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REINFORCED PLASTICS

Reinforced plastics are a relatively small, but very important part of the total plastics market. In 1994, U.S. production was approximately 1.4 billion kg, ∼4% of total U.S. plastics shipments. Reinforced plastics are commonly referred to as composites or more specifically polymer composites, although it should be noted that not all composites are reinforced plastics. Ceramic/metal-matrix composites and concrete are good examples of nonpolymeric composites (see Composite materials). A distinction is also drawn between reinforced plastics and advanced composites based on strength and performance. Reinforced plastics are also referred to as RP, FRP (fiber glass-reinforced plastic), and GRP (glass-reinforced plastic) interchangeably. The term fiber glass often is used to mean fiber glass-reinforced plastic, although it can also refer to insulation, textiles, and other forms of glass fibers.

Common to all reinforced plastics are two ingredients, resin and reinforcement. Resin is an organic material, usually of high molecular weight, that can be molded and set into a final shape. Resins are of two basic types. Thermoplastic resins soften upon heating, are shaped in a mold, and retain that shape when cooled. Common examples are nylon, polyethylene, polypropylene, and polycarbonate. Thermosetting resins are placed in a mold and cured by the use of a catalyst, heat, or both, until they harden in the shape of the mold. Common examples are polyester, vinyl ester, epoxies, phenolics, and polyurethanes.

The second main ingredient in reinforced plastic is the reinforcement, eg, fibers of glass, carbon, boron, mineral, cellulose, or polymers. Reinforcements can be configured in many ways, such as continuous or chopped strands, milled fibers, rovings, tows, mats, braids, and woven fabrics.

Reinforced plastics may also include fillers (qv), which are inexpensive materials such as calcium carbonate used to displace resin and reduce cost; curing agents (catalysts), promoters, inhibitors, and accelerators, which affect thermosetting resin cure; colorants; release agents (qv) to facilitate removal from the mold; and other additives which can impart a wide variety of properties to the finished part, such as fire resistance, electrical conductivity, static dissipation, and ultraviolet resistance.

It is important to note that reinforced plastics remain a combination of materials differing in form or composition on a macro scale. The main constituents (resin, reinforcement, and filler) retain their identities and do not dissolve or merge into each other; rather, they act in concert. These components can be physically identified and exhibit an interface between each other.

1. Manufacturing Method Selection Factors

There are many different manufacturing methods available for reinforced plastics. The selection process for a given application requires simultaneous consideration of the product design; the constituent materials; required physical, mechanical, and chemical properties; and production requirements. Assistance in selecting a manufacturing process is available from reinforced plastics manufacturers, material suppliers, and industry organizations such as the Composites Institute of the Society of the Plastics Industry and the Composite Fabricators Association. Selection factors that help to define the appropriate processes to consider for a given application may be categorized as product design factors, material factors, mechanical property factors, and production factors.

Product design factors
- overall part size
- shape complexity
- critical dimensions
- weight limitations
- potential for parts integration
- assembly requirements
- secondary operations

Material factors
- polymer type, thermoplastic or thermosetting
- reinforcement type, amount, and orientation
- surface requirements
- chemical exposure

Production factors
- total design life
- volatility of design, design modifications
- thermal properties
- electrical properties
- weather resistance
- fire performance

Mechanical property factors
- reinforcement type, amount, and orientation
- loads to be applied
  - static
  - dynamic
  - impact
  - assembly
  - shipping
- deflection limitations
- operating temperature range
- production rate buildup over time
- production rate (highest monthly rate)
- shipping range

All of these factors contribute to the manufacturing cost of the composite product and thereby determine not only the most cost-effective composite process to use but also the competitive position of composites with the other materials of construction.

In most cases volume requirement is the primary consideration for selecting the most cost-effective process. However, in many cases a lower volume process may be used during initial phases of a program and then be replaced by a higher volume process when the product has gained field acceptance.

2. Manufacturing Methods

2.1. Hand Lay-Up and Spray-Up

In hand lay-up, fiber reinforcements in mat or woven form are placed on the mold surface and then saturated with a liquid polymer, typically a polyester resin, that has been chemically activated to polymerize (cure) without the addition of heat. Multiple plies of reinforcement and multiple cure steps allow very heavy wall thicknesses to be achieved.

