METHOD TO UTILIZE ALIGNED CARBON-FIBER PREPREG TRIM SCRAP FOR STRUCTURAL APPLICATIONS

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Abstract

The pressure for increased fuel economy and low CO_2 emissions for automotive vehicles continues. In order to satisfy requirements, lighter vehicles will need to be manufactured making it necessary to replace metals in structural components with lightweight materials such as carbon fiber composites. The challenge associated with implementation of carbon fiber composites is to make them cost effective for high volume production because historically this class of materials was designed for low volume production scenarios. In order to apply carbon fiber prepreg derivatives to high volume automotive applications, the material must be designed so it can be robotically handled, and reduce expensive material usage inefficiencies while utilizing existing processing equipment.

This work presents an innovative mechanical method to incorporate uncured carbon fiber reinforced polymer “in-process” scrap to completely utilize the waste material in three-dimensional reinforcing rib features of a structural automotive application, and demonstrates an efficient material use method to provide cost savings with aligned carbon fiber prepreg designs. This paper compares the mechanical properties of the discontinuous fiber reinforced composites prepared using virgin carbon fibers and reutilized carbon fiber prepreg scrap.

Introduction

Carbon fiber reinforced polymer (CFRP) has attracted great attention because it offers the advantages of excellent mechanical properties, lightweight, and superior fatigue and corrosion resistance [1]. Its weight is only 1/5th of steel sheet metal, but can be better in terms of stiffness and strength. CFRP is being widely used as a structural engineering material in the aerospace as well as sporting equipment industries [2]. In the automotive industry, there are strong motivation of using CFRP in high volume automotive production, due to the global requirement of reducing CO2 emission and increasing vehicle fuel economy. The weight reduction enabled by CFRP is the key to boost this breakthrough. Dow and Ford Motor Company have established joint development partnership to develop processing methods and material formats to enable automated high volume production (>100k/vehicles) of carbon fiber composite parts to create next-generation vehicles which are around 750 lbs lighter than the current models [3].

It has been predicted that the carbon fiber reinforced plastics to have an annual growth rate of 16% from 2012 to 2020 [4]. As the utilization of CFRP continues to increase in industries, there is an increasing interest in reducing the waste CFRP generated during production, driven by both the regulatory pressure and the high cost of the CFRP material. One promising route is to re-utilize the CFRP scrap/waste in the production, such that the economic value in the scrap can be largely retained, and the environmental concerns of disposal can be alleviated. A variety of approaches have been developed by the industries and academia, which in general can be categorized into three major classes: thermal, chemical, and mechanical approaches.

- Thermal Approach: thermally decompose the polymer resin matrix of the CFRP waste under high temperature (450 to 800 °C) either in the near absence of oxygen to pyrolyze the polymer resin into volatized molecules, or in a controlled oxygen content to oxidize and combust the resin, to recover the carbon fiber from the scrap. Under this category, major approaches being investigated are pyrolysis [2, 5, 6], fluidized bed [7, 8], and microwave [9, 10].

- Chemical Approach: polymer resin matrix is dissolved/decomposed into large oligomers using a solvent such as water, alcohol, and glycol, while the carbon fiber are left behind and are subsequently collected. The reaction can be either carried out under low temperature (< 290 ºC), or at supercritical or near-supercritical state [11-13].

- Mechanical Approach: downsize the CFRP waste by one or a series of mechanical processes, such as shredding, milling and grinding. The downsized CFRP is typically used as fillers in composite and construction applications [14].

While all the three classes of reutilization approaches for CFRPs are potentially applicable to uncured scrap, mechanical approach provides the advantages of less environmental concerns and full reclamation of both the carbon fiber and the matrix resin. However, very limited success has been reported so far on implementing mechanical approach, majorly because of the difficulties in handling and downsizing the tacky uncured material.

