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SUMMARY OF POLYMER MATRIX PROCESSING

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Exam Preview:

1. The feature common to all composite processes is the combining of a resin, a curing agent, some type of reinforcing fiber, and in some cases a solvent.
 - a. True
 - b. False
2. According to the reference material, which of the following common thermosets is most commonly used in today’s PMC Industry?
 - a. Phenolic and amino resins
 - b. Polyamides
 - c. Epoxies
 - d. Polyurethanes
3. Thermoplastic resins require addition of a curing agent or hardener and impregnation onto a reinforcing material, followed by a curing step to produce a cured or finished part. Once cured, the part cannot be changed or reformed, except for finishing.
 - a. True
 - b. False
4. Which of the following is NOT a type of fiber reinforcement material that is discussed in the reference material?
 - a. Carbon/graphite
 - b. Aramid
 - c. Glass
 - d. Asbestos
5. Which of the following composite process is described by the following:
Thermoplastic granules are fed via a hopper into a screw-like plasticating barrel where

melting occurs. The melted plastic is injected into a heated mold where the part is formed.

- a. Injection molding
 - b. Resin transfer molding
 - c. Automated tape lay-up
 - d. Prepregging
6. According to the reference material, the potential for respiratory exposure is typically much greater than dermal exposure when working with epoxies.
 - a. True
 - b. False
7. Which of the following composite process is described by the following: continuous roving strands are pulled from a creel through a strand-tensioning device into a resin bath. The coated strands are then passed through a heated die where curing occurs. The continuous cured part, usually a rod or similar shape, is then cut to the desired length.
 - a. Hand lay-up of prepreg
 - b. Resin transfer molding
 - c. Pultrusion
 - d. Prepregging
8. Using Table III:1-1. Organ System Target, what is the common possible targeted organ system for reinforcing materials?
 - a. Skin
 - b. Lungs
 - c. Eyes
 - d. Liver
9. According to the reference material, in June 1987, the International Agency for Research on Cancer (IARC) categorized continuous-filament glass fibers as not classifiable with respect to human carcinogenicity.
 - a. True
 - b. False
10. Which of the following characteristics is NOT a useful characteristic of aramid fibers as outlined by the reference material?
 - a. Textile processibility
 - b. High strength
 - c. Flex performance
 - d. Chemically inert

Polymer Matrix Materials: Advanced Composites

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- III. The Manufacturing Process
- IV. Polymer Matrix Composite (PMC) Resin Systems
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Appendix III:1-1. Glossary

For problems with accessibility in using figures and illustrations in this document, please contact the Office of Science and Technology Assessment at (202) 693-2095.

I. Introduction

The composites industry in the United States includes three manufacturing areas: Polymers, metals, and ceramics.

A.

Composites are classified according to their matrix phase. There are polymer matrix composites (PMC's), ceramic matrix composites (CMC's), and metal matrix composites (MMC's). Materials within these categories are often called "advanced" if they combine the properties of high strength and high stiffness, low weight, corrosion resistance, and in some cases special electrical properties. This combination of properties makes advanced composites very attractive for aircraft and aerospace structural parts.

B.

This chapter deals with a segment of the polymer composite industry known as advanced polymer matrix composites, or advanced composites. Since the reinforced plastics, or polymer matrix composite industry is much larger than the subject of this chapter, the term "advanced composites" is used here to define this special segment

of the industry. Information on this industry has been developed for use by OSHA field personnel to help them understand this new and growing technology.

C.

Advanced composites have been identified as an important growth sector in U.S. manufacturing. This identification has led to more use of these materials in existing facilities as well as an increase in the number of advanced composites manufacturing locations. Field staff may expect to encounter composites more frequently in the course of their assignments. At the same time, much of the technology is new and not presented formally in secondary or undergraduate education.

D.

Information is presented here on the technology as practiced in current operations. The technology of advanced composites manufacture is continually evolving, and field personnel will learn here what to expect in these processing facilities in the way of materials handled, manufacturing methods, machinery, potential worker exposures, and other relevant health and safety information.

E.

The information presented necessarily makes reference to industrial hygiene and safe work practices, but this manual is not intended to provide comprehensive guidelines for assessing compliance with regulations. Much of the terminology used in this manual is peculiar to the composites industry, and for this reason a glossary of terms has been provided in Appendix III:1-1.

II. Overview of the Industry

Polymer-matrix composites manufacturing is a multibillion dollar industry in the U.S. and one of the few in which the U.S. is conceded to be slightly more advanced than competitors abroad. Composite products range from skateboards to components of the space shuttle. The industry can be generally divided into two basic segments, industrial composites and advanced composites. Several of the composites manufacturing processes are common to both segments. The two basic segments are described below.

A. Industrial Composites

The industrial composites industry has been in place for over 40 years in the U.S. This large industry utilizes various resin systems including polyester, epoxy, and other specialty resins. These materials, along with a catalyst or curing agent and some type of fiber reinforcement (typically glass fibers) are used in the production of a wide spectrum of industrial components and consumer goods: boats, piping, auto bodies, and a variety of other parts and components.

B. Advanced Composites

1. This sector of the composites industry is characterized by the use of expensive, high-performance resin systems and high-strength, high-stiffness fiber reinforcement. The aerospace industry, including military and commercial aircraft of all types, is the major customer for advanced composites. These materials have also been adopted for use by the sporting goods suppliers who sell high-performance equipment to the golf, tennis, fishing, and archery markets.
2. While aerospace is the predominant market for advanced composites today, the industrial and automotive markets will increasingly see the use of advanced composites toward the year 2000. At present, both manual and automated processes are employed in making advanced-composite parts. As automated processes become more predominant, the costs of advanced composites are expected to decline to the point at which these materials will be used widely in electronic, machinery, and surface transportation equipment.

3. Suppliers of advanced composite materials tend to be larger companies capable of doing the research and development necessary to provide the high-performance resin systems used in this segment of the industry. End-users also tend to be large, and many are in the aircraft and aerospace businesses.
4. Advanced composite systems are divided into two basic types, thermosets and thermoplastics. Thermosets are by far the predominant type in use today. Thermosets are subdivided into several resin systems including epoxies, phenolics, polyurethanes, and polyimides. Of these, epoxy systems currently dominate the advanced composite industry. Both thermoset and thermoplastic systems will be discussed in more detail in Section IV of this chapter.

III. The Manufacturing Process

A. Elements

The feature common to all composite processes is the combining of a resin, a curing agent, some type of reinforcing fiber, and in some cases a solvent. Typically, heat and pressure are used to shape and "cure" the mixture into a finished part. In composites, the resin acts to hold the fibers together and protect them, and to transfer the load to the fibers in the fabricated composite part. The curing agent, also known as hardener, acts as a catalyst and helps in curing the resin to a hard plastic. The reinforcing fiber imparts strength and other required properties to the composite. Solvents may serve three purposes:

- as part of the resin mixture;
- as part of the process; and
- as a cleaning agent for removing residue from the process equipment.

B. Major Processes

Diagrams of the major processes used in the advanced composites industry are provided in Section A of this chapter. The processes vary widely in type of equipment and potential worker exposure. Several of the processes are automated; however, some are manual and require worker contact with the part during manufacture. The basic process types are described below.

1. **Formulation** is the process where the resin, curing agent, and any other component required are mixed together. This process may involve adding the components manually into a small mixing vessel or, in the case of larger processes, the components may be pumped into a mixing vessel. The potential hazards involve skin, eye, and respiratory contact with the ingredients or final formulation.
2. **Prepregging** is the process where the resin and curing agent mixture are impregnated into the reinforcing fiber. These impregnated reinforcements (also known as prepregs) take three main forms: woven fabrics, roving, and unidirectional tape. Fabrics and tapes are provided as continuous rolls in widths up to 72 inches and lengths up to several hundred feet. The fabric or tape thickness constitutes one ply in the construction of a multi-ply layup. Impregnated roving is wound onto cores or bobbins and is used for filament winding. Once the resin mixture has been impregnated onto the fibers, the prepreg must be stored in a refrigerator or freezer until ready for use in the manufacturing process. This cold storage prevents the chemical reaction from occurring prematurely. Prepreg materials are used widely in the advanced composite industry, particularly in aircraft and aerospace. Potential exposure is generally from handling of the fiber or resin.
3. **Open Molding** processes are those where the part being manufactured is exposed to the atmosphere. The worker typically handles the part manually, and there is a higher potential for exposure. The resin mixture may be a liquid being formed onto a reinforcing material or it may be in the form of a prepreg material being formed for final cure.
4. **Closed Molding** processes are those in which all or part of the manufacture takes place in a closed vessel or chamber. The liquid resin mixture or prepreg material may be handled or formed manually into the container for the curing step. In the case of liquid resin mixtures, these may be pumped into the container, usually a mold of

some type, for the curing step. These processes usually have less worker exposure potential, particularly if the entire process is closed.