In the spray-up process a reinforcement, usually glass fiber, is substituted for the mat and a special spray gun simultaneously chops the glass fiber and applies it with catalyzed resin to the mold surface. Hand rolling techniques then consolidate the fiber and resin to conform to the mold surface contours. The shorter chopped fibers allow for more intricate design details than do mats. Both processes rely heavily on the operators' skills for product quality. These two processes require the least capital investment and have the largest product size capability of all the processes. A single-surface mold produces a part with one controlled (usually the visible) surface.

Gel coats are typically used to provide a part with a finished surface directly from the mold. Various inserts, stiffeners, and mechanical attachments can be incorporated in the molding step, thereby further reducing secondary operations. Final edge trimming is accomplished with a variety of tools such as routers, water jet cutters, or abrasive grinders with fixtures to define required dimensions. Typical products made by lay-up and spray-up include boat hulls, tub shower units, furniture, playground equipment, building facia, truck body parts, and corrosion-resistant tanks.

2.2. Vacuum Bag, Pressure Bag, and Autoclave Molding

These thermoset processes are variations of the hand lay-up process where pressure is applied to the reinforcement and resin during the cure step. With vacuum bag molding, a plastic film is placed over the resin-saturated reinforcement and carefully sealed around the perimeter of the part to form the bag. Air is then drawn from within the bag, allowing atmospheric pressure to be applied to the bag and the enclosed saturated reinforcement. This pressure permits higher reinforcement content (increasing strength) and reduces the labor needed to consolidate the resin and reinforcement. Additionally, the laminate is void-free, which makes this a common process technique for aircraft and other high performance components. A variation of this process provides for the addition of resin after the vacuum has been drawn on the bag. This technique has the advantage of reducing the emission of volatile components of the resin into the workplace.

Pressure bag molding substitutes air or liquid pressure for the atmospheric pressure, allowing higher pressures and higher fiber contents to be achieved. Autoclave molding uses a pressurized heating chamber to apply both heat and pressure to cure the product after it has been prepared using the vacuum bag method. Entire aircraft wing and tail sections can be fabricated from reinforced plastics using very large autoclaves and carefully controlled heat and pressure cure cycles.

A special pre-impregnated (prepreg) reinforcement system usually used with these processes combines the reinforcement, typically in a cloth or tape form, with a polymer that has been partially polymerized (B-staged). The prepreg is cut into the required shape and positioned onto the mold surface prior to application of pressure and heat. Prepregs offer precise resin/reinforcement ratios and control of end product properties. Prepregs of different reinforcements, such as glass, aramid, carbon, boron, and high molecular weight polyethylene, are available for a broad range of demanding performances needed in aerospace and sport equipment applications.

2.3. Resin-Transfer Molding and Cold Press Molding

Resin-transfer molding (RTM) and cold press molding are thermoset processes utilizing a clamping frame or press and matching male and female molds. The molds fully contain the reinforcement and resin during the consolidation and curing process which is accomplished at a relatively low pressure (<345 kPa (50 psi)). In both processes the reinforcement, either as a precut mat or preformed shape (preform), is placed in the open mold. In RTM the mold is closed and a catalyzed resin is then pumped into the mold cavity to saturate the reinforcement. The perimeter of the mold has a sealing gasket to contain the resin until it cures. In cold press molding the reinforcement and catalyzed resin are placed into the open mold and the resin is distributed through the reinforcement as the mold is closed and pressurized. Proper resin distribution in both processes requires experience in locating the injection port or in developing a resin pour pattern that results in a voidfree part.

The preform is a form of reinforcement also utilized in the other liquid molding processes, ie, structural reaction injection molding (S-RIM) and wet system compression molding. The preform is made in a separate manufacturing process where reinforcing fibers are chopped into 2.5–5 cm (1–2 in.) lengths and deposited on a screen shaped to conform with the part to be molded. Air is drawn through the screen to hold the chopped fibers in place while a binder, usually a liquid emulsion, is applied and dried to hold the chopped strands in the desired shape for placement into the final process mold. The binder also must resist the flow of resin in the fabrication process and keep the fiber orientation until the laminating resin has cured. An innovation to the preform process is robot-controlled fiber placement that results in rapid, uniform preforms for the liquid molding processes.

A special attribute of these processes is the ability to pre-position reinforcement, inserts, and core materials for stiffening ribs. Gel coatings can be applied to the mold surface to eliminate post-mold finishing. Because both surfaces of the part are formed in a mold to close tolerances, accurate assemblies are possible, which is a requirement for many automotive or truck body applications.

