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CARBON FIBER PRE-PREG RECYCLING – AUTOMATED PREFORM MANUFACTURING EQUIPMENT

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CARBON FIBER PREPREG RECYCLING – AUTOMATED PREFORM MANUFACTURING EQUIPMENT

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LIST OF ACRONYMS

CFRP	Carbon Fiber Reinforced Composite
CRTC	Composite Recycling Technology Center
CTE	Coefficient of Thermal Expansion
DFC	Discontinuous Fiber Composite
GHG	Greenhouse Gas
HexMC®	Hexcel Corporation Molding Compound
IACMI	Institute for Advanced Composite Manufacturing Innovation
Kg	Kilogram
m	Meter
MJ	Mega Joule
mm	Millimeter
MWh	Mega Watt hours
OEM	Original Equipment Manufacturer
P4	(Owens Corning) Programmable Powdered Preform Process
RD&D	Research Development and Demonstration
SAMPE	Society for the Advancement of Materials and Process Engineering
SMC	Sheet Molding Compound
WIP	Work In Progress

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1. EXECUTIVE SUMMARY

Discontinuous fiber composites have a compelling business case as related to light metals such as aluminum and magnesium machined or die cast components. DFC's have been in commercial production using carbon fiber/epoxy prepreg for both commercial aircraft and for military applications for a number of years and their usage is expanding into automotive and consumer goods components. Reasons for this include significantly lower cost as compared to continuous fiber composites easier design and understanding of the material by metal traditionalists, higher degree of part complexity with relatively simple and low cost molds when compared to high-pressure die casting, and potential for near zero waste.

IACMI's 10-year goals of reduction in carbon fiber reinforced plastics manufacturing cost by 25%, reduction in their embodied energy by 50%, and recyclability of 95% can all be advanced through robust recycling. With recycling We have shown that a 15% contribution in manufacturing cost reduction is feasible, that a significant reduction in embodied energy (over 90% for the recycled fraction) is achievable, and that when combined with primary pyrolysis recycling, the 95% target can be met.

Large-scale application of advanced composites began with the aerospace industry, and CRTC's location in Washington State provided access to a waste stream of nearly 900 tonnes/year that was going to landfill. As the aerospace industry has automated parts production, their material forms have become significantly easier to recycle, and some evidence of this exists for the future automotive and wind turbine components as well. CRTC decided to focus on re-purposing the carbon fiber/epoxy aerospace scrap streams through materials reformatting and reuse, and not on primary recycling (pyrolysis mainly) as this technology is commercially available. The main reasons for this were that it offers a route to effective use of the most widely available and consistent feedstock called edge-trim, as well as allows creation of complex and low-cost parts using rapid and cost-effective compression molding technologies. The reasons also include leading the way for potential automotive pre-preg recycling as the combination of roughly 85% virgin pre-preg and 15% recycled pre-preg directly supports IACMI's goals and enables significant part cost reduction and a path to zero-waste composite manufacturing at the OEMs or Tier 1's.

The purpose of the project was to develop equipment and technology to transform continuous fiber pre-preg in roll forms into smaller chip-format DFC feedstock, and to determine impacts on moldability and performance based on lessons learned along the path. The availability of scrap from pre-preg manufacturers was a significant value to the program even though the aerospace pre-preg is designed to be autoclave molded thus has handling, tackiness, and processing factors that are not ideal for DFCs. The scope of the project was to develop a Phase 1 system that could identify and resolve some of the major hurdles, determine where to focus effort on building a commercial-scale Phase 2 system, and develop technology for handling a wide variety of incoming scrap materials to produce the most usable product.

A chopping system was developed and reduced to practice via an experimental approach that enabled all forms of scrap coming from the pre-preg manufacturers and some forms of the scrap coming from OEM production lines to be very effectively re-purposed. The systems that were developed were not considered to be production robust but rather identified and resolved some of the major technical hurdles, and demonstrated the path towards effective full-scale commercialization.

The major recommendations are:

- Move the pre-preg chopping machine development forward in conjunction with two fiber/pre-preg suppliers (for redundancy and supply chain viability) and IACMI in a focused effort to optimize part manufacturing and cost. This will demonstrate the cost savings achievable at scale as the IACMI goals are driven forward.
- The second major recommendation is to further develop CRTC's direct-to-preform and compression molding recycling system to address the optimized use of "tailored-blank" DFCs to achieve best usage of combined virgin and recycled pre-preg. Technology development would include control of local fiber-to-resin ratio, pre-preg chip aspect ratio, and pre-preg chip orientation to achieve highly repeatable and optimal part cost/performance.

2. INTRODUCTION

The technology for chopping and placing carbon fiber recycled pre-preg chips is designed to enable large quantities of a very valuable commercial feedstock to be re-purposed into new product applications. Aerospace carbon-epoxy pre-preg has very high demands on quality and life-times, and thus even a small deviation in fiber alignment, resin quantity and distribution, or process excursion will render the rolls of material un-usable to the aerospace supply chain. With more and more of the aerospace production equipment being automated tape and fiber placement, it has become unfeasible to "cut-around" the defects and thus even a single small tolerance deviation in one area of a roll is cause for rejection of the complete roll of material. Previous production using ply cutting machines would allow the operators to identify and eliminate the defect region, however since it is impractical to segregate materials by potential end process, this is no longer an option for the industry.

As regards "aging" of the carbon-epoxy prepreg, testing has shown that much longer lifetimes than are specified in the aerospace production chain are achievable, and thus the issues of having to recycle/scrap the "timed-out" rolls of material are more of a construct of the aerospace industry than a defect of the material. Hence these rolls of pre-preg are fully usable for other applications with less-stringent quality gates, and large and ready forms of materials that have exceeded the "nominal" out-times can be put into reclaimed service with little downside as will be discussed.

The new emphasis on automated placement processing requires each production roll to be trimmed to an exact width dimension at the factory, which leaves us with two edge-trim spools for every roll of prepreg produced and the edge-trim varies from approximately 3 to 11 mm in width (on an approximate 25 mm paper backing). These edge-trims are also slightly resin-rich as a function of the pre-preg production process which can be a desirable feature of the scrap feedstock for some applications. A common concern of the recycling industry is access to supply, as it is in the manufacturers' best interest to eliminate all waste. Under the current production scenarios, scrap rates are steadily declining, yet the overall production volumes are increasing thereby offsetting some of the improved efficiencies. With increased production also comes increased availability of the edge-trim spools, and this is one of the primary reasons for setting up a chopping approach that can turn the edge-trim from relatively unusable to highly desirable feedstock.

Figure 1 Edge-Trim and Roll Scrap Pre-preg

The potential applications for the chopping technology start with transforming the pre-preg production scrap into usable material for press-forming, and extend to later chopping the scrap and even virgin materials from high-volume low-cost carbon fiber production into a usable format charge for compression molding. The intent is to be able to handle a wide variety of types of fiber and resin, which makes this process approach desirable for automotive light-weighting applications, as well as for items such as small wind turbine blade and housings, and impellers and the like for smaller (micro-hydro) hydrokinetic turbines. A fairly broad application space exists, with the only major barrier being that the materials are not returnable into aerospace applications due to the logistics/heritage rules of that industry. Some inroads to use of chopped scrap carbon-epoxy pre-preg for commercial construction (supporting specialty reinforcements in concrete work) are being made and many other building and transportation applications can be envisioned as the technology moves towards maturity and wider-spread adoption.