5. **Sequential or batch** processes involve manufacture of a single part at a time, in sequence. This type of process is usually required where the part being made is small and complex in shape, when the curing phase is critical, when finishing work must be minimized, or where a small number of parts is involved.
6. **Continuous** processes are typically automated to some degree and are used to produce larger numbers of identical parts relatively quickly. These processes are typified by pumping of the resin mixture into the mold, followed by closed curing.

IV. Polymer Matrix Composite (PMC) Resin Systems

The advanced composite processes are discussed in more detail in Section V of this chapter. Seven manufacturing processes are covered, along with two preliminary processes and two finishing processes. The number and variety of processes should give some indication of the wide spectrum of workplaces likely to be encountered by field personnel. Potential worker exposure obviously will also vary widely, depending on the size and type of process being used. Since the advanced composite industry is relatively new and still developing, other processes may be developing or changing to meet new performance requirements. Advanced composites exhibit desirable physical and chemical properties that include light weight coupled with high stiffness and strength along the direction of the reinforcing fiber, dimensional stability, temperature and chemical resistance, flex performance, and relatively easy processing. Advanced composites are replacing metal components in many uses, particularly in the aerospace industry.

A. Resins

The resin systems used to manufacture advanced composites are of two basic types: thermosetting and thermoplastic. Thermosetting resins predominate today, while thermoplastics have only a minor role in advanced composites manufacture.

B. Thermosets

1. Thermoset resins require addition of a curing agent or hardener and impregnation onto a reinforcing material, followed by a curing step to produce a cured or finished part. Once cured, the part cannot be changed or reformed, except for finishing. Some of the more common thermosets include:
 - epoxies
 - polyurethanes
 - phenolic and amino resins
 - bismaleimides (BMI, polyimides)
 - polyamides
2. Of these, epoxies are the most commonly used in today's PMC industry. Epoxy resins have been in use in U.S. industry for over 40 years. The basic epoxy compounds most commonly used in industry are the reaction product of epichlorohydrin and bisphenol-A. Epoxy compounds are also referred to as glycidyl compounds. There are several types of epoxy compounds including glycidyl ethers (or diglycidyl ethers), glycidyl esters, and glycidyl amines. Several of these compounds are reactive diluents and are sometimes added to the basic resin to modify performance characteristics. The epoxy molecule can also be expanded or cross-linked with other molecules to form a wide variety of resin products, each with distinct performance characteristics. These resins range from low-viscosity liquids to high-molecular weight solids. Typically they are high-viscosity liquids.
3. Since epoxies are relatively high molecular-weight compounds, the potential for respiratory exposure is fairly low. The potential for respiratory exposure is increased when the resin mixture is applied by spraying or when curing temperatures are high enough to volatilize the resin mixture. The potential for dermal exposure is typically much greater than respiratory exposure when working with epoxies. Several advanced composite

processes involve some worker contact with the resin mixture. These and the other processes are discussed in more detail in Section V of this chapter.

4. The second of the essential ingredients of an advanced composite system is the curing agent or hardener. These compounds are very important because they control the reaction rate and determine the performance characteristics of the finished part. Since these compounds act as catalysts for the reaction, they must contain active sites on their molecules.
5. Some of the most commonly used curing agents in the advanced composite industry are the aromatic amines. Two of the most common are 4,4'-methylene-dianiline (MDA) and 4,4'-sulfonyldianiline (DDS). Like the epoxies, these compounds have a very low vapor pressure and usually do not present an airborne hazard unless in a mixture that is sprayed or cured at high temperatures. However, potential for dermal exposure is frequently high. The aromatic amines may permeate many of the commonly used protective gloves and thus may be particularly difficult to protect against.
6. Several other types of curing agents are also used in the advanced composite industry. These include aliphatic and cycloaliphatic amines, polyaminoamides, amides, and anhydrides. Again, the choice of curing agent depends on the cure and performance characteristics desired for the finished part.
7. Polyurethanes are another group of resins used in advanced composite processes. These compounds are formed by reacting the polyol component with an isocyanate compound, typically toluene diisocyanate (TDI); methylene diisocyanate (MDI) and hexamethylene diisocyanate (HDI) are also widely used. While the polyols are relatively innocuous, the isocyanates can represent a significant respiratory hazard as well as a dermal hazard.
8. Phenolic and amino resins are another group of PMC resins. With respect to the phenol-formaldehyde resins, the well-known hazards of both phenol and formaldehyde must be protected against. In addition to traces of free formaldehyde, they may also contain free phenol, and contact with these resins in the uncured state is to be avoided. The urea- and melamine-formaldehyde resins present similar hazards. Free formaldehyde, which is present in trace amounts and may be liberated when their resins are processed, can irritate the mucous membranes.
9. The bismaleimides and polyamides are relative newcomers to the advanced composite industry and have not been studied to the extent of the other resins.

C. Thermoplastics

Thermoplastics currently represent a relatively small part of the PMC industry. They are typically supplied as nonreactive solids (no chemical reaction occurs during processing) and require only heat and pressure to form the finished part. Unlike the thermosets, the thermoplastics can usually be reheated and reformed into another shape, if desired.

D. Fiber Reinforcements

1. Fiber reinforcement materials are added to the resin system to provide strength to the finished part. The selection of reinforcement material is based on the properties desired in the finished product. These materials do not react with the resin but are an integral part of the advanced composite system.
2. Potential worker exposure is typically higher in facilities that manufacture the fibers or use them to produce prepreg material. Most of the fibers in use are considered to be in the nonrespirable range. However, they do have the potential to cause eye, skin, and upper respiratory tract irritation as a result of the mechanical properties of the fibers.
3. The three basic types of fiber reinforcement materials in use in the advanced composite industry are:
 - carbon/graphite
 - aramid
 - glass fibers

Fibers used in advanced composite manufacture come in various forms, including:

- yarns

- rovings
- chopped strands
- woven fabric
- mats

Each of these has its own special application. When prepreg materials are used in parts manufacture, woven fabric or mats are required. In processes such as filament wet winding or pultrusion, yarns and rovings are used.

4. The most commonly used reinforcement materials are carbon/graphite fibers. (The terms graphite and carbon are often used interchangeably.) This is due to the fact that many of the desired performance characteristics require the use of carbon/graphite fibers. Currently, these fibers are produced from three types of materials known as precursor fibers:

- polyacrylonitrile (PAN)
- rayon
- petroleum pitch

The carbon/graphite fibers are produced by the controlled burning off of the oxygen, nitrogen, and other noncarbon parts of the precursor fiber, leaving only carbon in the fiber. Following this burning off (or oxidizing) step, the fibers are run through a furnace to produce either carbon or graphite fibers. Carbon fibers are produced at furnace temperatures of 1,000-2,000° C, while graphite fibers require temperatures of 2,000-3,000° C. At these temperatures the carbon atoms in the fibers are rearranged to impart the required characteristics to the finished fiber. The PAN-based fiber is the more commonly used precursor in the advanced composite industry today.

5. Aramid fibers are another human-made product. These fibers are produced by manufacturing the basic polymer, then spinning it into either a paper-like configuration or into fiber. Aramid fibers have several useful characteristics:

- high strength and modulus;
- temperature stability;
- flex performance;
- dimensional stability;
- chemical resistance; and
- textile processibility.

6. Textile (continuous filament) glass fibers are the type used in composite reinforcement. These fibers differ from the wool type in that they are die-drawn rather than spun.

7. A number of solvents are used in the advanced composites industry. These may be introduced into the workplace in three basic ways:

- as part of the resin or curing agent;
- during the manufacturing process; or
- as part of the cleanup process.

Most of the solvents used may be introduced in any or all of the three ways above. For this reason it would be difficult, if not impossible, to separate the solvents into the categories of use. The solvents discussed in this section are grouped by chemical class:

- ketones
- alcohols
- chlorinated hydrocarbons
- others

Several solvents may be used in any one composite process. One or more may be introduced as part of the resin or curing agent, while another may be a part of the manufacturing process. Still another may be used for cleanup. Thus the hazard information for all products used in the process must be considered when evaluating potential exposures. The supplier's Material Safety Data Sheet (MSDS) should be consulted for more specific hazard information.

Composite residues are often difficult to clean from operation equipment and molds. Various solvents have been used for cleaning, with varying degrees of success. Solvents in the workplace may be found in several areas:

- in small containers near process equipment;
- in larger containers (drums or vats) for soaking and cleaning; and
- in process equipment containers (tanks, reactors, molds, etc.).

