CLOSING THE LOOP ON AUTOMOTIVE CARBON FIBER PREPREG MANUFACTURING SCRAP - FENDER CASE STUDY

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ABSTRACT

This case study demonstrates the successful use of recycled automotive carbon fiber in a thermoplastic injection molding automotive application. Vartega and project partners have shown that a closed-loop supply chain for automotive composites is viable. The source of the feedstock for recycling was unidirectional prepreg that was produced by Michigan State University (MSU) at the IACMI Scale-up Research Facility (SuRF) in Detroit, Michigan. Prepreg trim scrap was sent by MSU to Vartega in Golden, CO for recycling, value-added formatting, and fiber optimization via sizing application. The recycled carbon fiber (rCF) was then sent to Techmer in Clinton, TN for compounding at 10% loading in PA66. The finished compound was returned to the SuRF for injection molding into an automotive fender by MSU. The finished part exhibited excellent surface finish. Additional development is ongoing via IACMI Project 6.20 to produce 40% recycled carbon fiber reinforced PA66 for structural applications.

1. INTRODUCTION

This report details an IACMI project to demonstrate the feasibility of reclaiming carbon fiber manufacturing scrap and manufacturing new automotive parts using materials derived from this reclaimed scrap. The reclaimed carbon fiber originated as unidirectional prepreg that was produced by Michigan State University (MSU) for a separate IACMI demonstration project undertaken by Ford Motor Company, Dow Chemical and DowAksa. The prepreg trim was subjected to a chemical recycling process by Vartega that extracted the fibers from the semi-cured resin. These fibers were post-processed, compounded, and molded to create fiber reinforced PA66 automotive parts. This document details the process for converting scrap to a part, a life cycle assessment (LCA) comparing recycled to typical virgin material, and mechanical testing results of the recycled compound to a virgin baseline. In so doing, the viability of recycled carbon fiber (rCF) use in the context of injection molded parts can be quantified and evaluated.

This document is primarily intended for consumption by professionals in the manufacturing and sustainability industries, as a background in plastics processing and an understanding of mechanics of materials is helpful for contextualizing results. However, the processes and results are approachable for a broad audience.

1.1 Background

Carbon fiber is a strong and stiff synthetic fiber typically used for structural reinforcements of thermoset (usually epoxy) resins. Major applications include aerospace, performance automotive, and sporting goods where high material stiffness must be coupled with reduced weight.

While carbon fiber composites can be used to manufacture light-weight, high-strength parts, there are many potential manufacturing applications where carbon fiber composites are not currently used due to the high cost of carbon fiber. The high cost of carbon fiber composites is driven partly by the complex and energy intensive process of manufacturing carbon fiber and partly by the complexity of manufacturing parts from the carbon fiber using classical techniques such as lay-ups [1]. These economic and environmental costs can be mitigated respectively by using a recycled instead of virgin carbon fiber and by using a carbon fiber filled thermoplastic material.

The total life cycle emissions of a carbon fiber part can be reduced by using a recycled carbon fiber rather than virgin carbon fiber [2]. The energy-intensive carbonization and oxidation steps required to convert the fossil fuel-derived precursor material (typically polyacrylonitrile [PAN]) to carbon fiber correspond to a significant initial greenhouse gas footprint. This environmental effect is mitigated by fuel savings due to light-weighting in transport applications but the initial energy investment required to manufacture virgin carbon fiber is so large that the emissions benefits of using carbon fiber instead of a metallic material are minimal or possibly even negative in automotive applications [3]. By reusing fiber that would otherwise be disposed of in landfills, it is anticipated that this emissions burden could be reduced. Using a recycled carbon fiber also avoids the costly manufacturing process for virgin carbon fiber and reduces the economic cost of the composite part, thereby expanding market availability in automotive and other cost or environment-sensitive applications.

