Reuse and Upcycling of Aerospace Prepreg Scrap and Waste

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Recently, there has been a tremendous uptick in worldwide research on reclaiming high performance fibers, particularly aerospace-grade carbon fiber from end-of-life cured thermoset composites. Fiber reclamation remains the main focus of such composite recycling efforts. Recycling efforts have even been launched as full-scale commercial operations in some countries, notably Materials Innovation Technologies and Adherent Technologies in the US and ELG Carbon Fiber in the UK. While it should be apparent that the composites recycling industry would be widespread, have a strong foothold, and be commercially profitable because of the tremendous increase in usage and projected demand for carbon fiber across several industries such as aerospace (high volume, low production rate, long service life) and automotive (high volume; high production rate; medium service life), the reality is distinctly different. While European Union legislation appears to be the driving force behind accelerated composites recycling efforts in Europe, the US does not currently have such regulations in place. In the US, it continues to be more economically practical to dispose of cured composite waste in landfills. Nevertheless, legislation focused on recycling can provide only the "push" - the "pull" must arise from market demand for reclaimed carbon fiber and there currently doesn't appear to be a sufficiently large end market to compel users to recycle. While the argument can be made from an environmental and corporate social responsibility perspective, such arguments ultimately and inevitably succumb to market economics. There are also technological challenges

that must be resolved, primarily the disordered aggregate form of reclaimed carbon fiber that requires non-trivial additional processing before it can be further processed into saleable and competitive products. The targeted development of a consumer base and end-market for intermediate and end-products based on reclaimed carbon fiber could help spur recycling efforts and drive home the argument from a commercial viability perspective; however, such development efforts have not received much attention or traction.

Unfortunately, the same holds true with regard to reusing or upcycling uncured scrap carbon fiber prepreg that is generated during the manufacturing process. This scrap also makes its way to landfills because it is economically viable to do so and an established end-market and consumer base for scrap prepreg based products does not currently exist. Uncured prepreg scrap typically arises from two sources (see Figure 1). The first source is primarily generated during ply cutting operations in the form of off-cuts, skeletons, trim waste, and end-of -roll waste. Such scrap is mostly comprised of randomly sized and shaped pieces. The second source is out-of-spec material such as that beyond its out-life or freezer life and is often in the form of unopened or partially used prepreg rolls. It is cost prohibitive in the aerospace industry to re-certify such out-of-spec material and it is therefore disposed in landfills, donated to research universities, or consumed in-house for R&D purposes. While accurate data is not available, the volume of cured composites waste greatly outweighs the volume of uncured scrap prepreg by at least an order of magnitude and one would therefore expect recycling efforts to take precedence over reuse efforts. However, there is one important distinction. The issue of “recycling” is primarily targeted at end-of-life composites which for an aircraft could mean well over 30 years and for an automobile around 10 years, barring unforeseen events such as catastrophic damage through crash, whereas the issue of “reuse” must be tackled “here-and-now” as

scrap is continuously generated during the manufacturing process. The volume of scrap prepreg is expected to grow rapidly in the near future because of the huge increase in demand for carbon fiber prepreg, especially from the aerospace industry with the introduction of new composites-intensive aircraft such as the Boeing 787 and Airbus A380 and future models such as the 777X and A350. According to their respective market outlooks, both Boeing (source: Current Market Outlook 2014-2033) and Airbus (source: Future Journeys 2013-2032) expect the world aircraft fleet to double by 2030, with at least 27K-34K new airplanes valued between USD 3.5-4 trillion. Note that uncured scrap prepreg must first be cured before it is disposed of in landfills because of the potential for toxic chemicals from the uncured resin to leach into the soil and ground water. Therefore, the absence of immediate reuse efforts will only serve to delay the problem and add the volume of uncured scrap prepreg on to the total volume of cured composite waste that will eventually need to be recycled. However, there are other arguments to drive the need for reuse and upcycling efforts, as described next.

Figure 1: Exemplary uncured scrap prepreg – ply cutter scrap and out-timed rolls

1. The Need for Reuse

Reuse efforts are particularly appealing because both the carbon fiber and resin within the scrap prepreg are usable, high-value components and do not require destructive separation. The carbon fiber also continues to remain in its original continuous filament form whether as a unidirectional tape or woven fabric. The cost of uncured resin is not inconsequential relative to the cost of aerospace grade virgin carbon fiber. Consider a generic aerospace carbon fiber prepreg of 250 gsm (1 lb ≈ 20 sq.ft) and cost $45/lb. Typical ply cutter scrap, depending on the complexity of the shapes being cut out from the roll and the efficiency of the nesting routines can range anywhere from 20% to 50%.

