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Thermoset composite recycling – Driving forces, development, and evolution of new opportunities

Michael Overcash[1], Janet Twomey[1], Eylem Asmatulu[2], Eric Vozzola[1] and Evan Griffing[1]

Abstract

Thermoset composites represent a substantial challenge for recycling, even as composite products increase in market interest. The concept of putting all future thermoset composite products into landfills over the next decades is unlikely to continue. This paper examines the three eras in the history of thermoset product recycling, the drivers for increased recycling, and possible future trends. Technology for managing thermoset composite products at end-of-life first focused on retrieving fiber and to a lesser extent resin. Then in a second era, research focused on better utilization of recovered fiber and finally the third era is now keeping more of the original resin–fiber structure to reuse these composites. Drivers are emerging to stimulate thermoset recycling, including States with success in recycling other challenging products (tires, carpets, automobile parts, etc.) setting policy and fees to encourage recycling. The evolution of heat recovery as a thermoset recycling option in Europe is another driver. Additionally, efforts at certification of recycled fiber quality may stimulate greater reuse.

Keywords

Thermoset composite, recycling, end-of-life, thermal recovery

Driving forces for thermoset composite product recycling

Substantial growth is creating diverse uses for thermoset (TS) composite products particularly in automotive and aviation sectors. These TS composite parts are typically long-lived and so the social pressure to recycle may continue to increase as the awareness of the impending product end-of-life (EOL) increases. Faced with effectively zero economically viable TS composite recycling, the current outcome in the U.S is landfilling. It is thus likely that State regulations (such as developed in California on other challenging materials) will move to encourage or mandate TS composite recycling without regard for economic viability. As an example, California took a previously non-recovered product (carpet) and levied a fee on all new carpet which would go to companies involved in the actual recycling of carpets. The carpet industry had begun to develop post-consumer recycling and so with some lead time was able to increase to a 15% recycle level.[1] Another example is new tire fees in North Carolina, where the advanced recycle fee goes to the recycling industry of this problematic product. Here, the recycling rate has climbed to about 30%.[2] The longer life of TS composite products will potentially slow this pressure, but the full impact and regulatory response are likely to be the same as seen for carpet, tires, and other product recycling challenges.

For automotive TS composite parts, the earlier success with metal automobile parts may also suggest a path forward for at least some fraction of composite parts. With pressure to increase the recycle rate on junk cars, the automobile industry realized that recovered parts from wrecked or EOL vehicles were in fact a valuable asset. Recovered parts reduced the automotive

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[1] Industrial and Manufacturing Engineering Department, Wichita State University, KS, USA
[2] Mechanical Engineering Department, Wichita State University, KS, USA

Corresponding author:
Michael Overcash, Wichita State University, 1845 N. Fairmounth, Wichita, KS67260-0124, USA.
Email: mrovercash@earthlink.net

company cost of manufacturing replacement parts for their service centers, particularly for very old models. Automobile companies then supported the development of the recycling infrastructure and a viable parts recovery system emerged. Thus, a synergy of business objectives occurred and a robust recycling approach has developed. TS composite parts could adopt this model to achieve a significant direct recycling rate for recovered parts, thus demonstrating their movement toward sustainability. This mutual interest concept with direct support of the TS composite product manufacturers could be extended to products not of viable resale value. The traditional recovery of fiber from TS products would then be stimulated to grow and reach a critical infrastructure level, with at least reduced cost.

The American Composites Manufacturing Association (ACMA) has a Green Composites Committee (GCC) that has begun some critical steps to encourage recycling. They identified the avoided cost of landfilling as a stimulus to aid in TS recycling. In addition, they have developed initial certification standards for unused creel glass fibers. Such standards assure potential users of fiber quality and stimulate potential reuse of glass and carbon fiber. This brought to light a very basic need for standards and methods to certify that the material being repurposed or recycled meets a standard based on known manufacturing or product history.[3]

Another long-term goal might be to examine in the U.S. what technologies qualify with the Federal government as TS recycling. An interesting difference in what qualifies as recycling is that in Europe, incineration (with or without heat recovery) is acceptable. This is not the case in the U.S. The input of composites (especially glass fiber composites) to cement kilns is considered by the European composites industry as the most sustainable solution for EOL of TS products.[4] The energy value was explored by Palmer et al.[5] and reported conventional sheet molding compound (SMC) provides about 7 MJ/kg SMC. The European goal is to avoid landfills for TS composite products. This is a reflection that no viable recycling technology is now available. In the U.S., the lack of realistic TS recovery technology may be sufficient justification for the Federal or State governments to designate thermal recovery as an acceptable recycling technology for TS products.

