CHAPTER 11 ENVIRONMENTAL MANAGEMENT

11.1 INTRODUCTION

The objective of this chapter is to provide information for the environmental management of composite materials. Requirements for recycling of all classes of materials are increasing on a global basis and are not likely to be reduced. Many industries have found that taking a proactive approach to environmental management of their products can help to head off the enactment of complex regulations, which can be costly and less effective than market based solutions. Reuse and recycling of automobiles and components, for example, is performed by an efficient, nationwide network of used parts shops, automobile shredders, and resellers that extracts the maximum value out of recycled vehicles. This network is directed and motivated by interest in the value of the components and materials in end-of-use vehicles, rather than by an innate desire to comply with regulations.

The creation of a similar network for composite materials is an ongoing process at this time. It involves the development of size reduction and matrix digestion technologies, the organization of a collection system, identification of uses for recycled fibers and matrices, and perhaps most importantly, the education of the composites production and user community about recycling needs and opportunities.

Efforts to recycle composite materials are in an early stage of development compared with other aspects of composite's usage, and so much of the information in this chapter describes immature technologies. They are nevertheless included to provide an overview of the state-of-the-art and a resource for those interested in applying or developing composite reduction, reuse, and recycling technology.

11.1.1 Scope

The scope of this chapter is to provide guidance for the environmental management of composite materials as it pertains to the "reduce, reuse, and recycle" paradigm for controlling environmental impact. It does not address issues such as styrene emissions, handling of toxic materials, or disposal requirements for hazardous waste. Some aspects of composite manufacturing and use, such as lightweighting (defined later), prepreg usage, and the use of hybrid composites, are treated as they pertain to environmental management. These aspects will be discussed in this chapter only in the context of recycling, with other parts of the handbook referenced for broader discussions.

11.1.2 Glossary of recycling terms

Broad Categories -- General classifications of recyclable material, such as glass, plastic, metal, or paper.

Broker -- refers to an individual or group of individuals who act as an agent or intermediary between the sellers and buyers of recyclable materials.

Collector -- refers to public or private haulers that collect nonhazardous waste and recyclable materials from residential, commercial, institutional, and industrial sources.

Comingled recyclables -- refers to a mixture of several recyclable materials in one container.

Disposal Facilities -- refers to repositories for solid waste, including landfills and combustors, intended for permanent containment or destruction of waste materials.

Drop-Off Center -- refers to a method of collection whereby recyclable or compostable materials are taken by individuals to a collection site and placed in designated containers.

End-of-Service -- Components that have been used until failure or obsolescence.

End User -- Facilities that purchase or secure recovered materials for the purpose of recycling. Examples include recycling plants and composting facilities. Excludes waste disposal facilities.

Exports -- Waste and recyclables that are transported outside the state or locality where they originated.

Generators -- Producers of solid waste.

Imports -- Solid waste and recyclables that have been transported to a state or locality for processing or final disposition, but that did not originate in that state or locality.

Incinerator -- A furnace for burning solid waste under controlled conditions.

Industrial Process Waste -- Residues produced during manufacturing operations.

Industrial Waste -- Nonhazardous wastes discarded at industrial sites from packaging and administrative sources. Examples include corrugated boxes, plastic film, wood pallets, and office paper. Excludes industrial process wastes from manufacturing operations.

Lightweighting -- Reduction of system weight by using lighter weight materials, careful design, avoidance of overdesign, and other engineering changes.

Large Generator -- Commercial businesses, institutions, or industries that generate sufficient quantities of solid waste and recyclables to warrant self-management of these materials.

Material Recovery Facility (MRF) -- A facility where recyclables are sorted into specific categories and processed or transported to processors for remanufacturing.

Mixed Plastic -- Recovered plastic that is not sorted into specific categories (HDPE, LDPE....)

Nonhazardous Industrial Process Waste -- Waste that is neither municipal solid waste nor considered a hazardous waste under Subtitle C of the Resource Recovery Act.

Other Plastic -- Plastic from appliances, furniture, trash bags, cups, eating utensils, sporting and recreational equipment, and other nonpackaging plastic products.

Other Solid Waste -- Nonhazardous solid wastes, other than municipal solid waste, covered under Subtitle D of the Resource Conservation and Recovery Act, such as municipal sludge, industrial nonhazardous waste, construction and demolition waste, agricultural waste, and mining waste.

Plastics Handler -- Companies that prepare recyclable plastics by sorting, baling, shredding, granulating, and/or storing plastics until a sufficient quantity is on hand.

Plastics Reclaimer -- Companies that further process plastics after the handling stage by performing at least one of the following functions: washing/cleaning, pelletizing, or producing a new product.

Postconsumer Materials/Waste -- Recovered materials that have been used as a consumer item and are diverted from municipal solid waste for the purpose of collection, recycling, and disposition. Excludes materials from industrial processes that have not reached the consumer, such as glass broken in the manufacturing process.

Preconsumer Materials/Waste -- Materials generated in manufacturing processes, such as manufacturing scrap and trimmings/cuttings. Also includes obsolete inventories.

Primary recycling – Recycling clean materials and products to produce products that are similar to, or the same as, the original product.

Processors -- Intermediate operators that handle recyclable materials from collectors and generators for the purpose of preparing materials for recycling (material recovery facilities, scrap metal yards, paper dealers....) Processors act as intermediaries between collectors and end users of recovered materials.

Quaternary Recycling – Waste-to-energy conversion by incineration.

Recovery -- The diversion of materials from the solid waste stream for the purpose of recycling. Excludes reuse and source reduction activities.

Recyclables -- Materials recovered from the solid waste stream and transported to a processor or end user for recycling.

Recycling -- The series of activities by which discarded materials are collected, sorted, processed, and converted into raw materials and used in the production of new products. Excludes the use of these materials as a fuel substitute or for energy production.

Recycling Plant -- A facility where recovered materials are remanufactured into new products.

Residues -- The materials remaining after processing, incineration, composting, or recycling have been completed. Residues are usually disposed of in landfills.

Reuse -- The use, more than once, of a product or component of municipal solid waste in its original form.

Secondary recycling – Recycling mixed materials or products to produce a product that is lower in quality than the original product.

