Module-5

Composite Materials

Objectives:

To learn about composites such as

- Classification of Composites
- Types of matrix materials & reinforcements,
- Production of FRP's and MMC's
- Advantages and application of composites.

Outcomes:

1. Today's composite materials often outshine traditional materials; they are lightweight, corrosion-resistant, and strong. Used in everything from aircraft structures to golf clubs, and serving industries from medicine to space exploration, composites are an exciting field of study for students, engineers, and researchers around the world. New applications of these versatile materials are being found daily.

INTRODUCTION TO COMPOSITE MATERIALS

Composite materials (or **composites** for short) are engineered materials made from two or more constituent materials with significantly different physical or chemical properties and which remain separate and distinct on a macroscopic level and are not soluble to each other. one constituent is called the MATRIX and the other is called the REINFORCING phase. examples; concrete, fibre glass,wood

Composite material is a material composed of two or more distinct phases (matrix phase and dispersed phase) and having bulk properties significantly different form those of any of the constituents

The idea is that by combining two or more distinct materials one can engineer a new material with the desired combination of properties (e.g., light, strong, corrosion resistant). The idea that a better combination of properties can be achieved is called the principle of combined action. New - High-tech materials, engineered to specific applications

Properties that can be improved by forming a composite material are (Advantages of composites

Strength Stiffness Corrosion Resistance Wear Resistance Attractiveness lessWeight Fatigue life Fatigue life Temperature dependent behavior Thermal insulation Thermal conductivity, Acoustical Insulation

Limitations

High cost of production, Anisotropy, Mechanical characterization difficult Debonding, Delamination, Fiber pullout

Repair of flaws- difficult in metals Recycling-PMC

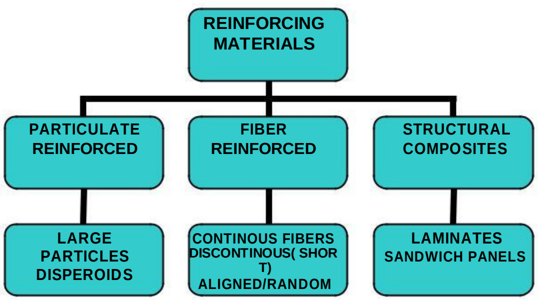
Historical Background

addition of straw to clay in making of mud huts -4000bc
glue laminated wood 500 bc

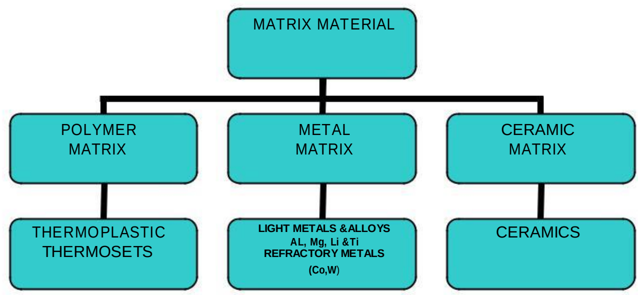
medieval swords and armor made with layers different metals
reinforced cement concrete-1800 ad

Classification of composites

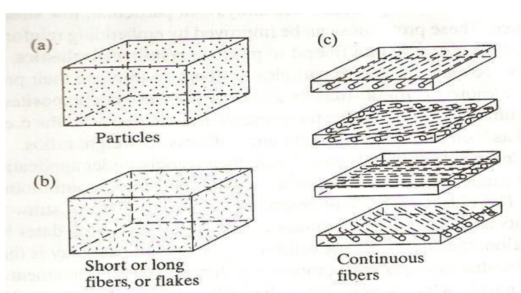
Based on reinforcing materials



Based on matrix material



Matrix phase The primary phase, having a continuous character, is called matrix. Matrix is usually more ductile and less hard phase. It holds the dispersed phase and shares a load with it



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Reinforcement Phase Discontinuous phase,

Particle Reinforced composites Fiber reinforced composites

Particulate reinforced composites consist of particles of one or more materials suspended in a matrix of another material. The particles can be either metallic or non metallic as can the matrix. The four different combinations are

Nonmetallic particles in Nonmetallic Matrix

Concrete- a mixture of sand, gravel, cement & water
Glass flakes in plastic resins

