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A Dielectric Assessment Framework for Sustainable Manufacturing and Recycling Pathways of Fiber-Reinforced Polymer Composites

By

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Abstract

Fiber reinforced polymer composite materials, (specially carbon fiber reinforced composite) have been widely used in different industries such as aerospace, automobile, marine, energy, and defense. The reason behind this wide application is its high strength-to-weight ratio despite low density, high stiffness, and durability. However, the rapid rise in carbon fiber composite demand raises sustainability concerns, including extensive waste, inefficient resource usage, and difficult recycling processes. Considering this real-world scenario of composite demand and waste, this research develops a dielectric-based characterization framework to address these sustainability concerns throughout the composite lifecycle from raw material evaluation and manufacturing quality monitoring to end-of-life recycling optimization. The study has been divided into four sections, discussing how dielectric characterization can be effectively utilized to assess the composite material quality and performance before throwing as waste which will help informed recycling or reuses decisions. The first study assesses the raw material for composite manufacturing, called prepreg. Here, the dielectric response of prepreg materials during room-temperature aging was investigated, where slow curing reactions gradually alter material properties. This is a major issue in composite manufacturing since it causes thousands of tons of raw material waste, almost 50% of total composite waste. A framework was established for prepreg age monitoring using broadband dielectric spectroscopy, which will help informed manufacturing decisions making. The second study uses the dielectric assessment framework during composite manufacturing. Inadequate curing during manufacturing can lead to heterogeneous properties and poor quality. A coupled experimental and computational framework linking epoxy cure kinetics with dielectric relaxation behavior has been developed. And a data-driven machine learning model was also used to assess post-cure quality and generate a degree-of-cure map with 96.7% accuracy, validated experimentally. The third study focuses on assessment of in-service composite samples where long-term reliability is affected by damage accumulation, particularly delamination. This part of the study addresses two challenges: (1) developing an ex-situ dielectric-based framework to sort composite materials based on damage severity, particularly delamination, and (2) understanding how damage in composites influences resin removal during recycling. The final study focuses on end-of-life composites where different techniques for recycling carbon fiber prepregs and composites were investigated.