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Development and Application of Oil-Resistant Conductive Thin Films

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ABSTRACT

Oil-resistant conductive thin films are essential for applications in electronics, medical devices, and industrial monitoring, yet conventional films suffer from oil contamination, reducing conductivity, mechanical stability, and durability. This study explores material classification, fabrication methods, and performance analysis to enhance oil resistance. Key fabrication techniques, including PVD, CVD, and electrospinning, are examined. Additionally, challenges in scalability and cost are discussed, with future directions focusing on advanced materials, large-scale production, and multifunctional applications. These insights provide a foundation for the development and industrial adoption of oil-resistant conductive thin films.

KEYWORDS

Oil-resistant conductive films; Anti-fouling materials; Super-oleophobic coatings; Nanostructured thin films; PVD; CVD; Electrospinning; Flexible electronics; Industrial monitoring; Surface modification

1 Introduction

In recent years, conductive thin films have played a critical role in electronic devices, medical applications, and environmental monitoring [1]. However, in oil-containing environments, traditional conductive thin films exhibit insufficient oil resistance and anti-fouling capabilities. Oil contamination can degrade their electrical performance and adversely affect mechanical strength and stability, making the development of oil-resistant conductive thin films an urgent priority [1]. This advancement can not only enhance adaptability to harsh environments but also extend the service life of these materials [2].

Current research focuses on material selection and modification, as well as surface structure optimization. By employing nanostructure design and surface treatment technologies, super-oleophobic properties can be achieved, effectively preventing oil adhesion [3]. Conductive thin films based on metal, carbon, and polymer materials each offer distinct advantages in terms of conductivity, transparency, and flexibility [4][5]. This study aims to evaluate the comprehensive performance of various materials, identify the optimal solution, and investigate their practical applications. Additionally, it summarizes the latest developments in the field to provide theoretical and technical support for future applications [6].

2 Material Selection and Classification

In the research of oil-resistant conductive thin films, material selection is a key factor influencing their performance and applications. Based on the characteristics of the film materials, they can be mainly categorized into three types: metal-based conductive thin films, carbon-based conductive thin films, and polymer-based conductive thin films. Each material exhibits distinct properties in terms of electrical conductivity, oil resistance, and mechanical performance, meeting various application requirements.

2.1 Metal-Based Conductive Thin Films

These films are primarily composed of metallic nanostructured materials such as silver nanowires (AgNW) and copper nanowires (CuNW). Owing to their excellent electrical conductivity and optical transparency, they are widely used in electronic devices and display technologies [7]. After surface modification, their oil-resistant performance can be significantly improved. For example, designing super-oleophobic coatings on metal film surfaces can effectively prevent oil contamination and extend service life [8]. Additionally, silver nanowires possess good anti-oxidation properties, enabling them to withstand harsh environmental conditions [9].

2.2 Carbon-Based Conductive Thin Films

These films mainly utilize materials like graphene and carbon nanotubes, which have attracted considerable attention due to their outstanding thermal stability, mechanical flexibility, and electrical conductivity [10]. Graphene's unique two-dimensional nanostructure endows it with extremely high conductivity and great potential for super-oleophobic surface design [11]. Chemical modification of graphene surfaces or optimization of nanostructures can significantly enhance oil-resistant performance. For instance, functionalizing graphene oxide can increase surface energy, thereby inhibiting oil adhesion. The three-dimensional network structure of carbon nanotubes enables the fabrication of films with combined electrical conductivity and mechanical stability [9].

2.3 Polymer-Based Conductive Thin Films

These films are primarily based on conductive polymers such as poly(3,4-ethylenedioxythiophene) (PEDOT). Due to their flexibility and transparency, they are particularly suitable for the fabrication of flexible electronic devices [12]. PEDOT exhibits high electrical conductivity and chemical stability, with its oil-resistant performance mainly achieved by incorporating surface oleophobic coatings [8].

Furthermore, combining PEDOT with nanomaterials such as nanoparticles or graphene can significantly enhance the mechanical strength and anti-fouling properties of the films [10].

Although metal-based, carbon-based, and polymer-based thin films each have distinct characteristics, practical applications often require their combination to achieve a balance of multiple properties. For example, the composite of graphene and silver nanowires can integrate the flexibility of graphene with the high electrical conductivity of silver nanowires, resulting in multifunctional thin films that exhibit excellent conductivity, flexibility, and oil resistance [13]. This composite design not only expands the application scenarios of thin films but also meets the functional requirements of various fields for advanced thin film materials.

