

# 金属表面防护涂层研究进展

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## 摘要

目前, 金属材料是现代工业与科技的基石, 其应用遍及所有关键领域, 从日常用品到尖端装备, 深刻塑造了人类文明。为了防止金属发生腐蚀, 已形成了多种系统的腐蚀防护策略, 如耐蚀合金法、电化学保护法、缓蚀剂法和涂层保护法等。本文探讨了金属腐蚀的原理及种类, 着重探究了涂层保护法的原理及涂层的种类。我们收集分析了无机涂层和有机涂层在金属防腐蚀领域的最新进展, 希望这篇综述能够为金属腐蚀防护提供更加高效、环保和可靠的解决方案。

## 关键词

涂层, 金属腐蚀

# Research Progress in Protective Coatings for Metal Surfaces

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## Abstract

Currently, electronic products are utilized in nearly every aspect of daily life and contain a significant amount of metallic components. To prevent metal corrosion, various systematic protection strategies have been developed, including corrosion-resistant alloys, electrochemical protection, corrosion inhibitors, and coating protection methods. This paper examines the principles and types of metal corrosion, with a particular focus on the mechanisms and categories of coating protection. By compiling and analyzing the latest advancements in both inorganic and organic coatings for metal corrosion protection, we aim for this review to contribute more efficient, environmentally

friendly, and reliable solutions for safeguarding metals against corrosion.

## Keywords

Coating, Metal Corrosion

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## 1. 引言

电子产品已深度融入人类生产与生活的各个领域，成为现代社会不可或缺的组成部分。然而，电子产品内部的金属构件(如电路板接点、外壳支架、散热组件等)在复杂环境条件下极易发生电化学腐蚀。腐蚀不仅会导致接触电阻升高、信号传输劣化、设备灵敏度下降，还会显著缩短仪器服役寿命，甚至引发系统故障，造成巨大的直接经济损失与安全隐患[1]。据统计，全球每年因金属腐蚀导致的电子产品失效约占设备总故障率的20%以上，在湿热、盐雾等严苛环境中该比例进一步升高。因此，开发先进的腐蚀防护技术已成为保障电子设备可靠性和延长服役寿命的核心课题[2]。

迄今为止，广泛应用的金属腐蚀防护手段主要有耐蚀合金法、电化学保护法、缓蚀剂法和涂层保护法。耐蚀合金法主要向普通金属中加入特定的合金元素，从而提高金属的耐腐蚀性能[3]。典型应用包括：含铬镍不锈钢通过致密钝化膜形成大气与水介质环境长效防护；钛基合金凭借高结合能氧化膜特性，兼具高强、耐蚀和热稳定性优势，已广泛应用于深海装备耐压壳体等严苛服役环境。电化学保护法通过改变金属的表面的电极电位来进行保护，根据保护方法主要分为牺牲阳极保护、外加电流阴极保护和阴极保护[4]-[6]。缓蚀剂法是通过微量添加缓蚀物质从而显著抑制金属的腐蚀进程[7]。例如，在酸性溶液中加入缓蚀剂(如有机胺类化合物)，可使大大降低金属的腐蚀速度。涂层保护法则是在金属表面涂覆一层耐腐蚀的涂层，将金属基底与环境中存在的腐蚀介质分隔开来，从源头上延缓或阻止金属腐蚀[8]-[10]。涂层保护法具有易操作、成本低、适用范围广等优点，可以说是目前防止金属腐蚀最有效、最方便的方法之一[11]。

## 2. 金属腐蚀原理和腐蚀种类

金属腐蚀本质是金属与其所处环境发生化学或电化学反应，导致材料性能退化并回归其热力学稳定状态(如氧化物、硫化物)的过程。其电化学机理可通过局部电池模型解释：在电解质存在下，金属表面形成阳极区(发生氧化反应： $M \rightarrow M^{n+} + ne^{-}$ )和阴极区(发生还原反应，如 $O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}$ )，电子通过金属基体流动，离子通过电解质迁移，构成腐蚀电流回路。腐蚀速率受材料特性(成分、微观结构)、环境因素(湿度、pH、离子种类、温度)及界面状态共同控制。

