

HOW CAN CFRP PREPREG SCRAPS BE REUSED? THE “CIRCE” LIFE PROJECT

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Abstract: *Prepreg scraps generated during the cutting phase of virgin Carbon Fiber Reinforced Polymers parts typically account about 30% of the total prepreg produced. At present, these scraps end up in landfill or in incineration facilities, with relevant consequences in terms of costs and environmental impacts. In this context, a solution has been proposed within the CIRCE (Circular Economy Model for Carbon Fibre Prepregs) EU LIFE project. 5 Italian companies are collaborating to identify possible solutions to successfully reuse prepreg scraps. The companies have tested an industrial process that transform the scraps and prepare them to be processed as secondary raw material. To validate the recovery process, the manufacturing of three different composite products has been addressed: toe caps for safety footwear, carbo-ceramics brakes and automotive parts. The preliminary results demonstrated that this recovery process can be successfully employed to produce high mechanical properties composite parts with low environmental impacts.*

Keywords: Circular economy; Prepreg scraps; Sustainability; CFRP

1. Introduction

In the last years, the demand of composite materials is constantly growing in different industrial fields where lightness and resistance are required, such as automotive, marine, energy and sporting equipment sectors[1].

These materials are commonly defined as a combination of two or more distinct materials, each of which maintains its own distinctive properties, to create a new material with properties that cannot be achieved by any of the components acting alone. Due to this combination, composite materials are characterized by low weight and high performance in terms of specific stiffness and strength. Among these materials, Carbon Fiber Reinforced Polymers (CFRPs) are widely used for their relevant engineering properties, such as high stiffness and strength, low density, thermal and electrical insulation and corrosion and chemical resistance [2–4].

The increasing demand for composites is expected to reach 194 kt (kilo tones) in 2022, while, for carbon fibers, is predicted a demand of 117 kt. Mostly of CFRPs use can be attributed to the transport sector, where composites allow to reduce the emissions related to the useful life by reducing fuel consumption [5,6].

However, CFRPs are also associated to significant environmental impacts: most of them are related to the manufacturing process of carbon fiber. It accounts for about 70% of the total

environmental loads of a composite product and it is mostly due to the high energy consumption required for the raw material production [7].

Another issue associated to this increasing demand of CFRPs is the generation of prepreg scraps, wastes produced during the cutting phase of laminates manufacturing, which constitute between 20-50% of the virgin prepreg used [8]. Nowadays, these scraps typically end up in landfill or incinerator with negative impacts on the environment and high costs. These end of life strategies are adopted because, even though several recycling methods for CFRPs prepreg based on mechanical, thermal (e.g. pyrolysis and fluidised bed process), and chemical process have been developed, the properties of the recycled materials are very poor despite to the very high recycling costs [9,10]. Indeed, due to the cross-linked structure of thermoset matrix, it cannot be remelted and easily reshaped and reused [11]; when it is recovered it is typically used as filler, fuel or chemical feedstock [12]. In terms of recovered carbon fibers they are reduced in size and usually show a reduction in mechanical properties, with respect to vCF.

These issues have made necessary the development of methodologies that allow the recover the residual end-of-life value of CFRPs prepreg scraps. Indeed, these scraps, due to the presence of continuous carbon fibers and uncured thermoset matrix, can be reintroduced in the manufacturing process for the realization of high-quality composite components.

A possible solution has been proposed within the CIRCE (Circular Economy Model for Carbon Fiber Prepregs) EU LIFE project, developed as a collaboration between five Italian companies (HP Composites, Alci, Base Protection, Cetma, and Petroceramics). The project goal was to develop a recovery system for uncured prepreg scraps and to find suitable production processes and products for the new raw secondary material [13]. This project is based on a zero-waste approach, reusing scraps produced during the cutting operation of virgin prepreg rolls, in a circular economy model that allows to reduce the environmental impacts of products, costs and gives a second life to these materials that otherwise would go to landfill or incinerator. This allows to reach a 100% valorization of the waste, recovering completely the uncured waste [14,15]. Three case studies to be realized with the recovered scraps have been identified: a component for the automotive sector, toe caps for safety footwear and carbo-ceramic brakes. To quantify the advantages related to the new recovery process environmental impacts, costs, cost-benefits (CBA) and business model analyses have been conducted on the products realized.

The cost and impacts analyses are carried out following the international standards for Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), in order to evaluate which processes are the most beneficial and identify critical issues and improvement possibilities.

In this paper, the CIRCE project and its main results are presented, highlighting potentialities and problems related to the recovery of carbon fiber prepreg scraps in the proposed applications.

2. Methodologies

The recovery process developed within the CIRCE project consists in an innovative solution, based on specific automated machines, able to transform the CFRPs prepreg scraps into a ready-to-use raw secondary material.

