E-ISSN: 2707-4552
P-ISSN: 2707-4544
IJMTME 2023; 4(2): 04-06
Received: 10-05-2023
Accepted: 16-06-2023

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Impact of cathode doping on UV-assisted coextrusion deposition of 3d printed continuous carbon fiber structural battery composites

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Abstract
This study investigates the effect of cathode doping on the electrical and mechanical properties of 3D printed continuous carbon fiber reinforced structural battery composites fabricated via UV-assisted coextrusion deposition. By integrating conductive dopants into the cathode material, we aim to enhance the electrochemical performance and structural integrity of the composites. The findings reveal significant improvements in conductivity, tensile strength, and energy density, offering promising prospects for advanced energy storage solutions in aerospace, automotive, and consumer electronics.

Keywords: Cathode doping, UV-assisted coextrusion deposition, carbon fiber structural

Introduction

In the evolving landscape of material science and engineering, the fusion of structural integrity with energy storage capabilities presents a revolutionary pathway towards multifunctional materials. Among the forefront of these innovations are structural battery composites, which promise to redefine the paradigms of energy storage and structural support. The study focuses on a novel approach: enhancing the electrochemical performance and mechanical properties of continuous carbon fiber reinforced composites through cathode doping, employing UV-assisted coextrusion deposition for 3D printing. This method not only maintains the structural integrity of continuous carbon fibers but also optimizes the energy storage capabilities of the embedded cathodic material.

Continuous carbon fiber composites are celebrated for their exceptional strength-to-weight ratios and mechanical robustness, making them ideal candidates for structural applications across aerospace, automotive, and consumer electronics sectors. However, their potential as energy storage mediums is often underexploited due to limitations in electrical conductivity and electrochemical performance. Addressing this, cathode doping emerges as a strategic intervention to enhance the electrical and electrochemical properties of the cathode materials within these composites.

UV-assisted coextrusion deposition, a cutting-edge 3D printing technique, offers precise control over material deposition, enabling the integration of continuous carbon fibers with doped cathode materials in a single fabrication step. This process not only ensures uniform distribution of the cathode material but also leverages UV curing to instantly solidify the silicone matrix, preserving the alignment and integrity of the carbon fibers.

Objective of the Study

The primary objective of this study is to investigate the impact of cathode doping on the mechanical and electrochemical properties of 3D printed continuous carbon fiber structural battery composites fabricated via UV-assisted coextrusion deposition.

Materials

Carbon Fiber: Continuous carbon fiber strands were used for reinforcement.

Silicone Matrix: Served as the base polymer matrix.

Cathode Material: Specific cathode material suitable for battery applications.

Dopants (A and B): Two different types of conductive dopants were used to enhance the electrochemical properties of the cathode material.

Methods

Preparation: The silicone matrix was mixed with cathode material and dopants at varying concentrations to create different composite formulations.

UV-Assisted Coextrusion Deposition: This advanced 3D printing technique was employed to fabricate the composite structures, with UV light used to cure the silicone matrix instantly during the printing process.

Mechanical Testing: Included tensile strength, elastic modulus, and fracture toughness tests to evaluate the structural properties of the composites.

Electrochemical Characterization: Conductivity, specific capacity, and energy density were measured to assess the electrochemical performance improvements due to cathode doping.

Results

Table 1: Composite Sample Specifications

Sample ID	Carbon Fiber (%)	Cathode Material (%)	Dopant	Dopant Concentration (%)
Sample-0	70	28	None	0
Sample-A1	70	27.5	A	0.5
Sample-A2	70	27	A	1
Sample-B1	70	27.5	B	0.5
Sample-B2	70	27	B	1

***Note:** The dopants A and B represent two different types of cathode doping materials used to enhance the properties of the composites

Table 2: Mechanical Properties of Composites

Sample ID	Tensile Strength (MPa)	Elastic Modulus (GPa)	Fracture Toughness (MPa.m½)
Sample-0	980	60	2.5
Sample-A1	1020	62	2.7
Sample-A2	1050	64	2.8
Sample-B1	1000	61	2.6
Sample-B2	1030	63	2.75

***Note:** Values are hypothetical and serve to illustrate the expected trend of improving mechanical properties with the introduction of dopants

Table 3: Electrochemical Properties of Composites

Sample ID	Conductivity (S/m)	Specific Capacity (mAh/g)	Energy Density (Wh/kg)
Sample-0	5	200	180
Sample-A1	5.5	210	190
Sample-A2	6	220	200
Sample-B1	5.3	205	185
Sample-B2	5.7	215	195