Source Reduction -- The design, manufacture, purchase, or use of materials, such as products and packaging, to reduce the amount or toxicity of materials before they enter the solid waste management system. This may involve redesigning products or packaging; reusing products or packaging already manufactured; and lengthening the life of products to postpone disposal. Also referred to as "waste prevention."

Sortation -- The process of sorting comingled recyclables into separate types of materials for the purpose of recycling.

Tertiary Recycling -- Recycling that is accomplished by completely breaking down a material to its chemical constituents and restoring it to its original quality.

Transfer Station -- A facility where solid waste is transferred from collection vehicles to larger trucks or rail cars for longer distance transport.

Waste Characterization Studies -- The identification and measurement (by weight or volume) of specific categories of solid waste materials for the purpose of projecting landfill capacity, determining best management practices, and developing cost-effective recycling programs.

Waste Generation -- The amount (weight or volume) of materials and products that enter the waste stream before recycling, composting, landfilling, or combustion takes place.

Waste Stream -- The total flow of solid waste from homes, businesses, institutions, and manufacturing plants that must be recycled, incinerated, or disposed of in landfills; or any segment thereof, such as the "residential waste stream" or the "recyclable waste stream."

Waste-To-Energy Facility/Combustor -- A facility where recovered municipal solid waste is converted into a usable form of energy, usually through combustion.

11.2 RECYCLING INFRASTRUCTURE

The development of a viable infrastructure for recycling composite materials should ideally be pursued as a coordinated effort by composite suppliers, fabricators, and end users. Such an infrastructure will benefit the entire composites industry by improving the efficiency of composite manufacturing, changing the perception that composites are not recyclable and that metals are therefore preferable, and reducing the environmental impact of composites use. This section outlines some of the requirements for recycling infrastructure development.

11.2.1 Recycling infrastructure development models

The infrastructures for recycling many other materials have already been developed and can provide guidance for the establishment methods for composite materials recycling. Studying these examples can facilitate composites recycling development work and avoid costly mistakes that have been encountered in other industries.

One important lesson learned is that while the technology for actually recycling a material is important, the logistical, educational, and economic issues are equally important. Advanced recycling technologies cannot succeed unless they are integrated with consistent sources of consistent recyclate sources, stable markets for the recycled materials, an efficient collection and transportation system, and a work force that has been educated in the requirements for proper handling of recyclable materials.

One of the most mature and efficient reuse/recycling infrastructures is in place for automobiles. A large, computer-integrated network of automobile recyclers procures end-of-service automobiles, removes fluids and toxic components such as batteries, catalogues reusable components, and either dismantles the vehicle or warehouses its parts in the vehicle. After all reusable components are removed, vehicles are shredded, ferrous metals are magnetically sorted, and lightweight "fluff" and other materials are separated. The result is that approximately 90% of the steel in automobiles is recycled, more than 12 million tons per year. Automotive manufacturers are increasingly paying attention to design for disassembly and recycling, and are giving consideration to the recyclability of the materials in their products.

A user-subsidized recycling model that may be instructive is that developed for nickel cadmium (NiCd) batteries in response to concerns about groundwater contamination from the cadmium content. Because of the widely dispersed nature of old NiCd batteries, a network of used battery collection centers was created by placing pre-paid, pre-addressed mailers at electronics retail outlets. When the mailers are filled with batteries, they are given to the parcel delivery service and transported to a single recycling facility for the entire North American continent. The recycler distills out the cadmium and processes the nickel content in an open hearth furnace along with other stainless steel waste. The high nickel content increases the value of the stainless steel recyclate and helps to pay for the process.

In contrast, the vast majority of end-of-service composite materials and composite waste generated in manufacturing, are commonly thrown into landfills (References 11.2.1(a) - (b)). Although this adds only a small volume to the solid waste disposal problem, it returns no value. As regulations that mandate recycling of various products take effect, particularly in Europe, non-recyclable materials will be increasingly excluded from consideration. The desirable environmental influence that advanced composites can have, such as greater fuel efficiency from lightweighting, will be lost if recycling techniques are not implemented.

11.2.2 Infrastructure needs

Although technologies exist for digestion of composite matrices and recovery of fibers with high strength retention (References 11.2.1(b) and 11.2.2(a) - (d)), these technologies have only been demonstrated on laboratory prototype or pilot scale. Additional efforts to optimize and scale up these processes to complete implementation are underway.

A resource recovery network must be established, or “piggybacked” onto existing networks, to collect and channel post-consumer composites back to these material recovery facilities (MRFs). Because of the relatively low volume of advanced composites in service, the most efficient transportation system may include a network of material transfer stations, which collect recyclables for consolidation into large shipments. A single transfer station may receive shipments of process waste and post-consumer composites from a state, or metropolitan area, and reship many small loads in a single truck or rail car load. Throughout this consolidation process, different types of composites must remain separate for the value of the recyclables to be maintained. It is almost always easier for materials to be kept separate in the first place than to go through sortation after the fact.

11.2.3 Recycling education

Although methods for reducing, reusing, and recycling thermoset matrix composites exist today, and services are available for exchanging unused fibers, prepreg, and other precursors, lack of awareness limits their application. Producers and users should familiarize themselves with opportunities for recycling as a first step in making it a routine part of their ways of doing business. An interest in recycling that is generated in both a top-down and bottom-up fashion can be the most effective in establishing programs, since programs that are mandated by management are likely to fail if not implemented on the shop floor, while individual efforts will not succeed without management support. Information from this chapter and its references can be used as a starting point for this education process.

11.3 ECONOMICS OF COMPOSITE RECYCLING

A complete discussion of the economics of recycling composite materials would need to address, in detail, numerous issues that are specific to the particular type of composite. Such a discussion is beyond the scope of this section. Some general considerations of composite recycling economics are helpful in designing and evaluating recycling programs and are discussed in this section.

The costs of recycling principally arise from collection, transportation, and processing. These costs should ideally be offset by the value of the products derived from the recycled material. There are also costs associated with disposing of waste, called “tipping fees,” particularly if the material is a hazardous waste, as is the case for uncured resins. The reduction or elimination of disposal costs should be considered when evaluating the cost of a recycling operation.

