Macromolecular Symposia

CONFERENCE Times of Polymers and Composites 2025 (TOP25)

Macromolecular Symposia

www.ms-journal.de

RESEARCH ARTICLE OPEN ACCESS

Validation of Industrially Recycled Carbon-Fibers Upcycling: Reuse of ReCF in a Component as Proof-of-Concept of Circular Economy

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Received: 7 April 2025 | **Revised:** 7 April 2025 | **Accepted:** 24 October 2025

Guest Editors: Alberto D'Amore and Luigi Grassia

Keywords: CFRP | pyro-gassification | pyrolysis | recycling | re-use

ABSTRACT

Carbon-fiber-reinforced polymers (CFRPs) are excellent candidates for lightweighting vehicle components. However, the lack and the cost of raw materials prevent their widespread application. Moreover, CFRPs are difficult to recycle. A recently started-up carbon fiber recycling plant (FIB3R, designed by HERAmbiente @Imola—BO—Italy, from a joint UniBo and Curti Costruzioni Meccaniche patent) produces now up to 320 tons per year of ReCF. Tailoring and optimizing the specific recycling process to boost the final ReCF properties, as well as the re-impregnation strategies to optimize composites production, are at the basis of a successful result. The use of greener alternatives is still far from being a diffused practice in the mobility industry. This is mainly due to the lack of specifically suited industrial processing methods, material knowledge, and design tools. Thus, it requires the common effort of sustainable materials experts, green manufacturing technologists, and a circular economy approach to support this transition step, the widespread use of ReCF within the CFRP value chain.

1 | Introduction

Carbon fiber-reinforced polymers (CFRPs) are increasingly used in automotive applications, in particular for metal replacement, owing to their favorable ratio between structural properties and density, which can also lead to a reduction of the carbon footprint during the components' life. On the other hand, this aspect could be totally different when considering the whole life cycle of the material, which poses several issues both regarding fiber fabrication and their final disposal at the end of life. In fact, significant quantities of energy are at stake associated with the emission of a large amount of CO_2 for processing stages [1]. Moreover, Western Europe's CFRP components producers lately faced a scarcity of virgin fibers due to the supply chain disruption provoked by COVID-19 and geopolitical events. It is thus clear that recycling of CF is beneficial for all aspects of sustainability [2, 3]:

- Environmental—reduces wastes and the energy required to obtain the raw material;
- Economic—allows the use of cheaper materials characterized by a potentially circular supply chain, based also on locally sourced actors;
- Social—establishes new know-how, increasing the need for a qualified workforce.

https://doi.org/10.1002/masy.70240

Validation of waste reuse in new upcycled applications is still one of the highest challenging issues within CFRPs recycling. Indeed, applying recycled reinforcements might raise doubts and skepticism in a field where high performance represents the materials' highest strength. It is nonetheless a fact that, in terms of sustainability, Re-CF, though they might lose up to 10% of their initial properties, still represent a significantly high-performing material, though lacking control over their shape [4]. Strong demonstrators, aimed at the automotive industry, and rooted in local actors, are thus one of the best demonstrator cases for a winning approach at closing the loop in the CFRP Italian value chain. This work points at using Re-CF produced at FIB3R, a recently set up plant from HeraAmbiente in Imola (BO)-Italy, which allows for an unprecedented potential for upgrading the quality of the recycled CF, offering possibilities ahead of the market conditions [5]. The plant allows for a targeted identification and control of the input material that can be sorted and treated in very tailored conditions for maximizing the final performance of the Re-CF. This condition is not found in the anyway scarce supply of Re-CF presently on the market, which typically offers a reinforcement based on an unknown and uncontrolled fiber type (almost never disclosed by the supplier). A tailored recycling process able to identify and separate different fiber scrap feedstocks could boost the potential for upcycling such materials for high-end applications, either within the same company that supplied the waste or oriented at a wider market. Indeed, previous studies from the involved research groups demonstrated that the pyro-gasification technology implemented in FIB3R requires optimized operative conditions depending on the actual resin and fiber type, which, however, in turn can produce Re-CF of the highest quality, free of resin residues and with a slightly oxidized surface offering good adhesion for epoxy resins re-impregnation.

In this regard, a significant and challenging prototype has been identified, which aims at redesigning a body-part switching from Aluminum to Nonwoven CFRPs for guaranteeing an acceptable mechanical performance but increasing pedestrian safety significantly, thanks to the improved crash behavior that the latter provides in the case of an impact. The benefit of using short, recycled carbon fibers would allow designing a component with calibrated failures at lower loads, compared to metal and long, woven virgin fibers, without excessively compromising stiffness and weight savings. This approach represents a premium case of secondary raw materials upcycling, serving as proof of the viability of Re-CF

2 | Materials and Methods

Epoxy composite prepreg cut-offs based on T700S fabrics were supplied by local companies. Non-woven mats were manufactured and reimpregnated via HeraAmbiente and FIB3R.

2.1 | Pyro-Gassification Experiments

The CFRCs pyrolysis experiments were carried out in an industrial plant, FIB3R, with the aim of optimizing fiber quality performance. The continuous plant was able to treat samples without downsizing - given that it fits within the pyrolysis chamber - and thus the maximum allowed size is slightly less than 1 m in length for rigid materials. The pyrolysis batches can be run in the 400°C–600°C range. In a typical run, CFRCs scraps are first subjected to heating in an inert atmosphere, degrading the polymer matrix. The solid residue that generates was removed by applying air (gasification), still at high T in a second dedicated oven. Re-CF were thus gathered upon cooling. They typically represent about 50% of the mass feedstock, depending on the type and quality of prepreg scraps used. Fibers were then sent for non-woven mats production and reimpregnation with commercial epoxy resins. During all the above operations, operational data were also gathered for LCA purposes. Finally, the most convenient prepregs obtained will be fully characterized using specimens from plates cured in an autoclave, in order to obtain data useful for designing a reliable prototype.