All forms and compositions of reinforcements, ie, mats, woven roving, glass, carbon, and aramid, are commonly used with these processes. Special continuous glass strand mats with a thermoplastic binder allow preforms to be made using thermoforming techniques. These processes are used for truck and autobody components, medical equipment cabinets, transportation seating, and other parts needed in the intermediate volume range (1,000–10,000 parts/yr).

2.4. Reaction Injection Molding

Two variations of conventional reaction injection molding (RIM) are used for reinforced plastic parts: reinforced RIM (R-RIM) and structural RIM (S-RIM). With R-RIM, very short reinforcing fibers are added to one of the resin components prior to being injected under high pressure through an impingement mixer into the closed mold. The mold is held closed during injection by a special clamping device that can be articulated to orient the mold for proper injection and to open the mold for part removal. The reinforcement reduces shrinkage and thermal expansion, and improves thermal performance of the base polymer, typically a thermoset polyurethane. Principal reinforcements include chopped and milled glass fibers and wollastonite, a fibrous filler. Applications for R-RIM include automotive facia, bumper covers, and other high volume components.

S-RIM utilizes the same polymers, molds, and process equipment. However, the reinforcement is in the form of a mat or specially shaped preform. The reinforcement is positioned in the mold prior to mold closure and resin injection. This allows the use of a greater percentage of reinforcement and results in higher strength in the part. Longer fibers also add to strength improvement. S-RIM allows production of larger and more structurally demanding parts than would normally be made by unreinforced RIM, such as automotive bumper beams, pickup truck beds, and large facia components.

2.5. Compression Molding

Compression molding processes dominate the higher production volume reinforced plastics applications. These processes use a hydraulically operated press to form the part in matching metal molds and to hold the densified molding material in the desired shape until the resin system has cured (if a thermoset) or cooled sufficiently (if a thermoplastic) to permit part removal. The presses typically are capable of molding pressures of 1.7–24 MPa (250–3500 psi) and have produced fishing boats as long as 4.9 m (16 ft), as well as one-piece tilting truck hoods. Modern presses have systems that control closing speed and pressure for proper flow of the material system in the mold. Following are the four variations of compression molding defined by the form and nature of the material system used.

2.5.1. Bulk Molding Compound

BMC is a combination of a thermosetting resin, most commonly polyester, with chopped reinforcement, fillers, pigments, and catalysts that form a dough-like, ready-to-mold material system. BMC can be extruded into logs or hand-formed into mold charges of the proper weight to produce net shape parts with a very high material efficiency. Molding pressures ranging from 2.4 to 13 MPa (350–2000 psi) and temperatures between 121 and 177°C (250–350°F) result in cure cycles from 30 seconds to several minutes depending on the thickness of the product.

BMC parts can be very complex with intricate detail and close dimensional tolerance, which can be used in assemblies with little or no post-molding machining steps. Molded-in inserts for screws, bearings, or other attachments are commonly used. Pigmented BMC eliminates additional surface finishing operations. Primary

BMC applications include circuit breaker bases, power tool housings, computer and business equipment bases, pump housings, appliance components, automotive heater and air conditioner housings, and many other high volume complex industrial components.

2.5.2. Sheet Molding Compound

SMC is a ready-to-mold material system that combines the reinforcement, thermosetting resin, fillers, pigments, catalysts, and other additives in a continuous sheet that is formable into complex shapes in a single molding step with minimal scrap material. SMC is produced on a continuous forming machine where the liquid and dry ingredients, with the exception of the reinforcement, are premixed to form a paste of $40,000-100,000\ \mathrm{mPa{\cdot}s(=cP)}$. The paste is metered by means of doctor blades onto two separate carrier films that are pulled continuously through the SMC machine. The lower carrier film moves under a chopper unit that chops and distributes the fibers uniformly over the resin paste. The upper and lower carrier films with paste and reinforcement are brought together, forming a sandwich that progresses through a compaction section whose mechanical action intimately mixes the paste and reinforcement prior to being rolled into convenient lengths or festooned into containers. The SMC is then stored under controlled temperature conditions.

