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Composites Classification and Manufacturing Operations: A Review

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***Abstract*: A composite material is composed of two or more dissimilar constituents with one constituent as the reinforcing phase and the other as the matrix. These constituents do not dissolve in each other and they work together to give the composite special properties which make it widely used in different aspects of the industry.**

This paper covers the classification of composite materials and a number of the manufacturing processes used in their production.

Keywords: Laminates, Curing, Pultrusion, Filament Winding, Composite Materials.

1. INTRODUCTION

Composites are a class of material which receives great attention not only because it is on the cutting edge of active material research fields due to the appearance of many new types of composites eg. Nanocomposites and biomedical composites but also because there is a lot of promises for their potential applications in various industries ranging from aerospace to construction due to their various outstanding properties. (1)

A composite material can be defined as a combination of two or more materials that results in better properties than those of the individual components used alone. In contrast to metallic alloys, each material retains its separate chemical, physical, and mechanical properties. The two constituents are reinforcement and a matrix. The main advantages of composite materials are their high strength and stiffness, combined with low density, when compared with bulk materials, allowing for a weight reduction in the finished parts. The reinforcing phase provides the strength and stiffness. In most cases, the reinforcement is harder, stronger, and stiffer than the matrix. The reinforcement is usually a fiber or a particulate. Particulate composites have dimensions that are approximately equal in all directions. They may be spherical, platelets, or any other regular or irregular geometry. Particulate composites tend to be much weaker and less stiff than continuous fiber composites, but they are usually much less expensive. Particulate reinforced composites usually contain less reinforcement (up to 40 to 50volume percent) due to processing difficulties and brittleness.

A fiber has a length that is much greater than its diameter. The length-to-diameter (l/d) ratio is known as the aspect ratio and can vary greatly. Continuous fibers have long aspect ratios, while discontinuous fibers have short aspect ratios. Continuous-fiber composites normally have a preferred orientation, while discontinuous fibers generally have a random orientation. Examples of continuous reinforcements include unidirectional woven cloth, and helical winding, Continuous-fiber composites are often made into laminates by stacking single sheets of continuous fibers in different orientations to obtain the desired strength and stiffness properties with fiber volumes as high as 60 to70 percent. Fibers produce high-strength composites because of their small diameter; they contain far fewer defects (normally surface defects) compared to the material produced in bulk. As a general rule, the smaller the diameter of the fiber, the higher its strength, but often the cost increases as the diameter becomes smaller. In addition, smaller-diameter high-strength fibers have greater flexibility and are more amenable to fabrication processes such as weaving or forming over radii. Typical fibers include glass, aramid, and carbon, which may be continuous or discontinuous.

The continuous phase is the matrix, which is a polymer, metal, or ceramic. Polymers have low strength and stiffness, metals have intermediate strength and stiffness but high ductility, and ceramics have high strength and stiffness but are brittle. The matrix (continuous phase) performs several critical functions, including maintaining the fibers in the proper orientation and spacing is and protecting them from abrasion and the environment. In polymer and metal matrix composites that form a strong bond between the fiber and the matrix, the matrix transmits loads from the matrix to the fibers through shear loading at the interface. In ceramic matrix composites, the objective is often to increase the toughness rather than the strength and stiffness; therefore, a low interfacial strength bond is desirable.

The type and quantity of the reinforcement determine the final properties. There is a practical limit of about 70 volume percent reinforcement that can be added to form a composite.At higher percentages, there is too little matrix to support the fibers effectively. (2)

II. EXAMPLES FOR COMPOSITE MATERIALS

1. Fiber reinforced plastics
A. Classified by type of fiber
Wood (cellulose fibers in a lignin and hemicellulose matrix)
Carbon-fiber reinforced plastic (CRP)
Glass-fiber reinforced plastic (GRP) (informally, "fiberglass")

B. Classified by matrix
Thermoplastic Composites
Short fiber thermoplastics
Long fiber thermoplastics or long fiber reinforced thermoplastics
Glass mat thermoplastics
Continuous fiber reinforced thermoplastics

C. Thermoset Composites
2. Reinforced carbon-carbon (carbon fiber in a graphite matrix)
3. Metal matrix composites (MMCs):
White cast iron
Hardmetal (carbide in metal matrix)
Metal-intermetallic laminate