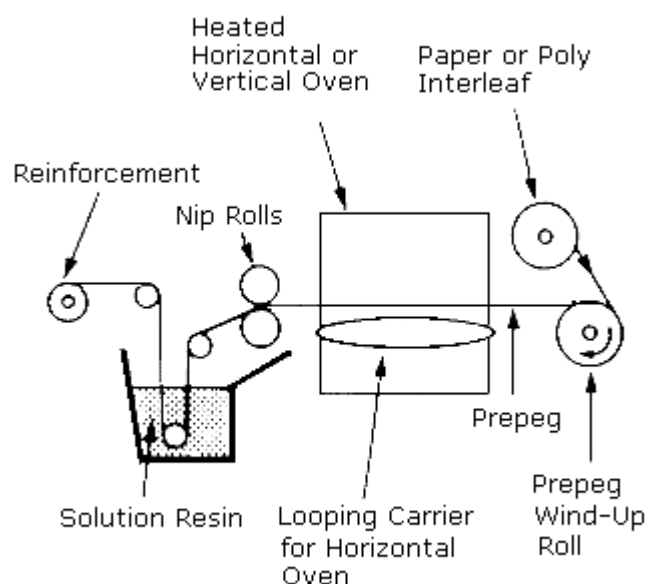
V. Description of Processes

A brief description of each process is given, followed by a basic diagram. Details on health hazard information and workplace controls are provided in Sections VI and VII of this chapter.

A. Resin Formulation

Resin formulation consists of mixing epoxy or other resins with other ingredients to achieve desired performance parameters. These ingredients may be curing agents, accelerators, reactive diluents, pigments, etc.

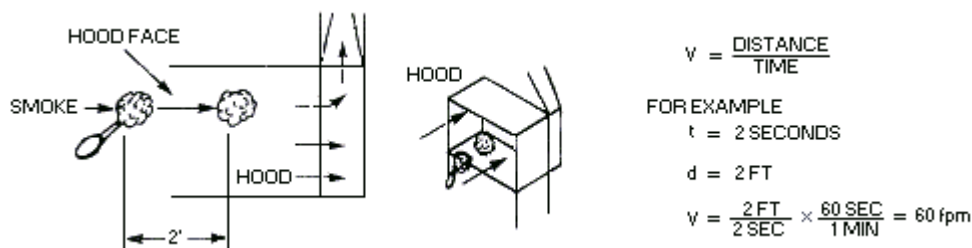
Figure III:1-1. Solution Prepregging



B. Prepregging

Prepregging involves the application of formulated resin products, in solution or molten form, to a reinforcement such as carbon, fiberglass or aramid fiber or cloth. The reinforcement is saturated by dipping through the liquid resin (solution form, see Figure III:1-1) or by being impregnated through heat and pressure (hot melt form, see Figure III:1-2).

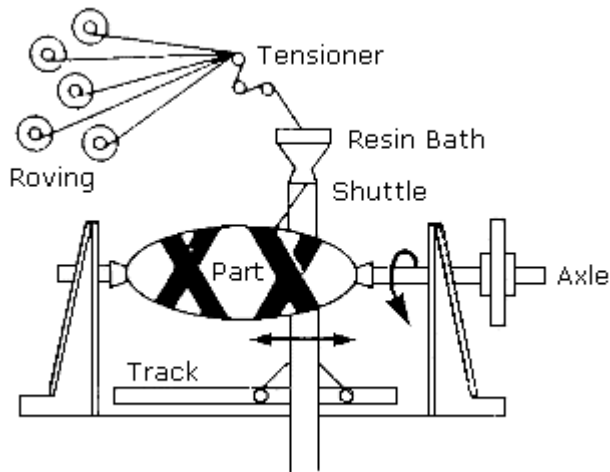
Figure III:1-2. Hot Melt Prepregging



C. Wet Filament Winding

In the filament wet winding process, continuous fiber reinforcement materials are drawn through a container of resin mixture (Figure III:1-3) and formed onto a rotating mandrel to achieve the desired shape. After winding, the part is cured in an oven.

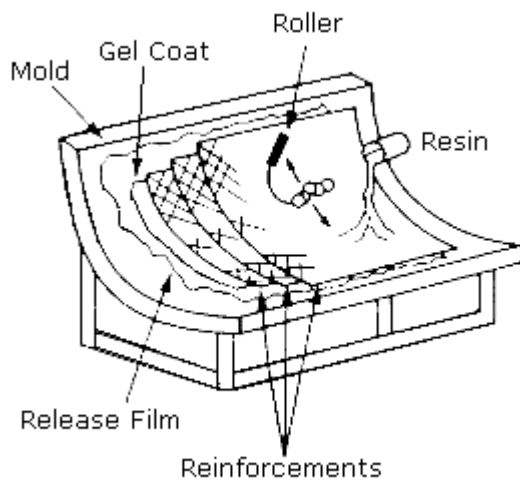
Figure III:1-3. Wet Filament Winding



D. Hand Lay-up of Prepreg

A prepreg product is laid down and formed to the desired shape (Figure III:1-4). Several layers may be required. After forming, the lay-up assembly is moved to an autoclave for cure under heat, vacuum and pressure.

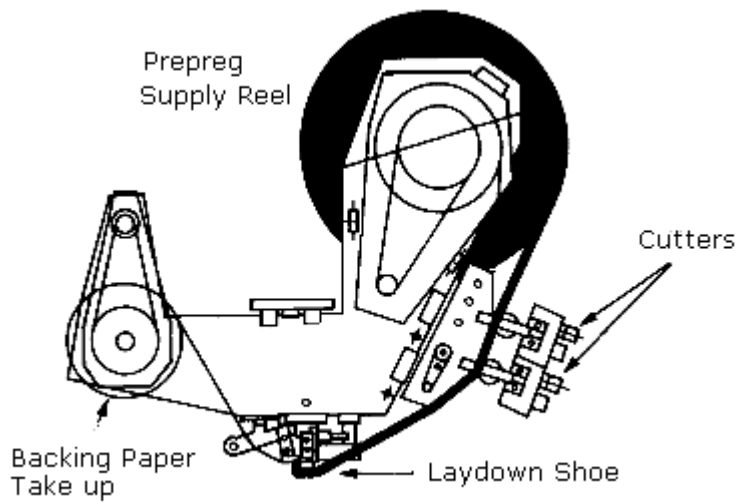
Figure III:1-4. Hand Lay-up of Prepreg



E. Automated Tape Lay-up

In this process, the prepreg tape material is fed through an automated tape application machine (robot). The tape is applied across the surface of a mold in multiple layers by the preprogrammed robot (Figure III:1-5).

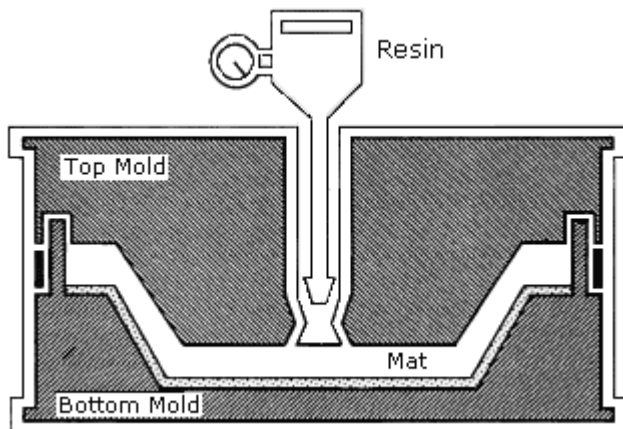
Figure III:1-5. Automated Lay-up



F. Resin Transfer Molding

Resin transfer molding is used when parts with two smooth surfaces are required or when a low-pressure molding process is advantageous. Fiber reinforcement fabric or mat is laid by hand into a mold and resin mixture is poured or injected into the mold cavity. The part is then cured under heat and pressure (Figure III:1-6).

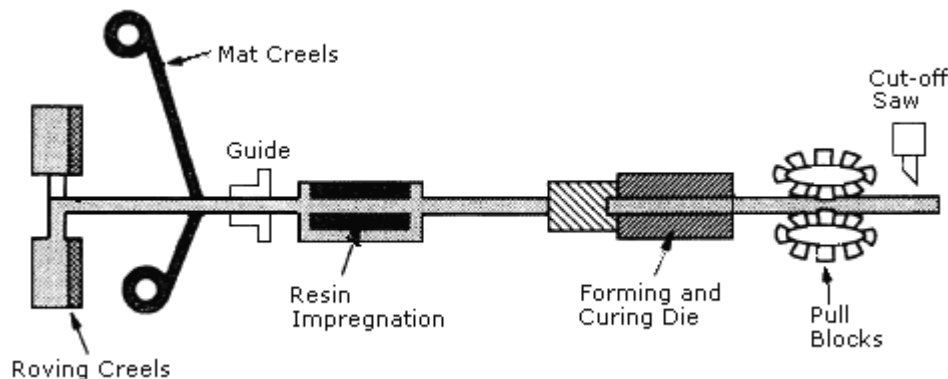
Figure III:1-6. Resin Transfer Molding



G. Pultrusion

In the pultrusion process, continuous roving strands are pulled from a creel through a strand-tensioning device into a resin bath. The coated strands are then passed through a heated die where curing occurs. The continuous cured part, usually a rod or similar shape, is then cut to the desired length (Figure III:1-7).