Thickening agents added to the paste cause the SMC to increase in viscosity after forming, a step called maturation. A viscosity from 6,000 to $75,000\ \mathrm{Pa{\cdot}s}$ (60,000–750,000 P) prior to molding is critical for SMC to flow well in the molding process and provide uniform mechanical properties throughout the molded part. More recent SMC technology, called low pressure molding compound (LPMC), has been introduced which uses a different resin thickening mechanism that provides uniform flow at much lower viscosity and therefore requires much lower molding pressures.

SMC with chopped reinforcement produces a part with essentially uniform mechanical properties in all directions. The mechanical properties are highly dependent on the flow of the SMC in the mold. When the flow is uniform, the properties are uniform. Both product and mold design must consider flow. Computer programs have been developed to predict the flow of SMC during the molding cycle to provide guidance in design of SMC products. By adding continuous reinforcements to the SMC process, directional strength properties can be increased if required for a specific application. Automotive bumper beams have used this type of system to increase beam strength while still retaining the flow characteristics of SMC with chopped reinforcement.

A variety of thermosetting resins are used in SMC. Polyesters represent the most volume and are available in systems that provide low shrinkage and low surface profile by means of special additives. Class A automotive surface requirements have resulted in the development of sophisticated systems that commercially produce auto body panels that can be taken directly from the mold and processed through standard automotive painting systems, without additional surface finishing. Vinyl ester and epoxy resins (qv) are also used in SMC for more structurally demanding applications.

Molding of SMC requires that the carrier film be stripped and a mold charge prepared. Special equipment is available to accomplish this step with minimum labor and good weight control of the mold charge. The carrier film is removed and rolled up for recycling (qv). Molding temperatures range from 121 to 177°C (250–350°F) for typical polyester systems. Molding pressures may vary from 3.5 to 17 MPa (500–2500 psi) depending on the size and complexity of the part. Low pressure SMC systems require from 0.7 to 2.4 MPa (100–350 psi) for the same part.

SMC materials have been used primarily in high volume applications in the automotive, appliance, electrical, and construction markets because of the tooling cost and high capital investment of the SMC and molding equipment. Automotive grill opening panels, bumper beams, exterior body components, engine valve covers, radiator surrounds, and wheels are in production. Appliance applications include dishwasher inner doors, air conditioner base pans and bulkheads, and business equipment housings. Bath tubs, showers, and door panels are principal construction applications. Steel assemblies of many individual parts can be replaced by a single SMC molding, as has been demonstrated with automotive grill opening panels and commercial air conditioner enclosures.

2.5.3. Wet System Compression Molding

Wet system compression molding was the first high volume method for manufacturing reinforced plastic parts, in such applications as the Chevrolet Corvette, industrial trays, tote boxes, luggage, refrigerator liners, and other commercial applications.

The process is similar to cold press molding with the exception that heated metal molds and higher molding pressures (1.7–6.9 MPa (250–1000 psi)) are used. The reinforcements used in the wet system are either a preform or in a mat form. The ability to achieve higher reinforcement weight loading and to preposition the reinforcement makes this material option viable for high volume structural applications. Low surface profile resin technology has been adapted to the wet molding systems for such applications as outboard motor shrouds, garden tractor shrouds, and snowmobile bodies, where both surface appearance and structural demand are required.

2.5.4. Reinforced Thermoplastic Sheet

This process uses precombined sheets of thermoplastic resin and glass fiber reinforcement, cut into blanks to fit the weight and size requirements of the part to be molded. The blanks, preheated to a specified temperature, are loaded into the metal mold and the material flows under molding pressure to fill the mold. The mold is kept closed under pressure until the temperature of the part has been reduced, the resin solidified, and demolding is possible. Cycle time, as with thermosetting resins, depends on the thickness of the part and the heat distortion temperature of the resin. Molding pressures are similar to SMC, 10–21 MPa (1500–3000 psi), depending on the size and complexity of the part.

Polypropylene sheet has been used most extensively; however, thermoplastic polyester, polycarbonate, and nylon versions are available (see Elastomers, synthetic; Polycarbonates). Continuous strand glass fiber mat is the typical reinforcement. The limited number of sheet suppliers reduces potential for competitive pricing.

The process provides fast molding cycles, unlimited shelf life for the sheet, large part capability, and design flexibility. The process also allows for scrap materials to be recycled. Trim waste from the molding operation and defective parts can be ground up and recycled into the basic sheet process in controlled amounts. Some of this waste has also been used as input for injection molding.