Considering a conservative 20% scrap rate results in ply cutter scrap of 0.2 lb (or ~4 sq.ft) per pound of virgin prepreg material, with an associated original material cost of $9. Typical waste disposal fees can range from $0.75 to $3 per pound and increases exponentially if the waste is considered hazardous. Considering waste disposal fees of $1 per pound results in a total disposal cost of $0.2 per pound of virgin prepreg material. Clearly waste disposal fees alone are not going to affect the bottom line of large companies, although it constitutes a loss of revenue no matter how small. However, the introduction of legislation that limits the extent of landfilling and mandates minimum levels of reuse and recycling, and imposes strict penalties, fines, and fees for non-compliance can quickly escalate the cost to company associated with waste disposal, thereby driving the economic argument for reusing or upcycling scrap. Clearly, considerable savings in material cost can be realized by minimizing the amount of scrap generated in the first place, or by focusing on "reduce" in the "reduce-reuse-recycle" mantra. However this may not always be possible.

Continuing with the previous example, obviously the material cost of the scrap prepreg is no longer $9, because it is no longer in the form of a continuous prepreg ply but rather an assortment of scrap pieces of random sizes and shapes or as a cut-out prepreg skeleton. Thus, there is an apparent material depreciation similar to the net value of an automobile the moment it is driven off the dealer lot. If this scrap prepreg is upcycled into commercial end-products, with value addition occurring at each stage of the upcycling supply chain through the incorporation of new technology and IP into the intermediate product form and the final end-product, then the scrap prepreg has some intrinsic value. If this value (resale rate per pound of scrap prepreg) exceeds current waste disposal fees, then the economic argument for reuse is apparent. This value is what companies can take advantage of to offset their original material costs, in addition to the amount saved on waste disposal fees and

potential non-compliance fines. Even if a company were to donate their prepreg scrap to an external party, there are still considerable savings to be realized. In turn, this creates an opportunity for new businesses to be created downstream from the major aerospace and composites industries that consume virgin prepreg, wherein these new entities consume the scrap prepreg and upcycle it into commercial end-products. This process may occur entirely within one new entity that converts the scrap prepreg into a usable intermediate form and immediately consumes that intermediate form, or as multiple entities. For example, the first entity in the supply chain may manufacture and distribute the intermediate form while the second entity consumes that intermediate form and manufactures the end-product. For these downstream entities to be profitable, value addition must occur at each stage of the upcycling and the margins must be sufficient. For this reason, it is important to identify high volume applications with appreciable margins over applications such as fillers for concrete or energy recovery that do not have any appreciable value addition.

The motive force for the incorporation of new companies to handle the upcycling of scrap prepreg arises from three assumptions (1) that the major players in the aerospace and composites industries do not want to be distracted from their core competency (2) liability concerns, wherein liability is minimized through the incorporation of new entities, and (3) the consumers of virgin prepreg material cannot always consume their own scrap. For example, it is not feasible to reuse scrap aerospace prepreg in primary or critical aerospace structures, as they won't meet the performance requirements or pass certification. Their incorporation in secondary or tertiary aerospace structures is as yet unclear given the potential lack of consistency in the feedstock material. In such cases, it is far more practical to find a completely different market segment to reuse the scrap aerospace prepreg, such as for sporting, recreation, and consumer goods. However, there are exceptions. For example,

it is entirely feasible for automotive composite scrap to be reused within the same automobile, and the BMW i3 model showcases one such innovative example.

There is a general consensus that it is only a matter of time before the US follows suit and incorporates legislation along the lines of the European Union that limits the extent of legal landfilling and mandates levels of reuse and recycling. Therefore, it may be advantageous for companies to quickly position themselves for looming environmental regulations and to avoid costly fines and penalties for non-compliance down the road. The lure of spurring job creation in today's depressed economy, particularly downstream manufacturing jobs, is another incentive for companies particularly if it results in additional incentives from the state and federal government. Finally, many companies want to be associated with the image of sustainability and being socially responsible in the public eye, or may want to obtain certifications such as ISO 14001, which is another reason for them to support, drive, and incorporate practices such as reduce, reuse, and recycling.

2. From Scrap Prepreg to Intermediate Product Forms

Figure 2 displays the five intermediate product forms that we envision arising from scrap prepreg, four of which are uncured and one fully cured form. They are, in order of increasing levels of additionally required processing: Resold Prepreg Roll Form (RPRF), Regular Cutout Form (RCF), Loose Chip Form (LCF), Reused Scrap Roll Form (RSRF), and Composite Construction Material (CCMat™). RPRF is comprised of unopened or partially opened prepreg rolls that are no longer within specification. Such material is typically used for in-house R&D work, donated to research

universities, or sent to landfills. For all practical purposes, RPRF is equivalent to virgin prepreg; it cannot be used in primary aircraft structures because it is no longer within the required specification. RPRF requires little to no additional processing before sale. RCF involves identifying scrap pieces that are large enough from which to cut out regular shaped pieces of prepreg that can be used as-is in subsequent manufacturing with vacuum bagging, hot pressing, etc. Figure 2 indicates how such pieces can be cut out from scrap (see dashed red outlines). RCF can be produced using standard conveyorized ply cutting equipment in conjunction with machine vision or simply processed manually. The leftover scrap pieces at the end of this process can then be converted into LCF. Higher margins can likely be expected from the sale of the RPRF and RCF forms as they most preserve the original form of the prepreg material compared to the other intermediate product forms described next.