The significant pressures needed to avoid the landfilling of composites may lead to dedicated facilities that manage this unique class of materials. The economics of product fees, collection cost, etc. would have to be developed as a shared cost of manufacturers and the recycling industry, but this may be the least cost solution. In the case of tires, the designation of fuel value from recovery in North Carolina has led to an additional 54% of scrap tires not being landfilled at an overall cost in new tire fees of $17 million per year in 2014–2015.[2] This is a useful precedent for TS composite products, possibly in the automotive sector.

The breadth of potential material to be recycled that is derived from the TS composites industry is substantial. This creates diverse opportunities for sustainability improvement by manufacturers, suppliers, and potential uses of recycled materials. In response to this diversity of supply, composite recycling technologies are evolving. TS are a much larger technology challenge for recycling and have had less commercial success than thermoplastics. This article reviews the status of TS composite industry recycling and highlights emerging trends.

Across the TS composite industry, the materials available for potential reuse cover a wide spectrum. Figure 1 uses the full TS composite life cycle profile to highlight the sources of materials for recycling, all

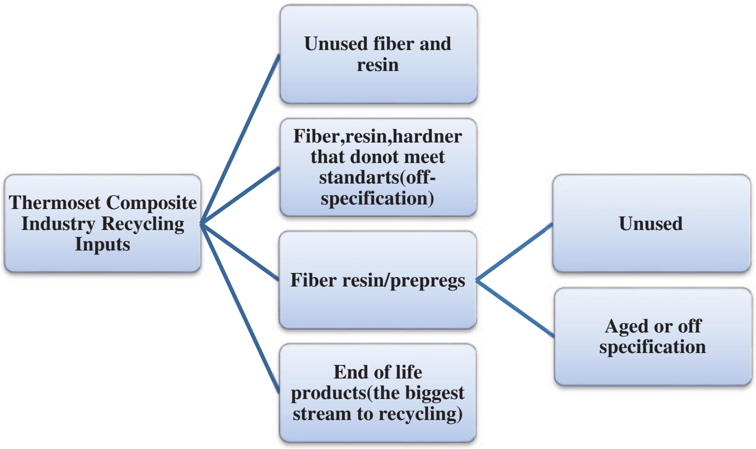

Figure 1. The recycling technology box for thermoset composites.

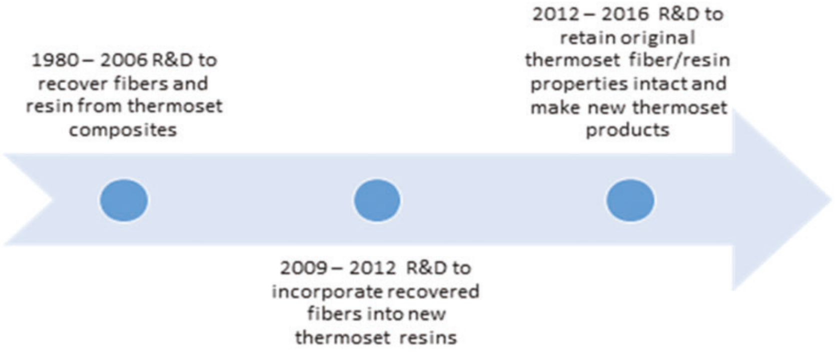

Figure 2. Timeline for developments in thermoset (TS) composite recycling as measured by journal publication dates.

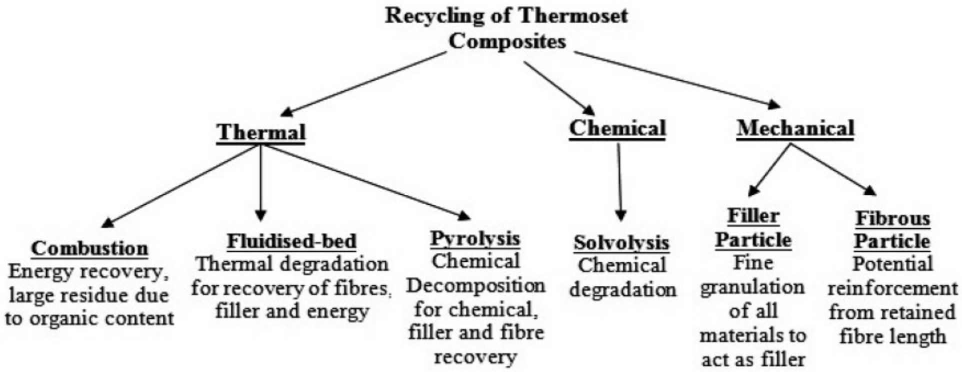

Figure 3. Recycling of thermoset (TS) composites using thermal, chemical, and mechanical methods.[5]