Metallic particles in Non metallic matrix

Copper in Epoxy resin increases the conductivity Aluminum paint – Suspension of aluminum flakes in Paint
Metallic additives to plastics improves the thermal conductivity, lowers the coefficient of thermal expansion and reduces the wear

Metallic particles in Metallic Matrix

Lead alloys in copper alloys to improve machinability, where lead is a natural Lubricant
Tungsten, Chromium (hard materials) suspended in ductile materials

Non metallic particles in Metallic Matrix

Chromium carbide in a Cobalt matrix has high corrosion and abrasion resistance Uranium oxide in stain less steel as a control rod in nuclear reactors
Ceramics suspended in metal matrix called as cermets.

Fiber reinforced composites:

Fibers are one of the oldest engineering materials in use. Jute, flax, hemp have been used for such products as rope, nets, water hose, and containers since antiquity. Plant fibers and animal fibers are used for papers, brush, or heavy structural cloth. Many synthetic fibers have been developed to replace natural fibers, because synthesis has more predictability and uniform in size. For engineering purposes glass, metallic, and organically derived synthetic fibers are most significant. Nylon is used for belting, nets, hose, rope, parachute, ballistic cloths and reinforcement in tyres.

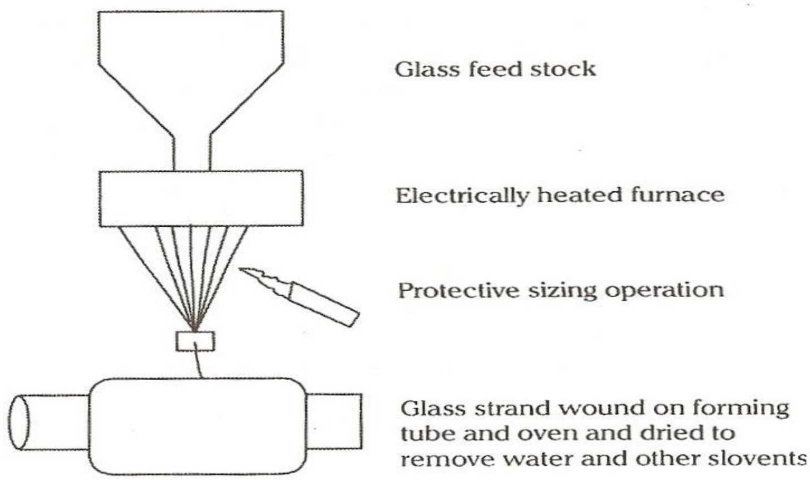
FIBERS

Glass-high strength low stiffness, high density lowest cost
Graphite-high strength low cost less dense than glass Boron-high strength & stiffness high density, highest density Aramids-highest strength to weight ratio of all fibers, high cost

Other fibers nylon silicon carbide silicon nitride aluminum oxide boron carbide boron nitride tantalum carbide aramids/ Kevlar

Chemical composition of different glass fibers

Constituents	E-glass	S-glass	C-glass
SiO2	54	64	65
Al2O3	15	25	4
CaO	17	<1	14
MgO	4.5	10	3
B2O3	8	-	5
Others	1.5	0.8	8



Wet Spinning Technique

Factors for Glass fiber selection

- Thermal properties
- Fiber cost
- Type of manufacturing process
- Forms of reinforcement

Thermal properties of Glass fibers

- Glass fibers loose tensile strength as temp increases.
- At high temp performance of C glass is inferior to E glass & S glass.
- Fibers with high CTE expand more as temp increases.
- S-glass has much lower CTE than E glass & C glass

Glass Fiber Manufacturing

Sand, Limestone & Al2O3 is fed to Feed stock & heated to 14000C. The melt is stirred at a constant temperature. The melt passes through the platinum nozzles containing around 934 nozzles of 10µmdia. The yarn coming out is wrapped up in the forming tube at a speed of 25m/s. Before the yarn is drawn, sizing is done

Sizing solution consists of

1. organic binders- to allow packing of strands
2. Lubricants- to prevent abrasion of filaments
3. Coupling agents-for better bonding with polymers.

