivity, while vertical orientation enhances load-bearing capacity; Ball milling or chemical modification can improve interfacial bonding and inhibit nanoparticle aggregation [4].

(3) Advantages of graphene/copper composite coatings in electrical contacts: The graphene/copper composite coating resolves the inherent contradiction between conductivity and wear resistance in traditional power contacts through material gene recombination. After applying a 50-200 μm composite coating on the surface of the circuit breaker's moving contact, the contact resistance fluctuation rate is significantly lower than that of pure copper contacts, effectively suppressing contact failures during switching. Meanwhile, the interlayer sliding properties and high thermal conductivity of graphene dissipate arc energy, reducing arc erosion pit density and extending device lifespan [5]. In contacts, the graphene/copper composite coating exhibits a markedly lower wear rate compared to pure copper. Additionally, incorporating 0.2% graphene by volume reduces the friction coefficient by 23% and the wear rate by 90% [6].

2.2 Research Content

2.2.1 Synergistic Strengthening Mechanism of Intragranular/Intergranular Graphene[7]

Plasma ball milling hot rolling process: in-situ exfoliation of graphene and dispersion in copper matrix, forming coexisting structures within the crystal (average 22nm) and between crystals (average 132nm). Intragranular graphene acts as a dislocation source to promote proliferation, while intergranular graphene hinders grain boundary slip, synergistically enhancing dislocation storage capacity, resulting in a tensile strength of 497 MPa (↑ 25.5%) for the composite material, while maintaining a conductivity of 84.2% IACS (almost no loss).

2.2.2 Development of Graphene Lubricant Additives and Composite Coatings [6]

The Cu/graphene additive prepared by plasma assisted ball milling has excellent dispersibility in base oil and the best anti friction performance (friction coefficient reduced by 50% compared to pure oil), while W/graphene has poor effect due to high metal hardness and irregular morphology. The cold spray Cu-W-grained coating achieves a synergistic effect of "hard phase (W)+lubricating phase (graphene)", reducing the friction coefficient to 0.16, lowering the wear rate by an order of magnitude, and suppressing the formation of brittle friction layer .

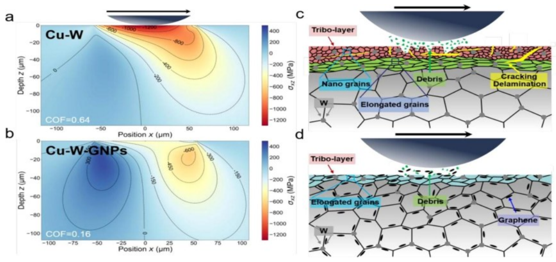

Figure 1 Development of Graphene Lubricant Additives and Composite Coatings [6]

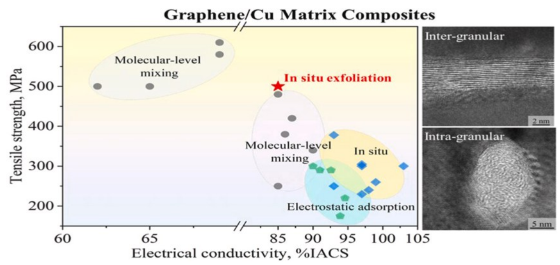

Figure 2 Intragranular/Intergranular Graphene Synergistic Reinforcement Mechanism [7]

3 Research Methods, Technical Route , Feasibility Analysis and Innovation of The Topic

3.1 Research Methodology

3.1.1 Inductive Summary Method

The first step of this project is to exclude literature that is repetitive and has little relevance to the content of the article, outdated literature, and literature with unclear arguments and evidence. Secondly, organize and summarize the included literature, with a focus on describing how to improve the conductivity wear resistance of graphene/copper through rational orientation and arrangement. Finally, summarize the methods and issues.

3.1.2 literature Research Method

Widely collect academic literature on the methods of improving conductivity wear resistance of graphene/copper coatings at home and abroad, and through the review and summary of existing literature from January 2020 to July 2025, provide the current research status and problems encountered in graphene/copper.

3.2 Technical Route

This project first elaborates on the importance of improving the conductivity wear resistance of current power contacts, then summarizes the methods for improving conductivity wear resistance, and then explains what methods are available and the problems encountered. The focus is on describing how the distribution and orientation of graphene can simultaneously optimize the conductive network and enhance the effect. Finally, summarize the current research methods both domestically and internationally, and propose key issues to be addressed.