The existing technology base for chopping carbon-epoxy pre-preg is very limited and closely held, as well as relying on (typically) specially made pre-preg formulations for example Hexcel's HexMC® and Tencate's Chopped Pre-preg Molding Compound. A review of available technologies led to no information readily applicable to CRTC's primary sources of materials (T800/3903 aerospace prepreg) and thus developing a new chopping approach and machine was determined to be the best available option for re-purposing these materials. Machine design was undertaken towards a goal of commercialization for internal products, then made available to others in the IACMI group as larger scales of carbon fiber were implemented in the chosen clean energy spaces.

3. BACKGROUND

The investigation into available equipment at the start of the project identified three sources of chopping systems that had been developed for carbon fiber SMC (sheet molding compound) production. These systems, by ChopCot of the Netherlands[1], Pierret of Belgium[2], and Finn&Fram Inc. of California all had downsides when it came to cutting the high-strength, low-resin content aerospace pre-preg. The toughness of the resin systems and the relatively high strain-to-failure of the fiber, coupled with a relatively tacky resin system that quickly heated to melting with the system input energy were the primary issues seen. Some of the more aged (very dry and boardy) pre-preg could be cut with the Finn&Fram system, and this was in fact used for the preparation of samples for the project described in the SAMPE-Japan paper by Toray and Boeing[3]. The ChopCot system however was primarily set up to chop dry fiber into a mat format that the resin could then be applied to, a more common methodology of using their equipment. Investigation into related processes indicated that the need to reduce the tack of the pre-preg was paramount for continual operations, and the Pierret system had the closest design capabilities to what would be required.

The Pierret guillotine approach was very similar in nature to the design/approach chosen by CRTC for chopping, however their machine design and dimensions were based around high-volume cutting of wide format and thick stacked materials (450 mm width and up to 75 mm compressed stack thicknesses). For the aerospace scrap pre-preg feedstock we were dealing with, the variable width and issues with compressing a large stack were deemed to be outside of this machine's capabilities. The key issues faced were the guillotine blade transitioning through the stack could easily melt-fuse the edges of the pre-preg layers together, and at 0.14 mm thickness per ply (without backing paper) the stack build-up to take advantage of a compressing/cutting system was not seen as technically feasible.

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[1] https://www.chopcot.com/fiber-chopping-machines/fiber-chopper-chopcot-T5.html

[2] https://www.pierret.com/en/coupeuses/r45/

[3] High Productivity Technology for Compression Molding Process - Recent Advancement of Pre-preg Compression Molding and Carbon SMC; Mattia Andolfatto, Hisashi Toyama (Cannon.S.p.A), SAMPE Japan JISSE16 2019-02-09

The ChopCot system was designed around a rotary cutting approach which we thought had promise. The CRTC purchased two of their systems and custom designed a different feed-in system to work with the hybrid rotary chopper. These were modified by Van der Mast Industries and supplied to CRTC for installation. The goal and intent was to try to develop a system that had variable fiber cut lengths, as indicated in patent literature that showed benefit to a mix of fiber cut lengths in molding parts.[4][5][6] The use of rotary chopping is commonplace in the dry fiber industry, and several adaptations of the typical glass-fiber choppers existed to try to work effectively with the more brittle carbon fiber, however there was little background on rotary cutter usage for cutting pre-pregs.

The specific aerospace pre-pregs to be recycled had varying widths of feedstock, variable resin content, differing degrees of 'age' of the pre-preg, and high sensitivity to local temperatures in the feed system and in the cutting and distribution systems. The combination of variables creates an extremely difficult design space which is not generally seen in the fabrication of stock chopped pre-preg product offerings. Hence the project goals and objectives had to first identify the range of materials being potentially utilized. Meetings and investigation into prior attempts to utilize these materials were held with the primary suppliers of the scrap pre-preg in Washington State University (Toray, Janicki, and Boeing) and demonstrated the range of possible issues that the project would face. Scrap materials that required processing included timed out rolls of virgin pre-preg from storage or production interruption issues leading to a range of known and unknown histories of the scrap.

As an example of what CRTC deals with for incoming scrap, one major offshore aerospace Tier 1 company from the Far East had container-loads of these pre-pregs en-route from our region to their manufacturing plant when a fire occurred on the container ship. Due to legal restrictions on managing the fire-impacted cargo back through borders, the material storage containers lost power, and then sat in an un-determined temperature environment and needed to be recycled when finally released. Scrap materials also include shop-floor timed out scrap, and although the manufacturing companies will carefully and thoroughly track the history of the pre-preg materials up until they are timed-out, once the window has passed there is little or no further documentation or tracking applied. Since the lowest-cost option has been land-filling, the companies will make no effort to retain the rolls in any storage condition that would preserve the pre-preg properties, leading to a large set of unknown variables about the product. Scrap materials of high interest included the edge-trim from manufacturing roll-stock for automated placement machinery as this is the only true dedicated and predictable feedstock for recyclers to procure. This edge-trim however, can vary from 3 to 11 mm in width (of the pre-preg) with a very large variation in the resin content which can be up to 50% higher than the primary pre-preg resin content. As it is on the roll-edge and collects the squeeze-out from processing, there can also be a significant amount of neat resin just beyond the fiber boundaries but still on the backing paper and thus in the chopping machine feed path. Finally, fiber rolls that have some in-process variation that was cause for rejection from aerospace usage are also a source of scrap feedstock. However, the locations of the defects and the nature of the defects are not known ahead of time (another legacy of the low-cost of land-filling creating dis-incentives for added documentation/tracking time during the materials manufacturing) and the input to the chopping systems needed to deal with these defects without interrupting the process.

Although not immediately recognized as a potentially significant issue, the handling and management of the pre-preg backing paper which must be removed prior to chopping is a major factor in system designs. This pre-preg backing paper can be several times the mass and volume of the pre-preg, in fact as much as 20x the mass of the pre-preg in the case of thinner edge trims. Concurrent lines for removal, separation,

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[4] JP4862913B2 2009-03-31 Pre-pregs and Preforms; Japanese Patent granted 2012-01-25

[5] EP2671991B1 Random Mat and Fiber Reinforced Composite Material, Konagai,Y. et.al.

[6] EP2151418A4; 2017-11-29; Chopped fiber bundle, molding material, and fiber reinforced plastic, and process for producing them, Taketa, I. et. al.

size reduction, and compaction/recovery of the backing papers needed to be addressed, as did the machine feed and handling systems where the edge-trim may be only a few mm but the paper may be 20-25 mm wide.

A two-phase approach was planned for this project, namely first demonstrating the issues and investigating routes to overcome them, and then it was planned to further move into commercialization of the down-selected technologies. Project budgets were planned accordingly, and the team leveraged off of previous efforts from the above-mentioned companies. The project plan was devised to de-risk the individual technologies from collecting and feeding the machines, to the individual chopping, and finally the application to molds so that the chopped pre-preg could be compression molded in a sequential operation. The volumes of materials the team was trying to recover led to identifying goals for the output, which then set parameters for chopping and feeding. With the chopping operation being the rate-limiting step, and rate of cutting having the largest impact on the energy input to the system (and thus internal thermal management demands), several approaches were identified as to how to accomplish the rates required. Experimental evaluation of selected methodologies of thermal management were built into the plan, and methods for global thermal control versus localized thermal control were investigated.

The project teams' backgrounds were highly varied. They included several team members with prior experience in chopping fiberglass from boat-building experiences, as well as team members with experience in chopping and compression molding using dry-carbon fiber. Applications that team members had worked on in the dry-fiber chopping space included hands-on operation of the DOE-supported P4 (programmable powdered preforming process) using carbon fiber to develop hybrid carbon/glass truck hood and fairing preforms for injection/compression molding (work performed at the National Composites Center in Kettering, Ohio); developing chopped heavy-tow recycled carbon fiber into compression molding formats for carbon-epoxy high-pressure molding of critical satellite antenna dish zero-CTE structures; developing fiber chop and placement systems for compression molding of scrap pre-preg for wheelchair axle brackets and other structural components; developing process control technologies for heating and cooling in high-temperature resin system curing; developing materials handling systems for various filament winding and resin transfer molding applications; designing and building custom composite processing equipment; and manufacturing tooling and CNC machining of structural parts and components.