As with SMC, applications are limited to high volume because of the capital investment in equipment and tooling. Thermoset compression molders require additional heating and material handling equipment to adapt their process to thermoplastic sheet fabrication. Applications include automotive bumper beams, load floors, radiator supports, battery trays, and package shelves. Chair shells, military containers, material handling pallets, trays, and concrete foaming pans are also produced.

2.6. Injection Molding

Injection molding is a thermoplastic or thermoset process that provides very high volume production capability. The basic process for injection molding reinforced plastics is similar to unreinforced plastics (see Plastics processing). The reasons for reinforcement differ depending on the specific polymer, but generally reinforcement increases certain mechanical properties, improves dimensional stability, and increases heat resistance, allowing the reinforced product to operate at higher temperature.

Injection molding of thermoplastics involves feeding a granulated or pelletized molding material into a screw-operated heating chamber, melting the molding material as the heated chamber fills, feeding the melt into the closed metal mold by means of the screw, allowing the melt to cool and solidify in the mold, opening the mold, and ejecting the finished part. Thermosetting reinforced plastics in BMC form are also injection molded. Different machine specifications are required for BMC in order to minimize the damage to the reinforcing fibers during feeding and injection, and the mold must be heated for thermoset cure rather than cooled as with thermoplastics.

Fast molding cycles, very low labor requirements, and complex part geometry are the primary advantages of the injection molding process. Reinforced thermoplastic polymers include nylon, PVC, acetal, polycarbonate, polyethylene, polypropylene, ABS, and SAN. Thermosets include polyester, epoxy, phenolic, and urethane. Reinforcements are typically chopped glass fibers from 3–13 mm (0.125–0.5 in.). Applications for injection molding include a wide range of automotive and appliance parts, electrical components, consumer products, and other markets that are served by unreinforced injection molding.

2.7. Pultrusion

Pultrusion is the reinforced plastic process that produces continuous profiles. In this process, reinforcements are pulled through a liquid thermoset resin bath into a heated mold where the cure reaction occurs. The pulling device has specially shaped gripping surfaces that continuously pull the cured profile out of the mold, thereby activating and controlling the speed of the entire process. A cut-off device trims the pultruded product to the required lengths. The pultrusion process is highly automated and once the process is started, very little direct labor is required. Long production runs provide the best economics. Tooling and capital equipment costs for pultrusion are generally less expensive than in the other high volume output processes. Pultruded products have a constant cross section that can be solid or hollow. Pultrusion requires a high degree of fiber orientation in the machine direction in order to activate the process, move the product through the curing mold, and provide the high tensile strength needed for applications such as oil-well sucker rods.

Many different thermosetting polymers are used in pultrusion, eg, polyester, vinyl ester, epoxy, and urethane. Reinforcements must be in a continuous form such as rovings, tows, mats, fabrics, and tapes. Glass fibers are the low cost, dominant composition, but aramid and carbon fibers are also used.

Pultrusion using thermoplastic polymers is a relatively new process variation that promises to grow rapidly in the future. Higher processing speed, a wide variety of available thermoplastics and polymers, and potential for post-forming of the pultruded part has stimulated development of this process. Pultrusion products include fishing rods, ladder rails, electrical strain rods, concrete rebar, structural shapes (angles, I-beams, channels, etc), tubing, electrical ducting, cable tension members, archery arrows, and window and door lineals.

2.8. Filament Winding

This is a process for products that are surfaces of revolution. Reinforcing fibers are drawn through a liquid resin bath and applied to a rotating mold surface or mandrel. For many applications, the reinforcement is precombined with the liquid resin to form a prepreg product. Prepregs are used for the most critically demanding applications, such as rocket motor cases and pressure tanks, because of the higher degree of product and process control they provide. By varying the rotating speed of the mandrel and the movement of the fibers across the mandrel, geometric patterns are formed that orient the fibers to meet the product strength requirements. The principal thermoset polymers used in this process are polyesters, vinyl esters, bisphenol fumarates, epoxies, furans, and phenolics. More recently, thermoplastics are also used in the form of roving or tape prepregs. These materials require localized heating during winding to consolidate the tape layers. Reinforcements for this process include continuous strands and tows, woven and unidirectional tapes, and chopped and continuous strand mats. Glass fiber is the dominant reinforcement with carbon, aramid, and high molecular weight polyethylene also used for the structural or weight-critical applications.