从环境介质维度划分，主要包括：大气环境中的气相腐蚀、土壤介质中的微生物-电化学耦合腐蚀、海洋环境下的氯离子渗透腐蚀以及工业电解液中的电偶腐蚀等。在腐蚀形态学分类层面，可分为均匀腐蚀与局部腐蚀形态。均匀腐蚀在金属表面相对均匀地发生，虽造成整体厚度减薄但易于监测与防护；局部腐蚀则危害性更大，可细分为点蚀、电偶腐蚀、缝隙腐蚀等；腐蚀机理方面则涵盖四个基本类型：物理溶解导致的机械性能退化(物理腐蚀)、非电化学氧化还原反应(化学腐蚀)、微电池效应驱动的阳极溶解(电化学腐蚀)以及微生物代谢产物引发的生物电化学腐蚀。

### 3. 涂层种类

#### 3.1. 无机涂层

常见的无机涂层主要有陶瓷涂层[12]-[14]、磷酸盐涂层[15] [16]、金属氧化涂层[17]-[19]和富锌涂层[20]。

陶瓷涂层主要分为热喷涂陶瓷涂层和溶胶-凝胶陶瓷涂层。热喷涂陶瓷涂层是指利用高温热源将陶瓷材料(粉末或丝材)加热至熔融或半熔融状态,并高速喷射到经过预处理的基体表面,快速凝固、堆积而形成具有特定功能的致密涂层。这种涂层具有优异的耐高温、耐磨蚀和化学稳定性,能有效抵抗各种腐蚀介质的侵蚀。溶胶-凝胶陶瓷涂层是通过将金属醇盐或无机盐前驱体在常温或较低温度下进行水解和缩聚反应,首先形成稳定的溶胶体系,再经过进一步反应形成三维网络结构的凝胶,最后经过干燥和热处理,在基材表面形成一层均匀、致密的陶瓷涂层。该技术尤其擅长制备成分精确可控、厚度均匀的纳米级薄膜。采用激光辅助 PEO (Laser/PEO)复合工艺,在 AZ31B 镁合金表面成功原位制备了 Laser/PEO 陶瓷涂层。此外,还探讨了激光辅助辐照对 PEO 陶瓷涂层腐蚀机理的影响[12]。

磷酸盐涂层,又称磷化,是一种通过化学或电化学反应,在金属(主要是钢铁、锌、铝及其合金)表面生成一层由难溶性磷酸盐晶体构成的转化膜的表面处理技术。这层膜本身具有一定的防腐蚀能力,但最主要的功用是作为基底,极大地提高后续有机涂层(如油漆、粉末涂料)的附着力和整体防护体系的耐久性。例如 Wang 等人用三水磷酸氢二钾(DKP)作为磷源,开发了一种耐用、环保的 MKPC 涂层,进一步探究了涂层的耐久性和防腐机理,为 MKPC 防腐涂层的实际应用提供了可行性指导[16]。

金属氧化涂层,通常指通过化学或电化学方法,在金属表面原位生成一层致密的金属氧化物薄膜或钝化膜。这层氧化物膜与基体结合牢固,具有较高的硬度和良好的耐腐蚀性,能显著改变金属的表面特性,是应用最广泛、最经济的表面防护与功能化方法之一。Ran 等人在铸铁盘上沉积了氧化铝涂层,显著提高了盘片和垫片材料的耐磨性[20]。

富锌涂层是指通过在涂层中高密度地添加金属锌粉,锌粉与腐蚀性介质反应生成稳定的腐蚀产物,填充涂层的孔隙。通过阻止水分和氧气的渗透来保护金属,是集物理屏障与电化学保护于一体的高效防护体系。Lin 等人制备了一种水性富锌环氧防腐涂料可以使锌片基底在盐雾室中放置 4392 h 时仍未出现明显的锈渍,具有长期的防腐蚀性能[20]。