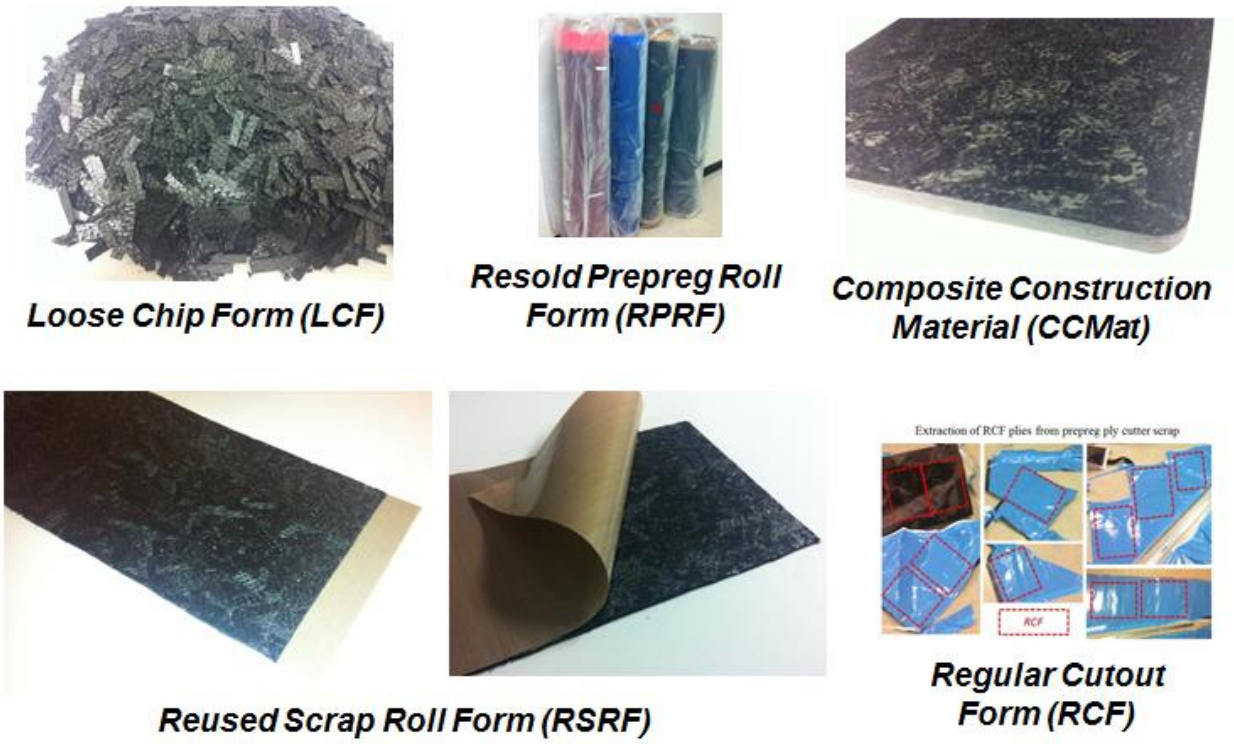


Figure 2: Intermediate product forms from scrap prepreg

The manufacture of LCF involves mechanically cutting down the scrap prepreg into rectangular shaped chips. In an automated process, the cut-outs must move along a conveyor belt through a two stage cutter, the first stage reducing the scrap pieces into a set of continuous lineal strips with constant width, with the second stage cutting the strips into chips of desired length. If the incoming scrap predominantly consists of extensively cut-out prepreg skeletons, another option is to use a die press to cut or stamp out the chips in a batch operation model. Manual labor or machine vision can be used to align the incoming scrap on the conveyor belt and align one of the fiber directions parallel to the cutting blades in order to maximize the fiber lengths in the final chips. While this is not terribly significant for woven fabric prepregs because of the bi-directional or orthogonal tows, this alignment step is important for unidirectional scrap prepreg. Also, the backing paper must be removed prior to cutting, which depending on the nature of the cut-outs, can be accomplished either manually or via an automated system comprising of suction cups and pressurized air nozzles to respectively hold the prepreg plies down while blowing off the backing paper. Figure 3 displays scrap chips cut from a 5HS woven fabric and a unidirectional carbon fiber/epoxy prepreg (Cytec CYCOM® 5320) with the arrows indicating fiber directions.