The second barrier to widespread use of carbon fiber in high volume automotive manufacturing is the cost of the complex manufacturing processes used to make parts from continuous carbon fiber. Classical use of carbon fiber composites involves performing a hand lay-up of sheets of carbon fiber composite. This process allows optimal utilization of the directional properties of long carbon fiber but is much slower than processes such as injection molding or progressive stamping that are ubiquitous in high-throughput manufacturing industries such as the automotive industry [1]. Carbon fiber may be adapted for use in high throughput manufacturing applications by compounding short (0.5-8 mm) fibers with a thermoplastic resin. While the use of carbon fiber in a compounded thermoplastic for injection molding results in a largely-isotropic short-fibered material with reduced strength relative to classical techniques, the ability to apply the material in a high-throughput cost-effective process can outweigh these drawbacks for high volume applications. As the fibers need to be chopped prior to compounding, recovered or recycled fiber may provide an ideal feedstock for producing carbon fiber filled thermoplastics.

This project demonstrates the engineering, economic, and environmental feasibility of manufacturing automotive parts from recycled carbon fiber filled thermoplastic materials. The project documents a case study where carbon fiber was reclaimed from manufacturing scrap using a novel chemical process, compounded into a thermoplastic material, and injection molded into a finished part. The mechanical properties of the recycled material are examined and a LCA of the part's emissions impact is presented. The results demonstrate that the use of recycled carbon fiber significantly reduces the environmental impact of the manufactured part.

2. EXPERIMENTATION

2.1 Feedstock Material

Unidirectional carbon fiber-epoxy prepreg was created at the IACMI Scale-up Research Facility (SuRF) located in Detroit, Michigan, for the purpose of making compression molded parts of interest to the automotive industry. Scrap for recycling comes from off-cuts generated during the manufacturing process. The prepreg scrap for this project consists of a standard modulus carbon fiber (Dow Aksa) and epoxy resin (Dow) at a loading of 65wt% fiber and 35wt% resin. A paper backing is attached to the prepreg system to assist in handling and layup. The scrap prepreg, including paper backing, was provided to Vartega for recycling.

2.2 Recycling

The feedstock prepreg trim scrap from the SuRF facility was delivered to Vartega for recycling. In order to prepare the feedstock for recycling, the material was roughly size reduced and the backing paper was removed from the prepreg. Resin was removed from the carbon fiber via Vartega's proprietary chemistry-based process. The efficacy of resin removal was less than desired due to temporary limitations of the existing process equipment at the time of the project, resulting in somewhat higher residue on the fiber than would otherwise be anticipated based on historical results. Thermogravimetric Analysis (TGA) of the fibers is shown in Figure 1. Samples were heated in high purity air at a ramp rate of 20 °C/min from 50 to 750 °C. Mass loss attributed to residual resin left on fibers is measured between 120-500°C. Mass loss above 500°C is attributed to degradation of the carbon fiber.

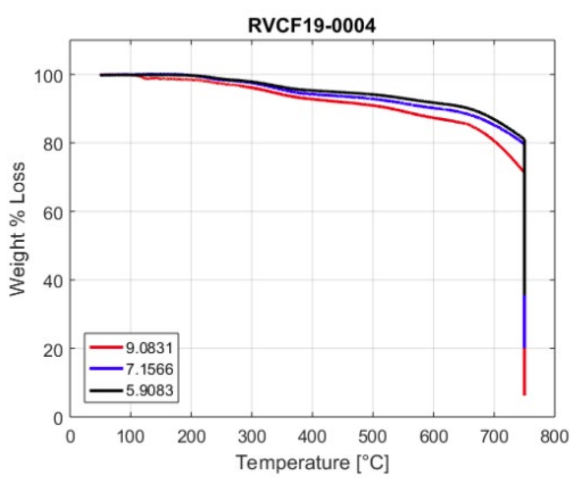

Figure 1: TGA testing showing an average residual resin account of 7.38%

Recycled fibers were chopped into nominal 6 mm lengths, although the actual length distribution is not quantified. It is understood from discussions with commercial compounders, that this semi-randomly oriented product format is difficult to work with due to both the tendency to bridge (i.e. interlock and jam) when feeding and the release of irritating dust during handling. To convert the carbon fiber into a more readily usable material, the fibers were overcoated with a water-soluble coating ("sizing") and formed into small bundles. The bundles are more uniform and denser than the raw cut fiber and are therefore less prone to bridging. The sizing serves to maintain bundle integrity, limit the dust produced during handling of the bundles, and act as an interface between the fiber and the resin matrix. The selected sizing had previously been tested and showed good interfacial properties with polyamides (PAs). Fiber bundles are dried to remove any moisture to levels below 0.2 wt%. Moisture values were determined using a Mettler Toledo HB43-S halogen moisture analyzer. Once dried bundles are sent for compounding.

