Manufacturing of Thermoset Composites

Products made from conventional materials, such a metals, and plastics, finished products are produced from raw materials. First, raw material is produced, and then using that raw material, the final product (e.g. door panel of a car) is fabricated.

In contrast, the same is not necessarily true of products made form composite materials.

For instance, a structural composite plate involves simultaneous creation of the product as well as the material. This is particularly true for composites with thermoset matrix materials.

In such a case, the raw materials are matrix (e.g. epoxy) and fibers (e.g. graphite fibers).

These materials are processed to produce composite plate, and the material properties of composite are entirely different from those of its individual constituents. Further, production of this composite material, and the plate occurs simultaneously.

In other cases, a primitive version of composite is formed first (e.g. prepregs), and this pre-fo rmed composite is later given the shape of final product by application of pressure and temp erature. However, even in such cases, the properties of the primitive composite material and those of final product, may be significantly different.

In case of composites with thermoplastics matrix materials, the situation may be somewhat different. Here, quite often, composite material is first produced, and then subsequently given the desired shape separately.

However, even here, the process of giving desired shape to composite may alter properties of composite, due to a variety of factors including fiber length reduction, change of fiber orientation, and thermal degradation.

Overall, composite materials are produced through a large number of processes. The choice of a specific production method strongly depends on chemical attributes of matrix, and also the nature of final product's shape.

Thermoset composites are fabricated either using "wet-forming" processes, or processes which used premixes or prepregs.

In wet-forming processes, resin in fluid state is used, while forming the final product.

The resin gets cured in the product while the resin is "wet". This curing may be aided by application of external heat and pressure.

Typical wet-forming processes include: Hand layup, Bag molding, Filament winding, RTM (resin transfer molding) and Pultrusion.

In alternative processes, which rely on premix or prepreg forms (and not wet-forms), pre-fabricated material in semi-cured form is used to provide shape to the final product.

This final product, which is still only partially cured, is then subjected to heat and pressure with the intention of completing the curing process.

The pre-fabricated material can be available as: Bulk molding compounds (BMCs) available in amorphous bulk form or Sheet molding compounds (SMCs) available in large rolls of sheets –Prepregs

BMCs and SMCs are produced by compounding resin, fibers, and fillers. This mix is then partially cured. Prepregs are sheets of oriented fibers bonded together by partially cured matrix material.

The matrix material in BMCs, SMCs, and prepregs is frequently thickened so that the semi-cured premix/prepreg is too tacky to make handling of the material problematic.

Thickening of these materials is accomplished by using specific thickeners, and also by semi-curing the resin.

In case the resin is in a semi-cured state, the material has to be stored and transported at reduced temperature, since exposure to even moderate temps may complete the curing process.

Use of premixes and prepregs simplifies the fabrication process of composites, and also facilitates automation of the process.

Such a process also helps in achieving high volume fractions, as well as uniform distribution of fibers.

Different Wet Process Techniques.

Hand Lay-Up: This method is also known as contact-layup. It is the oldest, most commonly used, and the simplest method for fabrication of thermoset composites.

This method is appropriate for low volume production, and when capital costs need to be minimized.

This method is frequently used to fabricate boats, ducts, pools, furniture, shells and sheets (corrugated or flat).

This method essentially requires a flat surface (for making sheets), or a mold and cavity for providing shape to the final product. The molding tool may be made from metals, plastics, wood, or some other appropriate material.

Hand-Layup

Fibers and resin pre-mixed with curing agent are manually placed against the molding surface

The placement of fibers and resin can happen in two ways. These are: – While fabricating composite products with long fibers, reinforcing fibers (in form of mats or fabric)are placed layer-by-layer over the surface, to ensure appropriate stacking sequence, as well as requisite thickness of the final product. Once a particular layer of fiber is placed, it is coated with a layer of resin either through a spray gun, or through a brush.

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Care is taken to ensure that resin is devoid of air bubbles, as it is applied to reinforcing fibers. For this, serrated rollers may be used, which help remove air bubbles, as well as ensure increased wetting of fibers. This manual method of layup may also be used for short fiber composites. While fabricating composites with short fibers, resin and chopped fibers are placed simultaneously on the molding surface. Quite often, the deposition of this fiber-resin mix is conducted using a spray-up process. Here, a spray gun with two nozzles is used. While one nozzle is used to feed chopped fibers on to the molding surface, the second nozzle feeds a mix of resin and hardener simultaneously.

In either of these processes, quite often, the composite product is covered with a t hin layer of randomly oriented fibers, known as surfacing mat. This layer provides a better surface finish to the product, and may also protect inside of composite against corrosion, if surface mats fibers are corrosion resistant.

In many cases, especially for large sized products, the mold has only one part (either the cavity or the male part). In such cases, the process is called open molding.