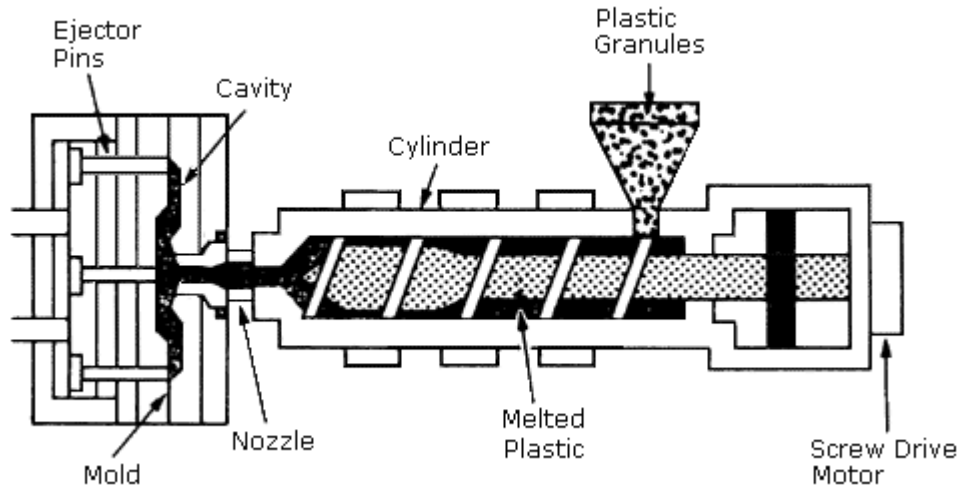
Figure III:1-7. Pultrusion



H. Injection Molding

One of the older plastics processes, injection molding is also the most closed process. It is not normally used in PMC processes due to fiber damage in the plasticating barrel. Thermoplastic granules are fed via a hopper into a screw-like plasticating barrel where melting occurs (Figure III:1-8). The melted plastic is injected into a heated mold where the part is formed. This process is often fully automated.

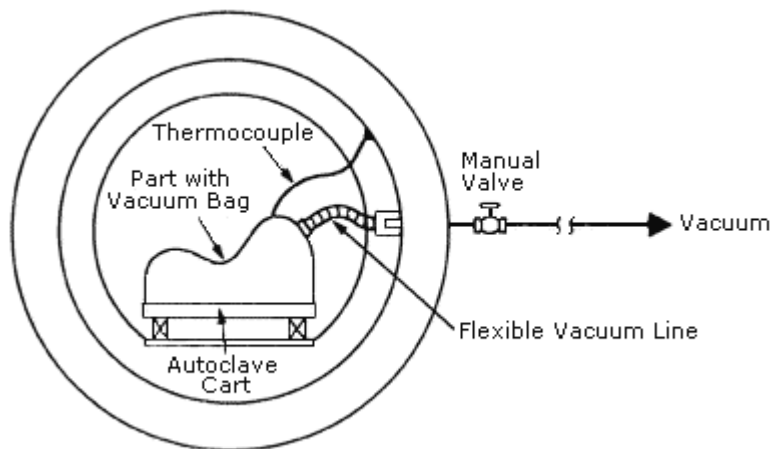
Figure III:1-8. Injection Molding



I. Vacuum Bagging & Autoclave Curing

Most parts made by hand lay-up or automated tape lay-up must be cured by a combination of heat, pressure, vacuum, and inert atmosphere. To achieve proper cure, the part is placed into a plastic bag inside an autoclave (Figure III:1-9). A vacuum is applied to the bag to remove air and volatile products. Heat and pressure are applied for curing. Usually an inert atmosphere is provided inside the autoclave through the introduction of nitrogen or carbon dioxide. Exotherms may occur if the curing step is not done properly.

Figure III:1-9. Vacuum Bagging and Autoclave



J. Machining Finishing

Many of the parts made in PMC processes require some machining and/or finishing work. This may involve drilling, sanding, grinding, or other manual touch-up work. These processes vary widely, depending on the size of the finished part and the amount of finishing work required.

K. Field Repair

Repair of damaged PMC parts is frequently required. The process may consist of several steps including cutting out of the damaged material, depainting of the surface to be repaired, patching and sanding of the damaged area, and repainting of the repaired area.

VI. Health Hazards

Potential health hazards associated with the use of advanced composites (Table III:1-1) can be controlled through the implementation of an effective industrial hygiene program. Use of safe work practices, engineering controls, and proper personal protective equipment depends upon an appreciation of health hazard information for a safe work environment.

A. Resins

The resins used in advanced composite processes have high molecular weights ($MW > 10,000$) with low vapor pressures. High molecular weight is generally associated with decreased volatility. In an epoxy system, the resin components have very low vapor pressures and they are not present as a volatilized airborne hazard.

1. As discussed earlier, **epoxy resins** are currently the most commonly used resins in the advanced composite industry. The basic epoxy molecule is a reaction product of epichlorohydrin (ECH) and bisphenol-A (BPA). Some epoxies contain trace amounts of residual ECH typically in the range of <1 to 10 ppm (by weight). Industrial hygiene air monitoring for ECH has been done in a number of workplaces, involving a variety of epoxy resin end-uses. Most of the monitoring has shown no detectable levels of ECH in the air. Uncured epoxy resins can present a significant dermal exposure hazard. In many workplaces, manual processing results in potential skin exposure. This can result in skin irritation, rashes and, subsequently, dermatitis if contact is prolonged. Sensitization to the resins can also develop and may require a change of work assignment.
2. **Polyurethane resins** are reaction products of polyols and isocyanates. The significant hazard associated with these resin systems is the presence of isocyanates. Exposure to highly toxic isocyanates can have adverse health effects. Exposure to the vapor may cause irritation of the eyes, respiratory tract and skin. Irritation may be severe enough to produce bronchitis and pulmonary edema. Polyurethane resins contacting the eyes may cause severe irritation, and if polyurethane resins are allowed to remain in contact with the skin, they may produce redness, swelling, and blistering of the skin. Respiratory sensitization (an allergic, asthmatic-type reaction) may occur. Among the isocyanates, there is also evidence of cross-sensitization, in which a worker is sensitized to one isocyanate but reacts to others as well.
3. The **phenol-formaldehyde resins** must be handled with adequate ventilation. Traces of free formaldehyde and phenol may be present. Contact with these resins should be avoided because of the toxicity of these components and the skin-absorption potential of phenol. These components may also be given off during the curing process.
4. The acute toxicity of **urea-formaldehyde resins** is very similar to the phenol-formaldehyde resins. Free formaldehyde, which is present in trace amounts and may be liberated when the resins are processed, can have an irritating effect on mucous membranes. Skin sensitization to formaldehyde has been observed.
5. The health effects of **bismaleimide resin** systems have not been extensively studied. Manufacturers of these materials indicate that prolonged or repeated contact may cause skin irritation or sensitization. Dust or vapor from heated products may cause irritation of the eyes, nose, and throat.
6. **Polyether** and **polyester polyols** present no particular health hazard in industrial processing.
7. **Thermoplastic resins** in general are not considered harmful to workers' health. These resins appear harmless when ingested, and no skin irritation has been reported. No toxic effects are known to be associated with the inhalation of thermoplastic-resin dust. Treating it as nuisance or inert dust seems appropriate, although the presence of unreacted monomers may be of concern. These materials present a thermal hazard when handling. Molding operations may give off vapors which are irritating to the eyes and cause cold-like symptoms. Some thermoplastics are styrene-based, and presence of this monomer may be of concern.