In addition, there are significant costs associated with complying with existing environmental regulations and those that may be enacted if an industry fails to take action on its own initiative. Some recycling efforts have been initiated by industries to head off legislation that would place a greater burden on them, and result in a less efficient recycling structure. There are significant public relations benefits from making good faith efforts to recycle and strong negative effects when these efforts are not made. Large-scale implementation of composite materials in the infrastructure, transportation, offshore oil, and other industries will eventually require the further development of composite recycling programs.

Several considerations are involved in identifying the most favorable economics for recycling a material. Minimization of collection and transportation costs is a vital requirement for efficient recycling. For fiberglass materials, for instance, which are heavy, and which do not yield high value recyclate, these costs could be prohibitive. For this reason it is most effective to situate recycling facilities close to the source of material.

Derivation of high value materials is another important requirement. Although carbon fiber composites can be completely incinerated for energy, in an open-hearth furnace, for example, their value would be reduced to that of the energy content. Some of the current technologies for fiberglass recycling grind the composite into a fine powder that is used as filler in new composite. This fill must compete with extremely inexpensive calcium carbonate fillers, and is therefore of low value. The primary benefits of these technologies are that the waste does not become a landfill, or disposal problem, and that the recyclate fill is less dense than mineral fill, resulting in a lighter weight composite.

Technologies that recover fibers in usable condition can achieve higher value for the recyclate, and can pay for the entire recycling process. Technologies that recover glass fibers have this advantage compared to grinding, but the fiber extraction process must still be very inexpensive to justify on an economic basis, due to the low cost of glass fiber. The greater cost of carbon fibers can, therefore, be an advantage for recycling of this class of material. If carbon fibers can be extracted from the matrix in sufficiently good condition to compete with low-end fibers in the $5/pound range, a substantial value can be obtained and the recycling process can be feasible on an economic basis.

Composite materials will always have to compete with monolithic metals, which can, in most cases, be recycled back to virtually their original quality, a process known as tertiary recycling. Finding high value secondary uses for composite recyclate is a necessary factor for successful competition.

Cyclical markets for recycled materials have been a problem for most types of materials (References 11.3(a) - (b)). Expensive plants have been built and commitments made when the value of recycled materials is high, and then market changes have left companies with unused capability or mandates to purchase materials at costs far greater than their value. The primary source of these market fluctuations has been a kind of teething pain, in which, at first, a great deal of material is recycled, but no buyers are available for a product that did not previously exist, and then when a market is created, demand exceeds supply. Paper and plastic materials have been particularly prone to these fluctuations.

These cyclical changes can leave manufacturers dependent on a flow of recycled material that cannot be reliably, or economically, procured. Robust manufacturing processes that can exploit recycled materials when possible, but can substitute virgin material when necessary, can alleviate these problems.

11.4 COMPOSITE WASTE STREAMS

The advanced composites industry was surveyed in 1991 (Reference 11.2.1(a)) and 1995 (Reference 11.2.1(b)) to determine the type, quantity, and current disposal methods of composite waste. As shown in Figure 11.4(a), for waste generated at the manufacturing source, 66% was in the form of unused prepreg material. Approximately 18% was in the form of cured parts, 14% was trimmings, and one or two percent was comprised of finished parts and bonded honeycomb. Pre-consumer advanced composite waste, therefore, consists of approximately two-thirds prepreg scrap and one-third trimmings and cured parts.

Because of the long service life of many military and civilian platforms containing advanced composite materials, it is difficult to predict when the composite components contained within those platforms will enter the composite waste stream at the end-of-service-life. A study (Reference 11.2.1(b)) of the composites contained within many military vehicles shows the kind, and in some cases, the quantity of various types of composite materials that will require recycling or disposal at some point in time. The composites in military vehicles are largely comprised of carbon fiber/epoxy, aramid fiber/epoxy, and carbon/carbon composites as shown in Figure 11.4(b).

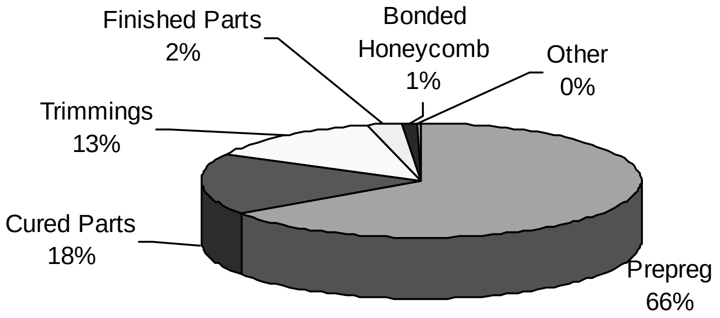
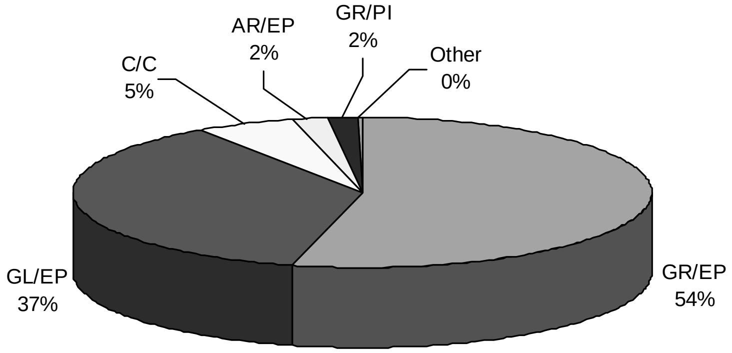


FIGURE 11.4(a) *The reported distribution of advanced composite manufacturing waste by type of material.*



GL/EP -- Glass/Epoxy
GR/EP -- Graphite/Epoxy
C/C -- Carbon/C
AR/EP -- Aramid/Epoxy
GR/PI -- Graphite/Polyimide

FIGURE 11.4(b) *The distribution of advanced composite materials in 1995 by matrix and fiber.*

11.4.1 Process waste

Because of the nature of most current advanced composite manufacturing processes, process wastes comprise a significant fraction of the overall composite waste stream. They are also the portion of the waste stream that must be disposed during production, rather than at the end of service, and so present immediate handling issues.