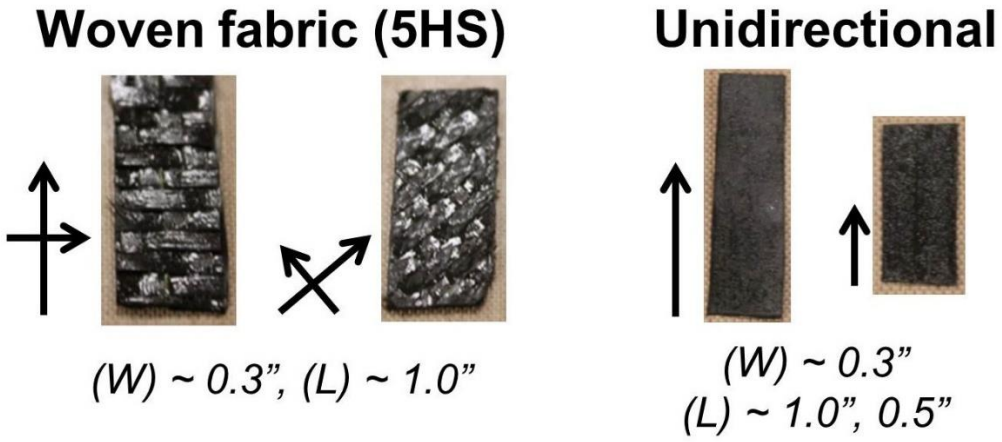


Figure 3: Individual scrap prepreg chips

RSRF is manufactured by compressing LCF at specific temperatures and pressures into a sheet form that is then packaged into a roll form with a wax backing paper and/or protective film much like a virgin prepreg roll. The applied temperature is just sufficient to cause low extents of resin flow required to bond the chips together, which is especially necessary when they have no tack. The applied high compaction pressures give RSRF a thin structure and a smooth surface. We envision four forms of the RSRF: general purpose roll, surfacing roll, hybrid roll, and a tooling roll. The general purpose roll is highly customizable in its composition (e.g. fiber bed architecture, resin system, chip shape and size) and structure (e.g. thickness, areal weight, distribution and orientation of chips) and can be tailored depending on the end application. The hybrid roll is a sandwich structure comprised of the general purpose roll at its core with skins comprised of either regular prepreg rolls (i.e. out-of-spec material) or large scrap pieces (e.g. RCF). Using out-of-spec rolls at the surface of the hybrid roll will keep overall material costs low, provide the same visual appearance and aesthetics that customers are accustomed to with regular prepreg composites, and have a cumulative effect on the mechanical performance (strength/stiffness). LCF and RSRF are better known as Infinipreg™; a name that derives from the "Infinite possibilities for scrap prepreg", a reference to the limitless potential end-products and applications for scrap prepreg.

3. Processing of Intermediate Scrap-Based Product Forms

The LCF form resembles a bulk molding compound (BMC) of which several commercial forms are available from companies such as TenCate and Hexcel in the form of chopped virgin unidirectional prepreg. LCF can be similarly compression molded into the final part. The RSRF form resembles a sheet molding compound (SMC) and can be processed by all the traditional routes used for virgin

prepreg such as autoclaving, vacuum bagging, hot pressing, and compression molding. However preferred processing routes for RSRF are through hot pressing and closed mold compression. Apart from being simple, rapid, and inexpensive, these two processing routes do not require consumables (sealant tape, breather, vacuum bags, et cetera) that would add to the overall waste stream. They also do not require lengthy room temperature vacuum holds or debulking cycles that add to the overall cycle times. Parts can be made continuously by placing the two caul/tool plates or closed mold fixture directly between the preheated platens of a hot press and removing them at the end of the dwell cycle without waiting for the part to cool. Another significant advantage of the RSRF form is the ability to use accelerated cure cycles which reduce the overall cycle times.

