ECONOMIC ASSESSMENT OF CARBON FIBER PREPREG SCRAPS REUSE IN AUTOMOTIVE COMPONENTS

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Abstract: An innovative reclaim system for Carbon Fibers Reinforced Polymers prepreg scraps was investigated from an economic point of view. The reclaim system was developed within the LIFE-EU research project CIRCE (Circular Economy Model for Carbon Fiber Prepreg Scraps) with the goal of completely recovering the uncured scraps produced during the cutting operations of virgin prepreg. Composite structural parts were produced using the raw secondary material in a compression molding process. The innovative developed process was compared with traditional compression molding of virgin prepreg. The economic analysis was carried out by means of the Life Cycle Costing methodology: both production and service life phases were investigated. The analysis proved that the CIRCE system can guarantee a production cost reduction; savings are expected to increase when high production rates and heavier parts are produced.

Keywords: Sustainability; prepreg scraps; zero waste technology; composite; recycling.

1. Introduction

Carbon Fiber Reinforced Polymers (CFRPs) are composite materials characterized by low density and high specific mechanical properties such as stiffness and strength. A large variety of applications are possible for these materials; some examples can be found in sectors such as automotive, aerospace, nautical, energy production and sport (1). The decrease in production cost of composite products is leading to a sensible growth of the use of CFRPs, with an expected global demand of 194 kt (kilotonnes) for these materials in 2022 and a global demand for carbon fibers (CF) equal to 117 kt (2).

The use composite materials in parts of employed in transports contributes to reducing the fuel consumption during the useful life. Thus, remarkable cost and CO_2 emission savings can be obtained. However, these benefits are counterbalanced by the high costs and environmental impacts related to these products' manufacturing. In fact, both CFRPs raw materials production and molding processes are cost and energy intensive (3). Hence, developing an efficient system to recycle polymer matrix materials is mandatory and several technologies have been developed throughout the years.

Typically, thermosetting matrix composites are characterized by higher mechanical properties with respect to thermoplastic matrix alternatives. As a matter of fact, during the curing process, covalent bonds are generated between the polymer molecules, strongly improving the characteristics of the material. The curing process is based on irreversible reactions, so no remelting or reshaping is possible once the material is cured; this makes it difficult the complete recycling of the composite (4). Indeed, most of the recycling processes, currently available on the market, allows only a partial recovery of the material: the reinforcement phase is recovered

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in the forms of short fibers with deteriorated mechanical properties while the matrix, when possible, is recovered as a filler or as a chemical feedstock. Recycling is not always convenient from an economic point of view, especially considering that the recovered materials are not usually suitable for structural applications.

Among possible composite raw materials, prepreg is one of the most used for high-end applications, with a forecasted global market value of 11.5 billion USD for the next three years; preperg is typically constituted by pre-impregnated composite sheets in which fibers are embedded in a partially cured thermosetting matrix (B-stage resin). Composite parts are built by stacking several layers of prepreg that are previously cut in order to match the mold geometry. Complete curing of the parts is obtained by applying high temperature and pressure in an autoclave or out-of-autoclave molding processes. One of the main issues related to prepreg environmental sustainability is determined by the waste produced during the cutting operations of the virgin material; in fact, due to the complexity of the cut shapes, nesting efficiency usually ranges between 50% and 70%, leading to a high volume of uncured waste in form of off-cuts, trim waste and end-roll waste (5). At the present moment, these wastes end up in landfill facilities of incineration plants without ever being effectively utilized. Considering the high purchase cost of virgin prepreg, the high quantity of scraps generated during the nesting phase results not only in serious environmental concerns but also in economic issues.