Prepreg comprises the largest fraction of process waste, as shown in Figure 11.4(a), and is, therefore, the most important target of source reduction and recycling efforts. Unused fibers, curing agents, and resins also contribute to process waste. After minimization by careful inventory control strategies (Section 11.5), these materials can often be reallocated or exchanged (Section 11.7.2).

11.4.2 Post consumer composite waste

Perhaps the greatest challenge for recycling of composite materials is finding a viable approach to collecting, sorting, processing and reusing post consumer composite wastes. Materials that have gone into service are likely to be dispersed geographically, may have picked up contaminants, require disassembly, and may contain fiber and matrix types that are not documented. The date of retirement from service for composite components may be decades after their production, making the logistics of planning for recyclability difficult, and of low priority. Nevertheless, addressing the issue of post–consumer composite recycling is essential if composite materials are to compete in systems that mandate recycling.

The quantities of composite materials that are produced can be derived from fiber manufacturer’s data. Another tracking method is to document the quantities and types of composites used in various vehicles and other applications, and then to monitor the procurement levels for those vehicles. A pie chart of the percentage distributions of actual usage of various types of advanced composite materials for 1995 is shown in Figure 11.4(b) (Reference 11.2.1(b)).

The greatest uncertainty in assessing the post consumer composite waste stream is in the dates of retirement of the systems containing the composite components, or, otherwise, the dates of failure or destruction of the composite components. Because many military and civilian craft remain in service for decades, while others are rapidly rendered obsolete, the extent and timing of the advanced composite waste stream is difficult to predict.

More reliable predictions can be made about the sheet molding compound and other composites used in automotive applications, since the life cycle of automobiles is less variable. Polymers and polymer composites currently comprise about 20% of the total weight of new automobiles and are steadily increasing. In contrast to the recyclability of the bulk of automobile constituents, these materials currently contribute to the generation of automotive shredder residue (ASR), a mixture of plastic, rubber, glass, and inorganic materials which is commonly landfilled. Efforts to develop recycling techniques for ASR are underway but are beyond the scope of this discussion. Recycling technologies for sheet molding compound are discussed in Sections 11.8.3.2 and 11.8.3.5.

11.5 COMPOSITE WASTE STREAM SOURCE REDUCTION

Reduction of the volume of waste materials is the best approach to environmental impact mitigation. Waste that is not created in the first place does not need to be paid for, recycled, or disposed. Efforts to reduce the production of waste materials should, therefore, be given the highest priority. Waste source reduction yields direct benefits in both decreased procurement costs and decreased recycling or disposal costs. Efforts should, therefore, be made to identify the sources of waste material and reduce or eliminate them. Approaches to the reduction of composite precursor waste are described below.

11.5.1 Just-in-time and just enough material delivery

Just-in-time inventory control systems have made a major impact on the production plans of manufacturers in recent years. The benefits of having materials arrive shortly before use, include reduced inventory and storage requirements, and more efficient production flow. For composites that are produced from prepreg with a limited shelf life and that require refrigeration, even greater benefits can be derived. Great care should, therefore, be taken to ensure that tight control is maintained over inventories of prepreg, resins, and any other material with limited shelf life.

Prepreg inventory can be effectively tracked by logging shipments of prepreg as they are received into a computer database and affixing a bar coded label before storage. The information in the database can be compared with production requirements to plan and time future procurements. The database system can also be set to flag materials that are in danger of reaching their expiration dates so that processing can be scheduled to avoid waste. In some cases, prepreg that has reached its expiration date can still be used if testing is performed to ensure that the quality of the components is not impaired. Prepreg that no longer meets the stringent requirements for primary structures can sometimes be reassigned to less demanding applications, or resold for use in non-critical structures. See Section 11.7 for information on materials exchange.

Procurement of excess quantities of material is also a significant source of waste. If arrangements can be made with the material supplier, obtaining the correct amount, with minimal excess, is an efficient means of reducing the generation of wastes.

11.5.2 Electronic commerce acquisition management

Electronic commerce is the process of specifying and procuring materials and components by digitally transmitting the required information, usually over the Internet. Composite precursor acquisition by electronic commerce can reduce inventory requirements and shipping lead-time. It can also interface directly with management of inventories to minimize waste.

11.5.3 Waste minimization guidelines

Guidelines for implementing procedures that minimize the production of composite and precursor waste are provided in this section.

11.5.3.1 Prepreg

Efficient use of prepreg is one of the most effective methods of waste minimization. Prepreg cutting waste typically amounts to 25-50% of the material. This waste adds to both procurement and disposal costs. Efforts to develop recycling methods for prepreg have been made (References 11.2.1(a) - (b), 11.5.3.1(a) - (c)), but most are not fully ready for implementation. Particular emphasis should, therefore, be given to efforts to optimize the nesting of patterns for cutting shapes out of prepreg materials. Computer programs are available to facilitate this task.

11.5.3.2 Resin

Uncured resin waste is classified as a hazardous waste material in the U.S., and must be handled and disposed of accordingly. Curing of resin for the purposes of disposal is considered to be processing of hazardous waste, which requires special permitting, even though the same shop cures resin on a routine basis for the purpose of composite production. Unless, and until, these requirements are eased or modified, it is doubly important to minimize the creation of waste resin. Careful planning of procurement and just-enough procurement of resins are tools for this minimization.

11.5.3.3 Fiber

This section is reserved for future use.

11.5.3.4 Curing agents

This section is reserved for future use.

11.5.3.5 Autoclaving materials

This section is reserved for future use.

11.5.3.6 Packaging materials

This section is reserved for future use.

11.5.4 Lightweighting

Reduction of the weight of composite components by careful design improves environmental management by reducing the amount of material consumed, and that must ultimately be recycled or landfilled. Although the primary motives for lightweighting are to improve structural efficiency, these additional benefits occur at no additional cost. Lightweighting of composite components should, therefore, be considered to be a part of any environmental management plan.