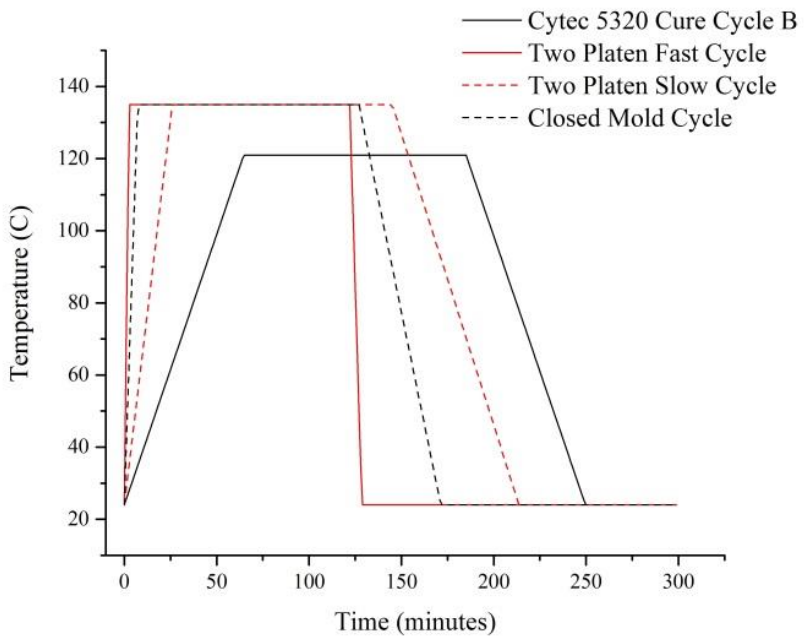
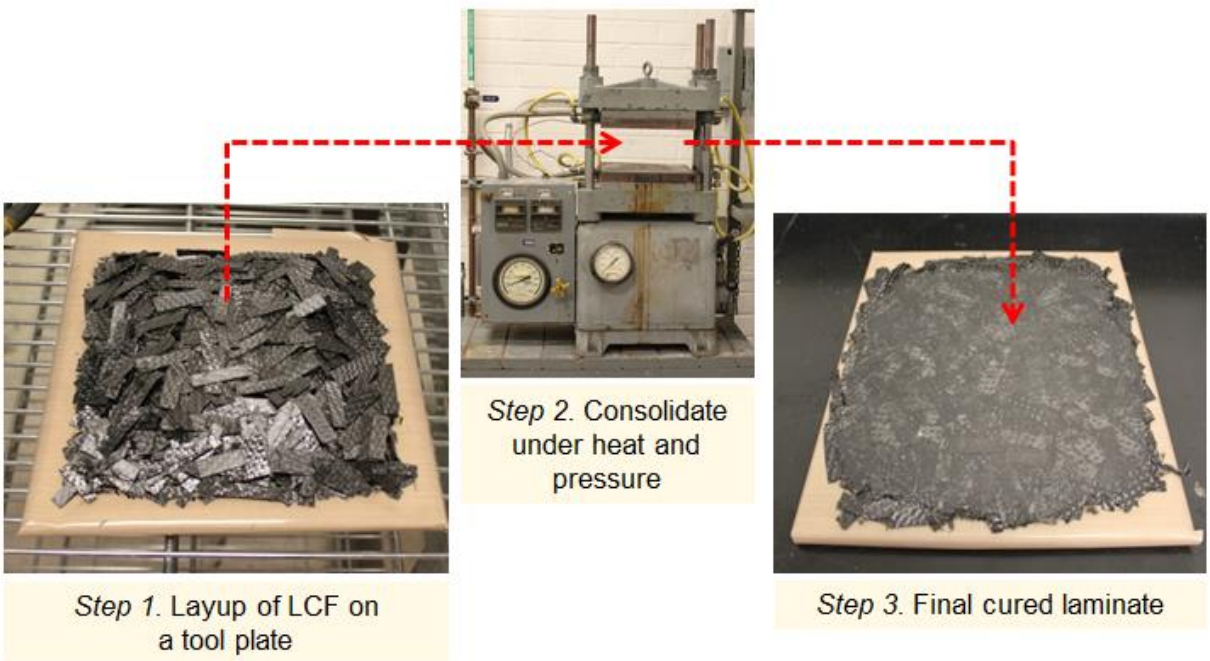


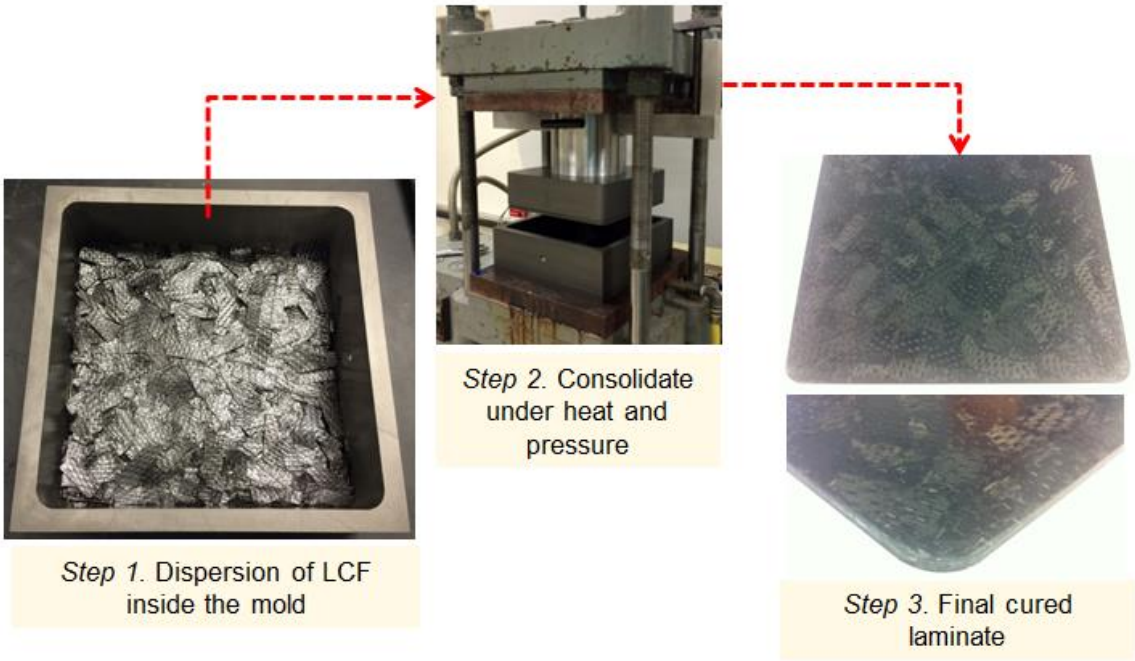
Figure 4: Cure cycles

For example, Figure 4 compares one of the manufacturer's recommended cure cycles for the CYCOM® 5320 prepreg system (1.5°C/min ramp up, 121°C dwell) along with the cure cycles we used when manufacturing 5320 prepreg scrap (5HS and UNI chips) based laminates in a hot press, where a 135°C dwell was used along with ramp up rates as high as ~40°C/min.