Table III:1-1. Organ System Target

Composite component	Organ system target (possible target)	Known (possible) health effect
Resins		
Epoxy resins	Skin, lungs, eyes	Contact and allergic dermatitis, conjunctivitis
Polyurethane resins	Lungs, skin, eyes	Respiratory sensitization, contact dermatitis, conjunctivitis
Phenol formaldehyde	Skin, lungs, eyes	As above (potential carcinogen)
Bismaleimides (BMI)	Skin, lungs, eyes	As above (potential carcinogen)
Polyamides	Skin, lungs, eyes	As above (potential carcinogen)
Reinforcing materials		
Aramid fibers	Skin (lungs)	Skin and respiratory irritation, contact dermatitis (chronic interstitial lung disease)
Carbon/graphite fibers	Skin (lungs)	As noted for aramid fibers
Glass fibers (continuous filament)	Skin (lungs)	As noted above
Hardeners and curing agents		
Diaminodiphenylsulfone	--	No known effects with workplace exposure
Methylenedianiline	Liver, skin	Hepatotoxicity, suspect human carcinogen
Other aromatic amines		
Meta-phenylenediamine (MPDA)	Liver, skin (kidney, bladder)	Hepatitis, contact dermatitis (kidney and bladder cancer)
Aliphatic and cyclo-aliphatic amines	Eyes, skin	Severe irritation, contact dermatitis
Polyaminoamide	Eyes, skin	Irritation (sensitization)
Anhydride	Eyes, lungs, skin	Severe eye and skin irritation, respiratory sensitization, contact dermatitis

B. Curing Agents

1. Curing agents, or hardeners, used with the epoxy resins are mostly amines, amides, or anhydrides. Two of the most widely used are the aromatic amines, MDA (4,4'-methylenedianiline) and DDS (4,4'-diaminodiphenylsulfone).
2. Analysis and review of epidemiologic data and human and animal toxicity data indicates that occupational exposure to MDA may result in reversible liver toxicity (hepatotoxicity). The retina of the eye might be damaged not only by direct contact but also from MDA absorbed through ingestion. MDA is an animal carcinogen and a suspect human carcinogen by any exposure route: ingestion, inhalation, or dermal.

3. Frequently, curing agents containing mixtures of these amines can cause skin staining in processes requiring dermal contact, even when protective gloves are used. Brown and orange stains on walls and ceilings have also been reported. The skin staining has been attributed to MDA; dermal absorption is approximately 2% per hour. Soap and water, rather than any organic solvent, should be used for skin clean-up to avoid any solvent increase of transdermal absorption.
4. The OSHA permissible exposure limits (PEL'S) for MDA are 10 ppb (parts per billion) expressed as an 8-hour time-weighted average, and a short-term exposure limit (STEL) of 100 ppb averaged over any 15-minute period for either general industry or construction uses of MDA. The FR 57(154): 35630 (August 10, 1992) issue published the Final Rule for 29 CFR Parts 1910 and 1926: Occupational Exposure to 4,4'-Methylenedianiline (MDA).
5. Another of the amines, DDS, has a significant amount of toxicological data as its pharmaceutical grade, Dapsone™, has been used for years to treat leprosy and certain types of chronic dermal inflammation. However, at low airborne concentrations, there are no known effects from workplace exposure.
6. Other aromatic amines used in the advanced composites industry include m-phenylene diamine and the various isomers of toluenediamine. These aromatic amines are considered to be only slightly irritating to the skin.
7. Aliphatic and cycloaliphatic amines are strong bases and are considered to be severe eye and skin irritants. Inhalation of these amines can cause irritation of the nose and throat, and lung irritation with respiratory distress. Some of these amines are also skin and respiratory-tract sensitizers. Vapors of the volatile amines may cause conjunctivitis and visual disturbances.
8. Polyaminoamide hardeners have a less irritating effect on the skin and mucous membranes than the aliphatic and cycloaliphatic amine hardeners, but may cause sensitization.
9. Amide hardeners generally have only a slight irritant effect. Should the handling of these hardeners generate dust, measures should be taken to prevent inhalation.
10. The dusts of high-melting solids like most anhydride curing agents are severe eye and skin irritants. Some hydrophthalic anhydrides have high vapor pressures at the usual processing and curing temperatures and the vapors evolved during use of these curing agents can have an irritating effect on the skin, eyes, and respiratory tract. Exposure to the high-melting solids like trimellitic anhydride and tetraphthalic anhydride can cause respiratory sensitization.

C. Reinforcement Fibers

Most of the reinforcing materials used in the industry have the potential to cause eye, skin, and upper respiratory tract irritation as a result of the mechanical-irritant properties of the fibers. The potential synergism has not been clearly defined. The chemical irritation caused by resins can compound the mechanical irritation caused by the fibers.

1. **Carbon/graphite fibers** dominate the advanced composites industry and may be made from any of three precursors, as discussed in Section C. However, the PAN-based carbon fibers are the predominant form in use today. It is important to ascertain which type of carbon-fiber precursor is used in order to evaluate the hazards.

Pitch-based carbon fibers may be associated with an increased risk of skin cancer, although the evidence is weak. PAN-based carbon fibers did not cause tumors when the same test was conducted. Standard mutagenicity tests conducted on PAN-based carbon fibers were negative.

The principal hazards of carbon-fiber handling are mechanical irritation and abrasion similar to that of glass fibers. Skin rashes are common and reportedly more severe than from glass fibers. Carbon fibers commonly in use are also greater than six micrometers in diameter, making them unlikely to be respirable. An ongoing survey of workers in a carbon-fiber production plant shows no pulmonary function abnormalities and no evidence of dust-related disease.

Carbon fibers may be coated with a material to improve handling, known generically as sizing. The sizing materials are typically epoxy resins. They may be biologically active and cause irritation or sensitization.

2. **Aramid fibers** are made from a polymer, poly(p-phenylenediamine terephthalate). Animal and human skin tests of Kevlar™ aramid fibers show no potential for skin sensitization and low potential for irritation. While Kevlar™ fibers are too large to be inhaled (12-15 mm), they may be fractured into respirable fibrils in some composite manufacturing processes. Industrial process monitoring shows that airborne respirable fibril levels are low in typical operations. Measured exposure levels from composite machining are typically below 0.2 fibrils per milliliter of air (0.2 f/ml), as an 8-hour, time-weighted average (TWA), while continuous filament handling generates less than 0.1 f/ml. The physical structure of aramid fibers makes it extremely difficult to generate airborne concentrations.
3. **Glass fibers**, used as reinforcement in PMC processes, are a continuous-filament form and not the glass-wool (random) type. Practically all glass fibers for composite reinforcement are greater than six microns in diameter. Airborne fiber of this diameter does not reach the alveoli and is nonrespirable. Glass fibers break only into shorter fragments of the same diameter. Their diameter cannot be reduced by machining, milling, or other mechanical processes.

Mechanical irritation of skin, eyes, nose, and throat are common hazards associated with glass-fiber exposure. Continuous-filament glass fiber is not considered fibrogenic. Lung clearance mechanisms are effective for glass fibers.

In June 1987, the International Agency for Research on Cancer (IARC) categorized continuous-filament glass fibers as not classifiable with respect to human carcinogenicity. The evidence from human and animal studies was evaluated by IARC as insufficient to classify continuous-filament glass fibers a possible, probable, or confirmed cancer-causing material.

Like carbon fibers, glass fibers may also be coated with a sizing material to improve handling. Sizing materials may be epoxy resins, polyvinyl acetate-chrome chloride, polyvinyl acetate-silane, polyester-silane, or epoxy-silane compounds. These materials may be biologically active and cause irritation or sensitization.

D. Dusts

1. Dusts may be generated in several ways in advanced composite processes. The most common dust-generating processes are machining and finishing of cured parts and in repair of damaged parts. Much of the dust generated in these processes can be very fine and should be considered respirable. Studies of some graphite-epoxy finishing operations found respirable fractions ranging from 25% to 100%.
2. More dust is usually generated in finishing and repair processes since large surface areas are involved. Grinding, routing and sanding are frequently used methods in both processes. The repair process may require the use of abrasive blasting as well as sanding to remove existing paint or coatings. Typically, a synthetic blasting agent, e.g., plastic media blast, is used. Ingredients of the paint or coating being removed, such as lead or chromates, may also be of concern. The repair process may also require cutting or sawing to remove the damaged part area, and both may generate significant amounts of airborne dust.
3. In general, studies on composite dusts indicate that:
 - The dusts are particulate in nature and usually contain few fibers;
 - The dusts are thermally stable up to 250 °C and exhibit a high degree of cure; and
 - Toxicology studies indicate the dusts should probably be controlled at levels below the PEL for inert dust, but not approaching the PEL for crystalline quartz.

E. Solvents

1. Many of the solvents used in advanced composite processes are volatile and flammable. Most are skin and eye irritants, and some may be readily absorbed through the skin. Precautions must be taken when using organic solvents because they can facilitate the entry of toxic materials into the skin and organ systems. They

may also enhance skin sensitization caused by the resin systems. Some (such as methyl alcohol) are poisonous, and all are capable of extracting fat from skin. Harmful effects from industrial exposures come principally from skin contact and inhalation.