A solution for this problem was proposed within the CIRCE (Circular Economy Model for Carbon Fiber Prepreg Scraps) project, funded through the LIFE-EU programme. The main goal of CIRCE was to develop a recovery process able to transform the uncured prepreg scraps into a ready-to-use raw secondary material, with a 100% valorization of the composite wastes. The new-developed process turns long fibers virgin prepreg trims into short fibers small chips of recovered material with almost uniform size and shape. Since the prepreg scraps are not cured yet, both the fibers and the matrix can be fully recovered and the secondary material can be employed in compression molding (CM) manufacturing processes as a replacement for virgin fabric prepreg or sheet molding compound (SMC).

Several literature studies evaluated the feasibility of the reuse of the prepreg scraps in different applications but they were mainly focused on the mechanical properties of the recycled materials (6). Moreover, the analyzed recovery processes were primarily executed by hands, without any industrial automatization. The CIRCE reclaim process was investigated only from an environmental point of view by means of Life Cycle Assessment analyses that quantified the reduction in environmental impacts that can be achieved by substituting virgin material with the recycled alternative (7). However, no economic evaluations of the automated reclaim process are available in scientific literature. In this context, this paper aims at evaluating the economic aspects of the CIRCE recycling process to verify that environmental sustainability is paired with cost-effectiveness. To this purpose, Life Cycle Costing (LCC) analysis was performed considering all the costs related to the innovative reclaim process (e. g. labor costs, mold manufacturing, etc.). The results were compared with those obtained by considering the manufacturing cost of a traditional CM process based on prepreg virgin material.

2. Methodologies

2.1 Processes description

The innovative recovery process is based on the use of an automated system. It allows to shred the prepreg scraps in small chips and to remove the polyethylene release paper that is used in virgin prepreg manufacturing processes to prevent undesired sticking of the uncured material. The backing paper can be collected at the end of the process to be sent to plastic recycling plants. As for virgin prepreg, once the secondary raw material is ready, it has to be kept in an industrial refrigerator to prevent the complete curing of the matrix and adhesion of chips. The peeled chips can be used as a replacement for virgin materials in an autoclave and out of autoclave processes. In this study, a compression molding process was considered. The chips are removed from the refrigerator and are manually placed into a steel mold. A release agent is applied to the mold surfaces (mold and countermold) to allow easy removal of the finished products. The composite part is cured through a heated plates press under controlled temperature and pressure conditions. Once cooled down, the molded part is then manually removed from the mold.

The molding process of virgin materials (prepreg fabric or SMC) is similar to the one described for the recycled scraps. Virgin material is taken out from the refrigerator and a computer numerical control (CNC) machine is used to cut the prepreg to match the mold geometry. Virgin material scraps are usually disposed of in landfill or incinerators. As for the previously described process, the material is manually placed into a mold and complete curing is achieved by applying heat and pressure.

2.2 Life Cycle Costing

The economic evaluation of the new reclaim process was conducted by means of a Life Cycle Costing (LCC) analysis. This methodology allows to consider the costs incurred during multiple phases of the life cycle of a product or a process (the system boundaries, for example the manufacturing and useful life phases). The LCC analysis is referred to a functional unit, i.e. a quantified description of the performance requirements of the systems to which all the inputs and outputs are related. Once the scenarios are clearly defined, the cost inventory data are gathered and employed to evaluate the product's cost. In this particular case, a parametric approach was employed: several parameters, identified as cost drivers, are used to evaluate the cost of unitary activities (8).

As mentioned above, the CIRCE reclaim process was already analyzed from the environmental point of view in a previous literature Life Cycle Assessment study. In that case, the functional unit was defined as the production of a CFRP sample with defined top and bottom surface areas (0.0056 m^2 and 0.0057 m^2) and tensile strength between 5 and 5.7 kN. The same functional unit was utilized for the economic evaluation. Two different scenarios were considered:

- Scenario 1 deals with the production of the functional unit by using virgin prepreg in a compression molding process.
- Scenario 2 considers the production of the functional unit with the reclaimed scraps as raw secondary material and a compression molding process.