of which contribute to the sustainability profile of the composite industry. Prepregs have a limited shelf life that can be changed based on the storage conditions. It can be stored at room temperature for a shorter time and at freezing temperature for a longer time. Thus, prepreg composites easily get aged at higher temperature depending on the selected prepreg types. Some of the purchased prepregs might be far from the required specifications, so those can be considered for the secondary use for different applications. The source of unused prepregs can also be cut-offs during the manufacturing process or expired pieces due to the limited shelf life. The evolution of research and development to foster TS recycling as measured by journal publication dates has occurred in three main stages (Figure 2).

Evolution of TS composite recycling – Early approaches for recovery

TS composite recycling technologies were first developed to recover composite constituents of potential value for EOL products (Figure 2). This first TS recycling period (1980 to mid-2000) basically focused on waste-to-product transformations where the original product qualities were lost and recovery of TS inputs was the goal (Figure 2). The challenges include complex product shapes and sizes, mixtures of non-composite materials, and variations of resins and reinforcing fibers.

In this initial TS recycle period, three primary recycling methods were explored (Figure 3). These three methods are reviewed briefly here, with more extensive details provided in the literature.[6–12] According to Guitierrez and Bono,[13] TS composites recycled, 98% are glass fiber reinforced and 2% are carbon fiber-reinforced composites. For all these methods, the typical first step is size reduction of the EOL products which can range from large structures like wind turbine blades to small products like automobile inserts. Some example energy requirements for this size reduction step are given in Table 1.

Mechanical recycling is a classical recycling process in which the composite material is shredded and ground to smaller sized pieces that are mixtures of filler, fiber, and resin. After typical product size reductions, further processing by high-speed mills brings the size into the range of 10–50 mm; cyclones or sieves then make separations by size. Cutting mills appear to give longer and more uniform fiber length distributions than hammer mills.[16]

Generally, the smaller particles contain greater percentages of filler and resin and the larger particles contain more fibers. Palmer et al.[5] concluded that while mechanical recycling is applied to carbon and glass fiber composites, the majority of studies have been on glass reinforcing fibers. Palmer recovered fiber from composites and reincorporated these into injection molded products. Tensile strength comparisons (Table 2) show the representative reduction in fiber strength. Fast drying cyanoacrylate adhesive was used for each fiber for mechanical testing. Much of the industrial uses for the mechanically recovered materials are as fillers in other composites to add strength and mass. Oliveux et al.[12] have catalogued the industrial facilities using mechanical recycling (Table 3). It appears that mechanical recycling has the greatest number of industrial facilities.

Table 1. Energy consumption of grinding process for some composite materials.[14,15]

Material	Electrical energy consumption (MJ/kg material)
CFRP	0.27
FRP sandwich	0.31
SMC	0.16
GMRT	0.14
PP/Flax	0.17

CFRP: carbon fiber-reinforced plastic; FRP sandwich: fiber-reinforced polymeric sandwich; SMC: TS glass fiber composite sheet molding compound; GMRT: glass mat-reinforced thermoplastic; PP/Flax: thermoplastic composite with polypropylene/flax as natural fiber (Courtesy of the authors).

Thermal process recycling of TS is also a traditional method developed in the early period of EOL management of composite products. Several approaches to thermal processes have been developed, including combustion, pyrolysis, and fluidized bed. Overall external heating is used to decompose the resin fraction and leave the glass or carbon fibers and inorganic fillers. Often exothermic energy can be converted to other uses. From Table 3, thermal industrial facilities are nearly as common as those practicing mechanical processing.