DIAGRAMS

Advantages of Hand Layup Process –

Appropriate for large and products with contoured surfaces

Requires limited capital expenses.

Setup costs, and production lead time are less.

Does not require highly trained and skilled personnel.

Flexible in terms of accommodating changes in design.

Complex feature can be fabricated through use of molded-in inserts.

Limitations of Hand Layup Process.

Inappropriate for large volume production.

Labor intensive.

Requires long cure time, as material hardens at room temperature.

Quality control is difficult as many processes are highly dependent on manual skills.

Products produced through open molding process yield one good molding surface. The other surface is rough and coarse in surface finish.

Wastage of materials may be high.

Product-to-product variations in quality may be high.

Bag Molding

Bag molding technique works well with wet-forming process, and also with premix/prepreg forming process. It is a very old, and yet versatile composite fabrication process.

In this process, layers of fibers, impregnated with uncured resin, are laid on top of a mold, layer-by-layer. Once the layup is complete, the overall fiber stack up is covered with a flexible bag or diaphragm.

The overall assembly is next subjected to external pressure and temperature for purposes of reliably curing the resin in relatively short period of time.

Once curing is complete, constituent materials become one integrated mass in desired shape. They can be subsequently trimmed, and finished, following which they can be used in actual application.

Laying up and proper bagging of the material are very critical steps in the entire process, as they influence the quality of part produced. To ensure this, an elaborate setup is required for bagging.

The layup is setup between a steel mold plate, and caul plate, which are coated with a spray of release coat film as well as release fabric, which ensure that the part does not get stuck to the mold plate. The composite part is covered with peel plies, which protect it against contaminating agents . Further, the laminate is also covered with bleeder plies, which absorb excess resin and breather plies, which act as a pathway for air bubbles and volatile materials to exit out from the composite during curing. The entire setup is sealed in a vacuum bag using appropriate sealants.

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In this process, while application of temperature is required to fasten the curing process, application of pressure is important to ensure good surface finish, dimensional accuracy and also to eliminate presence of air and porosity in the composite component.

Bag molding process can be categorized, based on the method of application of external pressure, into three groups.

Pressure bag molding: Here pressures exceeding 1 bar are applied on the composite material being processed.

Vacuum bag molding: In this process, the composite materials is subjected to vacuum to remove air bubbles from the laminate. Post this stage, the material may be subjected to atmospheric pressure while it undergoes curing process in an oven.

Autoclave molding: Here, the composite is subjected to vacuum pressures, and also elevated pressures simultaneously, while it undergoes curing at elevated temperatures. In this process, the part is enclosed in a bag connected to a vacuum pump. Further, the exterior of the bag is subjected to pressures exceeding 1 bar. Finally, curing of the resin is initiated through raising the temperature of material by placing it in an autoclave chamber.

In such a process, application of high pressure ensures increased removal of air and other volatiles, increased wetting, and improved impregnation of fibers with resin.

Pressure bag molding is relatively expensive due to tooling costs. In this method, tooling is expensive since it is integrated with curing pressure system.

Further, tools for this type of bag molding are part specific.

In contrast, vacuum bag and autoclave molding approaches are relatively inexpensive as the basic curing equipment does not change.

DIAGRAMS

Resin Transfer Molding

Resin Transfer Molding, commonly known as RTM, is a wet-process, where f ibers and resin are placed in the mold separately.

First, layers of fibers (or mats/fabrics, …) are placed in the mold layer-by layer. Once all the layers of fibers have been placed, pressurized resin is introduced in the mold to impregnate the fibers. The mold cavity, into which resin flows, has inlets for resin, and also vents for air.

Once the mold is full of resin, the system is heated to initiate curing. However, in certain applications, curing may occur at room temperature.

In this method, low viscosity resins are chosen, as such resins wet fibers, and also enter inter-fiber gaps relatively easily.

RTM ensures improved control over fiber orientation, as fluid pressure in resin is not sufficiently large enough to dislodge fibers from their intended location.

Vacuum assisted resin transfer molding (VARTM) is a variation of RTM, where vacuum pressure aids flow of resin, and also wetting of fibers. Compared to RTM, VARTM is significantly less expensive.

Filament Winding

Filament winding is a very popular method to produce composite parts which are axi-symmetric. Composite pipes, tubes, tanks, cylinders, domes, spheres are fabricated using filament winding technique.

In this process, an axi-symmetric mandrel with an outside surface similar to the inner surface of part to be produced is used to produce the axisymmetric composite part.

Fiber from continuous-fiber rovings gets wetted as it passes through a resin bath. This resin-wet , as it exits from resin bath gets wound on a mandrel, which continually rotates on its axis of symmetry.

Care is taken, that there is sufficient tension in fiber so that the winding remains taut on the mandrel.

