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ADVANCEMENTS IN ADDITIVE MANUFACTURING TECHNIQUES FOR AEROSPACE APPLICATIONS: A COMPREHENSIVE REVIEW ON PERFORMANCE-DRIVEN MATERIAL INNOVATIONS, PROCESS OPTIMIZATION, AND FUTURE PROSPECTS

Abstract

Additive Manufacturing (AM) has emerged as a transformative technology in aerospace engineering, enabling the fabrication of components made of metamaterials and showcasing high performance, lightweight, and geometrical complexities with improved accuracy and precision over the years. By consolidating multiple parts into single monolithic structures, AM has demonstrated a 50–80% reduction in component weight, a 30–50% increase in fuel efficiency, and a 70% decrease in material wastage compared to traditional subtractive methods. The criticality of AM in aerospace is underscored by its role in next generation propulsion systems, micro and nanomanufacturing for aero electronics, reusable space vehicles, and planetary colonization efforts such as Single Stage To Orbit (SSTO) vehicles, Mars and lunar habitats. Furthermore, AM driven advancements in hypersonic flight, turbine efficiency, and structural resilience are crucial for achieving sustainable interplanetary missions.

This study conducts a systematic review of AM advancements in aerospace manufacturing from 2014 to 2025, focusing on the evolution of AM techniques, material innovations, performance enhancements, and reliability improvements. Case studies, including GE Aviation's 3D printed fuel nozzle, achieving a fivefold increase in durability while reducing part count from 20 to 1 and NASA's RS25 engine components, which reduced lead time by 60%, illustrate AM's disruptive potential. This work also delves into state of the art AM techniques such as Laser Powder Bed Fusion (LPBF), Electron Beam Melting (EBM), Direct Metal Laser Sintering (DMLS), and hybrid multi material and sheet lamination based AM, each contributing to aerospace-grade components with superior mechanical properties. Furthermore, an extensive bibliometric analysis of 100+ scientific publications and industrial patents identifies key trends, technological gaps, and emerging frontiers in aerospace AM. Statistical modeling of cost efficiency and structural optimization through DFMA techniques further highlights AM's ability to reduce lead times by 40–60% and production costs by up to 30%.

The findings of this study provide a comprehensive framework for future AM research, emphasizing the need for enhanced process control, defect mitigation strategies, and high temperature resistant materials such as Ti-Al intermetallics, functionally graded materials, and refractory metal alloys. As aerospace manufacturers transition toward fully AM driven production ecosystems, the insights from this study will serve as a guiding reference for optimizing material selection, manufacturing parameters, and performance benchmarks. Ultimately, this research underscores AM's pivotal role in redefining aerospace manufacturing paradigms, paving the way for high-reliability, cost efficient, and functionally optimized components for atmospheric, orbital, and deep-space missions.