Figure 5 shows three potential manufacturing routes with LCF and RSRF. VBO-processed laminates produced with RSRF yield a breather-side finish similar to their virgin prepreg counterparts. The advantage of VBO processing using RSRF is that the part size is not limited by the size and capacity of the hot press, and a simple vacuum pump is sufficient to apply the compaction pressure (≤14.7 psi) regardless of the part size moreover, while large convection ovens are not cost prohibitive. The part can also be cured using simple thermal blankets or self-heated tool plates. The downside of using VBO and the corresponding reduced compaction pressure is that poorer compaction can result at sharp corners within the part, and in such cases, compression molding is preferable.



(a)



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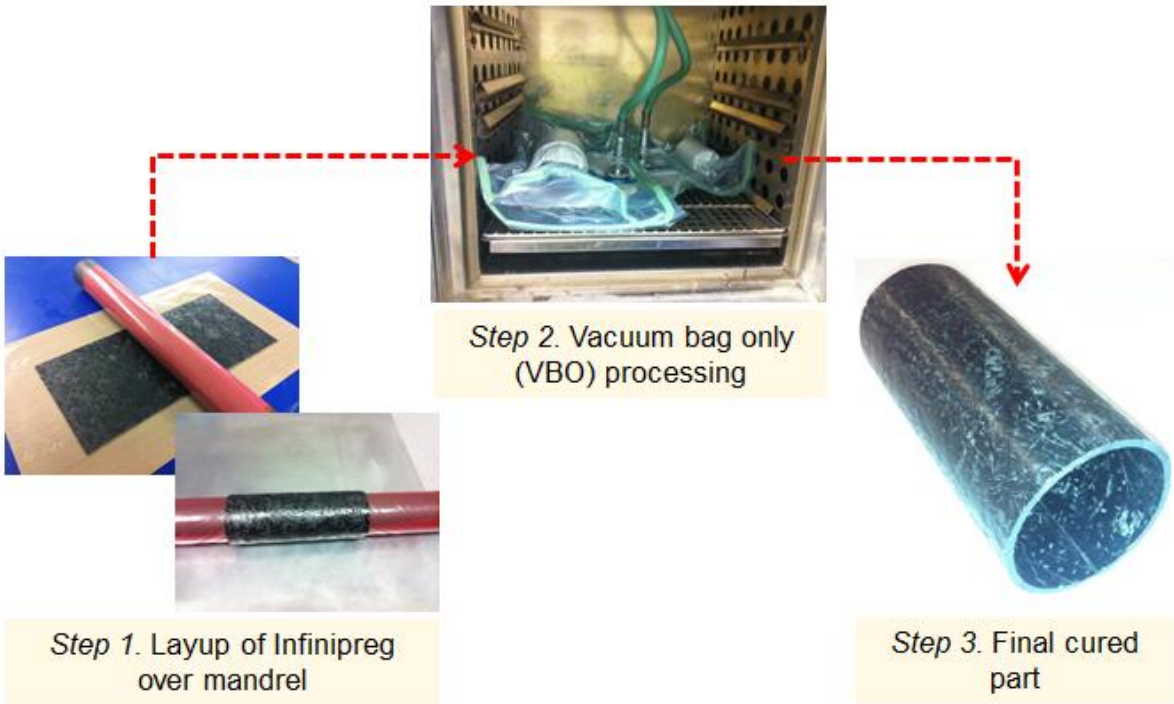


(c)

Figure 5: Exemplary manufacturing routes (a) open platen compression (b) closed mold compression (c) VBO processing

Blending glass and aramid fibers in varied proportions produced hybrid composite foams with significant improvements in modulus and strength over unreinforced foams, as shown in Table 1. The greatest improvements in modulus and strength were observed when glass and aramid fibers were added in the ratio of 3:1, respectively. This ratio resulted in a 126% increase in modulus and a three-fold increase in strength for the hybrid foam (glass: aramid, 3:1) relative to the unreinforced foam (for both axial and transverse directions). Fiber weight ratios of 1:1 and 1:3 (glass : aramid) yielded a nearly two-fold increase in modulus for both types of hybrid foams, and increases in strength of 250 and 230%, respectively. The results indicate significant increases in strength and modulus for the hybrid foam relative not only to unreinforced foams, but also to composite foams reinforced with only aramid fibers.