4. RESULTS AND DISCUSSION

The CRTC mission is to design, develop and manufacture products that utilize carbon fiber scrap to positively impact people's lives and our environment. To that end, based on the location in Washington State, the first stepping stone is to recognize and determine the range of carbon fiber scrap produced in the state and devise a business approach supported on a technology background and platform that most efficiently converts and uses the available materials. There are four basic forms of scrap materials that make up the majority of WA's roughly 900 metric tonnes of landfilled carbon composite scrap. These are: cured waste from aircraft component manufacturing from an aircraft OEM and their tier 1 suppliers; scrap dry fiber from aircraft and boat production; scrap carbon fiber un-cured pre-preg from both initial pre-preg manufacturing as well as from scrap off of tape and fiber-placement machinery; and, expired and timed out materials from the supply chain that have exceeded the shelf-life for the application.

The CRTC analyzed the landscape of available waste/scrap materials based on close interaction with the WA State Departments of Commerce and Ecology who have reporting requirements for landfilled bound materials. It was determined that the lowest hanging fruit and material with the best accessibility and guarantee of availability would be the scrap pre-preg from initial manufacturing as well as some timed out and WIP scrap. In a working session with DOE and IACMI the four items critical for success for the CRTC were defined as:

i. Supply relationships
ii. Product sales channels
iii. Pre-preg reformatting machinery
iv. Lean production cells

Since we were evaluating opportunities against the primary IACMI recycling goals, we looked at the mix of technologies and focal areas and jointly decided that the most benefit was to partner on the re-formatting machine to create the feedstock necessary to guide production opportunities, while partnering on the aspects of primary recycling from cured component pyrolysis with ELG Carbon Fibres. The team felt the objectives of Table 1 should be reasonable and achievable.

	5-Year Goal	**10-Year Goal**	**CRTC Progress**	**CRTC + Primary Recycler**
Reduce CFRP Manufacturing Cost	25%	50%	15% in 5 years*	20% in ten years*
Reduce Embodied Energy	50%	75%	14.5% immediately*	46.5% in 5 years*
Achieve Recyclability	80%	95%	Up to 20%	95% in 10 years

*With no other carbon fiber manufacturing/embodied energy reduction accounted for – only recycling, also includes 10-year product mix of 15% CRTC rCF content, 35% pyrolysis recovered fiber, and 50% virgin fiber.

Table 1 IACMI Goals Addressed Through Recycling

As the CRTC had already identified and addressed the two major market areas, supply relationships with the state's major generators of scrap pre-preg materials and identifying and cementing product sales channels, we focused on the immediate hurdle of developing the production methodologies. The primary aspects of the problem were summarized as:

i. Collection and re-storage of carbon/epoxy scrap from initial production and from automated production machinery.
ii. Removal and separation of backing paper and chopping the pre-preg into a useable, consistent, thin, direct-to-part feed-stock.
iii. Maintaining in-plane quasi-isotropic layering with near complete coverage, and
iv. Manipulating onto component production tooling with the integrity to ensure robust molding.

The initial deliverables developed were as follows;

i. Pre-preg re-formatting machine for flexible pre-preg feedstock recycling/recovery.
ii. Technology and IP to rapidly and robustly convert manufacturing offal into new pre-forms for secondary manufacturing.
iii. Demonstration of systems on commercial scale projects with actual manufacturing output.

The four primary task areas were defined as;

1) Design and Machine Requirements, culminating in virtual machine design and bill of materials
2) Machine Sub-Assembly Build,

3) Functional Analysis and Controls Development
4) System Operation and Implementation

The rationale for the above approach was that although there was excellent access to full rolls of scrap pre-preg, and that the nature and form of the defects in these rolls still rendered them highly useful for our products, we were looking to the future of higher volume scrap recovery, and to IACMI's goals of recycling capabilities applied to automotive and wind based pre-preg projects where very large quantities of scrap materials would be generated. Hence we were preparing for the future potential with IACMI as well as setting up our internal logistics and production systems. The major producers of scrap materials will push towards continuous improvement and reduction to hopefully near-zero waste and so would never be able to provide a guarantee of available feedstock for CRTC to handle, but one of their scrap streams would always exist and would grow in direct proportion to the plant output. This material is the edge-trim from the as-produced pre-preg roll, and it is cut off each end of the roll immediately after production. The edge-trim has a slight additional amount of resin and on slitting from the roll retains a fairly wide band of release paper with a narrow band of pre-preg plus some excess resin. The edge trim dimensions vary from roll to roll and are typically 3 mm to 11 mm wide on approximately 25 mm wide backing paper.

By concentrating our efforts on re-purposing edge-trim, we also knew that the balance of the scrap feed CRTC could access could also be prepared with relative simplicity to fit into the same system through slitting into desired widths. The balance of the materials identified were defective rolls, timed out rolls and timed out slit-tape from automated production, with typical variation in dimension of 3 mm to 1.5 m.

A significant benefit to utilizing the edge trim was the slightly higher resin content that exists as one gets to the roll exterior. Since the aerospace pre-preg has such a low resin content, and is designed specifically for an autoclave cycle wherein the time-temperature-pressure profile allows for proper resin flow and laminate compaction, we were trying to move the materials into a rapid compression molding cycle with much more aggressive thermal and pressure application which does not necessarily play well with the low-resin content materials due to localized flow inconsistencies. A major headache created in moving from the autoclave cycling to the compression molding cycle is surface finish, and extra resin is highly beneficial here. Being able to mix an edge-trim pre-preg chip with chips from typical rolls/tapes allowed this extra resin to be naturally placed and to have a beneficial impact on molding performance. Significant effort into this area led to much more detailed understanding of the balance of the factors which included chip aspect ratio, however this part of the effort is considered proprietary and will just be referenced here.

The project approach was primarily experimental in nature due to the broad potential ranges of feedstock for recycling. This has led to the definition of our primary GO/NOGO decision points for scaling to higher volume automotive applications which were selected as follows:

i. Can system accommodate multiple types of pre-preg scrap?
ii. Can the system demonstrate 500 tonne/year processing rate?
iii. Is the reformatting energy demand lower than the energy demand for primary recycling using pyrolysis?
iv. Can manufactured articles from output meet quality and production rate requirements?

The answers to the above were overall highly positive, with the caveat that the higher production rate especially on the guillotine-based machine was only feasible when using significantly longer/wider chips as output. The reasoning for this is that while the aspect ratio of the chips from the chopping machine may be similar, the additional length fed in at a constant blade chopping rate gave a much larger increase in mass cut per unit time. The limitation embodied in moving to longer cut lengths is a loss of flexibility in the molding and part options. There is a gain factor in here in that the longer chips are directly amenable to producing semi-oriented pre-forms that are very useful for applications in the construction industry.

CRTC ran (in addition to the above-mentioned slit tapes and edge trim) several versions of input pre-preg, including automotive pre-preg feed, medium-tow based pre-preg, and sporting goods based pre-preg. Systems with very fast (snap) cure to systems with very long processing windows were run, and systems using intermediate modulus and standard modulus fibers were run. Dry fibers were also put through the machinery, and we could consistently run the heavy tow low-cost fiber produced by the ORNL team at lengths down to under 1 mm. In order to test the recycling options, CRTC also ran the chopping systems with freshly produced pre-preg out to systems that had very aged (several years) of non-refrigerated storage. The faster iteration of the machinery, especially the ChopCot based system, require very specific machine feed designs and these will be highly dependent on the pre-preg to be reformatted. Thus the design should be custom-developed around the majority type of scrap pre-preg desired to be re-purposed, and design adaptations make it difficult to be able to develop a universal machine. Thermal management, feed path control, materials handling for input, and collection systems all need to be addressed for each pre-preg feed. The lack of a universal machine is not really a detriment except in a research and development environment, as we anticipate that specific systems would be procured by companies based on individual production line specifications.