The recovery process consists in the shredding of the prepreg scraps and in the removing of backing paper. This process is performed by exploiting innovative and patented systems which allow to obtain ready-to-use chips of uncured prepreg. The thermoplastic backing paper is collected and treated as recyclable waste, while the chips are conveyed into a dedicated collector. If their use is not immediate, they have to be stored in an industrial refrigerator to avoid complete curing of the resin and adhesion of the chips.

In the first phase of the reclaim process, a cutting machine is employed for the sizing and shredding of the scraps, allowing to produce small pieces of prepreg characterized by almost uniform size and shape. In particular, the prepreg scraps, still covered with the backing paper, are first cut into linear strips and then into chips by means of rotary cutters.

The chips are then fed into the peeling machine that automatically removes the polyethylene backing paper, making the scraps ready for their reuse as reclaimed raw material. This process exploits the friction generated on the surfaces of the release films to allow easy and automated removal of the backing paper from both the faces of the chips.

Subsequently, the thermoplastic backing paper is collected and treated as recyclable waste, while the chips are conveyed into a dedicated collector. If their use is not immediate, they have to be stored in an industrial refrigerator to avoid complete curing of the resin and adhesion of the chips.

The reclaimed material can be employed in a wide range of applications and production processes. Three different alternatives for the prepreg scraps use proposed and developed within the CIRCE project are:

- Automotive components

The solution proposed by HP Composites consists in the use of the recovered CFRP in an under-pressure process similar to the standard compression molding (CM) to obtain structural and aesthetic automotive components. In this process, metal mold and countermold are covered with a release agent and the reclaimed chips are placed inside the mold cavity. Thanks to a heated plates press, the prepreg material is cured under controlled temperature and pressure conditions. The part is then cooled down and removed from the mold and the production cycle can start again.

In the first stage of the project, in order to assess the mechanical properties of the recovered material, tensile and flexural specimens were produced by exploiting the CFRP scraps in a CM process. Tensile tests were carried out according to the ASTM D3039 standard for composite materials while flexural tests were conducted in line with the ASTM D7264 standard for polymer matrix composite material. A MTS universal testing machine equipped with a uniaxial extensometer was employed to carry out the tests and obtain stress-strain curves. The mechanical properties of the newly developed material were compared to those of a 6061-T6 aluminum alloy. This material was selected as it is one of the most commonly used aluminum alloy for general purpose use and automotive applications.

- Safety toe caps

A second application for the prepreg scraps is being developed by Base protection and CETMA to produce composite toe caps for work footwear. These safety equipment components are

crucial to prevent injuries to the frontal area of the foot and they must have adequate compression and impact resistance. At present, the toe caps are produced by means of an injection molding process by using a granulated thermoplastic compound mainly composed of polycarbonate. The goal of the project is to substitute the thermoplastic toe caps with recovered CFRPs ones; the latter are being produced by means of a compression molding process similar to that described for the automotive sector components. CETMA is evaluating the feasibility of the process in terms of the mechanical properties of the reclaimed products. In this context, the toe caps were tested to ensure compliance with the UNI EN 20345 standard in terms of impact and compression resistance.

- Carbon ceramics brakes

The third proposed solution for the reuse of prepreg scraps deals with the production of carbon ceramic brakes by Petroceramics. These ceramic matrix composite products are currently being produced by exploiting a liquid silicon infiltration (LSI) process; the first phase of LSI consists in the production of a green part by compression molding. At present, a patented compound constituted of thermoset resin and short virgin carbon fibers is employed as raw material. The project proposal is to substitute up to 10% of the virgin fibers with the prepreg scraps, leaving the rest of the production process unchanged.