Table 2. Tensile properties of injection molded thermoplastic reinforced with virgin and recycled glass fibers.[17]

		Gage length (mm)		
		5	10	15
Virgin fiber	Failure strain (%)	3.6 ± 0.6	3.1 ± 0.7	3.1 ± 0.7
	Tensile strength (GPa)	2.08 ± 0.59	2.09 ± 0.56	2.1 ± 0.61
	Young's modulus (GPa)	69.2 ± 13.5	70.35 ± 9.89	71.1 ± 13.5
Recycled fiber	Failure strain (%)	2.8 ± 0.9	2.6 ± 0.7	2.4 ± 0.7
	Tensile strength (GPa)	1.72 ± 0.59	1.64 ± 0.48	1.48 ± 0.46
	Young's modulus (GPa)	66.6 ± 14.1	64.9 ± 11.8	65.2 ± 10.3

Table 3. Active firms with full scale recycling of composites.[12]

Mechanical recycling		Thermal recycling		Chemical recycling	
Company	Country	Company	Country	Company	Country
Mixt composites recyclables	France	ELG Carbon fiber	UK	Adherent Technologies	USA
Filon products, Ltd	UK	Materials innovation technologies RCF	USA	Panasonic Electric Works, Co.	Japan
Reprocover	Belgium	Karborek Spa	Italy	Innoveox	France
Hambleside Danelow	UK	CFK Valley Stade Recycling GmbH	Germany		
Fiberline-Zajons-Holcim AG	Denmark and Germany	Hadeg Recycling Ltd	UK		
Eco-Wolf, Inc	USA				

Table 4. Pyrolysis products from sheet molding compound (SMC), expressed as % (weight) of SMC.[6]

Temperature	400°C	500°C	600°C	700°C
Gas yield (%)	10.5	11.0	11.5	12.8
Liquid yield (%)	14.5	14.2	14.9	13.7
Solid yield (%)	75.2	74.9	73.9	72.6

Pyrolysis maintains a largely oxygen-free environment to degrade the organic resins. Simple molecules are produced as gas, liquid, or char and these can often be used as fuels. Processing is between 400°C and 700°C,[6] with typical product yields given in Table 4. As defined by Pickering et al.,[18] the fluidized bed thermal process operates at lower range of temperatures (450–500°C) enabling carbon and glass fiber to be recovered. Glass fiber was about 50% of the virgin material, but stiffness of the resulting composite with recycled fibers was nearly the same.

A summary of the outcomes from this first phase in TS composite recycling is in Table 5. A ranking of technologies is made from highest recovered strength (solvolysis) to lowest (thermal), recognizing that each group is evaluated as a collection of results.

Evolution of TS composite recycling – Better use of recovered fiber

Having conducted extensive research and industrial studies in the first era to recover primarily fiber, the composites community entered a second period (Figure 2; note that there is some research overlap between these composite recycling periods). In this phase of composite recycling, the objectives shifted to methods that could actually allow fibers to be used to construct new composite products. This was an evolutionary step as the demand for composite recycle continued to increase. Improvement of fiber properties to be reincorporated as reinforcement of composites centers principally on the recovered fiber surface properties and reducing fiber debonding from resin which weakens the composite. The research to enhance recovered glass and carbon fiber properties for reuse in new composites fits into three general categories:

(a) Manipulation of recovered fibers as plies to achieve better reinforced composite properties.
(b) Extension of the operational range of conventional composite recycling methods to enhance fiber adhesion.
    (i) Thermal recycling.
    (ii) Chemical or solvolysis-based recycling.
(c) Surface reactivation of recovered fibers to enhance fiber adhesion.

In category (a), Pimenta[31] chopped recovered carbon fiber and then incorporated these in random alignment into discontinuous virgin fiber-reinforced sheet molding compound (SMC) and bulk molding compound (BMC) that met measurement standards for these products. By using fiber alignment and lay-down equipment, Wood[32] produced modified fiber-based products (veils and mats) as new products with recycled fiber. By putting more energy into the blending of recycled glass fiber with TS resin, Palmer[17] produced acceptable dough molding compound (DMC) with about 10 wt.% of recycled glass fiber.

The second category (b) of enhancing surface properties of recycled glass and carbon fibers builds on enhancing or extending current composite recycling technologies. Thermal processes are the dominant technology for which investigators have sought to obtain cleaner recycled fibers. Pimenta et al.[33] developed improved pyrolysis methods using lower temperatures for carbon fiber and was able to equal or exceed the interfacial shear strength (IFSS) in epoxy systems with the ELG Carbon Fiber Ltd process. Meyer and Schulte[34] used higher temperature for thermolysis to achieve low char residue on recovered fiber that showed activated surfaces. This enhanced the reincorporation into new composites, but the recycled fiber strength was reduced. The ELG Carbon Fiber Ltd process was used by Connor[35] to improve pyrolysis operations, almost completely removing residual char from recovered fibers and giving good adhesion in a polycarbonate matrix. Elghazzaoui [36] used chemical cleaning by supercritical propanol to remove residue from recycled fibers to achieve better IFSS in new composite matrices.