综上所述,在金属防护领域,无机涂层发挥着重要作用。不同无机涂层的优缺点及适用场景见表 1。根据具体使用要求可选择适合的无机涂层来保护金属免遭腐蚀(图 1)。

**Table 1.** Advantages, disadvantages, and application scenarios of different inorganic coatings

**表 1.** 不同无机涂层的优缺点及适用场景

涂层类型	优点	缺点	适用场景
陶瓷涂层	耐高温、高硬度、耐化学腐蚀	脆性大、成本高、结合力偏弱	航空发动机叶片、化工耐磨件、高温部件
磷酸盐涂层	附着力好、成本低、适合作底层	膜薄、环保差、前处理要求高	汽车/家电涂装前处理、紧固件短期防锈
金属氧化涂层	结合力强、耐磨、可装饰	能耗高、需封闭	铝合金型材、电子外壳、医疗植入体
富锌涂层	阴极保护、长效防腐、耐高温	表面处理要求高、对湿度敏感	船舶、桥梁、储罐等重防腐底漆

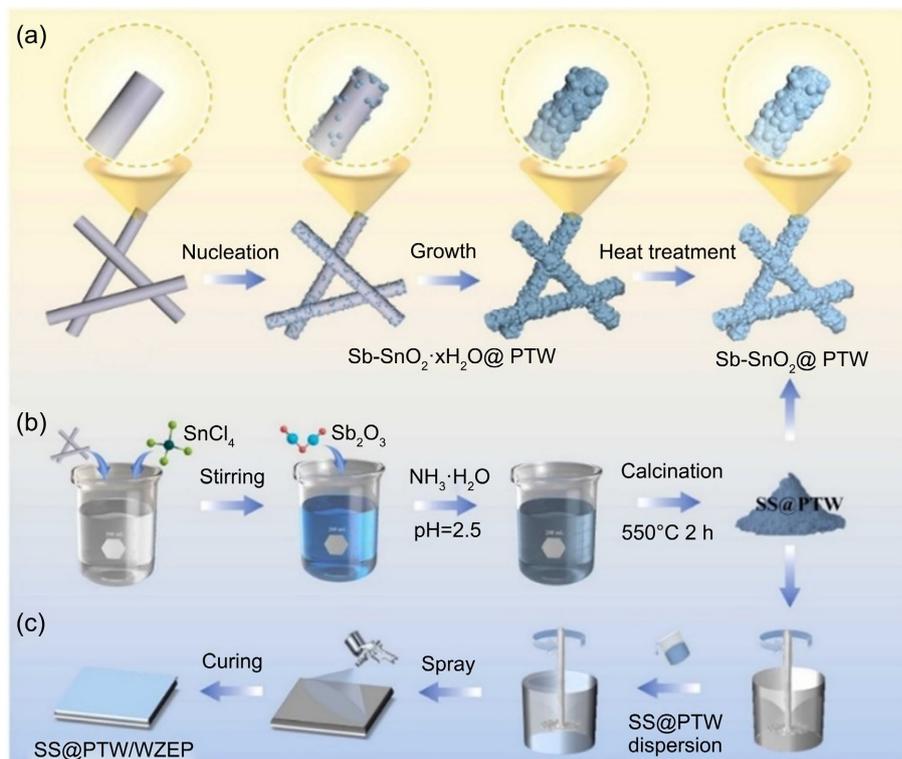


Figure 1. The preparation process of zinc-rich coatings  
图 1. 富锌涂层的制备过程

### 3.2. 有机涂层

按成膜物进行分类,有机涂层大致可分为聚氨酯涂层[22]-[24]、丙烯酸酯涂层[25]-[27]、环氧涂层[28]-[30]和含氟涂层[31][32]等。

聚氨酯涂层的形成本质上是异氰酸酯基团(-NCO)与含活性氢的化合物(主要为羟基-OH)发生逐步加成聚合反应,生成具有特征性氨基甲酸酯键(-NH-CO-O-)的聚合网络过程。该独特的化学结构赋予涂层可调的微相分离形态与强氢键作用,从而使其在机械性能、耐环境老化性与施工适应性之间实现出色平衡,成为高端防护与装饰应用中不可或缺的核心材料。例如,Wang 等人利用木质素多样的活性羟基对聚氨酯涂层进行改性,得到了木质素聚氨酯涂层,增强了涂层的长期耐腐蚀性能[33]。Mao 等人在聚氨酯分子中引入二硫基团,提出了一种基于水性有机硅聚氨酯的新型自修复涂料配方。在保留聚氨酯涂层优异的疏水性能的同时,又赋予了其优异的自修复能力[34]。尽管通过共混、共聚、纳米复合等手段对聚氨酯进行改性已取得显著进展,但以下根本性难点仍制约着其极限性能的提升:长效耐候性与成本的根本矛盾及高交联密度与良好柔韧性的平衡。