Overdesign of composite components commonly occurs because of uncertainties about the failure criteria, material properties, and behavior under complex in-service loading conditions. This overdesign reduces the performance benefits of composites in comparison with monolithic materials. As improved composite design capabilities are developed by ongoing efforts in this area, implementation of those capabilities will help to reduce waste generation.

11.6 REUSE OF COMPOSITE COMPONENTS AND MATERIALS

After reduction of waste generation, the next best approach to environmental management involves the reuse of systems, components, and constituents. The greatest value for a complete component can best be realized by reusing it in the same, or, possibly, in some similar application. This section provides information and ideas for reuse of composite components.

11.6.1 Reuse of composite components

By far the greatest part of the value derived from recycled automobiles comes from the reuse of serviceable or remanufacturable components that are removed and resold by a large network of automobile parts distributors. Used automobile parts are inventoried and shipped to buyers through a sophisticated, satellite-linked database network that exchanges information between buyers and sellers. Similar systems for reallocating composite components that are removed from damaged or decommissioned vehicles could avoid disposal costs and return the maximum value for the material.

11.6.2 Machining to smaller components

End-of-service or otherwise surplus composite components can sometimes be reconfigured for another application by machining. In this manner, sailboat spars have been produced from aircraft components, for instance. Because such reuse usually returns a greater value than recycling, consideration should be given to reconfiguration, or sale to a company that performs that function, before sending material to be recycled. The greatest difficulty in machining components to smaller sizes arises from finding matches in material and geometric requirements. Applications that allow some flexibility for the geometry are advantageous for this reason.

11.7 MATERIALS EXCHANGE

Materials exchange is a method of reducing waste and lowering acquisition costs by reallocating or reselling unused materials. This can be done either within an organization, or between organizations, often with the assistance of a broker. This section describes guidelines and techniques for exchange of composite precursors.

11.7.1 Reallocation of precursors

Excess precursor material that is maintained in properly documented, good condition can often be reallocated within a company. If some degradation has occurred, or if the material has passed its expiration date, sometimes applications that allow lower standards can be found. Although it is not a substitute for tight inventory control, the most common disposal method for uncured waste prepreg, other than landfilling, is fabrication into flat panels (Reference 11.2.1(b)).

11.7.2 Composite materials exchange services

Materials exchange services either buy surplus materials and resell them, or list materials that are available for sale and charge a fee for placing buyers and sellers in contact. A wide range of materials can be resold in this manner. Materials exchange services that specialize in exchange of composite precursors are available to assist in locating sources or users of composite precursors. These companies should be contacted for detailed, specific information about the requirements and opportunities for exchanging particular fibers, prepregs, and other precursors.

11.7.2.1 Care of unused materials

Unused materials must be maintained with the same care given to new material if they are to be resold to other manufacturers so that the components they are incorporated in will meet specifications. Thermoset prepreg material that requires refrigerated storage should be kept refrigerated so that its remaining shelf life will be well defined. Failure to refrigerate, or leaving the material at room temperature for unknown periods, is a common handling error that results in partial curing, lack of drape and tack quality, and material that is worthless for reuse. If such material is used in components because its condition was not known, serious safety hazards could result. Similar, appropriate care should be given to fibers, resins, and curing agents.

11.7.2.2 Packaging

Unused precursors should be returned to the original packaging and sealed to exclude moisture, air, and other contaminants. If the original packing materials are inappropriate, or too large to store the reduced volume of precursor, other packaging that will match the original protection quality should be used. Packages that are left unsealed can cause a significant degradation of material properties.

11.7.2.3 Documentation of care

Material property, constituents, care, etc. must be documented for the materials to be used for critical applications. This section describes some of the types of requirements for composite and precursor materials exchange. If proper care is taken of surplus precursors, but that care is not properly documented, the quality of the material cannot be guaranteed and it cannot be used with confidence. For thermoset prepreg materials, for instance, a tracking log should be maintained that records the duration of exposures to atmosphere and to non-refrigerated temperatures. This log should accompany the material when it is shipped to the materials exchange service or to other users.

11.7.2.4 Description of unused materials

A complete description of the nature of the unused materials should be transmitted together with them. The type of fiber(s), matrix, and any other information should be copied from the original procurement so that the exchange service or other users will be informed about the composition.

11.7.2.5 DOD resale restrictions

In many cases the DOD places restrictions on the disposal of unused materials from DOD-supported projects. Intended to prevent corruption, these restrictions can prevent the resale or transfer of unused materials until they have negligible residual value. Organizations attempting to exchange composite precursors should be aware of any conflicting legal and contractual stipulations.

11.8 RECYCLING OF COMPOSITE MATERIALS

If reuse or reconfiguration of composite components or materials is not possible, recycling provides the next highest value returned from the recyclable composite or precursor. This section provides guidelines to facilitate recycling and designing in recyclability.

11.8.1 Design for disassembly and recycling

Design for disassembly and recycling can greatly facilitate the recycling process for end-of-service-life components and systems. Component designers are already constrained by numerous requirements such as weight, envelope, strength, and toughness, so including the additional factors of recyclability may be difficult to implement in some cases. If design is performed while keeping in mind factors that either enhance or hinder disassembly and recycling, then better choices can be made at various decision points in the design process.

11.8.1.1 Fasteners

The choice of fastener can have a major impact on the ease of disassembly and recycling. Where possible, metal fastener inserts should be avoided, as they are difficult to remove during processing and present a source of contamination. Currently, adequate substitutes for metal fasteners do not exist for many applications. Research to develop such fasteners is required. These inserts should, ideally, be made from the same material as the rest of the composite component or at least material that is compatible with the matrix digestion process.

11.8.1.2 Adhesives

Whenever possible, adhesives for thermoplastic matrices should be selected that are compatible with the resins they are bonding after the melting and mixing operations involved in recycling. Many adhesives for thermoplastics are not compatible and would seriously degrade the properties of the recycled plastic or composite.

Compatibilizers have been developed that can allow some otherwise incompatible combinations of thermoplastics to be recycled in mixed form. It may be feasible to develop systems of adhesives, matrices, and compatibilizers that would expand the available range of recyclable adhesives and their properties.

Various welding processes are available as alternative bonding techniques that do not introduce foreign material and so produce bonds that are inherently recyclable.