Embodied Energy

Estimates were made of the energy consumption during chopping operations and included the following processes: spool motor operation; chillers; vacuum pump; backing paper chopper and paper suction motor draw; controller energy; pre-compaction heater; belt motors; lighting; and space conditioning. The net energy used (which can be considered equivalent to the re-formatting embodied energy contribution) was estimated at approximately 1.64MJ/Kg at 0.5 kg/minute processing rate. No attempt was made to estimate the storage contribution for the scrap pre-preg as that is a highly variable factor and should be negligible in a continuous production facility where the scrap is not re-frozen in-between process stages. Although CRTC does collect and store the aerospace scrap from our providers at approximately -20 C, we only do this as we are batch collecting from external sites (which would also add a transportation embodied energy contribution).

ELG Carbon Fibre Ltd presented a talk on the Lifecycle Assessment Benefits of Recycled Carbon Fiber[7] and although they did not present a calculation of direct embodied energy of recycled (pyrolysis based process) carbon fiber, they did show relative energies for conversion related to virgin carbon fiber and also the major automotive metals. Inferring from their numbers for GHG emissions, Figure 2, and virgin embodied energy, one sees that primary pyrolysis recycling energy used is at about 11% that of virgin carbon fiber embodied energy, or just about 31MJ/Kg of carbon fiber processed. Converting the ELG numbers to a pre-preg based feedstock with addition of epoxy and the concurrent decrease in carbon fiber volume fraction decreases the embodied energy per kg by approximately 30% to about 20MJ/Kg. Thus, we can readily see that the embodied energy is significantly lower for CRTC's chopping process (at

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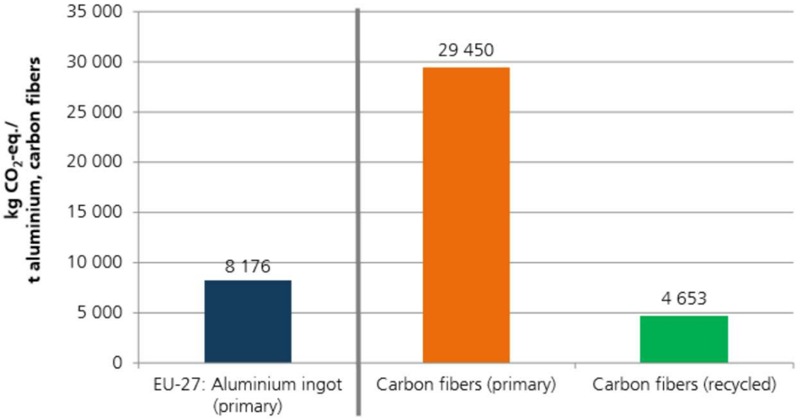
[7] "LCA Benefits of rCF" Marco Gehr, Composite Recycling & LCA, Stuttgart, Germany March 9th 2017

1.64MJ/Kg) as would be anticipated.

Figure 2 Virgin Fiber vs Recycled Fiber GHG Emissions



- Per tonne of material less GHG emissions are emitted by recycled carbon fibers compared to primary aluminum

CRTC has not yet performed a complete embodied energy calculation of our as-formed components based on the compression molding process, however this will be generated in the future with current draw and voltage meters on the presses recording energy intensity of forming. Feedstock resin system (cure kinetics), molding temperature and time as well as pressure-time cycle and de-molding temperature all impact the calculation. The specific heating system (induction heating versus platen electric heat-conduction) also has an impact. It is reported [8] that compression molding is roughly 50% of the energy contribution of autoclave molding. Hence, overall, the combined reformatting, chopping and applying direct to preform compression molding is highly energy efficient and a contributor to meeting IACMIs embodied energy goals.

Component Processing

The CRTC developed several processing options for the output of the reformatting machine, including trial components designed to test the limits of processing of the materials. Figures 3 through 8 demonstrate some of the trial components produced as an experiment prior to moving to other proprietary production components.

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[8] LCA Database – Wind, DACOMAT; Ares(2019)2067744 – 25/03/2019; Damage Controlled Composite Materials; LCA Database of environmental impacts to inform material selection process; Hill, C., and Norton, A.

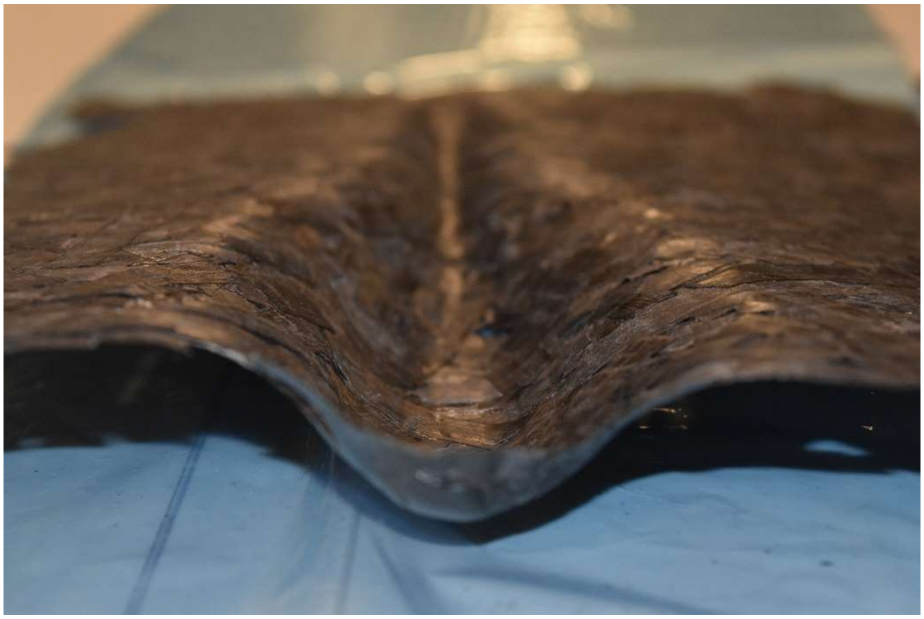

Figure 3 Variable Radius Tapered Preform

Figure 4 Flat Plate - 0.5 to 12.5 mm Thicknesses Molded

Figure 5 Flat Plate - High Flow Trials

Figure 7 Hyperbolic Paraboloid, High-Flow, High-Deformation

Figure 6 Ball Joint; hollow shaft, solid end

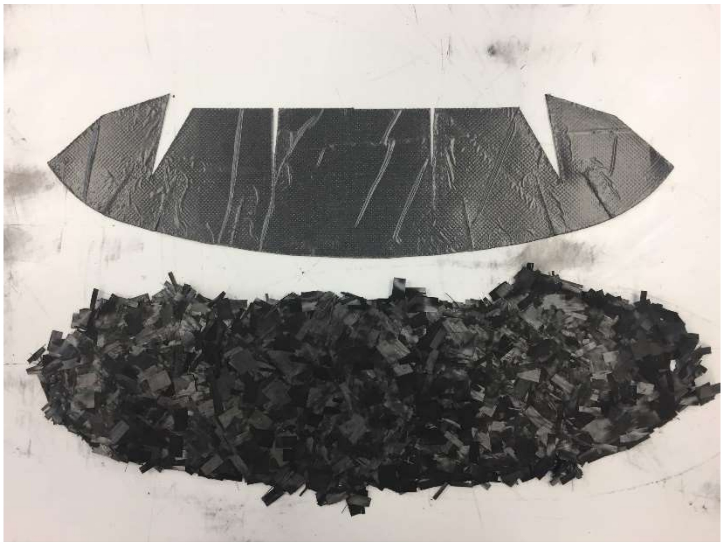

Figure 8 Continuous plus Chop Nested Preform

Figures 3 through 8 are a few of the many examples of trials and components produced in the course of the project, with an eye towards understanding what length of chopped pre-preg was necessary for the machine to be able to output, what mix of aspect ratios and physical length chips are needed, and what impact these have had on the downstream compression molding processing. Although details of these outcomes are proprietary, it can generally be recognized that a mix of chip dimensions had significant benefits, as did a mix of resin ratios where surface finish was critical.