3 Fabrication Strategies

In the research of oil-resistant conductive thin films, fabrication strategies directly determine the microstructure, physical properties, and practical performance of the films. To achieve an optimal combination of conductivity and oil resistance, researchers have developed various advanced fabrication methods, including Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), and electrospinning. Each of these techniques has unique features and can be optimized based on the characteristics of different materials and specific application requirements.

3.1 Physical Vapor Deposition (PVD)

PVD is a widely used technique for preparing high-quality conductive thin films. It involves the evaporation or sputtering of materials onto a substrate, forming a uniform and dense film layer. This process is simple, applicable to a broad range of materials, and allows precise control over film thickness and surface morphology to achieve desired functionalities. For example, carbon nitride films prepared via PVD exhibit excellent conductivity and oil resistance, making them suitable for electronic devices operating in harsh environments [14]. Moreover, PVD offers significant advantages in terms of energy efficiency and environmental sustainability, making it an ideal choice for fabricating oil-resistant conductive thin films [12].

3.2 Chemical Vapor Deposition (CVD)

Unlike PVD, CVD deposits materials onto substrates through chemical reactions, enabling deposition at the molecular level. This results in superior film uniformity and material adhesion. CVD is commonly used for fabricating carbon-based materials such as graphene and carbon nanotubes [15]. For instance, graphene films produced via CVD are ultrathin with outstanding oil resistance. By adjusting deposition parameters, it is possible to optimize the surface structure, thereby enhancing both electrical conductivity and mechanical flexibility [13]. CVD can also be combined with other techniques, such as PVD, to further improve film performance [16].

3.3 Electrospinning

Electrospinning is an emerging method for fabricating nanomaterials, utilizing electrostatic forces to stretch polymer solutions into nanofibers, which form thin films with unique structures. This technique is particularly suitable for producing flexible, highly conductive thin film materials [17].

For example, composite nanofiber films fabricated via electrospinning demonstrate excellent conductivity and oil-resistant properties [18]. Electrospinning enables the efficient production of nanofibers, and through composite design, it can enhance the mechanical strength and durability of thin films, offering broad application prospects in complex environments [19].

4 Performance Analysis

The performance analysis of oil-resistant conductive thin films is crucial for evaluating their reliability and durability in practical applications. The primary performance indicators include mechanical properties, electrical properties, and chemical stability. By studying and optimizing these key performance metrics, the adaptability of thin films to various environments can be enhanced, thereby broadening their application scope.

4.1 Mechanical Properties

Mechanical properties are key to assessing the stability of conductive thin films under external stress. During usage, films are subjected to bending, stretching, and friction; thus, excellent tensile strength and flexibility are essential for long-term stability [20]. For instance, films used in wearable electronic devices must withstand repeated bending without cracking or compromising conductivity [1]. Additionally, wear resistance and scratch resistance are critical, especially in industrial applications where films are exposed to oil contamination and abrasive particles. Sufficient hardness and durability can reduce surface damage and extend the service life of the films [21].

4.2 Electrical Properties

Electrical conductivity is a vital property of oil-resistant conductive thin films, directly affecting the efficiency and reliability of electronic devices. Key evaluation metrics include conductivity, resistivity, and electrical stability in oil-contaminated environments [22]. In practical applications, the accumulation of oil contaminants can impair conductivity, increase resistance, and even lead to the failure of electronic components [22]. Therefore, thin films must maintain low surface resistance and stable conductivity even when exposed to oil contamination, while ensuring consistent electrical performance under complex operating conditions [23].

4.3 Chemical Stability

Chemical stability refers to the film's resistance to various chemical environments, including oil resistance, corrosion resistance, and tolerance to organic solvents, acids, and alkalis [24]. Prolonged exposure to oil, moisture, and corrosive chemicals can lead to degradation and performance deterioration. To enhance chemical stability, oleophobic coatings or nanostructured surface modifications are often employed to reduce oil adsorption and prevent chemical corrosion [11]. In fields such as medical devices and petrochemical industries, chemical stability is a determining factor for the applicability of thin films in extreme environments [25].

5 Application Fields

Oil-resistant conductive thin films, with their outstanding electrical conductivity and anti-fouling properties, exhibit broad application potential across various industries. As technological advancements continue and market demands expand, these films are gaining increasing attention in the medical, industrial, and electronic sectors [26]. Their excellent durability and stability enable them to maintain superior performance in complex environments, ensuring the reliable operation of various devices [27]. The main application fields are as follows:

5.1 Medical Sensors

With continuous advancements in medical technology, biosensors are playing an increasingly critical role in disease diagnosis and health monitoring [28]. Since these sensors often come into prolonged contact with biological fluids, the materials used must exhibit both excellent electrical conductivity and strong oil resistance [29]. Contaminants such as skin oils and residual medications can compromise the performance of traditional conductive films. The application of oil-resistant conductive thin films allows sensors to operate stably in harsh environments, significantly enhancing device reliability and durability [30].