4. Ceramic matrix composites:
Bone (hydroxyapatite reinforced with collagen fibers)
Cermet (ceramic and metal)
Concrete

5. Organic matrix/ceramic aggregate composites
Asphalt concrete
Dental composite
Syntactic Foam
Mother of Pearl

6. Chobham armour

7. Engineered wood
Plywood
Oriented strand board
Wood plastic composite (recycled wood fiber in polyethylene matrix)
Pykrete (sawdust in ice matrix) ……(3)

III. MANUFACTURING PROCESS OF COMPOSITE MATERIALS

Generally, manufacturing using composites involves the processing of two main ingredient materials to make a final product. The ingredients involve the matrix and fiber materials. This processing requires the following:

-Good bonding between matrix and fibers
-Proper orientation of the fibers
-Good amount of volume fraction of fibers
-Uniform distribution of fibers within the matrix material
-Proper curing or solidification of the resin
-Limited amount of voids and defects
- Good dimensional control for the final part …(4)

In function of composite constructions, those can be divided into two categories:
- Laminates, which have layers bonded together,
- Sandwiches, which are multiple-layer structural materials containing a low-density core between thin faces (skins) of composite materials.

As an observation, in some application of advanced composite materials, the individual layer may themselves be composites, usually of fiber-matrix type.

Composites fabrication have many processes, some of the most important processes are:

- Hand and automated tape lay-up,
- Resin injection,
- Compression molding,
- Pultrusion,
- Filament winding.

Other classification of composites process can be after the process volume, which is of two categories: high and low volume. Low-volume processes are manual and low-pressure spray lay-up in low-cost molds with a high working cost. High-volume processes, such as lamination, filament-winding, pultrusion and resin transfer molding, have an initial high cost for tooling and installation, which are compensated by low-intensity of working. In addition, lamination processes can be found in both of them, lamination as a hand lay-up process, or as the automated using sheet-molding compounds. Lamination, filament winding, pultrusion and resin transfer molding are used in the production of continuous fiber composites with closely controlled properties, being used for obtaining comparative flat parts.

A potential and high-speed process in the fabrication of tubs and other cylindrical parts represent the filament-winding process, in which time the pultrusion process is applied for fabrication of parts with constant cross-sectional shapes, and resin transfer molding shares some similarities with injection molding.

1. Laminating Process

The laminating process is largely used in the fabrication of advanced materials. To improve the process a prepreg material can be used, which is a pre-impregnated reinforced material with high composite's property by fibers aligned parallel to each other.

A sample of product's form is cut off by various processes and the prepreg material is fixed into the desired laminate geometry. The final workpiece is achieved by curing the stacked plies under pressure and heat in an autoclave.(5)

The placement of the reinforcing fiber is often referred to as the *layup* process. In this process, the fiber, often in the form of dry or pre-impregnated (prepreg) composite fabrics are placed into a mold or tooling. During the layup process, the fiber has to conform to the mold without any wrinkling or waviness because wrinkles or waves can severely compromise strength and fatigue performance. Due to the difficulty and complexity of the layup process, it is most often done manually by skilled workers. In the layup process, the workers place the fabric into the mold, carefully smooth it with substantial force to make it conform to the mold geometry and watch for and eliminate any wrinkles or waviness.

The high-end composites manufacturing industry (e.g. aerospace industry) has been trying to address this issue by using automated layup technologies.

For example, Automated Tape Layup (ATL) and Automated Fiber Placement (AFP) were two such technologies developed in the late 1960s and have been slowly evolving ever since.

These two technologies make use of a layup head attached to a motion system to accurately place prepare fiber materials onto the mold. However, ATL and AFP require high capital cost which prohibits them from being used in low-cost applications such as the manufacturing of utility-scale wind turbine blades.(6)

2. Pultrusion

It is one of the technologies to fabricate the polymer composites to be used in many industries such as in aerospace, automotive and construction industries. The high performance pultruded products that are produced by this technique offer high fiber content of at least 70%. In order to produce high quality pultruded profiles, there are variables such as fiber impregnation, resin viscosity, pulling speed and curing temperature that has to be considered.