As noted previously, chip dimensions from the edge-trim varied in width from about 3 mm to about 11 mm, dependent on where the process operator at the pre-preg manufacturing factory placed the roll and slitters. For these products, the photos show that we typically would have 15 to 25 mm cut lengths, providing us with aspect ratios of 1.36 to 8.33. Ideally a mix of aspect ratios based on part performance and shape would be considered, and a future effort of the CRTC in conjunction with other partners will be looking at the capability to optimize design properties and processing capability to achieve minimum part weight and cost through optimizing the chopper output and material location/placement. This approach would likely be well suited to an automotive production system where cost/weight optimization is critical to compete with steel, aluminum, or magnesium, especially when it comes to competition with high-pressure die cast components.

In most cases for this project the CRTC was looking to be near quasi-isotropic initially, as the early application spaces were fairly simple components that needed to have a predictable final shape after molding. As the need became evident for much more complex parts wherein topographical contributions to stiffness start to be a significant factor, we looked less at the requirement for quasi-isotropic preforms and more at directionality in properties through fiber alignment. The raking mechanisms developed to redistribute the chopped pre-preg as pre-form shapes were being made were an area that needed more attention and would need to be addressed in a production-based machine designed for repeatable optimized part manufacture. In hindsight, this is an area that CRTC could have benefitted from more partner interaction and a dedicated focused automotive component project. There are substantial potential property gains from partial chip alignment technologies that would enable improvements similar to the benefits seen by the automotive steel industry as it moved into tailored blanks for stamping.

Equipment requirements included the need to cut down large roll feedstock into manageable widths to put through the chopper system. To that end the CRTC developed a roll slitter that re-purposed an old Engel filament winding system. Figure 9 shows the basics of the system with its indexable carriage manual feed slitter. As slitters are relatively common but fairly pricey especially for handling the size rolls we are dealing with (1.5 m length x 0.5 m diameter) it was simplest for this project to just create our own and look to purchase as future needs dictate. The system was set-up to handle these full-sized rolls as well as the already slit 0.3 m wide, 0.6 m wide etc. rolls that typically come to us from timed out Tier 1 and OEM facilities such as the fire-related shipping container loads previously mentioned.

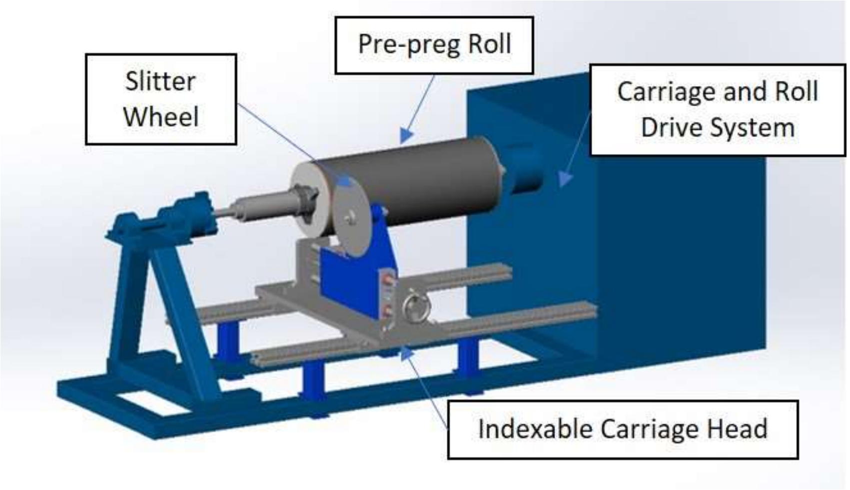

Figure 9 Isometric Diagram of the Basic Slitter System

The basic chopper system going through shake-down trials is shown in Figure 10 and in this case is actually operating inside the -20 C freezer. The system was custom built for CRTC and we would typically add on the localized heaters and chillers and assemble on the feed/take-off stand in order to achieve the localized thermal management and control necessary for continuous operation. For initial trials it is simpler to test it out in a cold environment holding the highly tacky pre-preg in a relatively firm and boardy state. Although this approach did impact the internal mechanisms somewhat, the local heat generated by the motor drives is enough to keep it in a stable operating condition. The impact of temperature on some of the hardened rubber mechanisms internally are an unknown, however we did not notice significant degradation of performance between this set-up and the integration into the overall stand systems. In Figure 10 notice our creel holding (3D printed) devices for the slit-down pre-preg tapes and a retaining brake integrated into the backside of this to prevent runaway spinning of the feed creel as the rpm’s are so high. This system here is running at an approximate 1.25 aspect ratio (chip length to width) using 12.5 mm wide feed at near 0.25 kg/min. Increasing the output simply requires ganging the internal cutting mechanisms and adjusting the drive motors. In the background are scrap rolls of uni-directional pre-preg awaiting processing.

Resource limitations did not allow some of the innovations we considered to be addressed. However, consideration of vertical ganging of the internal cutting rather than horizontal in-line width increases would be one specific area for development for increased production rates. The reasoning for this is to improve the robustness of the creel feeds and the ease of splicing new creels as each one runs out. Vertical ganging would also allow for the system to address cleaning and replacement/sharpening of internals without interrupting the processing of materials as each one can be on an extractable geared drive. This would overcome the limitation of a single shaft system that requires the machine to be stopped for any maintenance and also makes each cutting mechanism more compact with lower torque and associated wear. The trade-off of additional moving components is one that would be acceptable in a very high-volume processing plant in order to gain the reliability and durability.

Prior to the development of the system in Figure 10, several iterations were made with the basic chopping mechanisms. The initial trials were to evaluate a “pizza-cutter” style system that was nicknamed the SWORD – spinning wheel of rotating death, Figure 11. This type of system was very hard to stabilize with the edge-trim as the thermal mass was low and the heat transfer was quite high. Even at low temperatures the higher content of epoxies in the edge-trim led to gumming and issues in feeding and cutting the materials. We found it could work adequately with a low-tack, snap-cure resin system on standard modulus fibers and this provided us with decent quantities of chop feedstock to begin the molding trial work.