By using chemicals during fiber recovery or to resize recovered fibers, the third category of enhanced utilization in new composites has developed in this second era. Most of the development in this third category (c) has been with carbon fiber. This approach follows, in general terms, the sizing commonly used with virgin glass and carbon when manufacturing TS and thermoplastic composites. Bai et al.[37] discovered that adding oxygen to supercritical water solvolysis, they could remove nearly all residue on recycled carbon fiber, thus realizing better adhesion in new resins. The consequence was lower fiber tensile strength. Recovered glass fiber was successfully refunctionalized by using coupling to improve adhesion when utilized in BMC.[38] Recovered carbon fiber was resized to achieve sufficient adhesion in a polypropylene resin composite, as an example of generally greater success in thermoplastics. Greco et al.[39] and Feng et al.[40] utilized nitric acid to remove surface residues and achieve acceptable IFSS when the fibers were reincorporated in resin composites. Goodine[41] used a water soluble binder to orient recovered short carbon fibers, thus allowing these to be

Table 5. Fiber strength of recycled composite associated with recycling methods [fiber strength as % of virgin].

Recyclers	Recycling material	Recycling method	Initial fiber or composite strength	Recycled fiber or composite strength
Adherent Technologies, Inc.[19]	TS carbon fiber composite	Wet chemical breakdown	3500 MPa[a]	Recyclate fiber (3325 MPa[a]) (95%)
Nakagawa et al.[20]	Carbon fiber-reinforced plastic	De-polymerization	Mass production of glass fiber composite product 63.8 MPa	Carbon fiber composite product 89.7 MPa (71%)
Hernanz et al.[21]	Carbon fiber-reinforced composite	Solvolysis	3500 MPa[a]	of strength of virgin fibers, straight and long fibers 2975–3465 MPa[a] (85–99%)
Hyde et al.[22]	Carbon fiber composite	Solvolysis	4090 MPa	3900 MPa (95%)
Liu et al.[23]	Carbon epoxy composite	Solvolysis	3500 MPa[a]	Single-fiber tension strength loss of 1.1% of recycled carbon fiber 3461.5 MPa [99%]
Palmer[17]	Sheet molding compound	Mechanical recycling	1490–2670 MPa	1130–2310 MPa (83%)
Åström[15]	Polymer composite material	Mechanical recycling	Unreported	Unreported
Takahashi et al,;[24] Suzuki and Takahashi[25]	Carbon fiber-reinforced plastic	Heat recovery material recycling	CF/PP L-24%; based on JIS expected flexural strength of 120 MPa; CF/ABS (product almost same as virgin composite)	CF/PP L-24% ≈ 100 MPa (product basis) CF/ABS L-24% ≈ 180 MPa (product basis) (83%)
Ogi et al[26]	Carbon fiber-reinforced plastic	Mechanical (grinding)	Unreported	Composite product (CFRP/ABS) 100.8 MPa
Kouparitsas et al.[27]	TS composite	Mechanical (grinding)	Composite product of PP/glass 24 MPa; ionomer/aramid 12.5 MPa, ionomer/carbon 20.5 MPa	Composite product of PP/Glass 25 MPa; ionomer/aramid 14 MPa; ionomer/carbon composite 13 MPa (63%–104%)
Pickering et al.[18]	TS composite	Fluidized bed combustion	3500 MPa[a]	Half of virgin fiber 1750 MPa[a] (50%)
Kennerley et al.[28]	Scrap from Polyester Sheet molding compound	Fluidized bed combustion	3500 MPa[b]	Strength reduced to half of virgin glass fiber ≈ 1750 MPa (50%)
Turner et al.[29]	Scrap prepreg	Fluidized bed combustion	3500 MPa[a]	strength 1750–2625 MPa[a] (50–75%)
Palmer[17]	Glass fiber composite	Combustion process	Unreported	Unreported
Pimenta and Pinho[8]	Carbon fiber-reinforced polymer	Pyrolysis, fluidized bed,	Pyrolysis ≈ 3600 MPa; fluidized bed ≈ 4800 MPa;	Pyrolysis ≈ 3700 MPa; fluidized bed ≈ 3200 MPa (67%–100%)
Pickering[6]	Sheet molding compound	Pyrolysis	Unreported	Unreported
Torres et al.[30]	Sheet molding compound	Pyrolysis	Unreported	Unreported

[a] Approximate virgin carbon fiber strength: 4127 MPa.
[b] Approximate glass fiber strength (E glass): 3450 MPa.

reincorporated into new products. Sigmatex[42] has produced acceptable recovered carbon fiber in a polyethylene terephthalate (PET) matrix as a commercial composite product. Howarth et al.[43] worked extensively to optimize activation agents for recovered carbon fiber to establish needed fiber surface interface properties. Plasma treatment of recovered carbon fiber by Montes-Moran et al.[44] represents another refunctionalization method that improves interfacial properties in new thermoplastic resin products.