The on-going drive for improvements in vehicle fuel economy continues to spur new innovation in a wide array of vehicle technologies with vehicle mass reduction considered a critical element to achieving this goal. The latter has prompted renewed interest in lightweight body and chassis systems that take advantage of advances in materials such as high strength steel, light metals and composites. This report summarized joint effort by Dow Automotive, Ford and DowAksa focused on the development and implementation of novel carbon fiber composites. The result of this joint development has yielded, an epoxy based prepreg designed for high volume manufacture. The system enables room temperature shelf stable technology conducive to automated fast manufacturing of composite parts. The performance of these materials was validated in production processing scenarios culminating in full vehicle testing. The example application in this study is a B-pillar insert of a full-size automotive vehicle [3]. This study presents an innovative mechanical approach to reutilize uncured carbon fiber/epoxy prepreg "in-process" scrap.

The B-pillar insert is fabricated using carbon fiber/epoxy prepreg. During the fabrication process, the prepreg sheet is first trimmed to the contour of the B-pillar part. Then multiple layers of trimmed prepreg sheets are stacked and preformed, and eventually compression molded into the final shape, as shown in Figure 1.

Even with the effort trying to optimize the cutting process, the total amount of scrap generated could be still up to 30%. Using the approach proposed in this paper, all the scrap can be fully converted into a molding compound, which can be readily co-molded with the virgin prepreg material into three-dimensional reinforcing rib structure to replace one layer of virgin prepreg without compromising the part performance. This approach eliminates the waste and enables 100% utilization of the high-value carbon fiber/epoxy prepreg, which significantly improves the overall economics.

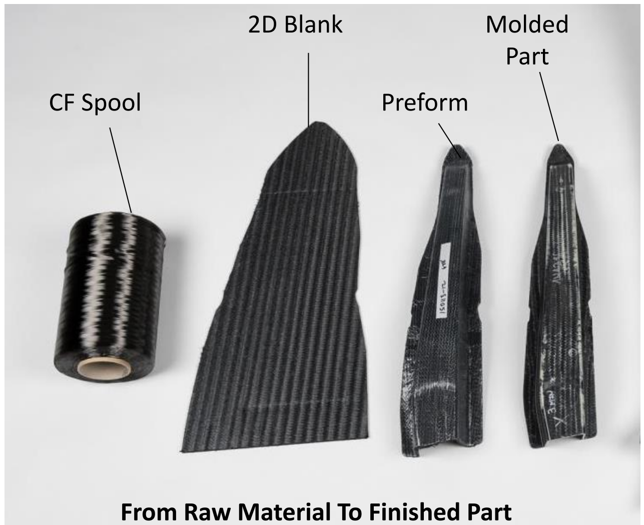

Figure 1: B-Pillar Insert (Raw material to finished part)

Materials and Methods

The material used in this study is VORAFUSE™ P6300 prepreg system [3] prepared using Dow proprietary epoxy resin blend and has the following characteristics:

- Room temperature shelf stability (30 days at 25°C)
- Tack free system to allow automated cutting, stacking and stitching
- Shelf stable preforms to allow automated preforming
- Snap cure (t < 2min) for automated molding
- Part glass transition temperature of 160°C.
- Excellent release characteristics with internal mold release
- Fully impregnated low void prepreg resulting in low void parts

Prepregs made with three different carbon fiber fabrics were used in this study:

- Unidirectional (UD) prepregs – 180 gsm
- Braid fabric – 733 gsm
- Non-crimp fabric – 590 gsm

A schematic of the proposed process for re-utilizing the trim scraps into the B-pillar insert is summarized in Figure 2. The proposed method is composed of the following steps:

(a) Downsize the offcut prepreg scrap generated during the trimming/cutting process into small pieces using a dual stage shredder. The shredding process was optimized to control the final size of the shredded pieces (0.5” – 2.5”). The final fiber size would control the properties (mechanical properties and flowability) of the resulting discontinuous CFRPs. For this study the length of the cut pieces were maintained at 1.0 inches.