2.3 Compounding

The PA66-rCF was compounded on a Coperion ZSK 40 mm co-rotating twin screw extruder at Techmer PM in Clinton, TN. The polymer and additives were fed by a gravimetric K-Tron feeder to the feed throat and the rCF was fed by a gravimetric K-tron feeder downstream. The extruder had an atmospheric vent at the side feeder and a vacuum vent prior to the die. The material was extruded into strands, cooled in a water bath, and chopped into pellets. The output rate of the extruder was approximately 135 kg/hr. Due to the relatively small quantity of rCF available, little optimization of the processing conditions and output rate was possible. The rCF format provided satisfactory feeding through the feed system (single screw fiber feeder with a pigtail auger). Fiber bundle integrity and flow properties were satisfactory for thermoplastic compounding processes. There were a small number of larger fiber clumps which did create occasional feeding difficulties. Those clumps of fibers were largely able to be manually sorted from the rCF and did not create significant processing issues. The compounding run yielded 240 kg of finished compound for molding trials. Ash burn-off testing of the finished compound showed that the fiber fill content was approximately 8.7%.

2.4 Injection Molding

Injection molding for this effort was conducted at the IACMI / Michigan State University Scale-up Research facility located in Corktown, a historic district of Detroit. This facility is a 100,000 square foot facility co-located with Lightweight Innovations for Tomorrow (LIFT). A Milacron MGS 3000 injection molding machine with a low shear screw design and an integrated Yaskawa Motoman robot was utilized to demonstrate manufacturing representative processing of the Vartega rCF-PA66 material.

Figure 2: Injection molding machine used to make fenders

A donated passenger side fender tool (courtesy of SABIC) from a Saturn ‘L’ series sedan was utilized to demonstrate representative production molding for a class ‘A’ exterior body panel application.

Figure 3: Fender tool used in injection molding process

The fender tool was initially developed for the Noryl GTX material system with a hot runner manifold system. For the PA66-rCF demonstration, single sided fill was utilized in a single cavity mold with the following molding parameters:

- Injection pressure: ~1200 psi
- Barrel temps: 580-590°F
- Tool temps: 230°F
- Backpressure: 150 psi

These molding conditions were derived based on visual appearance optimization for a class ‘A’ surface finish with the amount of material available. An overall cycle time of 74 sec was attained based on an average over ~70 consecutive parts. No gate or tooling modifications were made to the tool to tune for the PA66-rCF material. Based on previous industrial molding experience, it is believed that further reductions in cycle time and minor improvements to surface finish could be attained pending further tooling and process improvements.

Figure 4: The finished PA66-rCF fender

2.5 Mechanical Testing

Finished compound pellets were dried in an air circulating oven for 2 hours in preparation for molding test specimens for mechanical testing. ASTM test specimens were molded on a family mold on a 110 ton Arburg injection molding machine with a hot oil mold heating system. Molding machine barrel temperatures were approximately 530-560 F, and the mold temperature was 200F. Mechanical properties were tested dry-as-molded (DAM). Tensile properties were measured on an Instron tensile specimen test unit, flexural properties were tested on an Instron 3 point bend test unit. Notched Izod Impact resistance was measured using a Tinius-Olsen pendulum impact tester, heat deflection temperature was tested with a Tinius-Olsen deflection temperature/Vicat temperature test unit, and surface resistivity was tested with an Electro-tech Systems resistivity unit with a concentric ring electrode. The applicable ASTM test standard methods were used for each test.