To fulfill the functional unit requirements, the two scenarios lead to sample with different weights. Specifically, Scenario 1 sample weights 0.06 kg while Scenario 2 sample weights 0.07 kg (7).

In the presented model, all direct and depreciation costs were considered to assess the scenarios manufacturing processes costs. Moreover, further evaluations were conducted to consider the parts useful life. As a matter of fact, prepreg and other composite materials are widely used for automotive applications and it is a goal of the study to determine whether or not the new reclaim process is suitable for the production of structural or aesthetic automotive components.

Most of the inventory data were provided by the company involved in the CIRCE project and were retrieved by means of direct measurements or purchase data. Some examples are the cost of raw materials, the energy cost per kWh, the molds, the machines used, the hourly cost of labour and the cost for waste disposal.

The energy consumptions of the industrial refrigerator, the press, the sytem for the prepreg recovery, the cutting CNC machine for virgin prepreg were directly measured during the samples production. The quantity of each material used (prepreg, scraps, and the release agent) were measured as well as the time required for the manual lay-up. The deprecation costs of the machines were allocated to the functional unit by considering their purchase price, their capacity, their estimated useful life, and the time of use of the machines per production cycle. The molds cost was calculated considering their purchase cost and the number of molding cycles that they can safely run before substitution is needed.

For what concerns the useful life phase, automotive structural components with the same weights of the scenarios samples were considered. The only cost item considered for the useful life is fuel consumption. Fuel cost was allocated to the composite parts by considering their weight with respect to the total weight of the car. A model, initially proposed by Hakamada et al (9) for environmental sustainability analyses, was repurposed for economic evaluations:

$$Use\ cost\ \left(\frac{€}{kg}\right) = \frac{e_c \times life\ \ time}{\varepsilon \times M}$$
(1)

Where:

- M is the curb weight of the vehicle (kg). A value of 1400 kg was considered as the initial value.
- e_c is the cost of the gasoline per litre (€/L). Average price in Italy updated to February 2022 was considered.
- ε is the fuel efficiency (km/L). According to International Energy Agency data, average fuel consumption for European Union light-duty vehicles equal to 16.7 km/L was considered (10).
- Life time expresses the useful life of the vehicle in km. 200’000 km were considered according to Duflou et al (11).

Costs related to the useful life of the two scenarios were calculated by multiplying the use cost obtained in Eq. (1) by the weight of each sample.

3. Results and discussion

Table 1 reports the costs related to the manufacturing process of the functional unit for the two considered scenarios. Table unitary values were obtained considering an optimal deprecation of the tools (i.e. considering a production volume that minimizes the mold costs). Figure 1 shows

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the cost contribution for the samples production in terms of cost of the molds, of labor, and of materials and energy; different production volumes were considered as possible industrial cases.

Table 1 Cost inventory data and results for the two considered scenarios.

	Cost	Scenario 1	Scenario 2
		Production cost for one sample	
Raw materials			
Prepreg	80 €/kg	5.33 €	/
Prepreg waste disposal	0.65 €/kg	0.02 €	/
Release agent	20 €/kg	0.02 €	0.02 €
Labour	20 €/h	20.00 €	22.00 €
Mold and countermold			
Scenario 1	950 €	1.26 €	/
Scenario 2	1140 €	/	1.52 €
Machine deprecation			
Press	15000 €	0.32 €	0.32 €
Other machines			~ 0 €
Energy consumptions			
Press		0.17 €	0.20 €
Storage	0.17 €/kWh	0.01 €	0.01 €
Cutting CNC			~ 0 €
Recovery scrap			
Total		27.15 €	24.09 €

Scenario 2 is the best economic alternative and it guarantees a cost reduction per part produced of 3.06 € with respect to Scenario 1. This is mainly due to the low cost of the prepreg recovery process; this is a remarkable result considering the high technological value of the reclaimed scraps. The process has a high production rate and deprecation cost is negligible due to the long expected useful life of the recovery system. On the other hand, virgin prepreg is very expensive and determines about 20% of the total costs of Scenario 1.

