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Density-Based Defect Detection in Composite Materials Using Magnetic Levitation

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ABSTRACT

Magnetic levitation (MagLev) presents a non-contact, highly sensitive approach for identifying structural defects in high-performance composite materials through precise density-based measurements. Many composite materials—such as carbon fiber-reinforced polymers (CFRPs), glass fiber-reinforced polymers (GFRPs), reinforced elastomers, 3D-printed polymer composites, metal-polymer hybrids, aerogels, and natural fiber-based biocomposites—play crucial roles in aerospace, automotive, biomedical, and advanced manufacturing applications due to their lightweight, high-strength, and tunable properties. However, their mechanical integrity is often compromised by voids, delaminations, resin starvation, and interfacial adhesion defects, which can significantly impact performance.

In this study, an in-house MagLev tool was developed to evaluate the density distribution of composite samples and detect manufacturing defects. By utilizing Magneto-Archimedes Levitation, which balances gravitational and magnetic forces within a paramagnetic medium, the system enables fine-tuned density differentiation. The technique allows for sub-millimeter defect identification, distinguishing samples based on density variations indicative of internal voids, inclusions, or layer inconsistencies. Our findings reveal that different defect types, such as voids versus delaminations, alter the way composites respond to levitation, affecting their stability, orientation, and equilibrium position in the magnetic field. This insight enabled us to further fine-tune MagLev parameters to enhance multi-material defect identification, particularly in heterogeneous composite structures. Optimized multi-magnet configurations and tailored paramagnetic fluid selection improved resolution and defect localization across various composite types. CFRPs and GFRPs, widely used in aerospace and structural applications, exhibit characteristic density fluctuations when defects such as fiber waviness or delaminations occur, making MagLev a valuable tool for their non-destructive evaluation. Similarly, 3D-printed composites and aerogels, which are prone to layer voids and non-uniform porosity, benefit from MagLev-based quality screening to ensure structural consistency.

Preliminary results demonstrate that MagLev can accurately classify defective and defect-free samples, providing a rapid, cost-effective alternative to conventional X-ray CT scanning and ultrasonic testing. With further future refinements—such as multi-frequency MagLev scanning, real-time defect tracking, and AI-assisted density mapping—this method holds potential for automated material screening, defect localization, and quality control across additive manufacturing and aerospace composites. MagLev's ability to facilitate multi-material testing and real-time analysis makes it an optimal tool for defect detection and intelligent material design, while its versatility and precision position it as a convenient, cost-effective, and reliable method for characterizing composite and polymer materials.