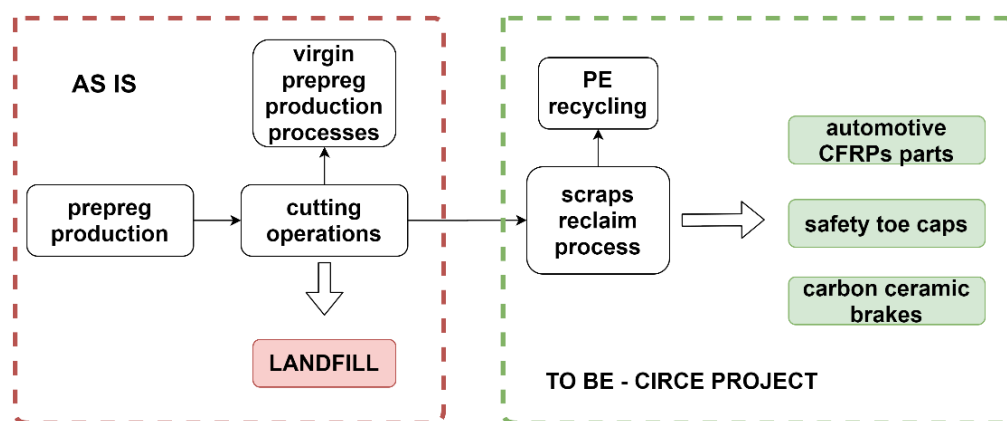


Figure 1 CIRCE project scenarios

In all the proposed applications, the reuse of prepreg waste allows to reduce the amount of virgin materials employed in compression molding processes (either virgin SMC or carbon fibers). Moreover, it prevents the CFRPs waste to be sent to landfills; overall, there are strong possible benefits in terms of environmental sustainability and cost reduction. In previous literature studies, Life Cycle Assessment analyses were carried out to evaluate the possible environmental impacts reduction that can be obtained by means of the proposed solutions. Overall, the recovery process showed negligible environmental impacts due to the low energy consumption required by the recycling system[16]. Great environmental benefits were showed for the reuse of the prepreg scraps for the production of CFRPs automotive and personal safety components.

For what concerns the carbon ceramic brakes production, an approximated evaluation of the emissions reduction obtained within the CIRCE project can be calculated by considering the environmental impacts of the virgin carbon fibers and of the reclaim process. In fact, as stated above, the production phases of the LSI process will remain unmodified except for the raw

materials mix employed for the compression molding operations. Hence, preliminary impacts reduction results can be obtained by comparing literature LCA analyses of the modelling of the raw materials footprints [16,17].

One of the main advantages of the CIRCE project will be the possibility of scaling up the process and globally extending the use of the new technology. The expected quantity of CFRP prepreg that will be produced in 2025 is equal to 250'000 tons; assuming an optimistic average nesting efficiency of 80%, about 50'000 tons of uncured waste will be disposed of in 2025. This is a relevant issue, in particular if the high environmental impacts and production costs of CFRPs are considered. In this context, the advantages of the CIRCE project could be extended to the global waste production of CFRP uncured waste, with important advantages in terms of CO₂ emission and costs reduction.

3. Results

3.1 Mechanical characterization

Figure 2 reports the results of the mechanical characterization in terms of specific tensile strength and specific flexural strength (i.e. the flexural and tensile strength divided by the density of each tested material). The reclaimed prepreg showed a specific tensile strength about 4.5% lower than that of the aluminum alloy. For what concerns the specific flexural strength, the recycled composite exhibited an average value 40% higher than that of the metal alloy alternative. This is a remarkable result considering the high mechanical properties of the 6061 aluminum alloy; the CIRCE reclaim process is able to transform the prepreg scraps into a raw secondary material with mechanical properties comparable with those of virgin prepreg. For this reason, the new material can be employed in a wide range of application in substitution to aluminum alloys and virgin SMC. The lower density of the recovered prepreg (about 1.5 g/cm³) could also reduce the weight of transport sectors components that are currently produced by using metal alloys. Moreover, the innovative material could be used as a replacement for a large variety of unreinforced plastic parts with possible advantages in terms of weight reduction and improved mechanical performances.

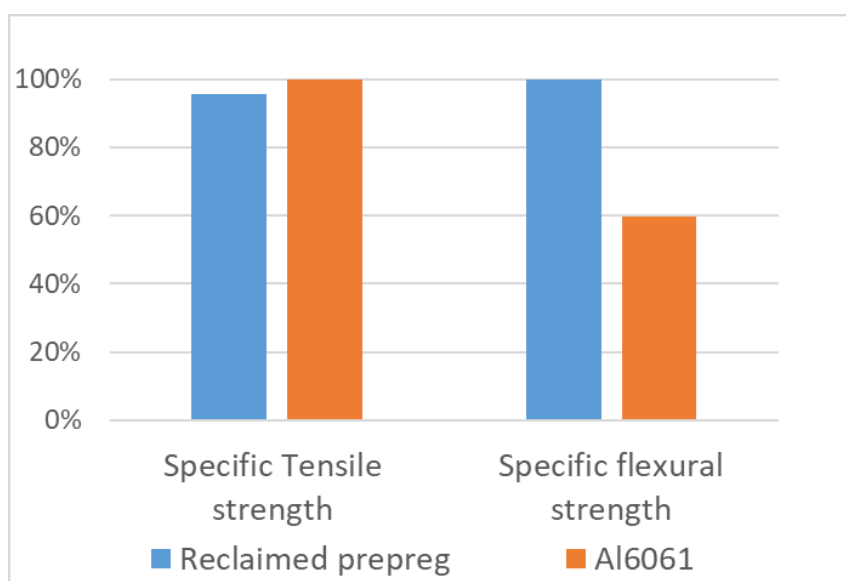


Figure 2 Results of the mechanical tests in terms of tensile and flexural strength

3.2 Environmental impact assessments

Environmental impact assessments were carried out for the three possible applications of the recovered material.