Evolution of TS composite recycling – Direct structural recovery

A new concept for composite product recycling emerged in about 2012, representing the third period or era in managing TS product EOL. This new concept is to maintain some or all of the original resin/fiber structure (the original product value) instead of devolving TS composites into separate recycled fiber and recycled resin. Asmatulu et al.[11] stated that the concept had been called "direct structural recovery" and appears at three structural levels:

1. as-is TS product or smaller subsections from EOL products;
2. as-is TS product or smaller subsections that can be thermoformed into new products by use of catalysts for reversible crosslinking chemistries;
3. recovery of smaller flakes of intact TS to be reintroduced into resin to produce sheets that can be reformed into products, not as filler, but for structural value.

In the level 1 concept, the TS composite products at EOL are represented as different shapes and compositions that can potentially be used directly in other products.[11] In this method, the long fiber length and resin bonding are largely preserved. These EOL products can be large structures (wind turbine blade, aircraft sections, etc.) or smaller structures (truck or rail liners, automotive parts, etc.). These EOL products need to be made available by the owner or firm that collects EOL products directly or after processing (cutting into sections). An interesting driver for this reuse approach is for the composite product collector or owner to make these sections and subsections available for free to potential new product manufacturers (that is, just avoiding the cost of disposal). The availability of such high value TS composites would then stimulate entrepreneurs to develop new products.

Denissen et al.[45] mentioned that in this third era, the second level concept for direct structural recovery requires the use of a reworkable, induced through the inclusion of an appropriate catalyst, and is typically triggered thermally. In this scenario, the sections cut from the wind turbine blade can be heated to reform the TS composite into a new TS composite product, ideally without substantial compromise of fiber length or resin bonding. As an example of this approach, the so-called vitrimers reported by the group of Leibler[46] show exactly this sort of behavior. In this context, a fiber-reinforced TS composite as a vitrimer, such as the sort of materials recently reported by the group of F. Tournilhac,[47] could be cut into desired sections, and then heated to activate the vitrimeric transition. Labile linkages present in the network reorganize, resulting in stress relaxation and enabling the TS to be deformed when heated, but to regain its strength and stiffness when cooled. The EOL product sections can be thermoformed into shapes or into flat sheets of cured fiber-reinforced epoxy. Wind turbine blades are typically cured with amine curing agents; however, the ability to rework TS via the transesterification process reported by Leibler requires the presence of ester groups only formed with anhydride or carboxylic acid-based curing agents. That said, this approach has been demonstrated to work in other systems as well,[44] emphasizing its broader applicability. Indeed, its application to bio-based TS composite systems would represent a particularly attractive means of addressing this lifecycle as a whole.

An important spinoff of EOL TS recovery by catalyst addition and reforming is to use this initially in making new products. The initial TS with catalyst is made into an easily manufactured shape (say a flat 55 m by 1 m shape) or (into a 21 cm by 1.5 cm shape). Then the 55 -m shape is heated and twisted to give the desired wind turbine blade shape thus reducing the complexity of many curved molds for changing designs. Similarly, the 54 inch 4 inch shape is heated and bends into a semicircular shape and becomes a part of an automobile leaf spring. Thus, only the flat shape mold would be varied so that the TS bending could give new designs.