丙烯酸酯涂层的形成主要基于自由基链式聚合反应。在光、热或引发剂作用下产生自由基,该自由基与丙烯酸酯单体中的碳碳双键(C=C)发生反复加成,促使分子链快速增长;最终通过自由基结合或链转移使反应终止,形成高分子聚合物。该类涂层具有干燥速度快、透明度高以及卓越的耐候性(抗紫外线、抗黄变)等突出特点。基于其良好的相容性与可调性,可通过添加不同颜料、填料或功能助剂,灵活调节涂层的颜色、力学性能、表面特性及特殊功能,从而满足多样化的工业与装饰需求。Patil 等人向丙烯酸酯涂料中加入二氧化硅作为增强添加剂,获得了二氧化硅丙烯酸酯复合涂层,表现出优异的耐磨性[35]。水性丙烯酸涂层的耐水性、耐溶剂性和早期硬度普遍低于溶剂型产品。如何在不使用有害成膜助剂的前提

下,提升其“早期抗性”和最终性能是持续挑战。

环氧涂层是一类以环氧树脂为主要成膜物质的高性能防护性涂层。其核心在于环氧基团(-CH(O)CH-)的化学反应性,这赋予了它良好的耐化学性、耐磨性和附着力,广泛应用于石油、化工等领域的金属设备和管道的腐蚀。同时,该涂层还具备优异的机械性能和电绝缘性,可用作电气绝缘涂层。Tessanan 等人将环氧树脂与胺类固化剂在水中简单混合,制备了水性环氧树脂,提高了涂层的附着力和弯曲性能[36]。Qiao 等人以  $\alpha\text{-Fe}_2\text{O}_3$  纳米粒子和环氧树脂为原料,采用旋涂法制备了  $\alpha\text{-Fe}_2\text{O}_3$ /环氧树脂复合超疏水涂层。该复合涂层表现出良好的机械耐久性及超高的缓蚀效率[37]。低温快速固化与储存稳定性的矛盾:开发能在低温(如  $0^\circ\text{C}\sim 5^\circ\text{C}$ )、高湿环境下快速固化的环氧体系是工程急需,但这类高活性固化剂通常储存稳定性差、施工时限短,给生产和施工带来困难。

含氟涂层是一类以含氟聚合物为主要成膜物质的高性能特种涂层。其卓越性能源于坚固的 C-F 键,赋予涂层超凡的耐候性,户外使用寿命可达 20 年以上,且保光保色性极佳。同时,它具有极低的表面能,表现出优异的疏水疏油、抗污和自清洁特性,并对酸、碱、盐等腐蚀介质有极强的抵抗力。尽管成本较高,但因其长效免维护的特点,已成为重大基础设施、超高层建筑及严酷工业环境等高端应用领域的首选防护方案。附着力与氟元素表面富集的根本冲突:氟元素必须向涂层表面迁移富集才能发挥低表面能特性,但这必然导致涂层/基体界面处氟含量低、附着力弱。设计既能保证表面性能,又能强附着的梯度结构或嵌段聚合物极具挑战。