11.8.1.3 Hybrid composites

Composite materials that use more than one type of fiber, such as aramid/carbon fiber structures, are far more difficult to shred and recycle than composites made with a single fiber type. After shredding and matrix digestion, the mix of fibers that results is difficult to reuse and so of much lower value than a single type of fiber would be. The use of hybrid composites should be avoided unless it is necessary to yield significant design advantages.

11.8.2 Recycling logistics

The logistics of recycling are of great importance for ensuring both the economic viability and quality of the properties of recycled materials that are produced. If the logistics of the recyclate collections system are inefficient or place an undue burden on those performing the collection, the process will probably fail.

11.8.2.1 Collection and transportation

Efficient collection of materials for recycling is an essential component of any economically successful recycling program.

Collection and recycling of pre-consumer waste, that is, seconds, overruns, and other scrap generated in-plant has a major recycling advantage because of the relative ease of collection, sorting, and quality control. Components that cannot be used because they do not meet specifications have the recycling advantages of containing a known matrix, a known fiber, and a known processing history. They are also available with minimal to no shipping costs. The case for in-plant recycling can be made to the manufacturer of composite materials that they have paid for the material in rejects and other waste, and should, therefore, seek uses for that material, rather than paying again for its disposal.

Shredded or ground reject components makes a particularly attractive filler or core material because it is made from an identical matrix and fibers as the rest of the components (References 11.8.2.1(a) - (c)). For the fiberglass boat industry, for instance, manufacturers collect the hatches and other cut outs, shred it, and use it as a replacement for wood core material.

11.8.2.2 Identification of fibers and matrices

Recycling of polymers is greatly facilitated by keeping the polymer waste streams separate. Mixed plastics usually have no value as structural materials because incompatibility of different polymers results in negligible mechanical strength. Keeping waste streams separate is generally easier than separating mixed waste streams.

Similar considerations apply in many cases to recycling of composites. If the waste stream has become mixed, containing vinyl ester/fiberglass and carbon fiber/epoxy, for instance, the process conditions required for shredding and digesting the different matrices will be less efficient, and the value of the reclaimed fibers will be greatly reduced by admixture. Although some types of fibers can be readily, visually distinguished, different types of carbon fibers are not distinguishable without elaborate and costly tests. It is strongly advised that the composite waste streams be kept separate throughout the collection, storage, and recycling processes.

11.8.2.2.1 Fourier transform infrared spectroscopy

Fourier transform infrared spectroscopy (FTIR) has been used as an identification tool for polymers sortation systems. The reflected infrared spectra of polymer containers, for instance, are acquired and correlated with stored spectra for the different classes of polymers that are recycled. The best match is found and each container is routed to the appropriate storage bin. Similar techniques could be applied to composite materials to identify their matrix material. Surface coatings such as paint or radar absorbing materials make FTIR more difficult. These surfaces must be removed before testing.

11.8.2.2.2 Densitometry

Density differences can be utilized as a simple, efficient means for segregating certain types of polymers and composite materials. For polymer separation, for instance, passage along a simple water trough can be used to separate polyethylene from other plastics. Similar processes with the fluid density increased by addition of a salt may be applicable to efficient sortation of polymer composites with different fiber and matrix densities.

11.8.2.2.3 Coding of components

Sortation of common plastics is facilitated by a coding system in which classifications are embossed on polymer containers. The system is comprised of seven classifications of polymer, such as polyethylene, polypropylene, PVC, and so forth. After consumer use, containers may be sorted by simply reading these numbers. Implementation of a similar classification system in which composites consisting of compatible fibers and matrices are placed in defined categories may be a useful approach to facilitating the eventual recycling of post-consumer composite products.

11.8.2.2.4 Routing of waste streams

This section is reserved for future use.

11.8.3 Processing of composite recyclate

This section describes some of the processes that have been developed for recycling of cured composite materials. Techniques for recycling or using waste prepreg materials are discussed in Section 11.7.4.

11.8.3.1 Size reduction

Components that are to be recycled, rather than reused, must usually be subjected to size reduction by shredding or grinding as a first process step. Steel knife shredders are commercially available that can rapidly and efficiently cut most composite materials into small pieces that are more convenient for shipping, storage, and subsequent processing. Sheet molding compound is often further reduced in size by grinding to form a filler powder. This powder is substituted for mineral fillers to produce new sheet molding compound with properties that meet the full specification requirements. The low cost of mineral filler, however, means that composite recycled in this manner is of very low value. Achieving higher value in the recyclate requires that the fibers be left with sufficient fiber length/diameter ratio to provide significant reinforcement.

After size reduction, recycled composite can be directly incorporated into new material to replace plywood, foams, or honeycomb cores. New composite can also be made by using shredded composite chips with new matrix material to produce a chipboard-like material.

11.8.3.2 Matrix removal

To recover fibers for reuse, they must generally be separated from the matrix material. Both thermoset and thermoplastic matrices can be readily digested by thermal, chemical, or thermochemical means without substantial fiber degradation. This section describes the current state of efforts to develop matrix removal processes.

Four matrix removal techniques have been used in attempts to develop recycling methods specifically for composite materials. These include catalytic conversion, reverse gasification, pyrolysis with indirect heating, and pyrolysis in fluidized beds. There are problems with each of these techniques, but refinement may make any of them technically and commercially viable.

Catalytic conversion of composite matrices is a technique that has been developed to remove matrix material at low temperatures (References 11.5.3.1(a) - (c), 11.8.3.2(a) - (d)). The process converts the matrix to a low molecular weight gas, which is removed for further processing or used as fuel. Because of the presence of a proprietary catalyst, matrix is removed at a relatively low processing temperature, on the order of 482°F (250°C), and fiber strength retention is likely to be good. Low temperatures also help to keep energy and reactor costs down, improving the chances of commercial viability. The technique has successfully decomposed epoxy matrix composites and other polymer materials, but was less effective with PEEK and PMR-15 matrices. The current implementation of this process involves a continuous feed reactor capable of processing 5 - 10 kg/hour of scrap composite. Efforts are being made to transition the process to a pilot plant scale operation.