3. RESULTS

3.1 Mechanical Properties

Mechanical test data generated from the PA66-rCF product is compared to expected values of a 10% oversized and chopped standard modulus carbon fiber in PA66. Mechanical performance of compound made with recycled fiber tested lower compared to the non-recycled product. Previous testing has shown that on a per fiber basis, recycled fibers maintain 100% of the strength as a non-recycled equivalent [4]. Similar testing that was completed, but not a part of this report, showed essentially equal performance between the recycled and non-recycled products. As such, the reduction of performance attributed to the recycled compound was unexpected. As mentioned above, the amount of residual thermoset resin on the rCF was higher than expected due to limitations in the experimental process equipment. This excess thermoset resin was included in the mass of fiber that was metered into the compounding process, resulting in a lower than targeted total fiber content in the finished compound. Therefore, it is expected that the mechanical properties of the PA66-rCF compound will be reduced compared to the PA66-vCF material. The higher than desired residual resin may also result in less optimal adhesion between the PA66 and rCF, negatively impacting performance.

Property	Unit	Test Method	10% SURF rCF in PA66	10% commercial CF Typical properties
Tensile Strength @ Yield	Psi	ASTM D638	17,200	21,700
Tensile Elongation @ Break	%	ASTM D638	2.2	2.4
Notched Izod Impact	ft*lb/in	ASTM D256	0.46	0.50
Flexural Strength	Psi	ASTM D790	22,800	28,000
Flexural Modulus	Psi	ASTM D790	913,000	1,000,800
Surface Resistivity	Log ohm/sq	ASTM D257	12.0	6-10
Heat Deflection Temperature @264 PSI	F	ASTM D648	455	462
Density	g/cm3		1.17	1.19

Table 1: Mechanical Performance of a 10% rCF-PA66 compared to typical commercial values of a non-recycled comparable

3.2 Life Cycle Assessment

A cradle-to-grave LCA was performed to evaluate the embodied energy (EE) within the supply chain of a Saturn thermoplastic fender containing recycled carbon fiber content from Vartega's solvolysis process. The functional unit considered for analysis is 1 injection molded fender part weighing 1.63 kg. The model considers the pathway of carbon fiber from its previous generation to account for the embodied energy of the recycled fiber used in the second-generation part. The SimaPro v.9.0.0.33 LCA software [5] was used for analysis with input for the various materials, processes, and waste scenario details obtained through extensive industry survey, complimented by literature, data from published library databases (Ecoinvent 3 –allocation, cut-off by classification; US-EI 2.2; USLCI [5-8]), and the FRPC Energy Estimator Tool developed by the Oak Ridge National Laboratory [9]. Medium voltage US electricity grid dataset from the DATASMART package, provided by Long Trail Sustainability (2015) is considered for all process steps with the United States considered the geographical focus of this study [7]. The Cumulative Energy Demand (CED) [10, 11] methodology was applied to calculate embodied energy values.

3.2.1 Estimations and Assumptions

The following are the assumptions within the study:

1. Transportation is not considered in this model as the idea is that Vartega will potentially possess modular systems across the country to cater to scrap content at the location of various manufacturers that will generate such scrap material.
2. The fuel blending process for generating the fuel from the captured epoxy is not considered as specific process steps and pathways are unknown at this stage.
3. Generally, 80% of machine load is considered for calculation, unless otherwise specified (as in the case of the prepreg machine).

4. No losses occur in terms of CF or epoxy during the solvolysis process as both are assumed to be 100% reclaimed and reused in later steps.
5. Other environmental impacts associated with the solvolysis process are not included in this study due to the proprietary nature of the solvents in use. There is scope for an additional analysis in the future to understand the other environmental impacts (greenhouse gas emission, acidification potential, effect on climate change, respiratory effects, etc.) in relation to the solvolysis process.
6. Use phase of the final fender product is outside the scope of this analysis.
7. Although the prepreg from the pre-pregging machine step goes on to become a cured product, the steps associated with such processes (SMC, trimming, compression molding, etc.) is not considered within the boundary of this study as it has no direct influence on the prepreg that is sent to Vartega.
8. Values have been back calculated considering the weight of the fender in order to associate those impacts directly associated with producing the amount of (CF) material from the first generation to the second.

