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Evolution Behavior and Mechanism of Residual Stress in Aerospace Components Under Multi-Field Coupling Control

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ABSTRACT

Aerospace components are highly sensitive to residual stress when subjected to extreme service environments, making precise control of such stress essential for ensuring structural integrity and long-term service reliability. To address this critical challenge, this study focuses on aluminum and titanium alloys—two material systems widely employed in the aerospace industry—to investigate the mechanisms underlying residual stress formation and relaxation, and to develop effective multi-field coupling control strategies. By integrating experimental characterization with numerical simulation, the evolution behavior and relaxation mechanisms of residual stress during both manufacturing and service stages are systematically examined. The synergistic effects of multiple physical fields on stress evolution are thoroughly analyzed. Based on these analyses, a thermal-vibration hybrid control method is proposed, which achieves effective residual stress reduction and microstructural refinement through the coordinated optimization of thermal history and vibration parameters. To further improve the overall stress state, a magnetic field is incorporated to establish a low-temperature-magnetic-vibrational multi-field synergistic control process, enabling a more comprehensive regulation of the residual stress field and leading to marked improvements in stress uniformity, dimensional stability, and fatigue performance. For additively manufactured components, the formation and evolution mechanisms of residual stress are systematically revealed, offering theoretical guidance for process optimization. Collectively, the findings provide effective technical pathways and scientific foundations for stress management and performance enhancement in the manufacturing of critical aerospace components, thereby supporting the development of high-performance aerospace structures.

KEYWORDS

Aerospace components; residual stress; stress relaxation; multi-field coupling; additive manufacturing

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