Reverse gasification has been applied to composite recycling by the University of Missouri at St. Louis working under a grant from the Department of Energy (References 11.2.1(b) and 11.2.2(c)). Waste composites and oxygen are fed into a reactor that operates at a high temperature to yield separated fibers and a combustible gas. The high temperatures required have the disadvantage of necessitating an expensive reactor and high energy costs, however, the method has an advantage in that it can be applied to any organic matrix material.

Fluidized bed combustion has been applied at the University of Nottingham, UK, in an effort to recover glass fibers from polyester sheet molding compound. The SMC was crushed and sized to <25 mm and fluidized by air. The fibers were subsequently recovered with a cyclone separator. The tensile strength of the fibers was found to be approximately 50% of that of the virgin fibers, and was found to be a function of bed temperature.

11.8.3.3 Fiber reuse

Fibers extracted from recycled composite materials represent the highest value and, therefore, the greatest potential economic driver for the process. The high cost of carbon fibers, which is not likely to go below $5/Lb in the foreseeable future, and their limited supply, provides a high value, reliable market for recyclate, a prime requisite for any successful recycling operation.

The mechanical properties of composites fabricated from recycled fibers are influenced by their strength and length distributions, and by their interfacial bonding. Degradation of fiber tensile strength by processing induced defects is a particular concern because very small surface defects can have a significant impact, and some of the potential matrix removal methods may have an affect on the fiber surface.

A potential application for recycled fibers is their combination with recycled polymers derived from other sources to produce a low cost composite material (References 11.8.3.3(a) - (b)). The fibers may help to mitigate the effects of mixed polymers, or of other contaminants by providing reinforcement.

11.8.3.4 Products of matrix removal

The composition of the products of matrix decomposition depends on the process used in their removal. Low temperature catalytic conversion primarily produces low molecular weight hydrocarbons in the form of a gas (References 11.2.2(a), 11.5.3.1(a) - (c), and 11.8.3.2(a) - (d)). This material may be distilled for use as a chemical feedstock or used as a fuel. The makeup of the hydrocarbons is somewhat dependent on the composition of the matrix material.

Matrix removal by reverse gasification yields a burnable gas when the process parameters are properly controlled (Reference 11.2.2(b)). This gas may be used for energy to drive the process, or compressed and stored for later use.

Matrix decomposition by fluidized bed combustion oxidizes the matrix in the bed, yielding energy and oxidation products. With sheet molding compounds (SMC) containing calcium carbonate fillers, the composite may be combusted along with coal to result in reduced emissions of sulfur oxides.

11.8.3.5 Other recycling and processing methods

Waste composite materials can also be recycled by grinding, or used in waste-to-energy incinerators to recover their value as an energy source. These techniques do not yield as much value from the composite as the methods that recover fibers intact, but may be appropriate for low value composites such as fiberglass and SMC.

Grinding has been used to recycle process waste SMC for a number of years (References 11.8.3.5(a) - (g)). Because glass fibers are inexpensive, it is necessary for recycled glass fibers to be recovered at very low cost for a fiber recovery-type recycling process to be economically viable for that material. Grinding is a less expensive operation than current fiber recovery methods. The products of grinding, however, have very low value because they are used as a substitute for the inorganic fillers in SMC, which are very low cost materials.

Waste-to-energy incineration is a relatively simple process that may be the most economically viable disposal technique for some kind of composite materials. Toxic emissions can be generated from some kinds of matrices, however, and so emission control scrubbers are required. It is also possible for carbon fibers to escape through exhaust flues, travel long distances, and short out electrical transmission wires. Waste-to-energy conversion is not considered to be a recycling process, although it is sometimes referred to as “quaternary recycling,” but is at least preferable to landfilling if done properly.

An assessment of various techniques for processing glass fiber reinforced plastic has been made (Reference 11.8.3.5(h)) in an effort to quantitatively determine the economic viability of different techniques.

11.8.4 Recycling of waste prepreg

Prepreg materials constitute a major portion of the waste composite material generated by composite manufacturers, over 65% according to one survey. In 1995 approximately 1.9 million pounds of waste carbon fiber prepreg was generated (Reference 11.2.1(b)).

Most waste prepreg material is generated as a result of nesting inefficiency during composite lay-up. Approaches to reducing the generation of this waste are described in Section 11.5.3.1. This section describes methods that have been applied to the reuse or recycling of prepreg scraps.

The highest value can be obtained from waste prepreg by reusing it to fabricate composite components. Waste prepreg at its source contains the correct proportions of uncured matrix and virgin fibers of known composition and processing characteristics. For the additional effort of assembling the prepreg into components and curing it, composite components can be produced and waste disposal rendered unnecessary.

Matrix removal by catalytic conversion has been successfully applied to prepreg material (Reference 11.2.2(a) - (b), 11.3(b)), completely removing the matrix and yielding fibers with high residual tensile strength. The technique worked in spite of the presence of silicone-treated release layers, making their removal unnecessary. A tendency of the prepreg to jam at the system’s intake was noted.

An effort to recycle waste prepreg by shredding it to produce a sheet-molding compound was investigated by McDonnell Douglas Corporation (Reference 11.2.2(a)). Other efforts to develop methods to recycle (Reference 11.8.4(a)) or reuse (Reference 11.8.4(b)) scrap prepreg are underway.

REFERENCES

11.2.1(a) Composite Prepreg Scrap Reclamation Program, McDonnell Douglas Corporation, MDC 95P0078, Final Report, Contract Number N00014-90-CA-0002 for Great Lakes Composites Consortium, 1995.

11.2.1(b) Unser, J.F., "Advanced Composites Recycling/Reuse Program," Final Report, WL-TR-95-7014, Wright Laboratory, Armament Directorate, Eglin AFB, FL, April 1995.

11.2.2(a) Allred, R.E., and Salas, R.M., "Chemical Recycling of Scrap Composites," Proc. AIA, SACMA, and NASA Joint Conference on Environmental, Safety, and Health Considerations, - Composite Materials in the Aerospace Industry, Phoenix, AZ, Oct. 20-21, 1994.