Fibers are drawn in to strands; each strand consists of more than 204 filaments. The wound array of strands are dried in an oven to remove water & other solvents

Forms of Glass fibers

- Continuous strands (group of 204 fibers)
- Rovings (group of parallel strands)
- Chopped strands (5 to 50mm length)
- Chopped rovings (5 to 50mm length)
- **Tow** (group of over 10000 fibers).**A strand** is a collection of continuous filaments
- **A roving** is a collection of untwisted strands. **Yarns** are collection of filaments or strands twisted together.

Reinforcing fibers for PMC's are generally Glass, graphite, aramids, boron, and other fibers.

Graphite; graphite fibers are more expensive than glass fibers. They have a combination of low density, high strength and high stiffness

All graphite fibers are made by pyrolysis of organic precursors commonly polyacrylonitrile (PAN) because of its low cost. Rayon and pitch (the residue from catalytic crackers in petroleum refining) can also be used as precursors.

Pyrolysis is a process of inducing chemical changes by heat-by burning a length of yarn and causing the material to carbonize and become black in color. The temperatures for carbonizing range up to about 1500 deg C: for graphitizing, to 3000 deg C.

The difference between graphite and carbon fibers depends on the temperature of pyrolysis and purity of material. Carbon fibers are usually 80-95%, graphite fibers are 99% carbon.

Conductive Graphite fibers: are used to increase the thermal and electrical conductivities of the reinforced plastic components. The fibers are coated with metals, usually nickel, by continuous electroplating process. The coating will be around 5 micron thick on a 7 micron graphite fiber core. Applications include electromagnetic and radio frequency shielding and lightening –strike protection.

Aramids: are produced from aromatic polyamide fibers. The trade name is **Kevlar** produced by DuPont. Kevlar fibers are compounds based on benzene rings. It is manufactured by a process called Dry jet wet spinning process.

Boron: boron fibers consist of boron deposited on tungsten fibers by chemical vapor deposition. These fibers have desirable properties like high strength and stiffness both in tension & compression & resistance to high temperature. Because of the high density of the tungsten they are heavy, expensive.

Other fibers: Nylon, silicon carbide, silicon nitride, aluminum oxide, sapphire, steel, tungsten, molybdenum, boron carbide, boron nitride, and tantalum carbide.

Whiskers are also used as reinforcing fibers. They are needlelike single crystals that grow to from 1 micron to 10 micron in diameter. They have aspect ratios ranging from 100-15000. (**Aspect ratio** is defined as the ratio of fiber length to fiber diameter.)

Because of their small size whiskers are free of defects. The elastic modulus ranges from 400 GPa -700 GPa and their tensile strength ranges from 15GPa to 20GPa.

Mats - is a non-woven fabric that provide equal strength in all directions Mats are of two types

1.Chopped strand-randomly distributed fibers cut in 1.5-2.5 inch, held with a chemical binder (styrene)-used in hand lay up, continuous laminating, closed molding application

2. Continuous strand-formed by swirling continuous strands of fiber onto a moving belt, finished with a binder are stronger than chopped strand.

These mats are used in compression molding, resin transfer molding, pultrusion

TABLE 9.2 Typical Properties of Reinforcing Fibers

Type	Tensile strength (MPa)	Elastic modulus (GPa)	Density (kg/m^3)
Boron	3500	380	2600
Carbon			
High strength	3000	275	1900
High modulus	2000	415	1900
Glass			
E type	3500	73	2480
S type	4600	85	2540
Kevlar			
29	2800	62	1440
49	2800	117	1440

Note: These properties vary significantly depending on the material and method of preparation.

Desirable characteristics of fiber reinforced composites.

While designing a fiber reinforced composites, the following factors have to be considered. Length of the fibers

Diameter of the fibers
Orientation of the fibers

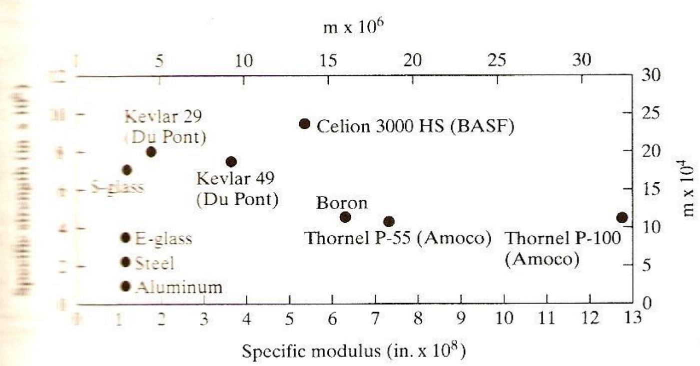
Amount or volume fraction of the fibers
Physical and Mechanical properties of Matrix
Bonding between matrix and fibers.