In typical filament winding machines, the rotational speed of mandrel, and also the traverse speed of resin bath, are variable process parameters. By choosing appropriate values of these parameters, the helix angle of filament wound can be controlled, layer-by-layer, and section-by-section in the desired part.

Using such an approach, the filament winding pattern can helical, or circumferential, or even longitudinal. Quite often, an optimally designed filament wound part would have a combination of winding patterns.

Once the winding is complete, filament wound part is allowed to cure. Post curing, the mandrel is taken out. To facilitate easy removal of mandrel, a variety of mandrel designs have been developed. Mandrel may be made of segmented and collapsible, inflatable, or made of materials with low melting points. They may also be fabricated from salts, soluble plasters, or plasters which can be broken post curing of the part.

As mentioned earlier, fibers in this process are continuous, and come as rovings. Several of these rovings may be mounted on a creel, which is essentially a shelf holding sveral roving packages.

Filament winding is also performed using prepreg tapes. Compared to filament winding using wet-process, parts produced from prepreg tapes exhibit less fiber damage, and better product quality.

Further, such an approach provides latitude to use resin systems, which may not be manageable in wet layup systems. Finally, usage of prepregs for filament wound parts also makes the overall production environment cleaner, and better controlled.

Filament winding process has specific advantages and limitations. These are listed below.

Advantages –Easily prone to automation and thus amenable to high production volumes. High strength products are produced due to fine and continual control of fiber angle.

Various sizes can be produced using this method.

Directional control of modulus and strength is feasible.

Limitations –Winding at angles when fiber is almost parallel to axis of symmetry is difficult. Reverse curvature parts cannot be produced easily.

Complex shapes, particularly parts with two-directional curvatures are difficult to produce. External surface finish is not always high.

Pultrusion

Pultrusion is a fabrication process used for composites, which is similar to the conventional process of extrusion. In this process. The reinforcing material, in form of a tape, or mat, or roving, passes through a resin bath.

Post bath, the reinforcing material passes through a pre-forming fixture, where it acquires its cross-sectional area partially. At this stage, it is also “squeezed” off its excess resin as well as voids. Finally, the reinforcing material passes through a heated die, where resin gets continuously cured and the composite acquires its final and intended cross-section.

Unlike extrusion, where the material is pushed thru a die, the process of pultrusion involves pulling of reinforcing materials (fibers, tapes, rovings, mats, etc.) through the die.

This difference is attributable to the fact that the reinforcing material, while passing through the pre-forming fixture, it is not cured yet, and hence is prone to buckling when subjected to compressive “push” forces. Pultrusion is used extensively to fabricate bars, tubes, rods, and other structural shapes. Profiles produced this way are very strong as well as stiff in the fiber direction.This process of fabrication works well with resins which cure without producing by-product. Occasionally, this process is also used with thermoplastic resins. However, in such cases, high power and specialty machines are required since the resin is highly viscous, and thus force required to pull the reinforcement is significantly higher vis-à-vis that required while pultruding composite sections with thermoset resins.

Also, due to high viscosity, proper wetting and impregnation of fibers with resin is more difficult. Hence, specialized equipment is used for this purpose.

Composite Fabrication Using Preformed Molding Compounds(PMCs)

Several thermosetcomposite products are fabricated using matched-die molds through processes such as compression molding and injection molding. While composite fabrication using matched-die molds can be a wet process it is more convenient to use premixes and prepregs. This is so because use of prepregs and pre-mixes increases production throughput, and makes the process more controlled.There are three types of preformed molding compounds. These are: Dough or bulk molding compounds (DMCs or BMCs); Sheet molding compounds (SMCs) and Prepregs.

BMCs/DMCs: These compounds have a consistency of dough, and are premixes of resin, chopped fibers, andfillers. The compound is often available in rope form, and its fiber volume fraction is approximately 20%.

SMCs: These compounds are available in sheet form. In SMCs, polyester resin is typically used as matrix material, while chopped glass, carbon or kevlar fibers may be used as reinforcements. Fiber volume fraction in such compounds is 20-35%. Fibers, though chopped, are longer vis-à-vis BMCs. Prior to molding, SMC sheets are trimmed to appropriate size, and then pressed and heated in the mold.

Preimpregnated Fiber Reinforced Plastics: These compounds, also known as prepregs, are used for producing high performance laminates. Prepregs are reinforced with rovings, fabrics, continuous unidirectional fibers, or even random and chopped fibers, and preimpreg nated with partially cured resins.

Prepregs, unlike SMCs and BMCs contain no additives like fillers, pigments, and other additives. Carbon, kevlar and glass are typical fibers used in prepregs.

Fabrication of final products using BMCs and SMCs is done through matched die molding process. In contrast, Prepregs are used in hand lay-up, bag- molding, and winding processes.

Fabrication of Thermoplastic Resin Matrix Composites:

Thermoplastic matrix composites may either have short fibers, or long fibers. The fabrication process for these two types of composites are significantly different.

