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Unified Interfacial Design for Dynamic Thermo-Mechanical Stability and Thermal Transport in Fiber Composites under Extreme Conditions

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ABSTRACT

Carbon fiber–reinforced polymers (CFRPs) are essential for lightweight structural applications, yet their performance degrades severely under coupled high strain-rate loading and elevated temperatures due to matrix softening and interfacial instability. Overcoming this limitation requires interfacial designs capable of simultaneously accommodating dynamic deformation and mitigating thermally induced damage. Here, we present a generalized hybrid interfacial engineering strategy that integrates nanoscale compliant layers with thermally stable ceramic interphases to construct hierarchical fiber–matrix interfaces. This metallic/polymeric–ceramic architecture is designed to regulate stress transfer under rapid loading while constraining thermal expansion mismatch and enhancing heat dissipation. Dynamic compressive behavior was evaluated at strain rates up to ~4000 s^{-1} over an extended temperature range reaching 300 °C. The engineered composites exhibit significantly improved strength retention, delayed thermal softening, and enhanced energy dissipation under extreme conditions, while maintaining stable post-yield load-bearing behavior. In addition, notable improvements in thermal transport properties, including thermal conductivity and diffusivity, are achieved, contributing to improved thermo-mechanical stability. Multiscale characterization reveals suppressed interfacial debonding, reduced delamination, and controlled crack propagation, indicating enhanced interfacial cohesion and structural integrity. Complementary finite element simulations incorporating temperature-dependent interfacial damage models reproduce the observed responses and elucidate the cooperative roles of compliant interlayers and rigid ceramic phases in governing deformation and failure evolution. This work establishes a versatile interfacial design framework for CFRPs that simultaneously enhances impact resistance, thermal stability, and heat transport capability, offering a scalable pathway for advanced structural materials operating under extreme thermo-mechanical environments.

KEYWORDS

Carbon fiber composites; interfacial engineering; high strain-rate deformation; thermo-mechanical stability; thermal transport; extreme environments; finite element modeling

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