Sophisticated structural analysis techniques make it possible to determine both the amount and exact orientation of reinforcement that the product will need to meet the critical stresses in actual service. Hybrid reinforcement systems containing different fiber compositions with different properties are being increasingly used. For example, hybrid carbon and glass fiber automotive drive shafts are in commercial use.

There are many different equipment options available to suit specific product needs including continuous winders for pipe, multiaxis winders for pressure vessels, and simple lathe-type winders for tanks and large pipe. Specialty machines combine a chopped reinforcement with continuous fibers for tank walls and large-diameter pipe where both stiffness and tensile strength are required. Textile braiders have also been adapted for use as continuous winders where both longitudinal and helical winding patterns can be formed. Although limited to surfaces of revolution, filament winding represents one of the most efficient reinforced plastic processes because of the highly controllable properties, and ability to achieve high strength performance at the lowest possible weight.

Products can be found in every principal market area including rocket motor and shell casings, air and gas pressure tanks, aircraft wing fuel tanks, utility poles, automotive and truck drive shafts, sailboat masts, vaulting poles, fishing rods, golf shafts, railroad tanks cars, and pipes and tanks for oil, gas, and chemical processing.

2.9. Other Processes

There are a variety of other processes that have been developed to suit specific product needs.

Continuous laminating produces flat and corrugated sheet used as translucent glazing, signs, wall covering, and recreational vehicle siding. Glass fibers are chopped onto a moving film and then saturated with resin. Another film is applied to the surface before shaping and curing in an oven.

Centrifugal casting is used to produce water softener tanks and pipe by saturating a reinforcement with thermosetting resin within a mold that is then rotated at high speed to consolidate the laminate before curing.

Rotational molding is used to form large shells of thermoplastic resin and chopped strands for such applications as agricultural tanks and fertilizer hoppers. The resin and chopped glass are placed in the metal mold that is then rotated in an oven where the thermoplastic resin melts and deposits the fiber on the metal surface. When cooled, the mold is opened and the part is removed.

The *rigidized thermoplastic sheet* process combines thermoplastic sheet vacuum forming with a spray-up or cold press molding process to add a thermoset composite structural backing to a decorative thermoplastic skin. Large parts such as bathtubs, hot tubs, recreation vehicle components, and camper tops have been produced by this process.

2.10. Hybrid Processes

There are also hybrid processes that have evolved to meet specific product needs. As an example, automotive leaf springs utilize a filament winding system to prepare impregnated fiber bundles that are then compression molded to final configuration.

3. Economic Aspects

The business climate of the 1990s is different from the past. Factors such as increased competition, a global marketplace, rapid technical shifts, and greatly compressed product life cycles constantly open new opportunities for plastics in general and reinforced plastics in particular. Reinforced plastics have become widely accepted for particular applications because they offer a combination of design, performance, and economic benefits to the user. These materials have had a proven record of success since the 1940s.

Totally new product applications, such as in aerospace, for example, are a minority of the successful applications that constitute the composite industry, and these uses tend to be small niche markets that are cost-insensitive. In most situations composite materials are substituted for existing materials, most often wood and common metals. Traditional materials, however, are often entrenched and hard to displace. There are established product specifications, widely accepted traditional economics, and often a long history of industry experience. The result is that the product requirements are usually a material rather than performance specification, and moreover they are usually established in terms of existing materials, thereby providing a barrier for substitution. Furthermore, if just a component of a larger system is being considered for substitution, other limitations on shape, size, choice of materials, etc, probably exist that prevent maximum benefit of composites from being realized. Nevertheless, in spite of these concerns, composites have been successful since the 1940s because of the benefits offered over the existing material. It is estimated that there are over 40,000 different applications for reinforced plastics.

3.1. Design Benefits

Design benefits include ways of making a finished part that eliminate fabrication steps needed for traditional materials. Parts with complex surface shapes are often good candidates for composite materials because composites can be made to virtually any predetermined shape from a mold. No cutting, stamping, shaping, or further processing is needed. Parts consolidation is another benefit that favors reinforced plastics. Composites can be designed in complex arrangements that can replace assemblies of many metal parts and fasteners, greatly reducing assembly labor costs and resulting in a better quality part. An example is in automotive front-end assemblies, where a single reinforced plastic piece has replaced a dozen or more metal pieces and fasteners.