The National Science Foundation project on sustainability and wind turbine blades has led to further vitrimer development by the research group of Schmidt and Reynaud.[48] Their work on catalysts is focused on achieving improved forming and recycling rates. Their work is applied to conventional wind turbine epoxies as well as biobased epoxies. In a life cycle study to utilize the vitrimer (catalytic) concept for a wind turbine blade, the mechanisms of producing sections of a large TS product (the 55 m wind turbine blade) were studied.[49] The material recovered from the wind turbine blade should meet the dimensional characteristics of the potential new product to be made from this material. What was learned is that there are four sections of a blade, Figures 4 and 5, where the epoxy/glass

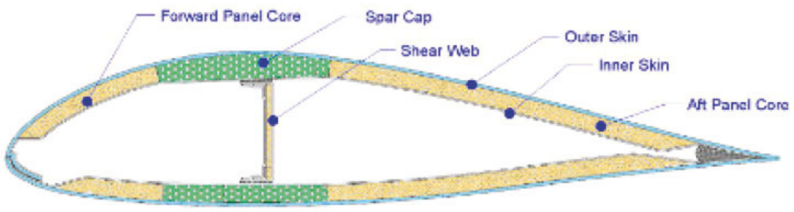

Figure 4. Cross section of a typical wind turbine blade with leading and trailing edges and spar cap shown.[50]

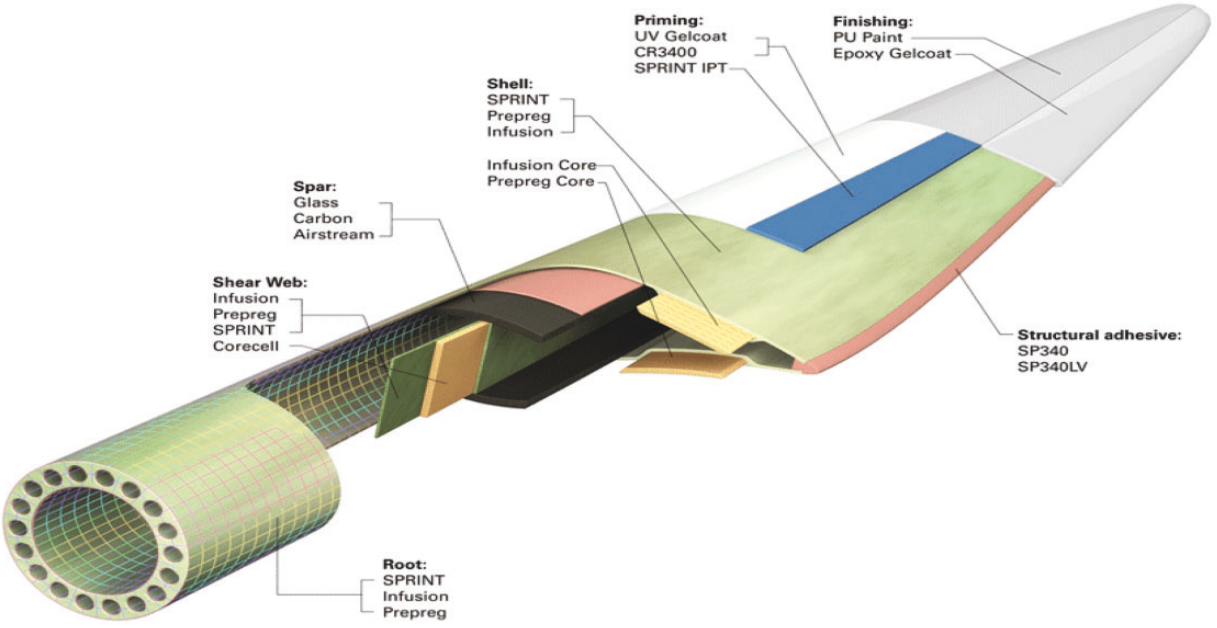

Figure 5. Root section of a typical wind turbine blade.[46]

fiber composites are the principal material with no foam, balsa, or other materials.[50] An example product (the cold shoe, an insulating surface for cryogenic processes), Figure 6 (the white material),[51] in which hundreds of these shapes would be cut from the wind turbine blade. These sections are,

1. Leading edge (forward panel core area).
2. Trailing edge (aft panel core area).
3. Spar cap.
4. Root section, Figure 5.

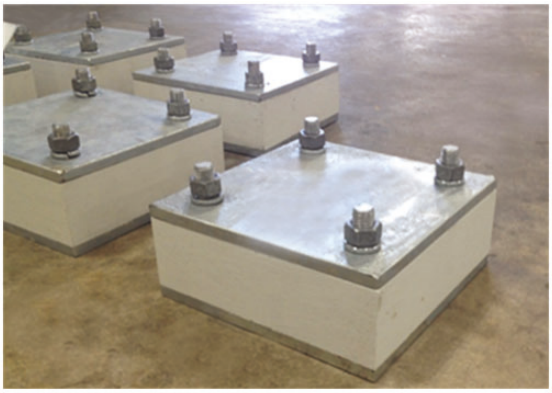

Figure 6. Micarta Isolation Blocks (http://www.rilco.com/products/isolation-blocks-additional-components).[51]