5.2 Industrial Electrical and Electronic Equipment

In high-pollution, highly corrosive industrial environments such as petrochemical facilities, the application of oil-resistant conductive thin films is crucial [31]. For instance, environmental monitoring devices like gas detectors and pollutant monitoring sensors frequently utilize conductive films. Traditional films tend to experience reduced conductivity after prolonged exposure to oil contamination, which affects monitoring accuracy and device stability [32].

Through modifications and surface treatments, oil-resistant conductive thin films offer enhanced anti-fouling capabilities, maintaining high reliability and measurement precision even in harsh environments, thereby supporting efficient environmental monitoring in industrial operations [33].

5.3 Electronic Devices

Oil-resistant conductive thin films are increasingly used in electronic devices, particularly in wearable technology and flexible electronic products [34]. In these applications, the films not only serve as conductive components but also directly influence the flexibility, thinness, and durability of the products. With the rapid development of smart wearables, smart home devices, and consumer electronics, the operational environments for these devices have become more complex. As a result, oil resistance has become critical for ensuring long-term stable performance [35]. These films effectively prevent oil and contaminants from adhering to device surfaces, safeguarding electrical performance, extending product lifespan, and enhancing the overall user experience.

6 Future Prospects

As a novel functional material, oil-resistant conductive thin films have demonstrated broad application potential across various fields in recent years. Despite significant research progress, several challenges and technical bottlenecks remain, necessitating further exploration and optimization in the future [36]. Future research will primarily focus on enhancing material performance, optimizing fabrication processes, and reducing production costs to promote the widespread adoption of these films in practical applications.

Oil-resistant conductive thin films face numerous challenges in real-world applications. The primary issues involve material compatibility, scalability of fabrication processes, and economic costs [37]. Among these, material compatibility and process scalability are the most critical challenges. While many new materials exhibit excellent oil resistance and conductivity in laboratory settings, their durability, flexibility, and electrical stability under diverse environmental conditions require further testing and improvement for industrial-scale production.

Additionally, fabrication techniques such as Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD), although effective, are hindered by high equipment costs and complex procedures, making large-scale production challenging. Thus, achieving a balance between material performance and fabrication efficiency is key to future research efforts [38].

From an economic standpoint, the high production costs of conductive thin films—attributable to expensive raw materials, sophisticated equipment, and complex manufacturing processes—pose adoption barriers for industries. Future research should prioritize the development of cost-effective, high-efficiency fabrication methods. This includes exploring renewable materials, optimizing manufacturing workflows, and incorporating automated production technologies to achieve cost reduction and efficiency improvements [39].

To unlock the full potential of oil-resistant conductive thin films, researchers need to delve into multiple directions to enhance their performance and market competitiveness [6].

Future research will focus on designing advanced material formulations using nanomaterials and functional polymers. The incorporation of nanofillers such as graphene, combined with innovative surface treatment techniques like super-oleophobic coatings, can significantly improve the films' conductivity, flexibility, oil resistance, and performance under extreme conditions [37].

Efforts will be directed towards improving the stability and reproducibility of laboratory-scale fabrication processes. The development of environmentally friendly, high-efficiency manufacturing methods and the exploration of continuous production models will be crucial for accelerating industrial applications [39].

To enhance market competitiveness and broaden application scenarios, future research will aim to integrate multiple functionalities into the films. This includes optimizing properties such as transparency, mechanical strength, and chemical resistance to meet the diverse demands of sectors like healthcare, electronics, and industrial monitoring [10].

By addressing these challenges and advancing research in the outlined directions, oil-resistant conductive thin films are expected to achieve broader applications, driving innovation across multiple industries.

7 Conclusion

As a novel functional material, oil-resistant conductive thin films have made significant progress in both research and application in recent years [27]. In terms of material selection, metal-based, carbon-based, and polymer-based conductive thin films each possess distinct characteristics, catering to diverse application requirements [30]. Fabrication strategies have been continuously optimized, with techniques such as Physical Vapor Deposition (PVD) enhancing the films' oil resistance, mechanical strength, and chemical stability [40]. Performance analyses have demonstrated their excellent conductivity, durability, and environmental adaptability.

Currently, these thin films show promising application potential in fields such as medical devices, industrial monitoring, and electronic equipment. Looking ahead, with ongoing technological advancements, oil-resistant conductive thin films are expected to be promoted in even more sectors, achieving higher cost-effectiveness while driving the maturation and widespread adoption of related technologies.