The reclaim process has almost zero environmental impacts if compared to virgin material production; specifically, the scraps preparation process has a cumulative energy demand (CED) equal to 5.8 MJ and a global warming potential (GWP) of 0.15 kg eq CO₂ per kg of waste processed (negligible if compare with 440.4 MJ and 24.40 kg CO₂ eq of virgin carbon fibers).

Considering CFRPs automotive components, the use of the reclaimed scraps can provide a reduction in energy use of 602 MJ and a reduction of equivalent CO₂ emissions of 37.4 kg per kg of CFRPs recovered waste[18]. The recovered material has slightly lower mechanical properties with respect to virgin SMC; hence, in order to guarantee the same mechanical performances of the automotive components, the recycled products are heavier than the virgin alternatives. This implies heavier molds and higher energy consumption for the curing phase of the reclaimed parts. However, virgin SMC has a strong carbon footprint and represents the main contribution on the impacts of virgin CFRPs parts; the CIRCE projects allows to substitute the high impacts virgin prepreg with a practically zero impacts recycled prepreg, with subsequent environmental benefits.

In the case of safety footwear components, the recovered scraps are employed as a substitute for a thermoplastic compound for an injection molding process. Overall, a reduction in CO₂ equivalent emissions of 2.5 kg can be obtained per kg of used reclaimed prepreg. This value is not as high as for the automotive components because the scraps are used to replace a raw material (polycarbonate) with relatively low carbon footprint. The reclaimed prepreg has better mechanical properties with respect to the thermoplastic material; hence, lighter toe caps can be produced with consequent ergonomic improvements of the safety footwear.

For what concerns the production of carbon ceramics brakes the expected reduction in impacts in terms of CED and GWP are equal to 434.6 MJ and 24.25 kg CO₂ eq per kg of scraps reused. These values were calculated by considering the environmental impacts of virgin carbon fibers and those of the CIRCE recovery process. The reuse of prepreg scraps in ceramic matrix composites does not require any changes in the production process with the exception of the raw materials. Therefore, these environmental benefits can be easily obtained without affecting the production line or the products quality.

If compared with other CFRPs recycling system, the environmental savings obtained by the uncured prepreg recovery system are even greater[12]. In fact, the CIRCE process allows to completely recover the scraps (both matrix and fibers), with a 100% valorization of the waste. On the other hand, the thermosetting composite recycling processes that are currently available on the market typically provide only a partial recovery of the products; in fact, recycled carbon fibers are usually reduced in size and they have deteriorated mechanical properties while the cured matrix are recovered in forms of fillers, fuel or chemical feedstock.

Considering the expected production of uncured CFRP waste in 2025 and the average impacts reduction that will be obtained by means of the CIRCE recovery process, the CO₂ equivalent emissions reduction that could be obtained globally every year is about 1.5 million of tons. This

estimate can give an idea of the potential that the project has to improve the environmental sustainability of composite products. Moreover, the project has strong economic repercussions because the reclaim process has very low costs and the reclaimed scraps can be employed to replace expensive virgin prepreg materials.

4. Conclusion

This manuscript had the objective of describing an innovative reclaim process for uncured prepreg scraps developed within the European CIRCE project. The system has the potential to improve the economic and environmental sustainability of composite products by recovering the scraps generated during the cutting phase of virgin prepreg and transforming them into a high technological value raw secondary material. The innovative technologies and three possible applications of the recovered material were presented; mechanical characterization and environmental assessments results were also reported.

The main outcomes of the paper can be summarized as follows:

- The reclaim material is suitable for a wide range of applications; recovered automotive and personal equipment sector components were developed within the project.
- The mechanical properties of the recovered scraps are similar to those of virgin sheet molding compound. If compared to a 6061 aluminum alloy, the recovered material has specific tensile strength about 4% lower and a specific flexural strength 40% higher.
- From an environmental perspective, the reclaim process has almost zero impacts and the prepreg secondary material can be used as replacement for high-carbon footprint virgin materials.
- Considering a global exploitation of the new technology, an annual reduction in emissions equal to 1.5 million of tons equivalent of CO₂ can be achieved by 2025.

For future development of the work, new structural applications of the recovered prepreg will be considered and analyzed. The recovery process will be optimized and improved to obtain a raw secondary material with even better mechanical properties. A large-scale diffusion of the process is expected with consequent improvements of the sustainability of composite products.

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