Tools and manpower costs are higher for Scenario 2. This is due to the fact that more material is needed to fulfill the functional unit requirements; however, this price increment is fully compensated by the use of an almost zero-cost recycled material. For low production rates, Scenario 2 is the most expensive alternative because the tools' costs are divided by an insufficient number of parts. In fact, tools represent the main cost item for low production volumes; if only one part is produced, the cost of the mold would determine 98% of the total cost of the sample in Scenario 2. The percentage contribution lowers to 67% of the total in the case of 25 parts produced and it goes down to 6% if the production rate goes up 1500 parts. In industrial applications production processes that require expensive dedicated tools are preferred only if the production rates are high enough. In the considered analysis, a break-even point (BEP) between the two scenarios is reached for a production volume of 57 units; this value is the minimum production rate that makes the reclaimed material a cheaper alternative in structural applications and the cost reduction increases as the production volume increases.

In this study, labour can determine even more than 90% of the total costs of the two scenarios This is in line with what was proved in previous literature analyses: in fact, high-end composite parts are typically produced by strongly relying on manpower for the lay-up phase (12). The development of automated lay-up systems for CFRP prepreg parts could contribute to improving their cost-effectiveness, making them an even more valuable alternative to traditional materials.

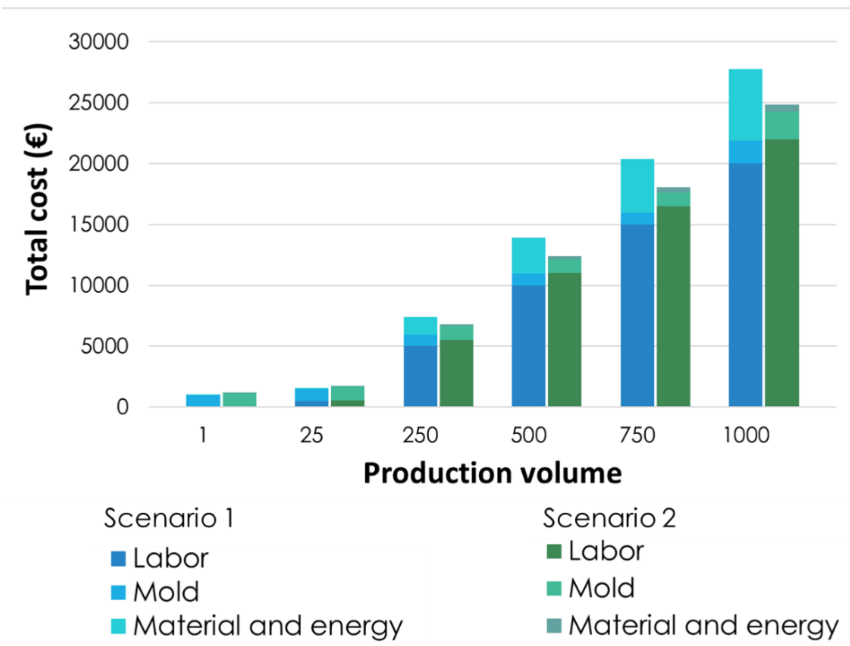

Figure 1 Production costs for the two scenarios in relation to the production volume

As far as the useful life of the considered components is concerned, Scenario 2 leads to a higher cost related to gasoline consumption (0.96 € for Scenario 1 vs 1.12 € for Scenario2, with an estimated cost per kg of 16 €). In fact, in the proposed model, gasoline cost consumption is linear with the weight of the part, so Scenario 2 has a useful life cost 20% higher than the virgin prepreg alternative. Service life is not a major cost item in the two scenarios as it contributes for only 3.5% in Scenario 1 and 4.6% in Scenario 2. So, even if the recovered scraps part has is heavier, overall its life cycle cost is still the lowest, with a total life cycle cost reduction of 2.9€ with respect to the virgin prepreg alternative.