**Table 2.** Advantages, disadvantages, and application scenarios of different organic coatings  
**表 2.** 不同有机涂层优缺点及适用场景

涂层类型	优点	缺点	适用场景
聚氨酯涂层	耐磨性极佳、柔韧性好、硬度可调、装饰性高	成本高、对湿气敏感	工程机械、木制家具、地坪涂料
丙烯酸酯涂层	耐候性优异、干燥快、透明度极高	耐溶剂性较差、硬度与韧性平衡难度大	建筑外墙涂料、户外金属构件
环氧涂层	附着力强、耐化学腐蚀性优异、电绝缘性好	耐候性差、柔韧性一般、低温固化慢	防腐底漆、电子电气绝缘涂层
含氟涂层	超耐候性、耐化学性极佳、表面能低、耐高温	成本极高、施工工艺苛刻	高端电子产品外壳、航空航天器外部涂层

总而言之,有机涂层由于具有多样化的类型和独特的性能特点,见表 2。在金属防腐蚀领域发挥着不可替代的作用。

#### 4. 总结

综上所述,金属腐蚀防护是保障现代电子设备及工业设施可靠性与耐久性的核心挑战。本文系统梳理了从耐蚀合金、电化学保护到缓蚀剂及涂层保护等主流防护策略,并重点聚焦于涂层保护法这一兼具高效性与实用性的技术路径。通过对无机涂层(如陶瓷、磷酸盐、金属氧化及富锌涂层)与有机涂层(如聚氨酯、丙烯酸酯、环氧及含氟涂层)的成膜机理、性能特点及应用范围进行剖析,可得出以下结论:

涂层保护法凭借其操作灵活、成本可控及适应性强等优势,已成为金属腐蚀防护中最为广泛采用的手段。其中,无机涂层侧重于高温耐受、硬度及化学稳定性,常在严苛工业环境中作为基础防护层;有机涂层则凭借其优异的附着力、耐候性及可设计性,在装饰、绝缘及长效防护等场景中发挥关键作用。特别是通过不同涂层的复合使用,可实现性能互补,构建多层次、一体化的长效防护系统。

未来, 随着材料科学与表面工程的发展, 涂层技术正朝着环保化(水性、无溶剂)、智能化(自修复、传感响应)及功能复合化方向演进, 进一步推动其在高端制造、新能源及重大基础设施等领域的深入应用, 为金属腐蚀防护提供更加高效、可持续的解决方案。