2. Selection of the proper glove for protection is important. Permeation data are available for many industrial chemicals, especially solvents. However, in the case of resins and curing agents, not much data are available. This also is true for mixtures of solvents, as little or no testing has been done. Often the glove selection process is one of trial and error. If a skin rash or dermatitis is observed there are several possible causes:
 - the wrong gloves may have been selected;
 - improper work practices are being followed;
 - the employee is deficient in personal hygiene practices; or
 - adequate washing facilities are absent.
3. Several of the solvent classes most commonly found in the PMC workplace are listed below, along with general hazard information.
4. Several ketones are frequently found in PMC manufacture. These include:
 - acetone (DMK)
 - methyl ethyl ketone (MEK)
 - methyl isobutyl ketone (MIBK)

These solvents may cause eye, nose, and throat irritation, and prolonged contact with the liquid may result in defatting of the skin and resultant dermatitis. In high concentrations, narcosis is produced with symptoms of headache, nausea, light-headedness, vomiting, dizziness, incoordination, and unconsciousness. Ketones are volatile and flammable. Acetone is a popular solvent used for cleanup and may be found around the workplace in containers for this purpose.

5. Some of the lower-boiling alcohols are sometimes used in composites manufacture. These include:
 - methanol (methyl alcohol)
 - ethanol (ethyl alcohol)
 - isopropanol (isopropyl alcohol)

These alcohols do not usually present serious hazards in the industrial setting. Toxicity is usually related to irritation of the conjunctivae and the mucous membranes of the upper airway. Contact with the liquid may cause defatting of the skin and dermatitis. These alcohols are volatile and flammable.

6. Three chlorinated hydrocarbon compounds in particular are found in the composites workplace:
 - methylene chloride (dichloromethane)
 - 1,1,1-trichloroethane (methyl chloroform)
 - trichloroethylene

Health effects typical of the group include irritation of the eyes and upper respiratory tract, dizziness, confusion, drowsiness, nausea, vomiting, and occasionally abdominal pain. Visual disturbances may also occur. Due to the solvents' defatting properties, repeated or prolonged skin contact with these liquids may cause dermatitis. Ability to depress the central nervous system is a characteristic property of all members of this group. These solvents are not particularly flammable. Many manufacturers have replaced the ketones with the above hydrocarbon solvents to reduce the risk of flammability.

7. Other solvents that may occasionally be used are:
 - toluene
 - xylene
 - tetrahydrofuran (THF)
 - dimethylsulfoxide (DMSO)
 - dimethylformamide (DMF)
 - gamma-butyrolactone (BLO)
 - n-methyl pyrrolidone (NMP)

- n-butyl acetate
- glycol ethers

Technical literature including MSDS's from the solvent supplier should be consulted about these or any chemicals used with advanced composites.

VII. Workplace Controls

Good workplace controls are essential in controlling exposure to process materials. Many of the materials, particularly the resins, curing agents, and fibers, present a potential dermal-exposure hazard. Many of the solvents and some of the curing agents present a potential inhalation hazard. Some materials present both a dermal and inhalation hazard. Ingestion may be a potential exposure hazard, but usually involves poor personal hygiene or contamination of eating facilities. The various types of workplace controls described below may typically be found in the advanced composite workplace.

A. Engineering Controls

Isolation (e.g., isolated storage, separate process areas, enclosures, closed systems) and local exhaust ventilation are the primary engineering controls found in advanced composites processes. These controls can be found in:

- Resin mixing areas;
- Heated curing areas including autoclaves;
- Finishing and repair areas; and
- Controlling off-gases from exotherms

B. Work Practice Controls

Work practices, as distinguished from engineering controls, involve the way a task is performed. Some fundamental and easily implemented work practices that can be used to minimize exposures when working with advanced composites are:

- good employee training and education;
- following the proper procedures for production, process and control equipment;
- proper use, maintenance, and cleaning of personal protective equipment;
- good personal hygiene program;
- housekeeping;
- periodic inspection and maintenance of production, process and control equipment; and
- good supervision.

C. Personal Protective Equipment

1. Gloves, protective clothing, and eye protection may frequently be required, especially when working with resins, curing agents, and solvents. Selection of the proper protective materials should be based on permeation data, if available. This type of data are often available for the solvents used, but very little data are available for the resins and curing agents.
2. In many advanced composites processes several chemicals or mixtures are involved. There are essentially no permeation data available for chemical mixtures. This means that, in many cases, glove and clothing selection must be a trial and error process.
3. Generally, the resins are of a larger molecular size and so are less likely to permeate protective materials than the curing agents and solvents. The aromatic amine curing agents are particularly difficult to protect against. In some advanced composites processes, close hand work and contact is required, and a glove must provide good tactility. Often this type of glove provides the least protection against the resin and curing agent.
4. Eye protection can be provided by standard safety glasses with side shields, goggles, or a face shield, as needed.

5. Respiratory protection is not required in many advanced composites processes, due to the low vapor pressure of the materials involved. However, respirators may be required where:
- Airborne solvent levels are high;
 - Dust levels are high (resin mixing, finishing, repair);
 - Large surface areas and significant hand work are involved; and
 - Exotherms are experienced.

D. Administrative Controls

Employee exposures also can be controlled by scheduling operations with the highest exposures at a time when the fewest employees are present.

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APPENDIX III:1-1. GLOSSARY

[Adapted from *Advanced Composites Magazine*, 1992 Bluebook, Edgell Plastics Publications]

A-stage An early stage of polymerization of thermosetting resins in which the material is still soluble in certain liquids and is fusible. Also called resole. See also B-stage, C-stage.

Ablative A material that absorbs heat through a decomposition process called pyrolysis at or near the exposed surface.

Addition A polymerization reaction in which no by-products are formed.

Additives Ingredients mixed into resin to improve properties.

Adhesive failure A rupture of adhesive bond that appears to be a separation at the adhesive-adherend interface.

Amorphous Polymers that have no order to their molecules, thus no crystalline component.

Anisotropic The tendency of a material to exhibit different properties in response to stresses applied along axes in different directions.

Aramid Aromatic polyamide fibers characterized by excellent high-temperature, flame-resistance, and electrical properties. Aramid fibers are used to achieve high-strength, high-modulus reinforcement in plastic composites.

Areal weight The weight of fiber per unit area (width times length) of tape or fabric.

Aspect ratio The ratio of length to diameter of a fiber.

Autoclave A closed vessel that permits application of pressure and heat used for curing composites.

Autoclave molding A molding technique in which an entire assembly (layup) is placed into an autoclave at 50 to 100 psi, in order to consolidate layers of the part by removing entrapped air and volatiles. Usually includes application of heat to trigger curing of the resin.

Axial winding A type of filament winding in which the filaments are parallel to the axis.

B-stage Intermediate stage in the polymerization reaction of thermosets, following which material will soften with heat and is plastic and fusible. Also called resistal. The resin of an uncured prepreg or premix is usually in B-stage. See A-stage, C-stage.

Bag molding A technique in which the composite material is placed in a rigid mold and covered with a flexible bag, with pressure applied by vacuum, autoclave, press, or by inflating the bag.

Balanced laminate All lamina except those at 0/90 are placed in plus-minus pairs (not necessarily adjacent) symmetrically about the layup centerline.

Bearing strength The maximum bearing stress that will not cause a composite to fail when applied through a cylindrical fastener surface.

Bearing stress Applied load divided by bearing area (hole diameter times thickness).

Bias fabric A fabric in which warp and fill fibers are at an angle to the length.

Biaxial winding A type of filament winding in which the helical band is laid in sequence, side by side, with no crossover of the fibers.

Bidirectional laminate A reinforced plastic laminate in which the fibers are oriented in more than one direction in the plane of the laminate.

Bismaleimide A type of polyimide that cures by an addition reaction, avoiding formation of volatiles, and has temperature capabilities between those of epoxy and polyimide.

Bleeder cloth A layer of woven or nonwoven material, not a part of the composite, that allows excess gas and resin to escape during cure.

Bleedout The excess liquid resin appearing at the surface, primarily during filament winding.

Bond strength The amount of adhesion between bonded surfaces. As measured by load/bond area, the stress required to separate a layer of material from that to which it is bonded.

Boron fiber A fiber usually of a tungsten-filament core with elemental boron vapor deposited on it to impart strength and stiffness.

Braiding Weaving fibers into a tubular shape.

Breather A loosely woven material that does not come in contact with the resin but serves as a continuous vacuum path over a part in production.

Broadgoods Fibers woven into fabrics that may or may not be impregnated with resin, usually furnished in rolls.

Buckling (composite) A failure usually characterized by fiber deflection rather than breaking because of compressive action.