(b) Characterize the initial glass transition temperature (Tg_i) of the prepreg trim scrap using a differential scanning calorimeter (DSC). Depending on the Tg_i results, the shredded trim scrap was processed via one of the following two steps:

   (i) $Tg_i < Tg_c$: If the Tg_i is below the critical glass transition temperature (Tg_c), the shredded trim scrap is formed into sheets and used in the molding process. The Tg_c level is specific to the epoxy formulation used in the prepreg, and is determined experimentally on a case-by-case basis. For VORAFUSE™ P6300 formulation, Tg_c was determined to be 35°C.

(i) $Tg_i > Tg_c$: If the Tg_i is greater than Tg_c, the shredded trim scrap is expected to have reduced flowability during compression molding that may require higher initial tool coverage (>90%). In order to restore the flowability of the final molding compound (tool coverage >60%), the shredded trim scrap is mixed with formulated epoxy resin blend in a low-shear batch mixer.

(c) Shape the shredded trim scrap or mixed compound into desired forms (sheet, cylindrical log, etc.)

(d) Compression mold the charge to make the cured composite part.

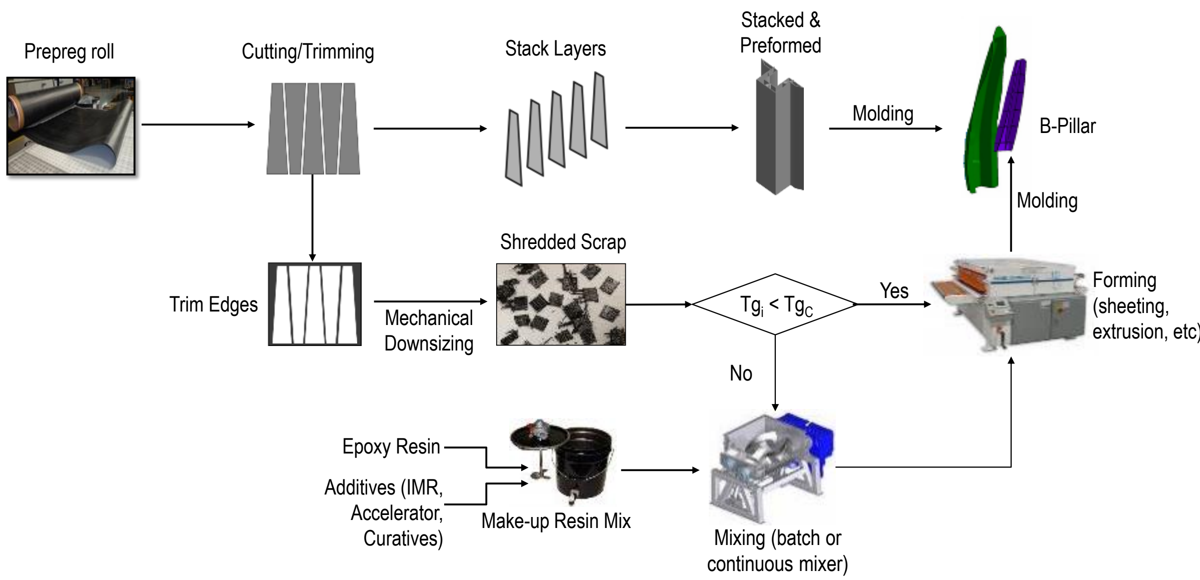

Figure 2: Process schematic of the proposed scrap reutilization method

The molding compound prepared using the proposed method was compression molded into a 12” x 12” plaque in a 250 tons LMG compression molding machine by pressing a 350g charge (10” x 10”, 70% tool coverage) at 150°C, for 3 min under 150 tons of applied force for characterization purpose. The test methods used for various characterizations are listed in Table I.

Table I: Characterization methods for molded composite plaques

Measurement	Method
Tensile Strength & Modulus	ASTM D3039
Compression Strength	ASTM D6641 (combined loading compression test fixture)
Molded Part Tg	ASTM D5418 (Dual cantilever beam)

For comparison control materials were prepared using:

(i) Sheet Molding Compound (SMC) Process [15, 16]: This control sample is used for comparing the samples produced following the re-utilization process when $Tg_i < Tg_c$. All control materials were prepared using 1" long chopped carbon fiber and an epoxy resin system with similar characteristics as P6300 resin system in a conventional SMC process.