Pultrusion is a continuous composite fabrication process where continuous reinforcing fibers are impregnated with thermosetting matrix and are pulled through a heated die to form composite profiles. It has the capabilities to run continuously with constant cross-section profile with the mass production volume.

Thermosetting pultrusion process can be divided into three zones; heat transfer zone, pressure zone and pulling zone. Firstly, the fibers are pulled from the creel through a resin bath with the proper resin viscosity. Then, the polymer solution is placed in the resin bath, which contains polymer resin, filler, catalyst, release agent, pigment, Ultra Violet (UV) stabilizer and other enhancement additives. Thereafter the fibers are guided by a guide plate where the fibers and resin are impregnated. The fibers are pulled through pre-form guides to eliminate excess resin before entering a heated die where the composites are cured.

The heated die in most of pultrusion process is divided into two zones; a low temperature for gelation and a high temperature to cure the resin. The pultrusion die is heated by a heater and the temperature is controlled using thermocouple sensor, which interacts with heater to ensure the temperature is sufficient and to avoid die from overheating which can cause the defect on the pultruded profile.(7)

3. The Resin Transfer Molding (RTM):

It is one of the most promising technologies available today. RTM is capable of making a large complex three-dimensional part with high mechanical performance, tight dimensional tolerance, and high surface finish. A good design by RTM leads to fabricate three-dimensional near-net-shape complex parts, offering production of cost-effective structural parts in medium-volume quantities using low-cost tooling. In addition to these advantages, the problems of the joints, typical of the metal structures, can be eliminated by integration of inserts. The final performances of a composite depend not only on the choice of the matrix and the fiber but also on the manufacturing process by which they are made. Since the starting of the composite life, the presence of imperfections due to manufacturing must be considered.

Such imperfections can be already damaging for the manufactured composite piece or lead to the damage quickly. The damage for composites can be defined as a change in the microstructure of the material that causes deterioration in the structural behavior of the component and sometimes its collapse. The damage in a composite structure can occur at the level of fibers and matrix as well.

The RTM is a process with a rigid closed mold. The lamination sequence (preform) is draped in a half mold, then the mold is closed and the preform compacted. After that, the resin is injected using a positive gradient pressure through the gate points replacing the air entrapped within the preform. Usually, a vacuum is applied at dedicated vents in order to favorite the air escape from the mold. When the resin reaches the vents, the gates are clamped and the preform is impregnated. At this point, the curing phase is considered to start. Finally, the mold is opened and the part removed. Especially for aerospace structures, an additional free-mold post-curing phase can be necessary in order to guarantee the polymerization of the matrix and release the internal thermal stress. The closing mold step is characterized by the compaction of the fiber reinforcement, which permits to reach the desired thickness and design fiber volume fraction. The compaction changes the microstructure and the dimensions of the preform, producing large deformations and nonlinear viscoelastic effects. These effects are accompanied by a change in energy within the material, which causes the residual stresses due to the viscoelastic behavior of the fibers. However, during the impregnation phase a release of stress, probably due to the balance, occurs.

The injection phase must guarantee the complete impregnation of the preform: a bad impregnation of the fibers results in dry spot areas with missing adhesion between the layers, which makes the surface rough and irregular. If partial impregnation occurs in the proximity of a connecting zone among elements, it can cause a bad integration with a consequent loss of mechanical properties.(8)

4. Filament Winding

Filament winding is an automated process for manufacturing advanced reinforced composite structural components. It entails the winding of resin impregnated fibers around a mandrel and then curing them so that the wound fiber can take the shape of the mandrel. The fibers are placed on the rotating mandrel by a horizontal carrier. The fiber orientation is controlled by controlling the speed of the horizontal carrier. Subsequently curing is done for an appropriate time and temperature. After curing, the wound composite is removed from the mandrel if the mandrel is not sacrificial; but, sometimes the mandrel can be a part of the design. It is used to manufacture pipes, tanks, gas cylinders, etc. the major advantages of the winding process are that it is highly automated and capable of producing accurate repetitive fiber orientation.