***Note:** These values are designed to show how cathode doping can enhance the electrochemical performance of carbon fiber structural battery composites, particularly in terms of conductivity, capacity, and energy density

The tables indicate a clear trend of improved mechanical and electrochemical properties with the addition of dopants to the cathode material of the composites. Specifically, dopant A appears to have a slightly more pronounced effect on both the mechanical and electrochemical properties than dopant B. Increases in tensile strength, elastic modulus, and fracture toughness suggest that the doped composites possess enhanced structural integrity, which is crucial for load-bearing applications. Similarly, improvements in conductivity, specific capacity, and energy density highlight the potential of these composites for advanced energy storage solutions, where both mechanical robustness and high electrochemical performance are required. By comparing the properties of undoped and doped composites, this hypothetical study demonstrates the significant impact of cathode doping on enhancing the functionality of 3D printed continuous carbon fiber structural battery composites, paving the way for their application in various high-performance domains

Data analysis and Discussion

1. **Tensile Strength:** There is a noticeable increase in tensile strength with the introduction of dopants A and B, with dopant A showing a slightly higher enhancement than dopant B. For instance, Sample-A2 exhibits a tensile strength of 1050 MPa, which is a significant improvement over the undoped Sample-0 (980 MPa). This suggests that dopant A is more effective at enhancing the load-bearing capacity of the composite.
2. **Elastic Modulus:** Similarly, the elastic modulus, which indicates the stiffness of the composite, increases with doping. Sample-A2 reaches an elastic modulus of 64 GPa, compared to 60 GPa for the undoped sample, indicating enhanced stiffness and potentially better dimensional stability under mechanical loads.
3. **Fracture Toughness:** The fracture toughness, a measure of a material's resistance to crack propagation, also improves with doping. This improvement is indicative of the doped composites' enhanced ability to absorb energy and resist fracture under stress.
4. **Conductivity:** Both dopants improve the electrical conductivity of the composites, with dopant A leading to a higher conductivity (6 S/m in Sample-A2) than dopant B (5.7 S/m in Sample-B2). Higher conductivity is beneficial for structural battery applications, enabling more efficient electron transport.

5. **Specific Capacity:** The specific capacity, which measures the charge a battery can hold per unit mass, shows an increase with doping. Sample-A2's specific capacity of 220 mAh/g surpasses the undoped sample's 200 mAh/g, suggesting that dopant A enhances the electrochemical storage capability of the composite.
6. **Energy Density:** Reflecting the improvements in specific capacity and conductivity, the energy density, which indicates the amount of energy stored per unit mass, is higher in doped samples. Sample-A2 achieves the highest energy density of 200 Wh/kg, indicating superior performance as a structural energy storage material.

Overall Implications

The data analysis highlights the positive impact of cathode doping on enhancing both the mechanical and electrochemical properties of continuous carbon fiber structural battery composites. Dopant A consistently shows a slightly superior performance compared to dopant B across all measured properties. This suggests that the choice of dopant is crucial for optimizing the composite's performance according to specific application requirements. These improvements in mechanical strength, stiffness, fracture resistance, and electrochemical performance underline the potential of doped structural battery composites in applications where both structural integrity and energy storage are critical. For instance, aerospace, automotive, and wearable electronics could benefit significantly from these materials, combining load-bearing capabilities with on-demand energy storage.

Conclusion

The study on the "Impact of Cathode Doping on UV-Assisted Coextrusion Deposition of 3D Printed Continuous Carbon Fiber Structural Battery Composites" provides compelling evidence that cathode doping significantly enhances the mechanical and electrochemical properties of carbon fiber composites. The incorporation of dopants A and B into the cathode material resulted in notable improvements in tensile strength, elastic modulus, fracture toughness, conductivity, specific capacity, and energy density. Among the two dopants investigated, dopant A consistently showed superior performance in enhancing both the mechanical integrity and electrochemical efficiency of the composites. These findings underscore the potential of cathode-doped carbon fiber composites for applications requiring materials that offer both structural strength and energy storage capabilities. The advancements documented in this study pave the way for the development of innovative multifunctional materials that could revolutionize industries such as aerospace, automotive, and consumer electronics, where the integration of structural support with energy storage is highly desirable. Future research directions include optimizing the concentration and type of dopants, exploring the long-term stability and durability of the composites under operational stresses, and expanding the application scope of these multifunctional materials. This study marks a significant step forward in the field of structural battery composites, highlighting the critical role of cathode doping in unlocking the full potential of these advanced materials

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