References

[1] Qu Y X, Xia Q Q, Li L T, et al. Rational design of oil-resistant and electrically conductive fluorosilicone rubber foam nanocomposites for sensitive detectability in complex solvent environments[J]. ACS nano, 2024, 18(33): 22021-22033.

[2] Chen X, Dong Y, Jin X, et al. Innovative Design and Construction of Poly (Vinyl Alcohol) Coatings by Plant-Inspired Cross-Linking and Hydrogen Bonding Enabled Oil-Resistant and Strong Paper-Based Composites[J]. ACS Sustainable Chemistry & Engineering, 2024.

[3] Aulin C, Gällstedt M, Lindström T. Oxygen and oil barrier properties of microfibrillated cellulose films and coatings[J]. Cellulose, 2010, 17: 559-574.

[4] Xia Z, Feng Z, Wu R, et al. A Tough, Hydrophobic, Oil-Resistant and Antifouling Material Based on the Copolymerization of Butadiene and Trifluoroethyl Methacrylate for Room-Temperature Shape Memory and Underwater Sensing[J]. Hydrophobic, Oil-Resistant and Antifouling Material Based on the Copolymerization of Butadiene and Trifluoroethyl Methacrylate for Room-Temperature Shape Memory and Underwater Sensing.

[5] An J, Kim J W, Kim S H, et al. Simultaneously improving vertical thermal conductivity and oil resistance of carbon fiber reinforced composite through layer-by-layer plasma surface treatment[J]. Surfaces and Interfaces, 2023, 37: 102723.

[6] Xia Z, Feng Z, Wu R, et al. Tough, Hydrophobic, Pressure-Resistant, and Self-Cleaning Underwater Engineering Materials Based on Copolymerization of Butadiene and Trifluoroethyl Methacrylate[J]. ACS Applied Polymer Materials, 2023, 5(10): 8241-8249.

[7] Alimohammadian M, Azizian S, Sohrabi B. Preparation of the graphene-based smart hydrophobic nanocomposite and its application in oil/water separation[J]. Scientific Reports, 2023, 13(1): 19816.

[8] Polymer-Based Nanoscale Materials for Surface Coatings[M]. Elsevier, 2023.

[9] Hatta F F, Mohammad Haniff M A S, Mohamed M A. A review on applications of graphene in triboelectric nanogenerators[J]. International Journal of Energy Research, 2022, 46(2): 544-576.

[10] Liu Y, Guo Z. Small functional hydrogels with big engineering applications[J]. Materials Today Physics, 2024: 101397.

[11] Bumbudsanpharoke N, Choi J, Ko S. Applications of nanomaterials in food packaging[J]. Journal of nanoscience and nanotechnology, 2015, 15(9): 6357-6372.

[12] Hasan M N, Sahlan S, Osman K, et al. Energy harvesters for wearable electronics and biomedical devices[J]. Advanced Materials Technologies, 2021, 6(3): 2000771.

[13] Wani N R, Dar A H, Dash K K, et al. Recent advances in the production of bionanomaterials for development of sustainable food packaging: a comprehensive review[J]. Environmental Research, 2023, 237: 116948.

[14] Gupta R K, Abd El Gawad F, Ali E A E, et al. Nanotechnology: Current applications and future scope in food packaging systems[J]. Measurement: Food, 2024, 13: 100131.

[15] Zhao Z, Xie H, Yang D, et al. A nanosheets-polyborosiloxane composite impregnated with shorter hydrogen-bonding clusters achieves combination of self-healing, shapeability and high-barrier properties[J]. Polymer, 2022, 254: 125013.

[16] Liu Y, Mo J, Fu Q, et al. Enhancement of triboelectric charge density by chemical functionalization[J]. Advanced Functional Materials, 2020, 30 (50): 2004714.

[17] Wang X X, Yu G F, Zhang J, et al. Conductive polymer ultrafine fibers via electrospinning: Preparation, physical properties and applications[J]. Progress in Materials Science, 2021, 115: 100704.

[18] Rivero P J, Redin D M, Rodríguez R J. Electrospinning: A powerful tool to improve the corrosion resistance of metallic surfaces using nanofibrous coatings[J]. Metals, 2020, 10(3): 350.

[19] Chaudhary P, Fatima F, Kumar A. Relevance of nanomaterials in food packaging and its advanced future prospects[J]. Journal of inorganic and organometallic polymers and materials, 2020, 30(12): 5180-5192.

[20] Matysiak W, Tański T, Smok W. Electrospinning as a versatile method of composite thin films fabrication for selected applications[J]. Solid State Phenomena, 2019, 293: 35-49.