Butt joint A joint in which parts are joined with no overlap.

C-stage The final step in the cure of a thermoset resin; results in essentially irreversible hardening and insolubility.

Carbon/carbon A composite of carbon fiber in a carbon matrix.

Carbon fiber An important reinforcing fiber known for its light weight, high strength, and high stiffness that is produced by pyrolysis of an organic precursor fiber in an inert atmosphere at temperatures above 1,800° F. The material may also be graphitized by heat treating above 3,000° F.

Catalyst A substance used in small quantities to promote or control the curing of a compound without being consumed in the reaction.

Caul sheet Plate or sheet the same size and shape used in contact with a composite layup to transmit normal pressure and temperature during cure.

Ceramic-matrix composites Materials consisting of a ceramic or carbon fiber surrounded by a ceramic matrix, usually SiC (silicon carbide).

Chemical vapor deposition (CVD) A process in which desired reinforcement material is deposited from vapor phase onto a continuous core; boron on tungsten, for example.

Circuit One complete traverse of the fiber feed mechanism of a filament-winding machine.

Circumferential winding A type of filament winding in which the filaments are perpendicular to the axis.

Co-cured Cured and simultaneously bonded to another prepared surface.

Coefficient of thermal expansion A material's fractional change in length for a given unit change of temperature.

Commingle yarn A hybrid yarn made with two types of materials intermingled in a single yarn; for example, thermoplastic filaments intermingled with carbon filaments to form a single yarn.

Composite A material created from a fiber (or reinforcement) and an appropriate matrix material in order to maximize specific performance properties. The constituents do not dissolve or merge completely but retain their identities as they act in concert.

Compression molding A technique for molding thermoset plastics in which a part is shaped by placing the fiber and resin into an open mold cavity, closing the mold, and applying heat and pressure until the material has cured or achieved its final form.

Compressive strength A material's ability to resist a force that tends to crush or buckle; maximum compressive load a specimen sustains divided by the specimen's original cross-sectional area.

Condensation A polymerization reaction in which simple by-products (for example, water) are formed.

Consolidation A processing step that compresses fiber and matrix to reduce voids and achieve a desired density.

Contact molding A technique in which reinforcement and resin are placed in a mold, with cure taking place at room temperature with a catalyst/promoter system, or in a heated oven. No additional pressure is used.

Continuous filament An individual, small-diameter reinforcement that is flexible and indefinite in length.

Continuous-filament yarn Yarn that is formed by twisting two or more continuous filaments into a single continuous strand.

Continuous roving Parallel filaments coated with sizing, gathered together into single or multiple strands, and wound into a cylindrical package. It may be used to provide continuous reinforcement in woven roving, filament winding, pultrusion, prepregs, or high-strength molding compounds, or it may be used chopped.

Core The central component of a sandwich construction to which the sandwich faces or skins are attached; also, part of a complex mold that forms undercut parts.

Co-woven fabric A reinforcement fabric woven with two different types of fibers in individual yarns; for example, thermoplastic fibers woven side by side with carbon fibers.

Creep The dimensional change in a material under physical load over time beyond instantaneous elastic deformation.

Crimp A fiber's waviness, which determines the capacity of the fiber to cohere.

Critical length The minimum length of a fiber necessary for matrix shear loading to develop fiber ultimate strength by a matrix.

Cross laminated Material laminated so that some of the layers are oriented at various angles to the other layers with respect to the laminate grain. A cross-ply laminate usually has plies oriented only at 0°/90°.

Crystallinity The quality of having a molecular structure with atoms arranged in an orderly, three-dimensional pattern.

Cure To change the physical properties of a material irreversibly by chemical reaction via heat and catalysts, alone or in combination, with or without pressure.

Cure temperature The temperature at which a material attains final cure.

Curing agent A catalytic or reactive agent that brings about polymerization when it is added to a resin.

Damage tolerance A measure of the ability of structures to retain load-carrying capability after exposure to sudden loads (for example, ballistic impact).

Damping Diminishing the intensity of vibrations.

Debond An unplanned nonadhered or unbonded region in an assembly.

Delamination The separation of a laminated plastic material along the plane of its layers.

Denier A numbering system for yarn and filament in which yarn number is equal to weight in grams of 9000 meters of yarn.

Design allowable A limiting value for a material property that can be used to design a structural or mechanical system to a specified level of success with 95% statistical confidence. B-basis allowable: material property exceeds the design allowable 90 times out of 100. A-basis allowable: material property exceeds the design allowable 99 times out of 100.

Doubler Localized area of extra layers of reinforcement, usually to provide stiffness or strength for fastening or other abrupt load transfers.

Draft angle A mandrel's taper or angle for ease of part removal.

Drape The ability of prepreg to conform to the shape of a contoured surface.

Dry winding A type of filament winding in which preimpregnated roving is used.

E-glass "Electrical glass"; the borosilicate glass most often used for the glass fibers in conventional reinforced plastics.

Fabric, nonwoven A material formed from fibers or yarns without interlacing.

Fabric, woven A material constructed of interlaced yarns, fibers, or filaments.

Fatigue The failure of a material's mechanical properties as a result of repeated stress.

Fatigue strength Maximum cyclical stress withstood for a given number of cycles before a material fails.

Fiber orientation The fiber alignment in a nonwoven or a mat laminate in which most of the fibers are in the same direction, thereby affording higher strength in that direction.

Fiber placement A continuous process for fabricating composite shapes with complex contours and/or cutouts by means of a device that lays preimpregnated fibers (in tow form) onto a nonuniform mandrel or tool. It differs from filament winding (below) in several ways: there is no limit on fiber angles; compaction takes place online via heat, pressure, or both; and fibers can be added and dropped as necessary. The process produces more complex shapes and permits a faster putdown rate than filament winding.

Filament winding A process for fabricating composites in which continuous reinforcing fibers, either preimpregnated with resin or drawn through a resin bath, are wound around a rotating, removable mandrel.

Filaments Individual fibers of indefinite length used in tows, yarns, or roving.

Film adhesive An adhesive in the form of a thin, dry, resin film with or without a carrier, commonly used for adhesion between layers of laminates.

Finish Material applied to fibers, after sizing is removed, to improve matrix-to-fiber coupling.

Fracture A rupture of the surface of a laminate because of external or internal forces, with or without complete separation.

Fracture toughness A measure of the damage tolerance of a material containing initial flaws or cracks.

Glass transition The reversible change in an amorphous polymer between a viscous or rubbery condition and a hard, relatively brittle one.

Glass-transition temperature (T_g) The approximate temperature at which increased molecular mobility results in significant changes in properties of a cured resin. The measured value of T_g can vary depending upon the test method.

Hand layup A fabrication method in which reinforcement layers, preimpregnated or coated afterwards, are placed in a mold by hand, then cured to the formed shape.

Hardener A substance used to promote or control curing action by taking part in it; as opposed to catalyst.

Heat-distortion temperature Temperature at which a test bar deflects a certain amount under specified temperature and a stated load.

Honeycomb Resin-impregnated material manufactured in, usually, hexagonal cells that serves as a core material in sandwich constructions. Honeycomb may also be metallic or polymer materials in a rigid, open-cell structure.

Hoop stress Circumferential stress in a cylindrically shaped part as a result of internal or external pressure.

Hybrid composite A composite with two or more reinforcing fibers.

Impact strength A material's ability to withstand shock loading as measured by the work done in fracturing a specimen.

Impregnate To saturate the voids and interstices of a reinforcement with a resin.

Impregnated fabric See Prepreg.

Interface The surface between two different materials: in fibers, the area at which the glass and sizing meet; in a laminate, the area at which the reinforcement and the laminating resin meet.

Interlaminar Existing or occurring between two or more adjacent laminae.

Interlaminar shear The shearing force tending to produce displacement between two laminae along the plane of their interface; usually the weakest element of a composite.

Isotropic Having uniform properties in all directions independent of the direction of load application.

Laminate ply One layer of a laminated product.

Lap joint A joint made by bonding overlapped portions of two adherends.

Layup The placement of layers of reinforcement in a mold.

Liquid-crystal polymers A newer type of thermoplastic, melt processible, with high orientation in molding, improved tensile strength, and high-temperature capability.

Mandrel. The form around which resin-impregnated fiber or tape is wound to form structural shapes or tubes.

Mat A fibrous reinforcing material comprised of chopped filaments (for chopped-strand mat) or swirled filaments (for continuous-strand mat) with a binder to maintain form; available in blankets of various widths, weights, and lengths.

Matrix A material in which the fiber of a composite is imbedded; it can be plastic, metal, ceramic, or glass.

Metal-matrix composites Materials in which continuous carbon, silicon carbide, or ceramic fibers are embedded in a metallic matrix material.