11.2.2(b) Eriksson, P.-A., Albertsson, A.-C., Boydell, P., Prautzsch, G., Manson, J.-A.E., Prediction of Mechanical Properties of Recycled Fiberglass Reinforced Polyamide 66, Polymer Composites, Vol. 17, No. 6, Dec. 1996, pp. 830-839.

11.2.2(c) Unser, J.F., Staley, T., and Larsen, D., "Advanced Composites Recycling," SAMPE Journal, Vol. 32, No. 5, Sept./Oct. 1996, pp. 52-57.

11.2.2(d) Allred, R.E., and Salas, R.M., Recycling Process for Aircraft Plastics and Composites, Final Report, Contract F08635-93-C-0109, December 1993, AT-93-5133-FR-001.

11.3(a) Thayer, A. "Plastics Recycling Up, but End Markets Down," Chemical & Engineering News, June 8, 1992, pp. 6.

11.3(b) Alexander, M., "The Challenge of Markets: The Supply of Recyclables is Larger than the Demand," EPA Journal, July/Aug. 1992, pp. 29-33.

11.5.3.1(a) Allred, R.E., Salas, R.M., and Gordon, B.W., "Tertiary Recycling Process for Plastics, Composites, and Electronic Materials," Proc. 40th Intl. SAMPE Symp. and Exhib., Anaheim, CA, May 8-11, 1995, pp. 1794-1805.

11.5.3.1(b) Allred, R.E., "Recycling Process for Scrap Composites and Prepregs," Proc. 41th Intl. SAMPE Symp. and Exhib., Anaheim, CA, March 24-28, 1996, pp. 21-31.

11.5.3.1(c) Allred, R.E., Coons, A.B., and Simonson, R., "Properties of Carbon Fibers Reclaimed from Composite Manufacturing Scrap by Tertiary Recycling," Proc. 28th Intl. SAMPE Tech. Conf., Seattle, WA, Nov. 4-7, 1996, pp. 139-150.

11.8.2.1(a) Pettersson, J. "Recycled Reinforced Plastics as Replacement for Coremat and Plywood Cores in Sandwich Laminate: A Comparison of Mechanical Properties," SPI 1996.

11.8.2.1(b) McDermott, J., "Fiberglass Recycling: Earning Respect," Composite Fabrication, May 1996.

11.8.2.1(c) "Process for Separating Fibres from Composite Materials," International Patent Application, International Publications No: WO93/05883, Phoenix Fiberglass Inc., April 1, 1993.

11.8.3.2(a) Allred, R.E., Doak, T.J., Coons, A.B., Newmeister, G.C., and Cochran, R.C., "Tertiary Recycling of Cured Composite Aircraft Parts," Proc. Composites '97 Manufacturing and Tooling Conf., Society of Manufacturing Engineers, Dearborn, MI 1997, pp. EM97-110 to EM97-110-17.

11.8.3.2(b) Allred, R.E., and Busselle, L.D., "Economical Recycling Process for Mixtures of Electronic Scrap," Proc. 1997 IEEE Int'l Symp. On Electronics and the Environment, IEEE, Piscataway, NJ, 1997, pp. 115-120.

11.8.3.2(c) Allred, R.E., Doak, T.J., Gordon, B.W., Harrah, L.A., and Hoyt, A.E., "Catalytic Conversion Process for Recycling Navy Shipboard Plastic Wastes," Polymeric Materials Science and Engineering, Vol. 76, American Chemical Society, Washington, DC, 1994, pp. 578-579.

11.8.3.2(d) Allred, R.E., Doak, T.J., and Coons, A.B., "Recycling Process for Automotive Plastics and Composites," Proc. 12th Annual Am. Society for Composites Tech. Conf., Dearborn, MI, Oct. 6-8, 1997.

11.8.3.3(a) Xanthos, M., Grenci, J., Patel, S.H., Jacob, C., Dey, S., and Dagli, S.S., Thermoplastic Composites from Maleic Anhydride Modified Post-Consumer Plastics, Polymer Composites, June 1995, Vol. 16, No. 3, pp. 204-214.

11.8.3.3(b) Kimura, T., Takeuchi, M., and Nakanishi, K., Recyclability of Waste Cord of Synthetic Fibers as Matrix Material of Thermoplastic Hybrid Composites, Proceedings of Tenth International Conference on Composite Materials (ICCM – 10), 1996, Volume IV, pp. 373-380.

11.8.3.5(a) Recycled SMC Now in Appearance Parts," Plastics Technology, Oct. 1993, pp. 94.

11.8.3.5(b) Etterson, J., and Nilsson, P., "Recycling of SMC and BMC in Standard Process Equipment," J. of Thermoplastic Composite Materials, Vol. 7, Jan. 1994.

11.8.3.5(c) Inoh, T, et. al., "SMC Recycling Technology," J. of Thermoplastic Composite Materials, Vol. 7, Jan. 1994.

11.8.3.5(d) Mapleston, P. Auto Sector’s Recycling Goals Keep Plastics on Hot Seat, Modern Plastics, May 1995, pp. 48-56.

11.8.3.5(e) Allred, R.E., Recycling Process for Automotive Plastics and Composites, Project Title: Tertiary Recycling Process for Polymer-Based Automotive Components, SBIR Phase I Final Report, NSF Award Number DMI-9660673, 1997.

11.8.3.5(f) Update on Recycling Automotive Plastics, Automotive Engineering, August 1997, pp. 41-44.

11.8.3.5(g) Design for Recycling, Automotive Engineering, August 1997, pp. 46-48.

11.8.3.5(h) Fiber Reinforced Plastics: Planning for Profitable Reuse, Recycling Feasibility Final Report, for Minnesota Technology, Inc. funded by and available from Minnesota Office of Environmental Assistance, 520 Lafayette Rd. St. Paul, MN 55155, 1993.

11.8.4(a) Michaeli, W., and Oelgarth, A., New Technologies for Processing of Non-Cured Prepreg Waste – Preparation of High-Strength DMC, Proceedings, 41st International SAMPE Symposium, March, 1996, pp. 1551-1562.

11.8.4(b) Unser, J., Reuse of Scrap Prepreg, Proceedings of 42nd International SAMPE Symposium, May 4-8, 1997, pp. 216-224.