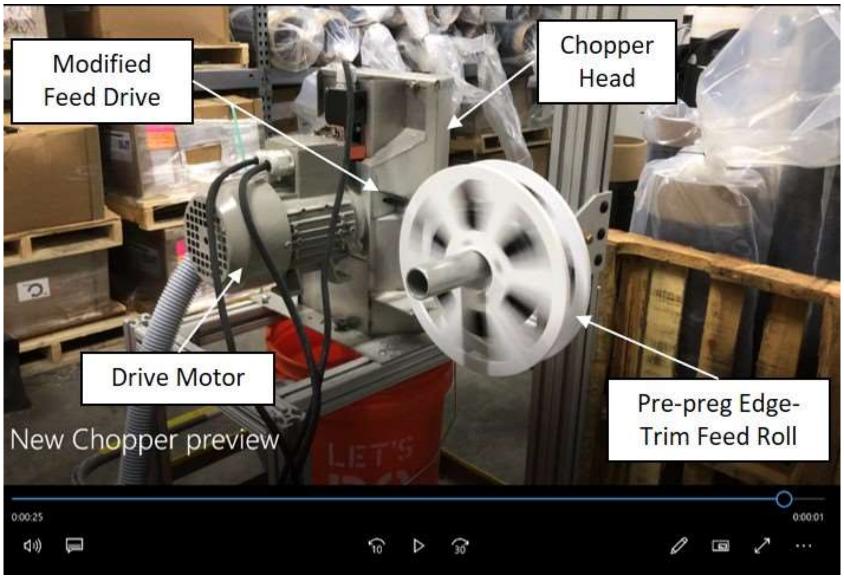

Figure 10 Basic Chopper System Undergoing Shake-down Trials

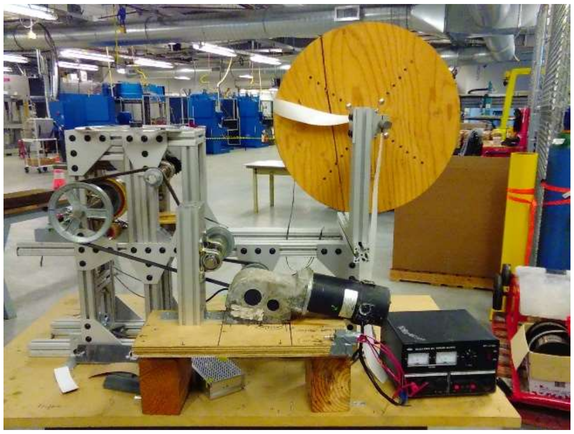

Figure 11 SWORD Initial Development System

The system was used in application trials for an L-angle bracket, Figure 12, that enabled feedback on the moldability and chip aspect ratio effects, and also identified surface finish impacts from various fiber to resin content trials.

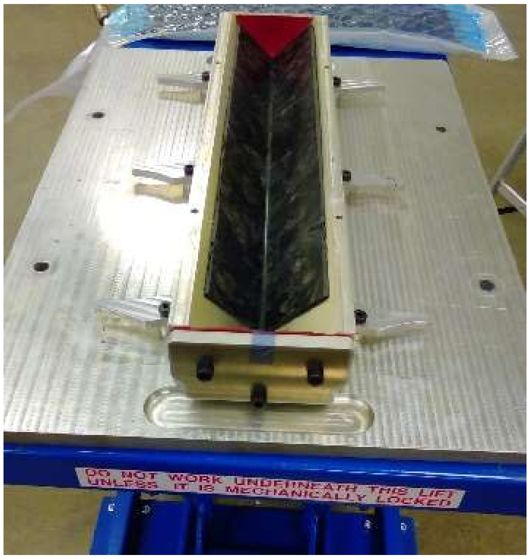

Figure 12 L-Angle Bracket Compression Molded in Aluminum Tooling at 190 C

Based on the information learned from initial process trials, two further systems were investigated, a rotary chopper, Figure 13, and a guillotine chopper, Figure 14. Both systems are designed for high-volume materials processing. The rotary chopper system is developed for extremely rapid materials throughput, and comes from the label-application industry where it is used for volume reduction of the backing films and label cutouts once the labels are applied to product. The rotary chopper we procured was deemed to be not as useful for the pre-preg operations as heat build-up inside the chamber was excessive, and difficult to manage if any loose fiber or strands entered the chambers. The rotary system was integrated into the backing paper take-off system and performed excellently in this role.

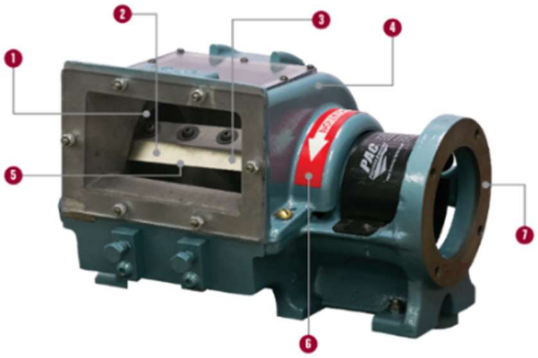

Figure 13 Rotary Chopper Showing Feed Chamber Entrance

The guillotine chopper, by AZCO Corp shown in Figure 14 was also procured and utilized a blade on shear-edge approach for its cutting mechanism. The initial system was quite sloppy with up to 0.1 mm gap deviation along the blade-to-anvil contact. It is designed for paper cutting with a different fiber cut mechanism than we required, and a major effort was undertaken on blade design and development. The blade to shear guide design was absolutely critical, and the CRTC ended up having a custom design blade fabricated from solid carbide materials. Several delays occurred throughout this process as North

American sources of the solid carbide blades proved inadequate and we sourced the blades eventually from Europe. The cutting was decent with slower feeds and very sharp blades, and we achieved near 0.5 kg/minute processing rates based on longer cuts of feedstock. The blade holding system, the guide (anvil) adjustment mechanism, and the shear contact adjustments all needed to be re-designed, modified and customized to work with the aerospace scrap materials effectively. As it provided the cleanest and most consistent chopping, it was decided to work with this system as we developed the balance of plant and as we searched for a hybrid system that could become more robust in nature than this one.

Figure 14 AZCO Guillotine Chopping System

The CRTC implemented this system on a moving sheet belt with vacuum draw underneath where a pre-form mold could be used to create an in-line pre-form suitable for subsequent molding. The backing paper takeoff was initially not added in the system and can be seen in Figure 15 to the side of the unit. However, it was fully integrated in later versions of the system. The idea was to use multiple parallel guillotine choppers to improve throughput rate and 150 mm wide cutting sections were selected as a good balance of cost and performance. It was immediately noticed that the high-speed steel blades dulled very quickly – within minutes of starting to cut, that the contact inconsistency of the blade to anvil created highly variable cutting, and the set-up, adjustments, and mechanicals were sub-par. These design deficiencies were corrected with much effort and we were able to greatly improve the chopping efficiency.

Two IACMI summer interns, alongside the project engineers, were used to develop controls and logic. The feed, cutting, and belt speeds were all integrated through an in-house built Arduino controller to enable various thickness and orientation preforms to be developed. Higher torque motors, colder localized chillers, and new carbide blades and guides were developed during this process. The unit was able to create and prepare several types of preforms, including ones that were used to fabricate very long reinforcements for structural applications form the scrap. Adjustability of the cut was excellent and the CRTC ran 1.0 mm to 3.0 m length prepreg strips off the machine with few issues. Variability in width from 3 mm to 125 mm chop was cut successfully albeit at lower rates than we hoped. The system showed significant promise to achieve increased rates with added attention to machine design details. The CRTC also developed an internally manufactured slitter, see Figure 16, to run in-line with this machine to enable continuous feed of a large supply of slit-tape scrap we received from the aerospace OEM.