Modulus A measure of the ratio of load (stress) applied to the resultant deformation of a material, such as elasticity or shear.

Multifilament A yarn consisting of many continuous filaments.

Nondestructive inspection (NDI) A process or procedure for determining material or part characteristics without permanently altering the test subject. Nondestructive testing (NDT) is broadly considered synonymous with NDI.

Nonwoven roving A reinforcement composed of continuous rovings loosely gathered together.

Oriented materials Composites whose constituents are aligned in a particular way.

Out-life The period of time a prepreg material remains in a handleable form and with properties intact outside of the specified storage environment; for example, out of the freezer in the case of thermoset prepreps.

PAN See Polyacrylonitrile.

Peel ply Layer of material applied to a prepreg layup surface that is removed from the cured laminate prior to bonding operations and leaves a clean resin-rich surface ready for bonding.

Peel strength Strength of an adhesive bond obtained by stress applied "in a peeling mode."

Pitch A residual petroleum product used in the manufacture of certain carbon fibers.

Planar winding A type of filament winding in which the filament path lies on a plane that intersects the winding surface.

Ply The number of single yarns twisted together to form a plied yarn; one of the layers that make up a stack or laminate.

Polar winding A type of filament winding in which the filament path passes tangent to the polar opening at one end of the chamber and tangent to the opposite side of the polar opening at the other end of the chamber.

Polyacrylonitrile (PAN) A product used as a base material in the manufacture of certain carbon fibers.

Polymer A very large molecule formed by combining a large number of smaller molecules, called monomers, in a regular pattern.

Polymerization A chemical reaction in which the molecules of monomers are linked together to form polymers.

Postcure An additional elevated-temperature exposure that is performed often without tooling or pressure to improve elevated-temperature mechanical properties, for example.

Pot life The length of time a catalyzed thermosetting resin system retains a viscosity low enough for it to be suitable for processing.

Precure The full or partial setting of a resin or adhesive before the clamping operation is complete or before pressure is applied.

Precursor For carbon fibers, the rayon, PAN, or pitch fibers from which carbon fibers are made.

Preform A fibrous reinforcement preshaped to approximate contour and thickness desired in the finished part.

Prepreg Resin-impregnated cloth, mat, or filaments in flat form that can be stored for later use. The resin is often partially cured to a tack-free state called "B-staging." Catalysts, inhibitors, flame retardants, and other additives may be included to obtain specific end-use properties and improve processing, storage, and handling characteristics.

Pressure-bag molding A molding technique in which a flexible bag is placed over the contact layup in the mold, sealed, and clamped in place, and pressure applied by compressed air, which forces the bag against the part while the part cures.

Pultrusion A continuous process for manufacturing composites in rods, tubes, and structural shapes having a constant cross-section. After the reinforcement is passed through the resin-impregnation bath, it is drawn through a shaping die to form the desired cross-section; curing takes place before the laminate can depart from that cross-section.

Quasi-isotropic Approximating isotropy by orientation of plies in several directions.

Ramping A gradual, programmed increase or decrease in temperature or pressure to control the cure or cooling of composite parts.

Reinforcement A material added to the matrix to provide the required properties; ranges from short fibers through complex textile forms.

Release agents Materials that are used to prevent cured matrix material from bonding to tooling.

Release film An impermeable film layer that does not bond to the composite during cure.

Resin A material, generally a polymer, that has an indefinite and often high molecular weight and a softening or melting range and exhibits a tendency to flow when it is subjected to stress. Resins are used as the matrices to bind together the reinforcement material in composites.

Resin rich Localized area filled with resin but lacking reinforcement fiber.

Resin starved Localized area lacking sufficient resin for wetout of the fibers.

Resin-transfer molding (RTM) A molding process in which catalyzed resin is transferred into an enclosed mold into which the fiber reinforcement has been placed; cure normally is accomplished without external heat. RTM combines relatively low tooling and equipment costs with the ability to mold large structural parts.

Roving A collection of bundles of continuous filaments either as untwisted strands or as twisted yarns.

S-glass Structural glass; a magnesia/alumina/silicate glass reinforcement designed to provide very high tensile strength.

Sandwich construction A composite composed of a lightweight core material (usually honeycomb or foamed plastic) to which two relatively thin, dense, high-strength, functional, or decorative skins (also called faces) are adhered.

Scarf joint A bonded joint in which similar segments of adherends are cut away, with cut areas overlapped and bonded.

Selvage The narrow edge of woven fabric that runs parallel to the warp. It is made with stronger yarns in a tighter construction than the body of the fabric to prevent raveling.

Shelf life The length of time a material can be stored and continue to meet specification requirements and remain suitable for its intended use.

Silicon carbide fiber A reinforcing fiber with high strength and modulus; density is equal to that of aluminum. It is used in organic metal-matrix composites.

Sizing A compound that binds together and stiffens warp yarn to provide resistance to abrasion during weaving; normally removed and replaced with finish before matrix application.

Skin A layer of relatively dense material used in a sandwich construction on the surface of the core.

Specific gravity The density (mass per unit volume) of a material divided by that of water at a standard temperature.

Starved joint A joint that does not have the proper amount of adhesive because of insufficient spread or excessive pressure.

Stiffness The relationship of load to deformation for a particular material.

Storage life The amount of time a material can be stored and remain suitable for use.

Strain The elastic deformation of a material as a result of stress.

Stress The internal force that resists change in size or shape, expressed in force per unit area.

Structural adhesive An adhesive used for transferring loads between adherends.

Structural bond A bond joining load-bearing components of an assembly.

Tack The stickiness of a prepreg.

Tape A unidirectional woven prepreg, in widths up to 12 inches for carbon fiber, for example.

Tape laying A fabrication process in which prepreg tape is laid side by side or overlapped to form a structure.

Tensile strength The maximum tensile stress sustained by a plastic specimen before it fails in a tension test.

Thermal conductivity The ability of a material to conduct heat.

Thermoplastic A plastic material that is capable of being repeatedly softened by application of heat and repeatedly hardened by cooling.

Thermoset A plastic material that is capable of being cured by heat or catalyst into an infusible and insoluble material. Once cured, a thermoset cannot be returned to the uncured state.

Tooling resins Plastic resins, chiefly epoxy and silicone, that are used as tooling aids.

Toughness Tendency of a material to absorb work

Tow An untwisted bundle of continuous filaments, usually designated by a number followed by "K," indicating multiplication by 1,000; for example, 12K tow has 12,000 filaments.

Unbond Area of a bonded surface in which bonding of adherends has failed to occur, or where two prepreg layers of a composite fail to adhere to each other; also denotes areas where bonding is deliberately prevented to simulate a defective bond.

Unidirectional Refers to fibers that are oriented in the same direction, such as unidirectional fabric, tape, or laminate, often called UD.

Vacuum bag molding A molding technique in which the part is cured inside a layer of film, from which entrapped air is removed by vacuum.

Viscosity The tendency of a material to resist flow.

Voids Pockets of entrapped gas that have been cured into a laminate.

Volatiles Materials in a sizing or a resin formulation that can be vaporized at room or slightly elevated temperature.

Warp The yarns running lengthwise and parallel to the selvage in a woven fabric.

Water jet A high-pressure stream of water used for cutting organic composites.

Weave The pattern by which a fabric is formed from interlacing yarns. In plain weave, the warp and fill fibers alternate to make both fabric faces identical; in satin weave, the pattern produces a satin appearance, with the warp tow over several fill tows and under the next one (for example, eight-harness satin would have warp tow over seven fill tows and under the eighth).

Weft The yarns running perpendicular to the warp in a woven fabric; also called "woof."

Wet layup The application of resin to dry reinforcement in the mold.

Wet winding A type of filament winding in which the fiber strand is impregnated with resin immediately before it contacts the mandrel.

Wetout The saturation of all voids between strands and filaments of porous materials with resin.

Wetting agent A surface-active agent that promotes wetting by decreasing the cohesion within a liquid.

Winding pattern The regularly recurring pattern of the filament path in a filament winding after a certain number of mandrel revolutions.

Woven roving A heavy, coarse fabric produced by the weaving of continuous roving bundles.

Wrinkle An imperfection in the surface of a laminate that looks like a crease or fold in one of the outer layers; it occurs in vacuum bag molding due to improper placement of the bag.

X axis The axis in the plane of the laminate used as 0 degree reference; the Y axis is the axis in the plane of the laminate perpendicular to the X axis; the Z axis is the reference axis normal to the laminate plane in composite laminates.

Yarn Continuously twisted fibers or strands suitable for use in weaving into fabrics.

Young's modulus The ratio of normal stress to the corresponding strain for tensile or compressive stresses less than the proportional limit of the material.

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