3.3 Feasibility Analysis

Based on existing research, graphene/copper composite coatings have clear theoretical feasibility for application in power contacts. Graphene compensates for copper's grain boundary scattering loss by constructing efficient electronic channels, and simultaneously utilizes pinning effect and interlayer shear mechanism to enhance wear resistance. The synergistic mechanism of conductivity and wear resistance has been experimentally verified. Mature processes such as plasma ball milling and hot rolling can achieve synergistic distribution within/between graphene crystals, maintaining 84.2% IACS conductivity while increasing strength by 25.5%[7]; The fluctuation rate of contact resistance is significantly lower than that of pure copper contacts, which significantly suppresses contact failure during the on-off process; At the same time, the interlayer slip characteristics and high thermal conductivity of graphene can dissipate arc energy, reducing the density of arc erosion pits and extending the device life [5]. In the future, it is necessary to focus on optimizing graphene orientation control and interface bonding to enhance performance synergy.

3.4 Innovation of the Topic

The research on this topic often adopts literature review and inductive summarization methods. Based on this research method, this article combines it to obtain results that are more suitable for practical applications.

This study combines the perspective of composite materials of graphene and copper to investigate the wear resistance and conductivity of graphene/copper. The integration of conductivity and wear resistance makes the research on graphene applications more diversified

4 Conclusion

This review focuses on the core issue of breaking through the mutual constraint between conductivity and wear resistance of power contact materials, and systematically outlines the integrated design strategy of graphene/copper composite coatings. Through literature research and inductive analysis, it has been clarified that graphene can synergistically enhance the conductivity and wear resistance of copper based composite materials by constructing efficient electron transfer channels and forming frictional interface lubrication transfer films. Research has shown that by using advanced processes such as plasma ball milling and hot rolling to regulate the formation of intragranular/ intergranular synergistic distribution structures in graphene, it is possible to significantly enhance material strength (such as increasing tensile strength by 25.5%) while maintaining excellent electrical conductivity (84.2% IACS). Further optimizing the spatial orientation and interface combination of graphene is the key to achieving the optimization of conductive networks and maximizing wear resistance enhancement effects, providing a clear theoretical basis and technical direction for the development of the next generation of highly reliable and long-life power contacts.

References

[1] Wang Juan, Liang Shuzhen, Liu Yufeng, Xiao Siqi, Liu Ziliang, Li Yong. Preparation and Performance Study of Graphene-Reinforced Copper Matrix Composites [J]. Materials Research and Application, 2025,19(6):1176-1180.

[2] Guangyuan Lin, Yife Pengi, Yusen Li, Hanzheng Liang, Zhilei Dong, Yihu Zhou, Zhenming Yue, Jie Zhang, Dingbang Xiong, Di Zhang. Remarkable anisotropic wear resistance with 100-fold discrepancy in a copper matrix laminated composite with only 0.2 vol% graphene[J]. Acta Materialia,2021,215:117092

[3] Yao-Long Li, Zhen-Guo Tian, Hai-feng Yin, Ren-Liang Zhang. Effect of interlayer bonded bilayer graphene on friction[J]. Chinese Physics B,2024, 33(8):086103.

[4] Yongfeng Geng, Xiaohui Zhang, Qigao Cao, et al. High strength and high electrical conductivity in copper reinforced with intra-/inter-granular graphene in-situ exfoliated from graphite [J].Composites Communications,2024,46: 101857.

[5] Cui Run. Preparation and Performance Study of Copper/Graphene Composite Coatings for High-Voltage Circuit Breakers [D]. Jiangxi: Nanchang Hangkong University, 2019.

[6] Yuantao Shi, Yan Lin, Jiahang Liu , Wanli Song, Cheng Zhang , Xiang Chen, Lin Liu , Jie Pan. Tailoring the tribological properties of Cu composite coatings via integrating strengthening W particles and lubricant graphene[J]. Applied Surface Science,2025,679:161248.

[7] Yongfeng Geng , Xiaohui Zhang , Qiga Cao, Dingbang Xiong . High strength and high electrical conductivity in copper reinforced with intra-/ inter-granular graphene in-situ exfoliated from graphite[J]. Composites Communications,2024,46:101857.