4. Technology Demonstrators and End-Products

We believe there are potentially hundreds of end-products that can be built partially or entirely from scrap thermoset prepreg. Carbon fiber composites are not just used for their lightweight properties and superior structural performance but also coveted for their distinctive visual appeal and therefore find dozens of aesthetics-based applications such as arm rests, cell phone cases, and cup holders which are non-structural, and customized home and office furniture which is structural in nature. Parts made from Infinipreg possess a unique and distinctive look of their own because of the random placement of chips on the surface that tends to reflect incident light differently and create a shimmering effect, which can therefore compete in the aesthetics-based product market. Preliminary studies have also established the good stiffness and strength retention properties of scrap prepreg chip based laminates thereby also opening up structural end-products to Infinipreg. We believe that

scrap prepreg based parts will be competitive for two reasons: (1) they can compete with some existing carbon fiber products because of the lower price points brought to bear by the much lower starting material costs (2) they can compete with other traditional materials in applications where carbon fiber was previously discounted for being cost prohibitive. Thus, Infinipreg can not only compete with but also open up new markets to carbon fiber composites. Figure 6 displays some of the major industries we have identified that would be highly amenable to scrap prepreg.

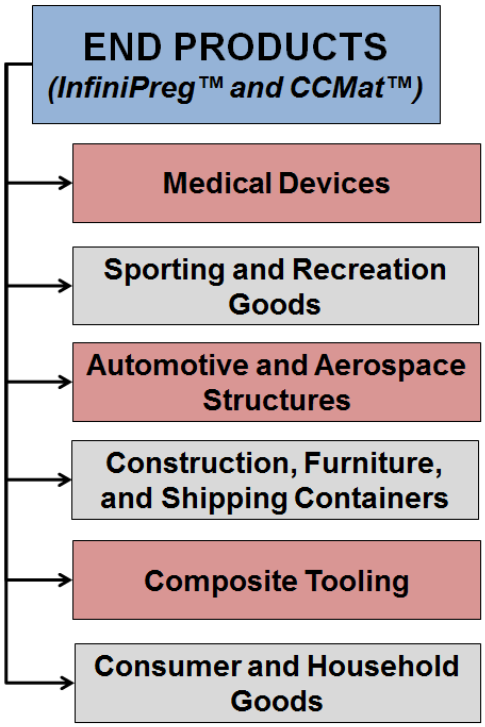


Figure 6: End product space for scrap prepreg

In the medical devices field, the radiolucent property of carbon fiber composites can be exploited to make hospital/ICU beds and structural casings for medical devices. We have also made a prosthetic running foot (Gazelle™) out of scrap CF/epoxy prepreg, see Figure 7a. Potential sporting and recreation goods include skateboards, snowboards, snow-sleds, go-karts, and kayaks. We have manufactured skateboards using only scrap CF/epoxy prepreg (Cobra-Z™) as well as a mix of scrap

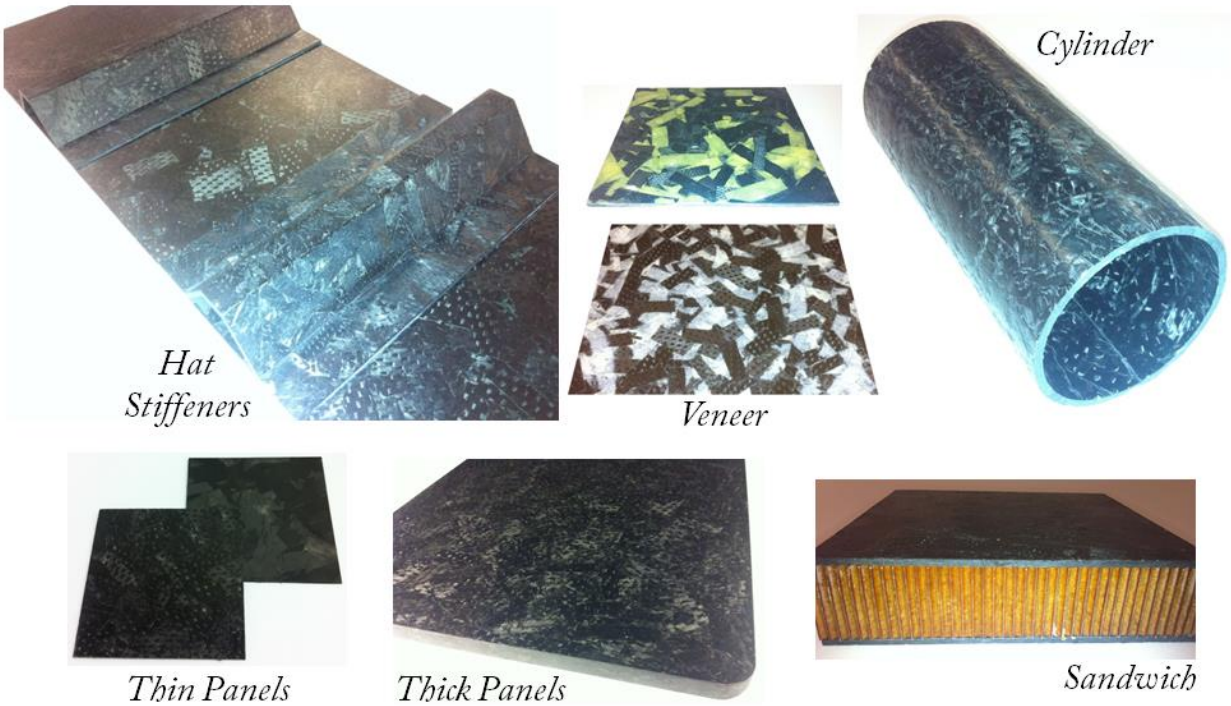
CF/epoxy and fiberglass/epoxy prepreg (Crazy Zebra™), see Figure 7b. Figure 7c displays several sub-structural or design elements that can be used in structural applications, such as thin and thick panels, hat stiffened panels, cylinders, sandwich structures with a honeycomb or foam core, and veneers. The black/yellow colored veneer shown in Figure 7c consists of scrap 5HS CF/epoxy prepreg chips + dry plain weave Kevlar fabric chips + custom formulated epoxy, just to illustrate how different fibers, architectures, and resins can be mixed together. Obviously, the use of scrap prepreg in aerospace and automotive applications must be restricted to non-critical components such as interiors and paneling.