## 参考文献

- [1] Bastidas, D.M. (2020) Corrosion and Protection of Metals. *Metals*, **10**, 458-463. <https://doi.org/10.3390/met10040458>
- [2] Hou, B., Li, X., Ma, X., Du, C., Zhang, D., Zheng, M., *et al.* (2017) The Cost of Corrosion in China. *npj Materials Degradation*, **1**, Article No. 4. <https://doi.org/10.1038/s41529-017-0005-2>
- [3] Wenga, T., Macdonald, D.D. and Ma, W. (2025) Multi-Scale Computational Study of High-Temperature Corrosion and the Design of Corrosion-Resistant Alloys. *Progress in Materials Science*, **148**, Article 101359. <https://doi.org/10.1016/j.pmatsci.2024.101359>
- [4] Cristoforetti, A., Parola, F., Parrino, F., Izquierdo, J., Souto, R.M., Rossi, S., *et al.* (2024) Sebacate Intercalated Ca Al Layered Double Hydroxide Pigments for Corrosion Protection of Low Carbon Steel: Anion Exchange and Electrochemical Properties. *Applied Clay Science*, **250**, Article 107300. <https://doi.org/10.1016/j.clay.2024.107300>
- [5] Sharker, T., Simonsen, K.R., Margheritini, L., Kucheryavskiy, S.V. and Simonsen, M.E. (2023) Optimisation of Electrochemical Deposition of Calcareous Material during Cathodic Protection by Implementing Response Surface Methodology (RSM). *Electrochimica Acta*, **444**, Article 141960. <https://doi.org/10.1016/j.electacta.2023.141960>
- [6] Vastag, G., Felhősi, I., Vraneš, M. and Shaban, A. (2024) Impact of N-Decyl-Nicotineamide Bromide on Copper Corrosion Inhibition in Acidic Sulfate Containing Environment: Electrochemical and Piezoelectrochemical Insights. *Heliyon*, **10**, e40184. <https://doi.org/10.1016/j.heliyon.2024.e40184>
- [7] Wang, X., Liu, J., Jin, M., Yan, Y., Tang, J. and Jin, Z. (2024) A Review of Organic Corrosion Inhibitors for Resistance under Chloride Attacks in Reinforced Concrete: Background, Mechanisms and Evaluation Methods. *Construction and Building Materials*, **433**, Article 136583. <https://doi.org/10.1016/j.conbuildmat.2024.136583>
- [8] Fürbeth, W. (2020) Special Issue: Advanced Coatings for Corrosion Protection. *Materials*, **13**, Article 3401. <https://doi.org/10.3390/ma13153401>
- [9] Xu, H. and Zhang, Y. (2019) A Review on Conducting Polymers and Nanopolymer Composite Coatings for Steel Corrosion Protection. *Coatings*, **9**, Article 807. <https://doi.org/10.3390/coatings9120807>
- [10] Zhang, D., Peng, F. and Liu, X. (2021) Protection of Magnesium Alloys: From Physical Barrier Coating to Smart Self-Healing Coating. *Journal of Alloys and Compounds*, **853**, Article 157010. <https://doi.org/10.1016/j.jallcom.2020.157010>
- [11] González-García, Y., Mol, J.M.C., Muselle, T., De Graeve, I., Van Assche, G., Scheltjens, G., *et al.* (2011) SECM Study of Defect Repair in Self-Healing Polymer Coatings on Metals. *Electrochemistry Communications*, **13**, 169-173. <https://doi.org/10.1016/j.elecom.2010.12.005>
- [12] Li, L., Yin, Y., Wu, G., Wang, Y., Yang, Z., Wen, C., *et al.* (2024) Effect of Laser-Assisted Irradiation on the Characteristics and Corrosion Behavior of Plasma Electrolytic Oxidation Ceramic Coating on AZ31B Magnesium Alloy. *Ceramics International*, **50**, 41364-41378. <https://doi.org/10.1016/j.ceramint.2024.07.447>
- [13] Wu, Q., Long, W., Zhang, L. and Zhao, H. (2024) A Review on Ceramic Coatings Prepared by Laser Cladding Technology. *Optics & Laser Technology*, **176**, Article 110993. <https://doi.org/10.1016/j.optlastec.2024.110993>
- [14] Zheng, W., Wang, J., Liu, P., *et al.* (2023) Research Progress of High-Entropy Ceramic Films and Coatings. *Rare Metal Materials and Engineering*, **52**, 4284-4294.
- [15] Byeun, Y. (2024) Study on Anti-Oxidation Performance of the Magnesium Phosphate Ceramic Coating on Steel at High Temperatures. *Journal of the Korean Ceramic Society*, **61**, 1198-1206. <https://doi.org/10.1007/s43207-024-00430-9>
- [16] Wang, M., Ming, X., Wang, Q., Ding, H., Dai, Z., Tian, L., *et al.* (2024) Environmentally Friendly Magnesium Potassium Phosphate Cement-Based Coating with High Anti-Corrosion Performance on Iron. *Journal of Materials Research and Technology*, **33**, 9951-9959. <https://doi.org/10.1016/j.jmrt.2024.11.220>
- [17] Bunyanidhi, P., Phattharasupakun, N., Duangdangchote, S., Prempluem, S., Joraleechanchai, N. and Sawangphruk, M. (2023) Exploring the Impact of Metal Oxide Coating and Metal Atom Doping on the Electrochemical Performance of Ni-Rich Cathode Materials. *Journal of Materials Chemistry A*, **11**, 23223-23227. <https://doi.org/10.1039/d3ta06104c>
- [18] Mandal, S., Kumar, P., Satpathy, B., Das, K. and Das, S. (2024) Nanostructured Metal Oxide Based Coating for the Protection and Conservation of Cultural Heritage: A Comprehensive Review. *Journal of Cultural Heritage*, **69**, 94-112. <https://doi.org/10.1016/j.culher.2024.08.001>
- [19] Sekkat, A., Sanchez-Velasquez, C., Bardet, L., Weber, M., Jiménez, C., Bellet, D., *et al.* (2024) Towards Enhanced Transparent Conductive Nanocomposites Based on Metallic Nanowire Networks Coated with Metal Oxides: A Brief