For thermoplastic resin composites reinforced with short-fibers, injection molding is the preferred method. Towards this end, conventional injection molding machine, either screw driven, or plunger driven, are used widely.

The raw material for product made from short fiber reinforced thermoplastic composites comes in pelletized form. These pellets have short fibers encapsulated in matrix material. Several resins reinforced with short glass fibers are commercially available. Some of these resins are: polypropylene, ABS, polycarbonates, and blends of polyphenylene oxide (PPO) and polystyrene.

Process parameters for short-fiber reinforced thermoplastics are significantly different from those for plain thermoplastics. These differences are attributable to: – Difference in rheological properties of molten pellets; Increased thermal conductivity; increased wear of tool due to presence of glass fibers ; difference in shrinkage of reinforced pellets vis-à-vis plain thermoplastics; direction dependent mechanical properties of reinforced plastics. In reinforced plastics, short-fibers tend to align with the direction of flow of resin in the mold.

There have been attempts to introduce dry blends of polymer and fibers directly into the injection molding machine, rather than using pellets which are pre-mixes of fibers and resin. However, it has been found that components produced this way have relatively coarser surface finish, and also variable strength due to non-uniform distribution of fibers in matrix.

Stamping and thermoforming are 2 other methods used for thermoplastic resin matrix composites.

These methods use reinforced thermoplastic sheets as the "raw" material. These sheets are produced by laminating chopped strand mats using a thermoplastic matrix material.

In certain cases the reinforcement could also rely on continuous rovings. AZDEL is one such commercially available materials in sheet form, which has 40% glass (by weight) bound in a polypropylene matrix.

Unlike conventional stamping process, where sheets of metals are usually formed into final shape at room temperatures, stamping of thermoplastic sheets requires application of temperatures to soften thermoplastic materials.

Fabrication of Metal Matrix Composites:

Metal matrix composites require embedding of reinforcing fibers into a metallic matrix. This requires either melting the matrix material, or hot pressing matrix into fibers. In either case, high temperature are required to produce these specialty composites.

A direct consequence of application of high temperatures is increased reactivity between specific fiber-matrix combinations. For instance, glass fibers react with aluminum at high temperatures. Such a reactivity may lead to degradation of composite's properties.

Further, metal matrix composites are frequently used at elevated temperatures. Under those conditions the specific matrix-fiber combinations may react leading to reduction of material's performance. Thus appropriate methods have been devised to manage such concerns. For non-reactive fiber-matrix systems, molten matrix material is simply poured to impregnate the fibers. However, in case of reactive fiber-matrix systems, fibers are individually coated with matrix material by drawing them rapidly through molten metal, such that there is very little time for fiber-matrix reactions to occur. These coated fibers are subsequently hot-pressed to form composite components.

In other cases, fibers are pre-coated with a non-reactive material, and only them immersed in the matrix material bath. For instance, nickel is used to coat graphite fibers, before the fibers are immersed in aluminum matrix.

In another method, matrix material is alloyed with substances that reduce the matrix melting point, and thus composite's processing temperature. Reduction in processing temperature significantly reduces rate of reaction between fiber and matrix. For instance, addition of 12% silicon to aluminum, reduces its melting pointfrom 660C to 580C.

Plasma spraying is one more method used to minimize reactions between fibers and matrix. Here, fibers, supported on a thin foil, are exposed to spray of matrix material. Such a process produces a thick tape of metal matrix composite.

This tape is porous, easy to deform, and amenable to hot-pressing for production of final product. In this method, metal spray cools very rapidly, thereby reducing the time for fiber-matrix reactions to occur.

In still other cases, solid matrix, in sheet or powder form, is hot pressed onto fibers Such an approach works only for fibers with large diameters (e.g. boron). The process requires tight control of temperature and pressure to ensure minimal mechanical damage and chemical interaction. Such a process is used to produce tapes, which have matrix sheets on either side of fibers. These tapes may be subsequently used to produce final components.

Chemical vapor deposition (CVD) is another method, through which metal matrix composites are produced.

Fabrication of Ceramic Matrix Composites

These composites are fabricated using a 2 stage process. First, fibers are coated with "green" matrix material. This is accomplished by passing a filament tow through a bath of slurry which contains matrix powder, an organic binding agent and a liquid medium. The fiber tow, post infiltration of the slurry is wound on a drum, and dried.

Next, the tow is cut, stacked, and laid as per design requirements. At this stage, it is either hot-pressed or fired at temperatures exceeding 1200 C. Exposure to high temperatures ensures rapid diffusion and compaction of the composite.

Care is taken, while fabricating ceramic matrix composites, to minimize porosity.

For this, it is ensured that matrix powder particles are smaller than fiber diameter, as this ensures increased removal of binding agents during the firing process.