We also see a large potential market for rail, truck and sea intermodal or freight containers and unit load devices used at airports. The potential weight savings over currently used materials such as weathering steel and aluminum could result in enormous fuel savings when transporting these shipping containers apart from the other obvious benefits of composite materials, such as good FST properties and resistance to corrosion and infestation. We also see applications of Infinipreg in low cost and potentially self-heated composite tooling for low volume and prototype jobs, where a skin of Infinipreg is supported by a carbon or polyurethane foam backing. Consumer and household goods could include cell phone cases, desktop computer cases, laptop and tablet covers, award plaques, cup holders, trays, and other such novelty items, see Figure 7d. Finally, the striking similarity between wood chip board and oriented strand board with scrap chip-based laminates leads to potential applications for CCMat as a construction material (e.g. flat stock and prefab), see Figure 7e.

Gazelle™ Prosthetic Foot

(a)

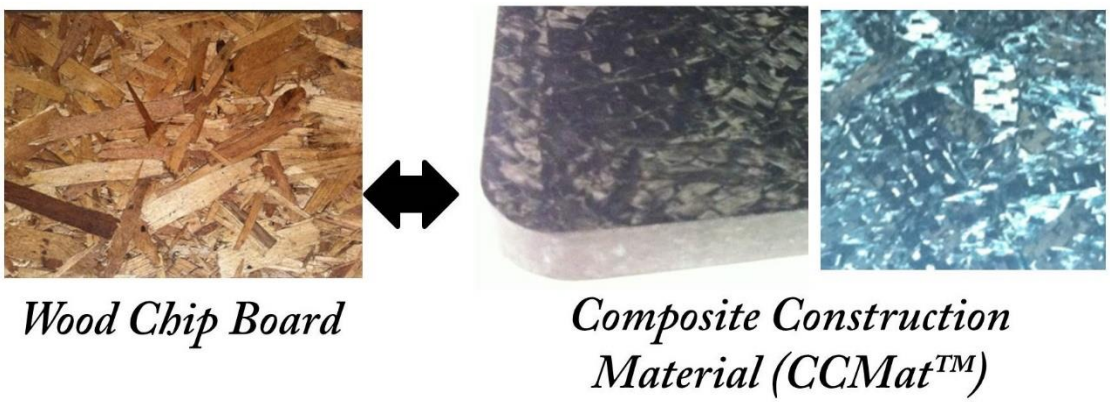
(b)


Hat
Stiffeners
Veneer
Cylinder
Thin Panels
Thick Panels
Sandwich

(c)


Infinipreg™
A product of Carbon-360
Dr. Gaurav Nilakantan
2014

(d)



(e)

Figure 7: Scrap prepreg based technology demonstrators and potential end-products, using Infinipreg and CCMat (a) Gazelle prosthetic foot (b) skateboards (c) design elements (d) novelty items (e) constructional material

5. Concluding Remarks

Whether driven by government regulations, corporate policy, or market economics, the 3 R's of Reduce-Reuse-Recycling represent the pillars of sustainability in the context of the global composites industry and the environment. Of the three, recycling has received perhaps the greatest attention both from academia and industry. However, active efforts to reduce and reuse waste lag considerably. With the ever increasing use of carbon fiber prepreg (thermoset) material across multiple industries, most notably commercial aerospace, the volume of uncured scrap prepreg will increase considerably in the future. The lack of any substantive previous reuse efforts for uncured scrap prepreg spurred us to address this issue directly to demonstrate a potentially cost-effective and feasible solution to responsibly manage the scrap prepreg stream. Ultimately, it is not just the basic technology "push" that is important to develop from an early stage, but also the end-market "pull". Our intent through our ongoing work at the University of Southern California is to steer attention to near-term reuse efforts on a large scale by demonstrating both the technical and economic feasibility

along with several potential end-products. We anticipate a significant first-mover advantage in this emerging market.

Further Information

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