- Review. *Journal of Materials Chemistry A*, **12**, 25600-25621. <https://doi.org/10.1039/d4ta05370b>
- [20] Lin, D., Wang, R., Gao, S., Shao, Z., Shi, Y., Pei, L., *et al.* (2024) A Waterborne Zinc-Rich Epoxy Anti-Corrosion Coating with Electron Transport Pathways Constructed by Conductive Potassium Titanate Whiskers. *Corrosion Science*, **236**, Article 112250. <https://doi.org/10.1016/j.corsci.2024.112250>
- [21] Cai, R., Nie, X., Rosén, M.E., Lyu, Y. and Wahlström, J. (2025) Reducing Emissions and Metallic Content of Brake Wear Particles Using Alumina-Coated Brake Discs. *Materials Today Communications*, **49**, Article 114003. <https://doi.org/10.1016/j.mtcomm.2025.114003>
- [22] Chen, J., Zeng, Z., Liu, C., Wang, X., Li, S., Ye, F., *et al.* (2023) Aqueous Cationic Fluorinated Polyurethane for Application in Novel UV-Curable Cathodic Electrodeposition Coatings. *Polymers*, **15**, Article 3725. <https://doi.org/10.3390/polym15183725>
- [23] Liu, H., Liu, X., Rao, Y., Shen, X., Tang, Z. and Chen, H. (2023) Facile Fabrication of Robust and Universal UV-Curable Polyurethane Composite Coatings with Antibacterial Properties. *Polymer Engineering & Science*, **63**, 3371-3381. <https://doi.org/10.1002/pen.26452>
- [24] Wei, H., Liu, H., Li, M., Fu, Z., Liu, L., Zhang, H., *et al.* (2024) Multifunctional Polyurethane Coatings with Excellent Antifouling and Self-Healing Properties. *Journal of Coatings Technology and Research*, **21**, 1333-1342. <https://doi.org/10.1007/s11998-023-00896-y>
- [25] Beach, M.A., Davey, T.W., Subramanian, P. and Such, G.K. (2024) A Self-Healing Waterborne Acrylic Latex Coating Based on Intrinsic Hydrogen Bonding. *Progress in Organic Coatings*, **188**, Article 108189. <https://doi.org/10.1016/j.porgcoat.2023.108189>
- [26] Bi, J., Yan, Z., Hao, L., Elnaggar, A.Y., El-Bahy, S.M., Zhang, F., *et al.* (2023) Improving Water Resistance and Mechanical Properties of Waterborne Acrylic Resin Modified by Octafluoropentyl Methacrylate. *Journal of Materials Science*, **58**, 1452-1464. <https://doi.org/10.1007/s10853-022-07956-5>
- [27] Gao, X., Li, X., Chen, J., Huo, D., Yin, Y. and Nan, D. (2024) TiO<sub>2</sub>-Modified Graphene Oxide Fillers Strengthen Acrylic Coated Samples Corrosion and Weathering Resistance on Q235 Steel. *Langmuir*, **41**, 1418-1428. <https://doi.org/10.1021/acs.langmuir.4c04379>
- [28] Nguyen, D.T.T., Do, D.B., Nguyen, T.H., Nguyen, C.T., Nguyen, T.X., Dao, H.P., *et al.* (2024) Effect of Silica Nanocomposite Modified with Some Polythiophene Derivations on Characteristics and Properties of Waterborne Acrylic Coatings. *Journal of Coatings Technology and Research*, **21**, 2063-2077. <https://doi.org/10.1007/s11998-024-00954-z>