3.2.2 Results

Vartega collects the uncured prepreg scrap from various industries as feedstock for the solvolysis process. In the model, the prepreg machine produces a prepreg with 65% carbon fiber (CF) and 35% epoxy content whose scrap is sent to Vartega for the fiber recovery process. Vartega then recovers 100% of the CF and epoxy wherein the recycled CF (rCF) is sent to be compounded with virgin PA 66 to generate pellets for the fender containing 10% rCF (90% resin). The recovered epoxy has three pathways for consideration, which are explained below. The pellets are then fed into the injection molding machine where they are used to form the final fender part. Although there is potential for the fender to potentially be recycled, the second generation considers this part to be landfilled in this model, marking the end of its life cycle. Table 1 demonstrates the various process steps and exported embodied energy values for every material, process, and disposal option considered in both generations (Life 1 & Life 2).

While modeling recycling systems, various approaches may be applied. In this case, the cut-off by classification approach was applied to the product system [9]. With this approach, the recycler is rewarded (burden is not counted for that life), all burden relating to landfilling and virgin material are considered in every generation, and refurbished material take on the value of the recycling process depending on the amount of refurbished material used in the subsequent lives. Considering such an approach, it is seen that Life 1 has a total EE of 203 MJ while considering the amount of CF that is required from the prepreg scrap (0.163 kg as 65% from a total prepreg amount of 0.2507 kg) to accommodate the fender part (as 10% of the fender weight is 0.163 kg rCF) in the later downstream process. There is a small amount (25%) that is disposed to the landfill in Life 1 in the form of the prepreg backing which may contain material such as PE, PET, or wax paper. The EE of Life 2 is found to be 241 MJ, which is 19% more than Life 1. This is owing to the fact that only 10% of rCF is used in the fender with 90% coming from virgin epoxy resin and the part considered to be landfilled at the EOL stage. Energy decreases as more recycled content is used in Life 2. Ultimately, the reduction in the EE of carbon fiber from Life 1 to 2 as a result of undergoing the solvolysis process is overwhelming. Virgin CF exhibits EE at 1155 MJ/kg [8]. This is drastically reduced by 96% in Life 2 with EE of 43 MJ/kg, proving that recycled carbon fiber via the solvolysis process makes a compelling case for both energy and cost savings.

	Category	Process Steps	Embodied Energy (MJ)	Notes	Data source	Data
Life 1		Carbon fiber (65%)	188	1 kg of CF has an EE of 1155 MJ => 0.163 kg (65% of 0.2507 kg = 0.163 kg) is 188.265 MJ ~188 MJ	FRPC	Commodity PAN, 50k tow
	Raw material	Epoxy (35%)	12	1 kg of epoxy has an EE of 135 MJ => (35% of 0.2507 kg = 0.0877 kg) is 11.8395 MJ ~12 MJ	SimaPro	Epoxy resin, liquid, at plant/US- US-EI U Cradle-to-gate (until delivery at plant)
	Prepregging	Heating elements & compaction units	3	2 oil heaters heat up the compaction rollers, pre-impregnation bed and resin bath; 4 compaction rolls work simultaneously. This is run 3 times to create 2 epoxy films with fabric then being sandwiched = 10.77 MJ/kg = 2.7 MJ/0.2507 kg prepreg ~3 MJ	SURF Data + SimaPro	Electricity, medium voltage, consumer mix, at grid/US* US-EI U
	EOL	Landfill	0.01	25% of the prepreg backing material that comes with the prepreg scrap is landfilled. This amounts to a minute amount of energy = 0.0097 MJ/0.2507 kg of prepreg ~0.11 MJ	Vartega Data + SimaPro	Disposal, plastics, mixture, to US sanitary landfill/US US-EI U
	EOL	Solvolysis & Post Processing	11	Taken from the Solvolysis process LCA. This step will not be considered in the model as the final product is considered to be 100% recycled and cut-off by classification approach rewards the recycler for the amount of product that is recycled in every generation. = 43.16 MJ/kg = 10.8218 MJ/0.2507 kg prepreg (43 MJ/kg)	Vartega Data + SimaPro	Electricity, medium voltage, consumer mix, at grid/US* US-EI U
Life 2	Refurbished material	Carbon fiber (10%)	7	Considering 10% refurbished material is used in Life 2, that amounts to 0.163 kg of rCF taken from the solvolysis step. [This value changes according to the percentage of virgin-to-refurbished raw materials considered]. Therefore, 0.163 kg rCF has EE of 7.042 MJ	FRPC	Commodity PAN, 50k tow
	Virgin Raw material	PA 6/6 (90%)	201	1 kg of PA 6/6 has an EE of 137 MJ => EE of (90% of 1.63 kg = 1.467 kg) is 201.2245 MJ ~201 MJ	SimaPro	Nylon 66, at plant/US-US-EI U Cradle-to-gate (until delivery at plant)
		Compounding	22	1 kg of twin-screw compounding at Techmer has an EE of 13.4058 MJ/kg. Compounding 1.63 kg required for the fender equates to 21.8515 MJ/part ~22 MJ	Techmer Data + SimaPro	Electricity, medium voltage, consumer mix, at grid/US* US-EI U
	Manufacturing	Injection molding	11	1 kg of Injection Molding has an EE of 6.8332 MJ/kg. IM the fender part weighing 1.63 kg has an EE of 11.1382 MJ/part ~11 MJ	SURF Data + SimaPro	Electricity, medium voltage, consumer mix, at grid/US* US-EI U
	EOL	Landfill	0.3	Plastics mixture was taken for modeling consideration of Generation 2 part (1.63 kg) =>0.2522 MJ. All burden of landfilling is taken up in this generation as there is no mention of recycling at this stage.	SimaPro	Disposal, plastics, mixture, to US sanitary landfill/US US-EI U