It does have some limitations, however, which include difficulty in placing fibers parallel to the axis of the mandrel, high mandrel cost, and special treatment on the external mandrel surface needed to ensure evenness. (9)

5. Hot Mould Processes

Hot press molding techniques are used for high volume production of composite components. The principle of the process is that reinforcement and a controlled quantity of catalysed resin are enclosed and cured between heated, polished, matched metal molds. A hydraulic press is used to bring the molds together under pressure at temperatures between 100ºC and 170ºC. Cycle times, which are dependent on temperature, molding complexity and weight, are generally between 2 and 4 minutes but can be as low as 30 seconds.(10)

The strategy for weight and cost reduction has promoted the development of long-fiber-reinforced thermoplastics (LFRTs) and thermoset sheet molding compounds (SMC) and bulk molding compounds (BMCs) with high fiber volume and /or quick-cure resin formulations. But the relatively poor in-mold flow characteristics of these materials has challenged the limits of existing compression molding press design, particularly in terms of press speed.

Use of these new materials reduces the process window-time available to accomplish the various stages in the molding process. A significant factor is heat loss. Parts with thinner walls require less material. In addition, the poor flow has prompted designers to load the mold with a thinner charge that covers a greater area of the mold surface, requiring the material to flow a shorter distance during the molding process, which reduces the incidence of fiber breakage. The result is a much thinner charge with the greater surface area that cools very quickly. The time it takes to load the charge and close the mold becomes a critical factor in success.(11)

6. Pulsed Infusion

A new innovative infusion technology, pulsed infusion, has been developed for the manufacturing of fiber-reinforced thermoset -based composites. Pulsed infusion is a double-bag vacuum infusion process that is based on the use of a properly designed reusable pressure distributor and able to better control the vacuum pressure in a pulsed way. Thus, the transverse resin flow through the dry fiber reinforcement is promoted and a better adhesion between the resin and the fibers is achieved. In the conventional vacuum - assisted risen transfer molding (VARTM), the impregnation of the dry fiber reinforcement by a thermoset liquid resin occurs by vacuum application.

The process basically involves three steps: layup of a fiber preform, vacuum application and fiber impregnation by a thermoset resin, and cure of the resin. The reinforcement, typically carbon or glass fabric, is placed onto a one-sided rigid mold, a formable vacuum bag material replaces the common RTM-matched metal tool. The resin is injected through one or more inlet gates, depending on part size and shape. Vacuum is applied through a single or multiple vents in order to remove the air from the fiber preform and to drive the fiber impregnation of the part by resin. A resin distribution net medium is placed onto the reinforcement to promote the resin flow, to allow complete wet-out of the preform and to eliminate voids and dry spots. In the case of the pulsed infusion, two vacuum bags are adopted and the resin distribution net is eliminated. The lower vacuum bag determines a lower chamber where the resin infusion occurs most likely in the VARTM. The lower vacuum bag is stacked on the dry fiber reinforcement without placing the resin distribution net. A properly designed pressure distributor is positioned on the lower vacuum bag and under the second upper vacuum bag allowing to identify an upper chamber. By applying a different vacuum pressure in the two chambers and controlling timely the pressure difference between the two chambers, the resin flow is pulsed and promoted both in the plane and through the thickness of the reinforcement.

The new process allows obtaining laminates with the same fiber volume fraction and tensile properties of those produced by conventional infusion technologies. An average increase up to 9% for the flexural modulus and up to 24% for flexural strength has been assessed for pulse-manufactured composites compared to traditional vacuum infusion ones. Furthermore, due to a minor consumption of resin and the absence of the distribution net, pulse infusion provides a material cost-saving advantage around 19% and a significant waste reduction.(12)

7- Manufacturing Processes of Composite Grid Structures

Composite Grid Structures (CGS) are manufactured with varying geometries such as circular (cylindrical and conic) and flat. They are applied in high-tech industries including aerospace industry.

Today, the application of composite grid structures (CGS) is evident in many weight-sensitive areas in the aerospace industry. These structures are applied to fairing interstate and adaptor structure of launch vehicle and fuselage of aircraft. This wide range of applications is due to their high specific strength and specific stiffness properties. In fact, these structures are substitutes for sandwich structures with honeycomb core and ring and stringer stiffened shells as well as aluminum grid structures. These CGS are manufactured using filament winding and fiber placement automatically. Composite grid structures are substitutes for aluminum grid structures, ring and stringer stiffened structures and honeycomb sandwich structures. Yet, they are superior to the above structures in some aspects.