[21] Jiang F, Ju W, Pan Z, et al. Conformal Cu Coating on Electrospun Nanofibers for 3D Electro-Conductive Networks[J]. Advanced Electronic Materials, 2020, 6(2): 1900767.

[22] Vempati S, Ranjith K S, Topuz F, et al. Electrospinning combined with atomic layer deposition to generate applied nanomaterials: a review[J]. ACS Applied Nano Materials, 2020, 3(7): 6186-6209.

[23] Kim N K, Kim K, Jang H, et al. Microheater with copper nanofiber network via electrospinning and electroless deposition[J]. Scientific Reports, 2023, 13(1): 22248.

[24] Rodrigues B V M, Dias V M, Fraga M A, et al. Atomic layer deposition of TiO2 thin films on electrospun poly (butylene adipate-co-terephthalate) fibers: Freestanding TiO2 nanostructures via polymer carbonization[J]. Materials Today: Proceedings, 2019, 14: 656-662.

[25] Shang S M, Zeng W. Conductive nanofibres and nanocoatings for smart textiles[M]//Multidisciplinary know-how for smart-textiles developers. Woodhead Publishing, 2013: 92-128.

[26] Nihmath A, Ramesan M T. Comparative evaluation of oil resistance, dielectric properties, AC conductivity, and transport properties of nitrile rubber and chlorinated nitrile rubber[J]. Progress in Rubber, Plastics and Recycling Technology, 2021, 37(2): 131-147.

[27] Niu Z, Wu R, Huang L, et al. Low-temperature oil resistance ester polysiloxane with excellent reprogrammable, reprocessable performance[J]. Materials Today Chemistry, 2023, 33: 101724.

[28] Wang S, Pei L, Wei J, et al. Preparation of Environmentally Friendly Oil-and Water-Resistant Paper Using Holo-Lignocellulosic Nanofibril (LCNF)-Based Composite Coating[J]. Polymers, 2024, 16(8): 1078.

[29] Yu K, Yang L, Zhang S, et al. Preparation of strong, tough and highly ion-conductive nanocellulose hydrogels based on freeze – thaw cycles: performance evaluation under different freezing temperatures[J]. International Journal of Food Engineering, 2025, 21(1): 1-13.

[30] Niu Z, Wu R, Huang L, et al. Shape-Shifting, Conductive, Reprocessable Acrylate Polysiloxane with Excellent Low-Temperature and Oil-Resistance Performance[J]. Available at SSRN 4177607.

[31] Gaines L G T. Historical and current usage of per-and polyfluoroalkyl substances (PFAS): A literature review[J]. American Journal of Industrial Medicine, 2023, 66(5): 353-378.

[32] Shit S C, Shah P M. Edible polymers: challenges and opportunities[J]. Journal of Polymers, 2014, 2014(1): 427259.

[33] Mazumder M K, Sims R A, Biris A S, et al. Twenty-first century research needs in electrostatic processes applied to industry and medicine[J]. Chemical Engineering Science, 2006, 61(7): 2192-2211.

[34] Shajari S, Rajabian M, Kamkar M, et al. A solution-processable and highly flexible conductor of a fluoroelastomer FKM and carbon nanotubes with tuned electrical conductivity and mechanical performance[J]. Soft Matter, 2022, 18(39): 7537-7549.

[35] Loher T, Manessis D, Heinrich R, et al. Stretchable electronic systems[C]//2006 8th Electronics Packaging Technology Conference. IEEE, 2006: 271-276.

[36] Liu S, Xu L, Yu J, et al. Amphiphobic, thermostable, and stretchable PTFE nanofibrous membranes with breathable and chemical-resistant performances for protective applications[J]. ACS Applied Polymer Materials, 2023, 5(2): 1464-1473.

[37] Javaid S, Saleem N, Rehman S U. Polymeric nano-emulsion in functional textile finishing[J]. Design and Applications of Self-Assembly Aggregates-From Micelles to Nanoemulsions: From Micelles to Nanoemulsions, 2024: 141.

[38] Alam M N. Advances in Functional Rubber and Elastomer Composites[J]. Polymers, 2024, 16(12): 1726.

[39] Imam S H, Bilbao-Sainz C, Chiou B S, et al. Biobased adhesives, gums, emulsions, and binders: current trends and future prospects[J]. Journal of Adhesion Science and Technology, 2013, 27(18-19): 1972-1997.

[40] Du G, Wang J, Liu Y, et al. Fabrication of advanced cellulosic triboelectric materials via dielectric modulation[J]. Advanced Science, 2023, 10 (15): 2206243.