

Valorization of waste streams for aerospace composites production

Abstract

This doctoral dissertation was carried out within the framework of an industrial Ph.D. program in collaboration with Leonardo S.p.A., a leading company in the aerospace and defense sector. The project was designed to strengthen the connection between academic research and industrial application, combining scientific rigor with technological relevance. The research aimed to develop and characterize advanced composite materials for aerospace structures, with particular emphasis on sustainability, multifunctionality, and process scalability.

The work followed a multidisciplinary approach, integrating material design, processing, and characterization. Its objective was to identify and optimize novel material systems matching the increasing demands of performance, reliability, and environmental accountability in the aerospace field. The thesis is organized into six chapters, each addressing a specific aspect of the research activity. The introductory chapters provide an overview of the evolution of materials in aeronautics and discuss the growing importance of recycling technologies and functional composites for electromagnetic interference (EMI) shielding. These topics have become central in aerospace research due to the need for lightweight materials that combine structural efficiency with environmental sustainability and electromagnetic compatibility.

A wide range of characterization techniques were employed, including morphological, mechanical, chemical, thermal, and electromagnetic analyses. These methods enabled a detailed understanding of the structure–property relationships governing the behavior of the developed materials.

The experimental work represents the core of the thesis and includes several interconnected research lines. The first focuses on a novel carbon-based nanomaterial, morphed graphene (RH6-II), synthesized in collaboration with University of Houston. The study demonstrated that RH6-II can be incorporated into polymer matrices at very high loadings up to 70 wt.% while maintaining processability and providing excellent EMI shielding efficiency above 3 GHz. These results are particularly significant, as conventional carbon allotropes such as graphene or carbon nanotubes typically exhibit severe dispersion and viscosity limitations at much lower concentrations.

A second research line examined natural reinforcements, specifically hemp fibers and hemp hurds, as sustainable alternatives to synthetic fibers. Their mechanical and morphological characterization provided valuable insights into their potential use in semi-structural applications, particularly in non-critical aerospace components or in lightweight panels for automotive applications.

Further work investigated hybrid fillers derived from waste materials, including iron nitrate-modified biochar and red mud-modified biochar. These fillers were evaluated for their influence on electrical, magnetic, and mechanical properties. The results demonstrated that biochar-based composites exhibited stable dielectric behavior and tunable conductivity suitable for high-frequency applications. The combination of biochar and red mud provided a multifunctional filler with both conductive and magnetic characteristics, enabling the valorization of two industrial waste streams within a single composite system. This approach supports the implementation of circular economy principles in the design of advanced polymer composites.

Another important research activity focused on carbon fiber recycling, comparing thermochemical and plasma-assisted solvolysis processes. The plasma-assisted treatment was shown to better preserve the structural integrity and surface quality of the recovered fibers, resulting in improved interfacial adhesion and enhanced mechanical performance. These results contribute to the development of efficient recycling routes for high-value carbon fibers and their potential reintegration into secondary aerospace components.

During the mandatory period abroad at the National Technical University of Athens, two additional studies were carried out. The first investigated the production of carbon fibers from lignin, a renewable and low-cost precursor that could reduce the environmental impact of carbon fiber manufacturing. Although challenges remain in terms of filament continuity and degree of graphitization, the preliminary results confirmed the feasibility of lignin as a carbon precursor. The second study involved the surface functionalization of recycled carbon fibers by sizing treatment to restore their interfacial performance. Both activities align with the general objective of developing sustainable and recyclable fiber-reinforced composites for aerospace applications.

Overall, this thesis provides a comprehensive framework for the development of next-generation composite materials that combine structural performance with environmental sustainability. The key outcomes include the formulation of highly filled RH6-II composites with outstanding EMI shielding capability, the optimization of hemp-based natural reinforcements, the development of waste-derived hybrid fillers, and the validation of plasma-assisted carbon fiber recycling.

Future research directions include the optimization of filler–matrix interfaces, the improvement of dispersion and adhesion mechanisms, the refinement of lignin-based fiber processing, and the assessment of long-term material stability under environmental and fatigue conditions representative of aerospace service environments. Furthermore, techno-economic and life-cycle analyses will be essential to evaluate the scalability and industrial implementation of the proposed material systems.

This work contributes to advancing the scientific and technological foundations of sustainable composite materials and provides practical insights to support their integration into aerospace manufacturing, where performance, durability, and environmental impact must be jointly optimized.