These CGS are composed of an integrated grid by the placement of unidirectional composite ribs (tapes) in 2 to 4 directions (right-rounded and left-rounded cross, circumferential and longitudinal). Geometrically, they are classified into three groups: flat plates, open and closed shells of revolutions. These grids are generally without internal skin. This is because the main load-carrying components are ribs. Yet, they can have one or two skins based on the application environmental conditions.

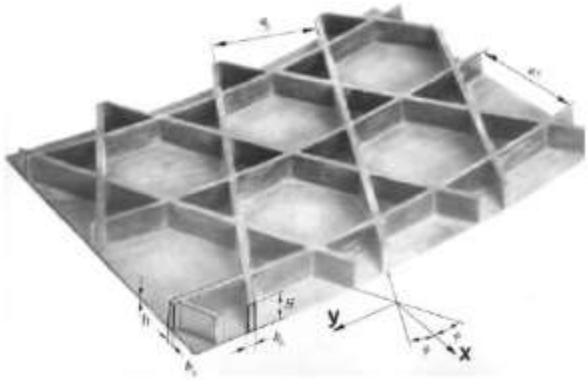

Fig 1 Grid geometrical parameters n of them.

The Advantages of Grid Structures versus Other Stiffened Structures

Aluminum grid structures are produced by machining of thick aluminum plates.They have less stiffness and more weight as compared to the composite structures.

Based on the US Air Force Research Laboratory (AFRL) report, the composite sample of the fairing was made and tested, 61% lighter, 300% stronger, and 1000% more stiffened as compared to its aluminum equivalent.

The advantages of grid structures (as compared to sandwich structures with honeycomb core) can be put in three parts.

1- Structural efficiency of these structures is higher. Due to the unidirectionality of the ribs. It is because the distribution of the applied loads at the direction of the ribs and maximum exploitation of the strength and the stiffness of the fibers in these directions increase CGS load-carrying properties.

2- The better performance of these structures in environmental conditions; CGS have higher damage tolerance. Grid structures have shown a tendency to contain delamination, a result of impact damage in a cell. They prevent from its spreading and catastrophic failure of the structure. Unlike honeycomb sandwich structures, these structures do not absorb and keep humidity during their service life. The absorbed humidity in honeycomb core results in the corrosion of the structure.

3- Another advantage of the CGS is their automatic, continuous, and low-cost manufacturing process.

The Manufacturing Processes of Composite Grid Structures:

Manufacturing of these types of composite structures can be classified from three viewpoints:

1- Winding method (filament winding or fiber placement).

2- Type of mold or mandrel, and 3- a type of structure curing cycle. The production process is mainly aimed to provide appropriate quality and mechanical properties for (cross) spiral (for cone winding) or helical (for cylinder winding) ribs. These are the main load-carrying components in the structure. The winding is carried out in two ways: wet filament winding and dry (tape) winding.

Wet filament winding is a process where a bundle of continuous fibers is dripped in resin pool is aligned on a circular mandrel by predetermined arrangement. When the resin is cured, the mandrel is separated from it and the process is finished. This method is usually applied to manufacturing circular grid structures (like cylinders and cones). In the dry winding process, prepreg tapes are in fact placed on the desirable area by a robot. This is also called fiber placement.
Grooves guided winding can be carried out on the mandrel composed of various materials. The metal mandrel (aluminum or steel) is made by helical and circumferential groove cutting. Mandrels must be made in several pieces. Then, they can be assembled on a shaft. They have suitable dimensional stability and are reusable (i.e. they can be used several times). At the same time, they are costly and time-consuming. Plaster mandrels are also made by molding plaster on a metal shaft.After creating grooves and winding, in order to extract the grid stiffened or lattice structure, plaster must be separated from the structure mechanically or via washing by water.(13)

SUMMARY

As mentioned above a composite material is composed of two or more distinct components that do not dissolve in each other, in order to produce a material with properties that excel the properties of the individual components used apart.
The paper addressed the following topics:

- The classifications of composite materials.
- The widely used manufacturing operations of composite materials.

Further readings could be done in the field of non-destructive techniques of composite materials.

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