(ii) Direct Long Fiber (DLF) Technology [17, 18]: This control sample is used for comparing the samples produced following the process when $Tg_i > Tg_c$. All materials were prepared using the same carbon fiber and P6300 resin system using 1" chopped fiber in a batch mixer.

Results & Discussion

In the first part of the study, VORAFUSE™ P6300 prepreg made using the braid fabric was used to understand the effect of re-utilization process on the thermal and mechanical properties of the resulting material. The trim scarp generated from the conventional prepreg molding process was converted into molding compounds following the schematic presented in Figure 2.

For the case when $Tg_i < Tg_c$, the trim scrap was shredded into 1" x 0.25" long pieces and was converted into sheet format by passing through a lab scale laminator. Plaques made from this compound were tested for thermal and mechanical properties and were compared with SMC materials prepared using comparable resin system. The relative comparison of the mechanical and thermal properties are presented in Figure 3.

As shown in Figure 3, all the properties of the parts made from prepreg scrap are comparable with the SMC control sample with less than 10% change in the properties indicating that with controlled size reduction the re-utilized trim scrap performs similar to virgin SMC material.

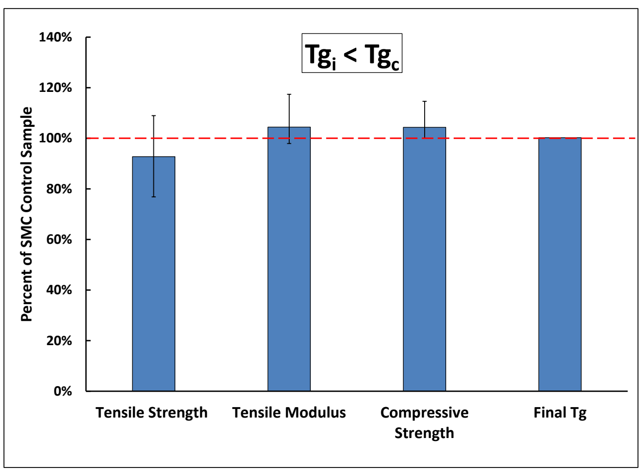

Figure 3: Relative properties comparison between SMC control material and molding compound prepared from the trim scrap when the trim scrap $Tg_i < Tg_c$

For the case when $Tg_i > Tg_c$, the shredded trim scrap (1" x 0.25" long pieces) was mixed with additional formulated epoxy resin in a batch mixer. The increase in Tg_i was due to prolonged storage of the trim scrap in an uncontrolled storage area that resulted in gradual increase in Tg_i of the material with time that led to partial cross-linking of epoxy over time (up to 6 months). This resulted in slight reduction in the flowability of the material and required a higher tool coverage (>

90%) to mold a complete plaque. Addition of small amount of freshly formulated epoxy resin (< 5%) via a batch mixer allowed to mold parts with 70% tool coverage.

Plaques made from this compound were tested for thermal and mechanical properties and were compared with molding compound prepared using DLF technology. A different control sample was chosen for this comparison because it was expected that the mechanical properties could change due to additional mixing of the resin with the trim scrap in the batch mixer. The relative comparison of the mechanical and thermal properties with the DLF material are presented in Figure 4.

As shown in Figure 4, all the properties of the parts made from prepreg scrap when $Tg_i > Tg_c$ are comparable with the DLF control samples with less than 10% change in the properties indicating that even when the trim scraps were stored in an uncontrolled environment for up to 6 months, the material can still be re-utilized and perform similar to a freshly prepared DLF material with similar resin system and chopped fibers.