Length of fibers: Usually the ends of fibers have lower load carrying capability and hence more no of ends will lower the load carrying capacity of the composite. Longer the fiber, no of ends will be lower and hence the load carrying capacity will be higher. An important parameter characterizing the length of the fiber is the aspect ratio (l/d). if the aspect ratio is greater than 15, the fiber is termed as continuous, otherwise it is termed as discontinuous.

Diameter of fibers:

Reducing the diameter of fibers has the following advantages. The numbers of defects are reduced and the strength is increased

Specific tensile strength (tensile strength-to-density ratio) and specific modulus (modulus of elasticity-to-density ratio) for various fibers used in plastics. Note the wide range of specific strengths and stiffnesses available.



LAMINAR COMPOSITES

Of all the composites devised the laminar type is the oldest. It differs from the other types by the presence of layers. They are made up of films or sheets. Laminar composites consist of two or more different layers bonded together. The layers constituting a composite can differ in material, form and / or orientation. Laminar composites are anisotropic in nature.

In plywood, though the layers are often of the same material, the orientation differs. A reinforced plastic sheet may be clad with copper to make a printed circuit board

A **Lamina** is a single layer of uni-directional fibers or woven fibers arranged in a matrix.

The constituents of lamina ie fiber and matrix exhibit different types of stress strain behaviour. Fibers generally show linear elastic behaviour. The fibers or filaments, the main load carrying agent, are strong and stiff. The matrix may be plastic ceramic or metallic. Its function is to transfer the load , support and protect the fibers.

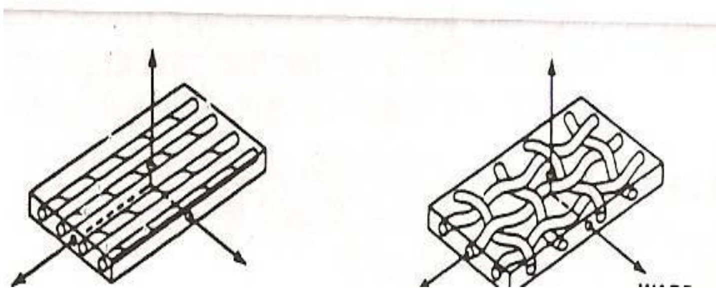


Fig 1 Lamina with unidirectional fibers. Fig 2 Lamina with woven fibers

Laminates are defined as composite materials consisting of two or more superimposed layers bonded together. Laminate is a stack of plies of composites. Each layer can be laid at various orientations and can be different material systems. Laminate is a stack of laminae.

Generally laminates are designed to protect against corrosion, high temp oxidation, to cut costs, to improve appearance etc

Laminar composites can be divided in to laminates and sandwiches.

A major purpose of lamination is to tailor the directional dependence of strength and stiffness of a material to match the loading environment of the structural element.

Sandwiches a special case of laminates, consists of a thick low-density core (such as honey comb or foamed material) between thin faces of comparatively higher density. In sandwich composites the primary objective is to improve the structural performance.

Matrix materials:

POLYMER MATRIX COMPOSITES

Polymers make ideal matrix material as they can be processed easily, possess light weight and have desirable mechanical properties. Polymers in general have poor strength and modulus. They get degraded on prolonged exposure to ultra-violet rays. They also cannot withstand high temperatures. They are poor conductors of electricity and have high coeffient of thermal expansion. Polymers do not have fixed melting point. The temp at which the crystallinity is destroyed is called glass transition temperature. There are two types of polymers a) Thermo plastics b) Thermosets

Matrix materials are usually thermosets. Commonly used are epoxies, polyester, phenolic, fluorocarbons, polyether sulphone or silicone. The most commonly used are epoxies and (80%)

and poly esters, which are less expensive than epoxies. Polyamides which resist exposure to temperature in excess of 300 deg C are being developed for use with graphite fibers. PEEK (polyetheretherketone) is also used as matrix material. They have higher toughness than thermosets, but their resistance to temperature in being limited to100 deg-200deg C.