Figure 15 Guillotine Chopper Mounted to Preform Draw Belt

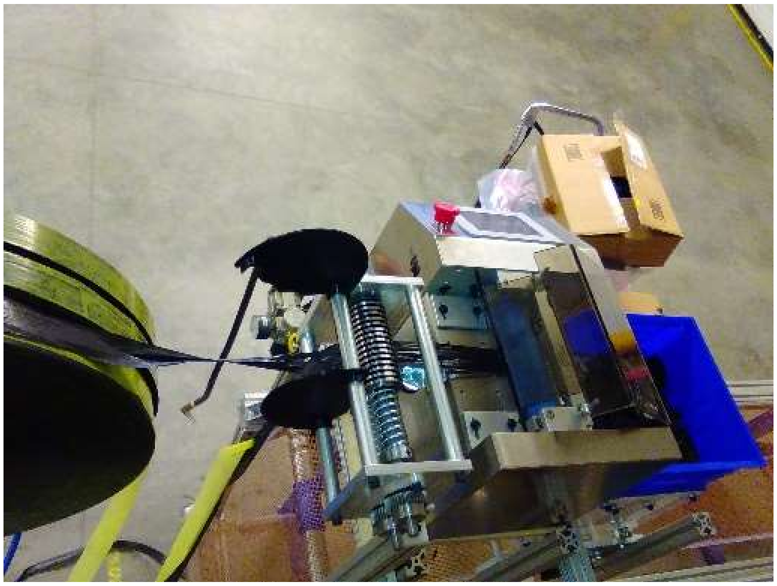

Figure 16 In-line Slitter with Multi-Tow Mounted Directly to Guillotine Chopper

During this portion of the development process, the team was working on molding trials in parallel with the creation of the feedstock. A series of customized steel and aluminum flat plate molds with variable cavity dimensions was created to allow compression molding trials to be rapidly performed. Through addressing chip size, resin content, orientation, and packing, the CRTC was able to make excellent quality panels that could be used for manufacturing coupons for structural testing. These panels were also done in conjunction with the providers of the scrap materials and they were involved in hands-on process development and investigation at the CRTC's facility. The flat plate molding trials provided data to enable us to move to shaped components as noted above, with a high degree of confidence in the performance and quality results. These data are proprietary but in a follow-on project in partnership with University of Washington, methodologies for predicting performance and optimizing discontinuous pre-preg molding will be carried out and these results published.

The next stage in the development process focused on the need to increase robustness of the system. A company called ChopCot of the Netherlands came across our radar screen that had a high-volume dry fiber cutting system with several of the attributes we desired already in place. Their system both bends and slices the fiber, so essentially is a hybrid rotary/guillotine system. The approach in their design is to impart some strain to the fiber prior to blade contact which is something we recognized for our needs early on. However, to achieve their performance it was necessary to have a sharp angle feed-in, and so we contacted ChopCot to run some trials for us on frozen feed pre-preg. With some success, it was decided to partner with ChopCot to purchase a system with feed modification, provide feedback on our design ideas, and develop some of the features mandatory to work with the aerospace pre-preg. The modifications proved successful and a significant improvement was seen from the Gen 1 model. The Gen 2 model we then procured was very successful and the CRTC feels this can be the basis for moving forward to a Phase 2 fully commercialized design. The Gen 2 design is the unit illustrated in Figure 17, and the original design with the sharp-angle feed is shown in Figure 18..

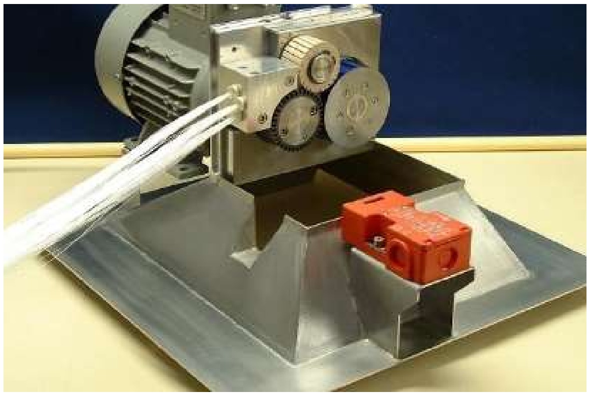

Figure 17 ChopCot Gen 1 Machine and Cutter System

Figure 19 Cutting Internals

5. BENEFITS ASSESSMENT

The scale of the opportunity is such that this technology could impact not only the recycle/repurpose of scrap pre-preg, but also enter into high-volume new production systems. It is estimated[9] that about 15% scrap would be generated during automotive production operations of carbon-epoxy components utilizing pre-preg for a large SUV roof (plus closures) structure, and availability of the chopping and compression molding technology could return that 15% back into integrated reinforcement products in the roof production line thus reducing costs substantially, eliminating a factory waste stream, and improving the utilization of a very limited source of raw carbon fiber material. Using those numbers, a carbon-fiber-intensive vehicle with a body structure weight of approximately 190kg[10], produced at 100,000 vehicles per year would require approximately 2,850 tonnes/year less carbon-epoxy feedstock utilizing full internal recycling, amounting to somewhere in the neighborhood of $31.35 million in avoided materials purchase costs. This equates to an approximately 8% savings from the typical materials input costs for the overall vehicle body, a not insignificant cost factor for the automakers.

The potential energy savings on the above application would amount to approximately 275,000

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[9] Private communication regarding automotive OEM body closure project.

[10] Design and manufacture of an affordable advanced-composite automotive body structure; Cramer D. and Taggart, D., EVS-19, 2002

MWh/year through avoided embodied energy from not using virgin pre-preg[11] when coupled with the avoided transportation and handling/storage energy associated with internal recycling. Similarly, other high-volume production applications would have direct and significant manufacturing cost and avoided energy benefits, provided the chopped, recycled materials can be used internally and captured within serial production. With external usage of the scrap material (similar to what CRTC practices for the aerospace industry suppliers), there is a more complex relationship of energy benefit and cost savings. Embodied energy production of pre-preg carbon fiber materials is between 420 and 460 MJ/Kg[12] for virgin materials, however CRTC is not typically utilizing the carbon-epoxy pre-pregs in applications that are directly off-setting virgin fiber choices, but rather in competition with wood and steel/aluminum products where carbon fiber has not previously been used. The net benefit to utilizing these materials is more of a land-fill avoidance and new application stimulation. Should CRTC use its product as a direct offset for virgin fiber materials, there would be about 95% reduction in embodied energy. Achieving full landfill avoidance of aerospace pre-preg in Washington State would result in a net societal energy benefit of approximately 50,000 MWh/yr, not counting the energy savings from use of the materials in lightweight mobile applications having ongoing in-service energy benefits.

CRTC is investigating the use of chopped recycled carbon pre-preg for structural building applications, Figure 19, and in this case the potential net benefit is extremely large. The applications in upper storeys of high-rise sky-scraper buildings reduces weight significantly even accounting for the added fire protection necessary. This weight reduction cascades into reduction of the mass of steel and concrete all throughout the balance of the building and into foundation mass reduction. CRTC is currently working with architects on applications and embodied energy benefits and sees the value potential across several areas of future building opportunities. At this time, carbon fiber is a very long way from being produced in volumes that can meet construction industry demands, so this benefit is one that will only develop after a significant time-frame and a significant investment in RD&D and carbon fiber production capacity. Architects, developers, and building owners are beginning to recognize and evaluate the overall energy footprint of their offerings, including embodied energy, especially as higher and higher efficiencies are realized in building operation, since built systems now shifts to become the primary metric for building energy usage.

Figure 20 Scrap Carbon Fiber-Epoxy Components for Infrastructure

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[11] Song et. al. 2009

[12] Ashby, M. - Materials and the Environment: Eco-informed Material Choice, 2012

6. COMMERCIALIZATION

The initial devices were developed internally specifically to provide feedstock for the various compression molding products that the CRTC manufactures from recovered scrap aerospace pre-preg. The primary market for chopping pre-preg in the near-term that would require a fully developed commercial machine are the automotive composites programs using pre-preg such as the IACMI supported DowAksa-Ford project that used the Dow non-tack resin system. Other areas where this will develop utility for commercial customers are in recycle research, internal re-purposing of tow-pregs by aerospace and sporting goods providers, and new product developers who wish to use recycled materials prior to engaging in full commercial deployment.