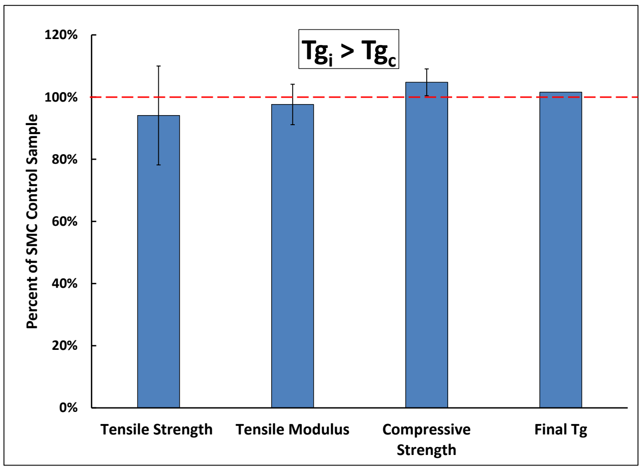

Figure 4: Relative properties comparison between material made from DLF process and molding compound prepared from the trim scrap when the trim scrap $Tg_i > Tg_c$

Influence of Fabric Types

In the real implementation of the proposed approach, it is likely that prepreg scrap with different types of carbon fiber woven fabric could go into the waste stream and need to be processed using the same approach. Different prepreg fabric may behave differently during the shredding, mixing, and forming processes. In order to understand whether the fabric type is going to lead to any significant influence over the final part properties and to decide whether sorting will be needed, in this study, prepreg scrap with three types of fabric were processed and tested: unidirectional (UD), braid, and non-crimp fabric (NCF). The tensile test properties were presented in Figure 5 below. Please note that the tensile property values were presented in the form of percentage, and the properties of braid fabric scrap was chosen to be the 100% reference.

As shown in Figure 5, the tensile properties of the parts made from these three types of prepregs do not exhibit significant difference, regardless if the scrap was formed directly as a fresh material ($Tg_i < Tg_c$), or if it was used after 30 days of storage ($Tg_i > Tg_c$). These results indicates that the proposed approach is robust enough that the difference in scrap fabric type would not lead to any major difference in part tensile properties, and thus sorting the scrap prior to processing may not be necessary.

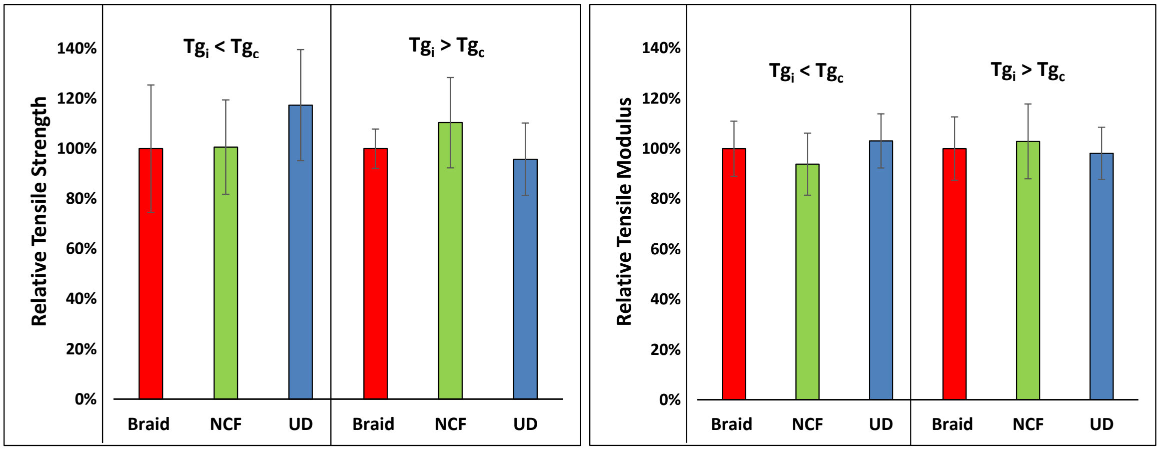

Figure 5: Relative tensile properties comparison (left) tensile strength, and (right) tensile modulus of parts made from trim scraps of three types of prepreg fabric

Molding Trial Using a Full-Size B-Pillar Insert Design

A molding trial was conducted to validate the applicability of the reclaimed prepreg scrap in making a full-size real component in conjunction with virgin prepreg material. In this trial, the part design used is a B-pillar insert of a full-size vehicle [3]. The goal is to explore if the reclaimed prepreg scrap,

(a) can flow in the 3-dimentional tool and form a complete part,
(b) can be co-molded with the prepreg material,
(c) can eventually substitute a fraction of prepreg material based on mechanical performance of the molded B-pillar insert with ribs.