The matrix in reinforced plastics has three functions.

a) To support the fibers in place and transfer the stresses to them, while they carry most of the load

b) To protect the fibers against physical damage and the environment.

c) To reduce the propagation of cracks in the composites, by virtue of the greater ductility and toughness of the plastic material.

METAL MATRIX COMPOSITES:

Metal matrix composites have a metal as a matrix usually a light metal such as Al, Mg, or Ti or a super alloy (Ni based or Co based super alloy). The reinforcement materials include Boron, Silicon Carbide, carbon, Graphite, alumina, boron carbide, boron nitride. The form of reinforcement material can be either a fiber or whisker or particulate. Metals are reinforced to either to increase certain properties like elastic modulus and tensile strength or decrease certain properties like coefficient of thermal expansion and thermal conductivities.

CERAMIC MATRIX COMPOSITES:

They are hard and brittle, have low toughness, low thermal coeffient of expansion, very low mechanical shock resistance. Examples are

1. SiC particles in alumina matrix used as tool materials.
2. SiC particles in SiC matrix used as cutting tool inserts.
3. Glass fibers in alumina matrix used in aircraft engine parts.

FIBER REINFORCED PLASTIC

PROCESSING: Need for development of composite materials Advantages of composites:

1. High specific Strength and modulus – aerospace industries, automobiles.
2. Advantage of moulding in to desired shape and size using open or closed moulding process.

TABLE 9.3 Metal-Matrix Composite Materials and Applications

Fiber	Matrix	Applications
Graphite	Aluminum	Satellite, missile, and helicopter structures
	Magnesium	Space and satellite structures
	Lead	Storage-battery plates
	Copper	Electrical contacts and bearings
Boron	Aluminum	Compressor blades and structural supports
	Magnesium	Antenna structures
	Titanium	Jet-engine fan blades
Alumina	Aluminum	Superconductor restraints in fission power reactors
	Lead	Storage-battery plates
	Magnesium	Helicopter transmission structures
Silicon carbide	Aluminum, titanium	High-temperature structures
	Superalloy (cobalt-base)	High-temperature engine components
Molybdenum, tungsten	Superalloy	High-temperature engine components

DEFINITIONS

Aspect ratio: The ratio of length to diameter of the fiber.

Coeffient of elasticity: the reciprocal of Young's modulus in a tension test.

Coeffient of expansion: The fractional change in dimension of a material for a unit change in temperature.

Coeffient of friction: A measure of the resistance to sliding of one surface in contact with another surface.

Felt: A fibrous material made from interlocked fibers by mechanical or chemical action, moisture, or heat, made from asbestos, cotton, and glass.

Flexural modulus: The ratio within the elastic limit, of the applied stress on a test specimen in flexure to the corresponding strain in the outer most fibers of the specimen.

Flexural rigidity: For fibers this is a measure of the rigidity of individual strands or fibers. The force couple required to bend a specimen to unit radius of curvature. For plates the measure of rigidity id D = EI where E is the modulus of elasticity and I is the moment of Inertia,

D = E h2/ 12(1-v) mm/N where E- modulus of elasticity, h- thickness of plate, V- Poisson's ratio

Flexural strength: The resistance of a material to breakage by bending stresses

Notch sensitivity: The extent to which the sensitivity of a material to fracture is increased by the presence of surface inhomogenity such as notch, a sudden change in section, a crack, or a scratch. Low notch sensitivity is usually associated with the ductile materials and high notch sensitivity with brittle materials.

Poisson's ratio: A constant relating change in cross-sectional area to change in length when a material is stretched.

Resilience: The ratio of energy returned on recovery from deformation to the work input required to produce the deformation- expressed as percentage. 2) The ability to regain an original shape quickly after being strained or distorted.

Stiffness: A term often used when the relationship of stress to strain doesn't confirm to the young's modulus of elasticity.

