交通装备用先进复合材料:轻量化、功能化与智能化

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李华,上海交通大学特聘研究员、低空科学技术研究院副院长、复合材料研究所副所长。国家级人才项目获得者、教育部联合创新团队负责人、科技部重点研发项目首席科学家、上海市“优秀学术带头人”。主要研究方向为:多功能复合材料、复合材料绿色回收与循环利用。获得省部级一等奖2项,在国际期刊和国内核心期刊上发表论文逾170篇,授权国家发明专利30余项。多项成果已应用于船舶、航天、航空、电子与兵器等领域的重要装备。主持/参与建设了4条多功能复合材料构件加工、复合材料回收与再利用产线/示范线。

交通装备用先进复合材料:轻量化、功能化与智能化

随着高速铁路、大飞机、新能源汽车等交通装备向轻量化、高可靠、长寿命方向持续演进,先进复合材料的应用正从次承力结构向主承力结构、从单一承载向结构/功能一体化、从固定状态向智能响应发展。碳纤维增强树脂、碳化硅纤维增强碳化硅等先进复合材料已为众多交通装备的减重增效提供了可靠解决方案。然而,围绕工程化应用的终极目标,在材料层面依然存在一些瓶颈有待突破:非金属基体导电性差导致的雷击防护困难、极端热力水氧环境下材料性能退化机理不明、有机绝缘材料高安全环境的阻燃性能不足,面向智能运维的传感功能集成尚属空白等,迫切需要纤维增强高分子复合材料、复合材料表面工程、先进复合材料失效分析与智能材料设计等多领域协同攻关。为此,本期推出“交通装备用先进复合材料”专题,从“基础机理”“工程验证”“安全保障”“创新探索”四个层次,系统遴选四篇代表性研究成果,贯通材料表面改性、极端环境失效分析、阻燃防护与新型传感应用,力图呈现复合材料研发从保障结构安全向赋予部件智能感知功能演进的学术脉络。

首篇《Al、Sn、Zn粉末冷喷涂碳纤维增强树脂基复合材料的机理研究》聚焦工艺源头,针对金属粉末在热固性CFRP表面沉积机理不明的瓶颈,提出金属-环氧双相中间层嵌入策略,系统揭示了Al、Sn、Zn三种粉末在不同中间层体系上的沉积与侵蚀竞争机制,为CFRP结构冷喷涂金属化涂层的优化设计提供了理论依据。第二篇《MI-SiC_f/SiC复合材料高温水氧疲劳行为与失效机理》聚焦航空发动机热端部件的环境耐久性,依托自主搭建的多场耦合试验平台,系统对比了1200 ℃下大气与水氧环境中的拉-拉疲劳行为及水蒸气的影响机理,系统分析主导的界面失效机制转变过程,揭示了应力水平通过调控裂纹开口尺寸影响腐蚀进程的竞争机理,为寿命预测模型建立与环境障涂层优化提供了关键实验支撑。第三篇《溴锑-硼酸锌协同阻燃在架空绝缘导线电缆料中的应用》着眼于交通能源安全保障,采用三氧化二锑/十溴二苯乙烷为主体阻燃剂、硼酸锌为协效剂和抗滴落剂,系统优化了阻燃SXLPE电缆料的力学、电气与阻燃性能,为电力传输防火安全提供了经济高效的解决方案。第四篇《埃洛石纳米管增强离子凝胶及其传感应用》展望下一代智能交通传感技术,以热塑性聚氨酯为基体、离子液体为导电介质,引入埃洛石纳米管,并利用溶剂挥发诱导自组装与剪切取向策略构建有序离子传输网络,所得离子凝胶呈现优异的线性电阻响应,能准确识别人体关节弯曲、面部表情及语音振动等不同尺度形变,为构建“结构-传感”一体化部件提供了新思路。

本专题四篇文章从工艺机理、失效物理、安全防护到智能感知,构成一条从基础研究到工程应用的完整链条。可见,先进复合材料在交通装备领域的深度应用,不仅依赖材料自身性能的持续突破,更需要与机理探索、制造工艺、安全标准及智能化需求协同并进。希望本专题汇集的研究成果可为相关领域科研人员与工程技术人员提供有益参考,更期待激发出更多跨学科合作,推动复合材料在交通装备中实现更可靠、更智能、更可持续的应用。