All the rest of the epoxy/fiberglass composite (about 15% of blade) is bonded tightly to the inner skin. For the balance of the blade (about 85%), each of the areas are potential materials for recycling as direct materials:

1. The leading edge is estimated to be about 200 mm wide on the top and 200 mm wide on the bottom and as long as the blade (55 m). This area is about 5–10 mm thick.
2. The trailing edge is also about 200 mm wide on top and bottom and 55 m long. For these two areas, one

Table 6. Potential recovered sections of 55 m wind turbine blade weighing about 11,500 kg.

Section recovered	Possible recovery operation	Largest area of recovered pieces	Approximate thickness of recovered pieces	Number of pieces	Approximate weight of entire recovered section, kg
Spar cap	Cut one from top and one from bottom of blade	55 m × 0.5 m = 27.5 sq m	Max 45 mm tapering to very thin	2	7000
Leading edge	Cut from blade and then split into two pieces	55 m × 0.2 m = 11 sq m	5–10 mm	2	500
Trailing edge	Cut from blade and then split into two pieces	55 m × 0.2 m = 11 sq m	5–10 mm	2	500
Root	Cut from blade and then cut top to bottom	3.3 m × 6 m = 20 sq m	10–30 mm	1	2000

might cut the 200 mm section off the blade at whatever lengths might be useful. Then the two 200 mm sections may be cut apart to achieve two flatter pieces of DGEBA/long fiber sheet-like structures (two 200 mm × 55 m × 5–10 mm thick sheets per blade). These two edge pieces weigh about 1,000 kg in total.

3. The spar cap is 400–600 mm wide and varies from about 45 mm thick down to near-zero along the 55 m length. Some sections have constant thickness and others are tapered. When removed, this comprises two structures (one on each side of blade) of about 500 mm wide × 55 m long and of varying thickness. Each of these sections is about 3500 kg in weight (for a total of about 7000 kg).
4. The root cap is about 10–30 mm thick, encircling the blade, and estimated to be 3.3 m in diameter (Figure 3). Cutting this from the blade and then from top to bottom yields a piece that is about 6 m × 3.3 m × 10–30 mm thick. This section is DGEBA with long glass fibers and weighs about 2,000 kg.

The sizes and preparation steps for these sections of the blade are given in Table 6.

The third level of new approaches for TS reuse in this third era, began with early efforts by Takahashi et al.,[52] who created TS flakes in the 1 cm^2 size range. These were incorporated into polypropylene and acrylonitrile-butadiene-styrene thermoplastic resins and injection molded into specimens. The resulting composite had better properties than other recycled fillers in various applications. More recently, Englund[53] prepared ground flakes in the 6–7 cm^2 range from whole wind turbine blades, representing a mix of the various microstructures present in this TS product (mostly cured epoxy resin and glass fiber with some carbon fiber, balsa wood and poly(styrene-co-acrylonitrile) (SAN). These flakes were loaded into virgin epoxy resin at high levels (85–90 wt.%) and the mixture was then thermoformed into sheet products. The range of fiber lengths present coupled with good resin bonding enabled the retention of a significant fraction of the properties of the original TS composite.

A variation of this third level concept is to create these same flakes sizes using a reworkable TS resin (see above). This material might then be heated and molded directly into another TS product of arbitrary size and shape. In this case, much of the original fiber and resin properties (at the flake level) would be realize in new products.

Conclusions

The magnitude and growth of TS composite products are considerably large. Since these are typically long-lasting products, the immediate interest is in manufacturing-related TS and TS components Because landfilling, as the EOL alternative for TSs as a rapidly increasing product, is unlikely to be viewed as socially acceptable, the increase in recycling and reuse seems likely be a trend. Impetus for TS recycling technology or market may emerge from States that have achieved other difficult product recycling, the Federal government as a part of composite purchases, or as a reflection of European TS recycling progress (often as heat value). This review shows a historical progression toward efforts to recover as much of the in-situ resin/fiber mechanical properties and away from just fiber recovery. The use of catalysts to reform whole sections of TS either into new products or from EOL TS into new products and of blending TS flakes to form usable shapes are two of the best examples of high composite property (an value) recovery. This review provides a state-of-the-technology assessment and so progress will advance into the future from this stage in TS composite development.

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