- [29] Le Huy, C.H. and Thanh, A.T. (2023) Study on Fabricating Epoxy Coatings Reinforced with Iron Oxide Flakes and Nano Silica. *Journal of Reinforced Plastics and Composites*, **42**, 724-740. <https://doi.org/10.1177/07316844231162562>
- [30] Liu, Y., Zhang, Q., Wang, J., Shao, Y., Xu, Z., Wang, Y., *et al.* (2023) Effect of High-Temperature Mechanochemistry Method Modified TiO<sub>2</sub> on the Dispersibility and Corrosion Resistance of TiO<sub>2</sub>-Epoxy Coatings. *Anti-Corrosion Methods and Materials*, **70**, 449-458. <https://doi.org/10.1108/acmm-05-2023-2809>
- [31] Ovchinnikov, E.V. (2025) Orientation Effects in Thin-Film Fluorine-Containing Coatings. *Surface Engineering and Applied Electrochemistry*, **61**, 362-366. <https://doi.org/10.3103/s1068375525700309>
- [32] Kazachenko, V., Dvorak, A., Razanau, I. and Li, H. (2018) Structure, Chemical Composition, Mechanical Properties of Fluorine-Containing Coatings Based on Diamond-Like Carbon. *Journal of Physics: Conference Series*, **1121**, Article 012016. <https://doi.org/10.1088/1742-6596/1121/1/012016>
- [33] Wang, X., Gao, K., Zhang, X., Zhang, Z. and Jiang, J. (2024) Mild Condition Lignin Modification Enabled High-Performance Anticorrosive Polyurethane Coating. *International Journal of Biological Macromolecules*, **280**, Article 135719. <https://doi.org/10.1016/j.ijbiomac.2024.135719>
- [34] Mao, T., Feng, H., Wu, J., Li, M., Luo, S., Chen, J., *et al.* (2023) Waterborne Organic Silicone Polyurethane with Excellent Self-Healing Performance for Oil/Water-Separation and Oil-Recovery Applications. *Sustainable Materials and Technologies*, **36**, e00631. <https://doi.org/10.1016/j.susmat.2023.e00631>
- [35] Patil, H.A., Maske, V.A. and More, A.P. (2024) Synthesis and Characterization of Eco-Friendly Epoxy Resins and Novel Fillers for Enhanced Corrosion Protection of Mild Steel. *Polymers for Advanced Technologies*, **35**, e70027. <https://doi.org/10.1002/pat.70027>
- [36] Tissanan, W., Ratvijitvech, T., Thanawan, S., Amornsakchai, T. and Phinyocheep, P. (2024) Development of Waterborne Epoxy-Based Resin Incorporated with Modified Natural Rubber Latex for Coating Application. *Scientific Reports*, **14**, Article No. 26603. <https://doi.org/10.1038/s41598-024-77990-7>
- [37] Qiao, Y., Tao, X., Li, L., Ruan, M. and Lu, L. (2024) Robust A-Fe<sub>2</sub>O<sub>3</sub>/Epoxy Resin Superhydrophobic Coatings for Anti-Icing Property. *Journal of Wuhan University of Technology-Mater. Sci. Ed.*, **39**, 621-626. <https://doi.org/10.1007/s11595-024-2918-2>