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Advanced Composites for Transportation Equipment: Lightweight, Functionalization, and Intelligentization

As high-speed railways, large aircraft, and new-energy vehicles continue to advance toward lightweight, high-reliability, and long-life configurations, advanced composite materials are progressively expanding from secondary structures to primary load-bearing applications, and from single-function load-bearing members to multifunctional integrated systems. Carbon fiber reinforced polymer (CFRP) has become a key enabler for weight reduction and structural efficiency, while continuous silicon carbide fiber reinforced silicon carbide (SiC_x/SiC) ceramic matrix composites offer unique high-temperature solutions for aero-engine hot-section components. Nevertheless, several critical bottlenecks remain unresolved. For example, inadequate electrical conductivity of nonmetallic matrices poses challenges for lightning strike protection. Degradation mechanisms under extreme thermo-mechanical and water-oxygen environments are not yet fully understood. Balancing flame retardancy and mechanical performance in organic insulation materials remains difficult, and the integration of sensing functions for intelligent operations is still in its infancy. Addressing these issues requires interdisciplinary efforts spanning material preparation, failure physics, safety engineering, and smart sensing. In response, this special issue, Advanced Composite Materials for Transport Equipment, presents four selected studies organized along the logic of fundamental mechanisms—engineering validation—safety assurance—future exploration. Collectively, these papers span surface modification, extreme-environment failure analysis, flame-retardant protection, and emerging sensing technologies, tracing the evolutionary trajectory of composite materials R&D from ensuring structural safety toward enabling intelligent perception in components.

The first paper, "Mechanism study of cold spraying Al, Sn, Zn powders on CFRP Composites", tackles the unclear deposition mechanisms of metal powders on thermosetting CFRP surfaces. The authors propose a metal-epoxy dual-phase interlayer embedding strategy. Through finite element simulation and experimental validation, they systematically reveal the competitive deposition and erosion mechanisms of Al, Sn, and Zn powders on different interlayer systems, identifying Sn powder as exhibiting the best deposition performance due to localized melting and material jetting upon impact and providing a theoretical basis for optimizing cold-sprayed metallization coatings on CFRP structures. The second paper, "High-temperature water-oxygen fatigue behavior and failure mechanisms of MI-SiC_f/SiC, composites", addresses the environmental durability of aero-engine hot-section components under extreme service conditions. Using a self-developed multi-field coupled test platform, the authors compare tensile-tensile fatigue behavior at 1200 ℃ in both air and water-oxygen atmospheres. The study further clarifies the competitive mechanism by which stress level modulates corrosion kinetics through crack opening dimensions, and identifies the proportional limit stress (~150 MPa) as a critical fatigue design threshold, offering essential experimental support for life prediction modeling and environmental barrier coating optimization. The third paper, "Application of bromo antimony-zinc borate synergistic flame retardant in overhead insulated conductor cable material", focuses on safety assurance for transportation energy infrastructure. Using antimony trioxide/decabromodiphenyl ethane as the primary flame retardant and zinc borate as a synergist and anti-dripping agent, the study systematically optimizes the mechanical, electrical, and flame-retardant properties of SXLPE cable compounds, thereby providing a cost-effective solution for fire protection in power transmission systems. The fourth paper, "Halloysite nanotube reinforced ionogels for sensing applications", looks toward next-generation intelligent transportation sensing technologies. Using thermoplastic polyurethane as the matrix, ionic liquid as the conductive medium, and halloysite nanotubes as nanofillers, the authors construct ordered ion transport networks via solvent-evaporation-induced self-assembly combined with shear orientation. The resulting ionogel accurately detects joint bending, facial expressions, and vocal cord vibrations, offering a novel pathway toward structure-sensing integrated components.

Together, these four papers form a complete research chain, from fundamental mechanisms to engineering validation, safety protection, and intelligent sensing. They collectively demonstrate that the deep adoption of advanced composites in transport equipment relies not only on continuous improvements in material properties, but also on synergistic advancements in manufacturing processes, environmental adaptability, safety standards, and intelligent system integration. The findings compiled in this special issue provide valuable references for researchers and practitioners in related fields, and are expected to stimulate interdisciplinary efforts toward more reliable, smarter, and more sustainable composite applications in future transport equipment.

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