The functional unit of this study is a structural component that has a weight between 0.06 kg and 0.07 kg; however, in industrial applications, it is not unusual to produce automotive components with considerable higher weight (up to tens of kg) (13). Hence, some evaluations were carried out to assess the total production costs of virgin prepreg and recovered scraps automotive components with different weights. Molds costs and labor time were estimated in collaboration with the involved company experts and by considering similar products production processes. Materials cost is assumed to be linear with the used quantity. Figure 2 reports the results of the weight analysis and shows that, as the produced components weight increases,

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the CIRCE recovery process guarantees higher cost reductions. In Scenario 1, the percentage contribution of the raw materials increases as the part weight increase. For example, for a 1 kg component, the raw material contribution is 49.6% of the total cost (80 € out of 161.07 €). The corresponding component obtained by using the reclaimed scraps (with a weight of 1.2 kg) has a total cost of only 79.53 € and the raw material cost is almost negligible.

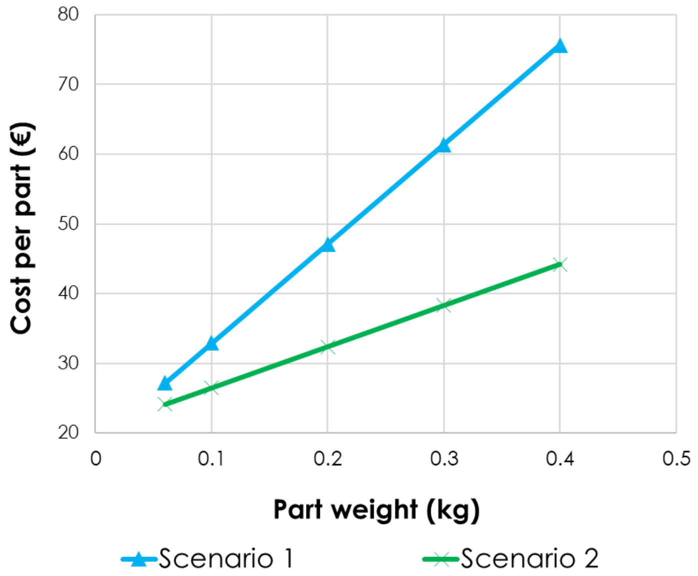

Figure 2 Manufacuring cost with respect to the parts weight

4. Conclusions

In this paper, an innovative reclaim process for prepreg scraps was investigated from an economic point of view. The process is based on the use of a new specifically designed system that allows to fully recover the prepreg scraps, with a 100% valorization of both the fibers and the matrix. In order to assess the economic sustainability of the new system, a Life Cycle Costing analysis was conducted. The functional unit was identified as a sample with defined mechanical properties and two different scenarios were analyzed: a virgin prepreg sample produced via compression molding was compared to a sample produced by using the reclaim material. The main results are summarized as follows:

- The CIRCE process allows recovering a raw secondary material with an high technological value with almost zero cost.
- The recovered scraps can be employed as a substitute for virgin prepreg in structural applications with economic advantages. A reduction in production cost equal to 3.06 € is achieved by using the recovered scraps for each produced sample.
- For low production volumes, the higher cost of the molds makes the recovery scenario the most expensive one. A break-even point is reached for a production rate of only 57 units.
- Due to its higher weight, the recovered sample has higher costs associated with its useful life. However, fuel consumption costs determine a little contribution on the Life

Cycle cost of the considered samples (less than 5%) so, despite being heavier, the recovered material sample has a lower life cycle cost.

- Economics savings are expected to increase as heavier parts are produced.

The reclaim material proved to be an optimal solution not only from an environmental point of view but from an economic perspective too. Future works could carry out a detailed economic investigation of industrial application of the CIRCE process. In addition, a comparison with other CFRPs recycling technology can be made.

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