The CRTC has entered into discussions with above entities, and is looking at the requirements and whether a general-purpose machine is useful in addressing their needs, or whether these must be purpose-built for the specific application and materials feed-stream. Initial results indicate that each system is different enough in requirements that although a general starting chopping machine can form the basis of the system, the overall individual systems must be customized based on the input and output requirements. As of January 2020, one of the chopper systems was in development for a customer planning to provide pre-preg carbon fiber automotive materials.

Commercial usage of the chopped output at CRTC is underway, with chopped scrap pre-preg being generated to use in the brackets and fixtures of our bench product. The materials are subsequently compression molded and a major part of the cost-share development effort undertaken was to in fact define the limitations and requirements of the chop format for differing molding requirements (thickness, surface quality and finish, paintability, molding times, age of the feedstock, and molding parameters.)

It was estimated early on in the project that development of a full-scale commercial machine would be an approximately $1.5 million effort, given that the resultant machine would be required to handle continuous operation (3-shifts, 350 days/year), and would require very robust internal systems and controls. There is still fairly limited uptake of carbon fiber pre-preg in the automotive world, and these existing production systems are not well suited to the current pre-preg materials that CRTC works with from aerospace production. On-going discussion will hopefully lead to creation of a chopping system that can create the primary feedstock for a highly complex molding preform approach, as the sheet-goods approach with relatively constant thickness feed can be met with existing commercial products that we are not trying to compete with. The CRTC is evaluating other methods for funding a more highly developed and robust commercial chopping machine, however in the interim we have moved forward with procurement of additional cutting heads and feed stations to internally keep up with our demand for chop from edge-trim.

7. ACCOMPLISHMENTS

An advanced chopping system as shown in Figure 20, was developed after multiple trials that could successfully convert both slit roll scrap as well as edge trim waste from carbon fiber/epoxy pre-preg manufacturing directly into usable pre-forms for compression molding. Several components were made, including: flat panels; developing carbon fiber components at near-net shapes for machining; CRTC internal components for the legs and brackets used in recycled carbon fiber benches and the like.

Figure 20 Test Machine in Early Phases of Development

Approximately 500 panels were made over the project period which included flat and shaped in a range of dimensions and curvatures. The project additionally supported aerospace OEM and carbon fiber supplier joint RD&D activity carried out at the CRTC facilities.

Vanderbilt University developed a non-contact measuring system shown in Figure 21, to determine and provide feedback for location and size of defects to enable an automated, in-line bulk preform repair system to operate via machine vision which proved quite effective in defining and locating defects of the size and quantity necessary to fabricate a viable preform.

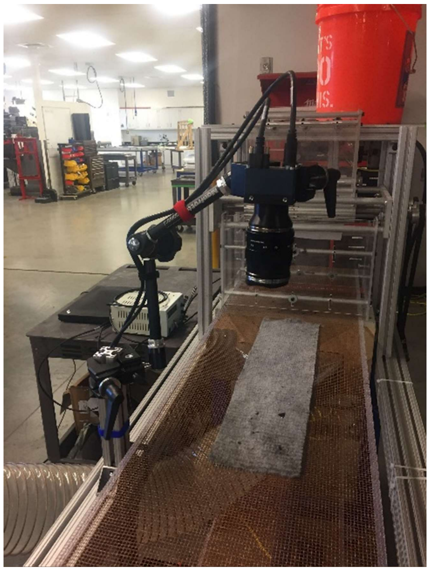

Figure 21 In-Line Non-Contact Chip Coverage Measurement

CRTC used the systems to chop and prepare materials from "fresh" scrap with a high degree of room temperature tack all the way to running very aged materials that had no tackiness at all at room temperature. Slitter systems were developed to manage the incoming feedstock as this varied from 3 mm to over 150 mm in width.

Paper backing take-off was developed along with a parallel chopper to reduce the bulk of the waste release paper and to direct the paper over to a separate collection area where it could be compacted for disposal.

Several engineering co-op students (3rd and 4th year), Figure 22, worked on the project during Summer and Fall sessions as part of their IACMI supported internships, and they were paired with CRTC engineers for development of aspects of the machine including automation, process control, feed systems, and mechatronics.

Figure 22. IACMI Interns Installing Control Systems

8. CONCLUSIONS

A successful phase 1 project was undertaken that developed chopping of scrap pre-preg coming from several different feedstock streams but with a common aerospace grade fiber and resin system. Added trials on automotive carbon fiber pre-preg from other IACMI projects that had different fiber and resin systems showed great promise and CRTC is looking forward to opportunities for evaluating fabrication of chopping systems for these under future programs. The CRTC concentrated on chopping with a goal of direct-to-preform output rather than looking to create roll or sheet goods, and this approach provided significant value for new and existing applications.

The most important lesson learned on the project was the recognition of the difficulty and work level necessary to overcome some of the issues seen with such a variable and inconsistent feedstock. Early trials on a narrower band of samples of scrap materials led to thinking the cutting section was going to be manageable in a shorter time-frame and the bulk of the unit development would be modifying and adapting the cutting mechanisms as we learned how to feed material variations to the cutting system. With experience it was determined that the industry really did not have a baseline cutting system that would work across the many types of inputs we needed, and much time was then spent on the physical cutting mechanism and not leaving enough time and resources for addressing balance of plant systems.

A successful system was developed that could re-purpose scrap pre-preg based on an aerospace grade intermediate modulus fiber and a highly toughened resin system with a resin content that varied from around 37% to well over 50%. Guillotine based cutting proved the most effective but not the fastest, and a modified hybrid guillotine plus rotary cutting system appears to be the best route forward. Looking at the future requirements of the high-volume carbon fiber industry applications, especially for automotive and consumer goods and eventually construction and infrastructure, the technology will be a very necessary part of the automated processing needed to keep production costs at optimum. The rates of materials handling and throughput mandate that the scrap recovery, transport, chopping and preform preparation be fully automated. This will require a fully integrated initial design where the recycle may well be one of the most critical parts of the process. In higher volume runs made with the systems, it may well be necessary to design for scrap recovery which is very different than designing for optimum value of only the work-in-progress virgin pre-preg. We noted in several instances that having even a slightly lower utilization of the primary pre-preg provided scrap with significantly higher value and ease of recovery by moving the scrap from being un-recoverable to being useful.

9. RECOMMENDATIONS

1. It is recommended that a team that includes two fiber/pre-preg suppliers, IACMI/ORNL, and CRTC take the existing developmental Phase 1 system and move the technology forward with an eye towards an integrated virgin/recycle component development program. Such a program would involve a process design for the approximately 85% virgin fiber/15% recycle fiber and look at this as an integrated platform for a zero-waste pre-preg to part facility. The pre-preg would be created in-line with the other systems, and all scrap from front to back door should be re-usable. Processes can be optimized around total part cost, rather than solely maximizing use of the main virgin feedstock, thus optimizing production cost for high-volume automotive components. The systems would need resources to demonstrate both operations and robustness, and would enable the Phase 1 chopping system to be moved into a commercial system with very specific targets and mandates while integrated with a full production line.

   This is of course a major undertaking and requires partnership across competing companies. Benefits include: a) provision of automotive OEM supply chain certainty; b) shared risk in scaling to capacity; and c) the OEMs will see this as a step towards their preferred method of operating with minimal platform risk. It would resolve many of the issues that have hindered individual carbon fiber suppliers (even in direct partnerships with OEMs) from getting to market.

2. It is also recommended that the CRTC approach of direct-to-preform fiber chopping be expanded to automated pre-forming into compression molding (similar in intent to but obviously with significant differences than the original Automotive Composites Consortium’s Owens Corning P4 systems.) Combined continuous fiber placement and chopped fiber preform molding should be an end-goal of such a program.