As shown in Figure 6, the outcome of the molding trial was successful. The reclaimed prepreg scrap exhibited good flowability during the molding process, and formed the rib structure with good dimensional precision and stability. The molded part demonstrated excellent demolding behavior from the tool. Component level testing was conducted using B Pillar sections containing ribs fabricated from reclaimed materials. Experimental test results indicated good correlation to predictive CAE results and comparable performance when compared to the B pillar design without a rib structure.

Given essentially equivalent performance in both CAE and experimental testing, it is technically feasible to reclaim the offal generated when cutting 2D blanks and generate a random fiber molding compound to create out of plane geometry. This translates to an approximately 15% reduction in the required prepreg while also reclaiming the offal versus disposal of the waste. A cost reduction is also expected in this scenario versus a 100% prepreg design but the magnitude will be dependent upon the additional processing costs to reclaim the offal and manufacture molding compounds.

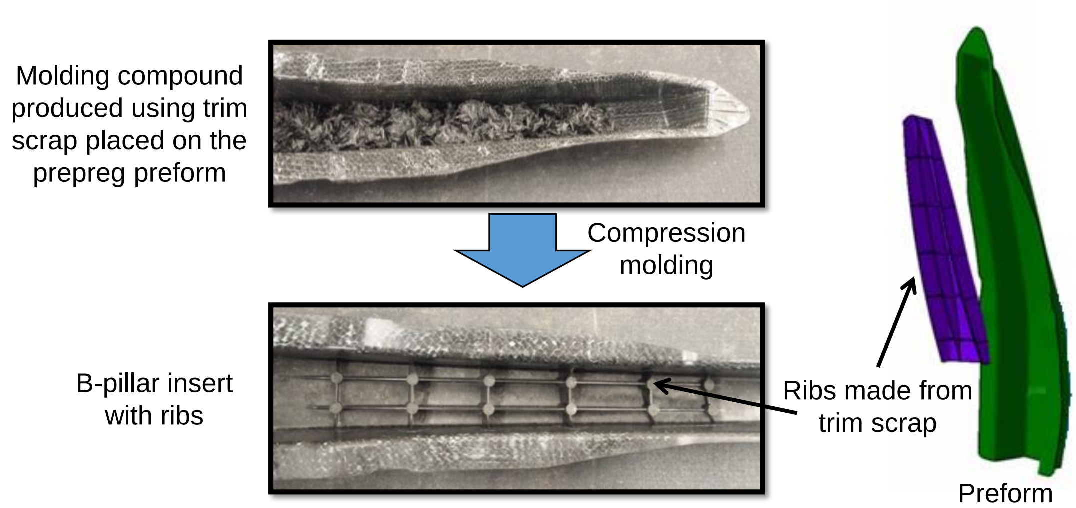

Figure 6: Illustration of co-molding the reclaimed prepreg scrap with virgin prepreg

Conclusions

A process to re-utilize the offal generated when cutting 2D blanks from prepregs to generate a random fiber molding compound was presented. The thermal and mechanical performance of the plaques made from the reclaimed random molding compound was comparable to those prepared for an equivalent conventional SMC or DLF compound. The reclaimed molding compound was successfully co-molded with prepreg to create and out-of-plane geometry (B-pillar insert with ribs in the orthogonal direction). This translates to a savings in virgin prepreg material and 100% utilization of the prepreg material thereby eliminating the waste generation and its disposal.

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