2.2 | Methods

Thermogravimetric analysis (TGA) to set up pyrogassification conditions was carried out using a TA Instruments TGA 550 apparatus. Preliminary oxidative treatment experiments were carried out on approximately 15–30 mg of material in an oxidizing atmosphere (air: flow rate 100 mL/min) from RT to either 500°C or 600°C, where samples were kept isothermally for 60 min. TGA runs intended for fiber fraction determination were carried out in triplicate for each sample, on approximately 20–30 mg of composite, heating them from RT to 500°C at 20°C/min heating rate in inert atmosphere (nitrogen: flow rate 100 mL/min) leaving it in isotherm for 15 min, then cooling the sample down to 300°C before switching to oxidizing atmosphere (air: flow rate 100 mL/min) before heating again at 20°C/min heating rate up to 500°C, where the sample was once again kept isothermally for 15 min. In order to investigate the morphological aspect of the fibers and the fracture surface of the composites, micrographs were taken with a benchtop PHENOM Pro X Scanning Electron Microscope (SEM), equipped with an EDX microanalysis system. The distribution of fiber diameters was determined with the help of an image analysis software, measuring about 100 fibers in two different images (50 fibers per image) per fiber type, while the surface oxidation was evaluated by the O/C ratio from EDX maps.

3 | Results and Discussion

While the re-use of carbon fiber has often been tested and validated on lab-scale production specimens (TRL 3), the up-scale of such a process toward industrial validation is of paramount importance. However, this step requires the potential to attain industrially relevant production of the recycled fibers, to be used as secondary raw materials (TRL5) for obtaining a reliable feedstock to be scaled up in the final demonstrator to be produced in a company's productive line (TRL 7–8 endpoint of C-UP).

In this regard, fibers are tested and proved to perform mechanically in a comparable way with respect to the original ones. Moreover, the setup of the plant allows for tracking and isolation of single waste streams, thus leading to a high-quality final non-woven. The final re-use of such non-woven is presently under evaluation for final performance, providing preliminary results which are highly encouraging.

Moreover, the environmental performance of the process proposed is being evaluated by a life cycle assessment approach to estimate the associated carbon footprint and cumulative energy demand. Preliminary evaluation [6], based on pilot plant data, shows that the pyro-gasification process attains a reduction of 40 $kgCO_2eq$ per kg of recycled CFs, compared to virgin CFs. In the case of pyro-gasification, Re-CF could be implemented in the CFRPs manufacturing value chain; the estimated reduction of the carbon footprint could be up to 15%, boosting up to 59%–73% when cutting and trimming waste-optimized remanufacturing is combined with circular economy strategies based on the ideal recycling of CFRPs at end-of-life.

Acknowledgements

This research was funded by the European Union—NextGenerationEU (National Sustainable Mobility Center CN00000023, Italian Ministry of University and Research Decree n. 1033—17/06/2022, Spoke 11—Innovative Materials & Lightweighting) Project CO-SMART, Flagship Linea A funded by the National Sustainable Mobility Center CN00000023, together with Resilience Plan (NRRP), Mission 04 Component 2 Investment 1.5—NextGenerationEU, Call for tender n. 3277 dated 30/12/2021, Award Number: 0001052 dated 23/06/2022, within Spoke 1 activities—Materials for sustainability and ecological transition—(CUP J33C22001240001), and project C-UP funded within Ecosyster.

Conflicts of Interest

The authors declare no conflicts of interest.

References

1. Y. S. Song, J. R. Youn, and T. G. Gutowski, "Life Cycle Energy Analysis of Fiber-Reinforced Composites," *Composites Part A: Applied Science and Manufacturing* 40 (2009): 1257–1265, https://doi.org/10.1016/j.compositesa.2009.05.020.

2. L. Giorgini, T. Benelli, G. Brancolini, and L. Mazzocchetti, "Recycling of Carbon Fiber Reinforced Composites Waste to Close Their Life Cycle in a Cradle-to-Cradle Approach," *Current Opinion in Green and Sustainable Chemistry* 26 (2020): 100368, https://doi.org/10.1016/j.cogsc.2020.100368.

3. M. Ateeq, "A State of Art Review on Recycling and Remanufacturing of the Carbon Fiber From Carbon Fiber Polymer Composite," *Composites Part C* 12 (2023): 100412.

4. L. Mazzocchetti, T. Benelli, E. D'angelo, C. Leonardi, G. Zattini, and L. Giorgini, "Validation of Carbon Fibers Recycling by Pyro-gasification: The Influence of Oxidation Conditions to Obtain Clean Fibers and Promote fiber/Matrix Adhesion in Epoxy Composites," *Composites Part A: Applied Science and Manufacturing* 112 (2018): 504–514, https://doi.org/10.1016/j.compositesa.2018.07.007.

5. "Carbon Fibre Recovery Plant in Imola (BO)," https://ha.gruppohera.it/carbon-fibre-recovery-plant-in-imola-bo.

6. L. Ciacci, G. Zattini, C. Tosi, B. Berti, F. Passarini, and L. Giorgini, "Carbon Fibers Waste Recovery via Pyro-Gasification: Semi-Industrial Pilot Plant Testing and LCA," *Sustainability* 14 (2022): 3744, https://doi.org/10.3390/su14073744.