Composites are superior materials for applications that require large part size. Large boat hulls, for example, can be molded in a single piece, eliminating costly cutting and fastening operations needed with wood or metal. Composites generally entail reduced finishing costs. They are easier to design into a finished product than a bulk material, such as lumber or rolled steel, which has to be cut, shaped, fit together, fastened, sanded, painted, and otherwise finished.

Strength can be engineered to the magnitude and in the direction needed for the application. Strength can be tensile, such as oil-field sucker rods; flexural, such as sporting goods; compressive, such as large pipes; or impact, such as in automotive wheels. Stiffness can also be engineered as needed. Composites generally have high impact strength that allows them to absorb a large amount of energy before failure. They also lack ductility so that products, when properly designed, maintain alignment through their life cycle.

Some design factors, however, work against composites. For example, glass fiber-reinforced plastics generally have lower modulus (stiffness) than metals. Thickness and shape adjustments are required where stiffness is a critical design requirement. With appropriate reinforcement, any modulus, even greater than that of metals, can be achieved. However, it may become expensive and uneconomical to do so.

Service temperature limitations must be considered in the use of composites, not only in the selection of polymer and process, but sometimes in the selection of the reinforcement as well. Composites cannot generally perform as well as metals or ceramics in very high temperature applications, but they can be made fire resistant to meet most construction and transportation codes.

3.2. Performance Benefits

Fiber-reinforced plastic (FRP) components are lightweight and deliver more strength per unit of weight, or less weight for a given strength requirement than unreinforced plastics and most metals. In transportation applications light weight means better fuel economy, and in marine and aerospace usage, light weight is critical for flotation and aerodynamic performance, respectively.

Reinforced plastics provide long-term corrosion resistance to many chemical and temperature environments, making them especially suited for chemical and power plants, and oil-field collection and distribution.

Composites can have high dielectric strength. They are usually excellent electrical insulators and do not absorb moisture, making them suitable for use in such products as ladders and printed circuit boards because they provide a stable, nonconducting structure. Composites can have low thermal conductivity, making them suitable in applications that call for thermal insulation. An FRP bathtub, for example, retains heat longer than a cast-iron tub.

Under mechanical and environmental stresses, composites are dimensionally stable. They maintain their shape and functionality, a critical requirement in such applications as dish antennas, construction girders, and in appliance and business machines. Color and surface texture can often be molded into an FRP product for long lasting, low maintenance permanent surface appearance. Boats are a good example. The surface color is molded in and requires minimum maintenance, an advantage in saltwater environments.

3.3. Economic Benefits

The traditional costs of a product include raw materials, processing, overhead, and so forth. Designers and engineers considering potential composite applications cannot compare material costs only. Polymer composites, except for inexpensive fillers and small amounts of additives, consist mostly of resin and reinforcement, whose materials costs are usually higher than traditional materials.

Process costs must also be carefully considered. Almost all the composite processes are batch processes, producing one or at most a few parts at a time. Pultrusion and some pipe winding processes are exceptions; even though these processes are continuous, they are relatively slow as compared to plastic extrusion or some of the metal fabrication processes. Molding times for composite processes range from less than one minute to hours. Although productivity may appear to put composites at a disadvantage compared to faster manufacturing methods, such as metal stamping, the design benefits usually more than compensate in reduced assembly and finishing work required. Moreover, tooling costs can be lower for composite molding than for metalworking, especially when they need to be allocated over a limited number of parts.

Designers and engineers have successfully substituted composites into many applications because not only traditional costs, but the overall life cycle economics of the product in the manufacturing process and in the product's later application have been considered. Designers and engineers recognize that the real cost of a product is the total cost of everything associated with it. Life cycle economics thus include nontraditional costs such as planning, design, and development costs; purchasing, installation, and maintenance costs; loss and wear costs; liability and insurance costs; downtime and lost business costs; and replacement, disposal, and recycling costs.

The difference between life cycle costs and the traditional accounting cost is that traditional costs are fairly easy to quantify, whereas life cycle costs are usually difficult to quantify and are usually either lumped into general overhead costs or ignored altogether. They are very real, however, and when examined in detail and fully quantified, the economics of composites allow them to displace the traditional materials.

There are no simple rules of thumb in defining the cost of reinforced plastic components. Their successful use has resulted from proper design, utilizing the benefits these materials offer, process selection, tooling cost advantages that fit the production needs, and consideration of life cycle economics. Each existing application illustrates the cost-performance advantage of reinforced plastic over the traditional material that is displaced.

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