Legend

Material	EOL Recycling
Manufacturing process	EOL Disposal

Table 2. The embodied energy of carbon fiber as a prepreg scrap in Life 1 and thermoplastic fender in Life 2

3.2.3 Reuse Options

As mentioned previously, Vartega has the capability to capture epoxy and CF entirely from the prepreg scrap. Some alternative options considered for potential reuse of the recovered epoxy are as follows:

1. Option 1: Resin is sent for fuel blending with the combustion energy captured and used.
2. Option 2: Resin is blended into a virgin epoxy system to offset a portion of the virgin amount.
3. Option 3: Resin is used directly as a product in composite or other applications.

Considering option 1, industries likely to use said fuel after blending are cement kilns. Portland cement data from Ecoinvent was taken to compare how Vartega's potential fuel would decrease the overall energy consumption within a cement kiln process. The default EE of Portland cement is found to be 6 MJ/kg. Data obtained from a partner of Vartega who performed testing on their resins mentioned a heat of combustion of 13,000 BTU/lb (30.49 MJ/kg taking 1 lb = 0.45 kg) tested by bomb calorimeter method. This value when taken as avoided energy (electricity offset) substantially decreases the overall energy of the cement kiln process resulting in excess energy of -96 MJ/kg being produced with a difference of 102 MJ (as 30.49 MJ translates to a CED of -95.65 MJ) and a 1700% decrease in energy due to its high calorific content. Further practical testing is required along with the understanding and implementation of the fuel blending process and transportation considered for analysis.

Similarly, option 2 considers replacement of part of the virgin epoxy with recycled epoxy recovered from the solvolysis process. Vartega has successfully made blends with up to 90% recycled resin thus far. This value was taken to project potential savings in energy in relation to 1 kg of virgin epoxy. Default EE of virgin epoxy is 135 MJ/kg. Incorporating 90% of the recycled epoxy, the new EE becomes 52 MJ/kg with a 61% decrease (83 MJ difference) in embodied energy.

Option 3 would be dependent on the specific raw materials used and the process considered. Research is currently ongoing to understand future applications and other capabilities to achieving this sort of circularity.

4. CONCLUSIONS

The feasibility of producing an automotive part using rCF sourced from automotive prepreg scrap via injection molding has been demonstrated. While the PA66-rCF material produced in this first experimental demonstration showed reduced mechanical properties relative to a standard PA66-vCF material, it is anticipated that the material properties of the PA66-rCF will be improved with further work that is currently ongoing. The mechanical properties of the present demonstration material were sufficient to injection mold a functional automotive body part. Furthermore, using rCF in the injection molding compound significantly reduced the EE of the injection molding compound. These results demonstrate the overall feasibility of the Vartega solvolysis prepreg recycling process as a means to return automotive prepreg scrap to further automotive manufacturing applications.

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