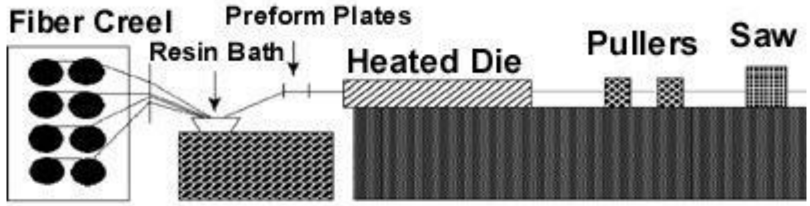
Boron Fibers

Definition: Filaments produced by a chemical vapor deposition process. Boron can be deposited on a tungsten wire core, and on a glass or graphite filament core. The filaments thus produced have nominal diameters ranging from 0.1-0.2 mm. They are characterized by low density, high tensile strength and high modulus of elasticity. They are extremely stiff, e.g., five times stiffer than glass fibers. This stiffness makes boron filaments difficult to weave, braid, or twist, but they can be formed into resin impregnated tapes for hand lay-up and filament winding processes. The high cost of boron filaments has limited their use to experimental aircraft and aero-space applications

Pultrusion: Pultrusion is a continuous, automated closed-moulding process that is cost effective for high volume production of constant cross section parts. Due to uniformity of cross-section, resin dispersion, fibre distribution & alignment, excellent composite structural materials can be fabricated by pultrusion. The basic process usually involves pulling of continuous fibres through a bath of resin, blended with a catalyst and then into pre-forming fixtures where the section is partially pre-shaped & excess resin is removed. It is then passed through a heated die, which determines the sectional geometry and finish of the final product. The profiles produced with this process can compete with traditional metal profiles made of steel & aluminum for strength & weight.

Pultrusion: Process Technology The process begins when reinforcing fibres are pulled from a series of creels. The fibres proceed through a bath, where they are impregnated with formulated resin. The resin-impregnated fibres are preformed to the shape of the profile to be produced. This composite material is then passed through a heated steel die that has been machined precisely to the final shape of the part to be manufactured. Heat initiates an exothermic reaction thus curing the thermosetting resin matrix. The profile is continuously pulled and exits the mould as a hot, constant cross sectional member. The profile cools in ambient or forced air, or assisted by water.

The product emerges from the puller mechanism and is cut to the desired length by an automatic, flying cutoff saw. A schematic representation of pultrusion process is given in following figure:



Schematic Diagram of Pultrusion Process

THERMOPLASTIC COMPOSITE PROCESING

THERMO FORMING Thermo forming consists of heating a thermoplastic material to its softening point and forming it against the contour of the mold. Fiber reinceforced thermoplastic such as ABS, nylons, polycarbonates polysulphones, polybuteneterepthalate and PET are used in this method, since they exhibit good melt characteristics even with fiber reinforcements and filler contents of 40% volume or more. Parts are formed by heating the sheet of reinforced thermoplastics to a temperature above the glass transition temperature of the resin and then mechanically forming the sheet in to a mould or over a mandrel. The formed parts cool to a temperature below the plastic range and are removed from the mold. At this point the point the part is still hot and is placed on a fixture to cool to the room temperature. Cycle time varies between seconds to mins.

Thermoforming methods;

There are at least dozen methods of thermoforming
Vacuum assisted forming
Pressure forming
Plug assisted forming
Drape forming
Matched mold forming
Slip forming
Free forming

INJECTION MOLDING.

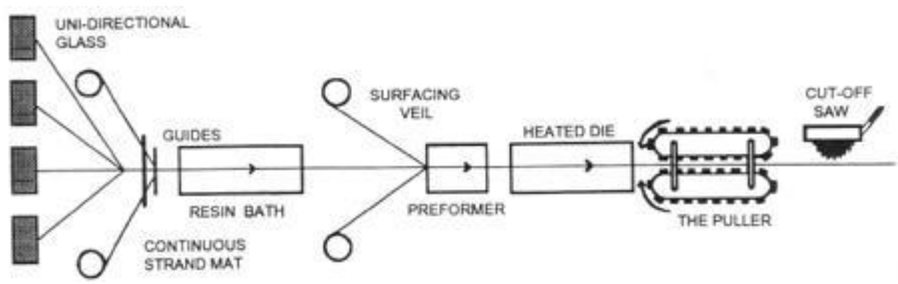
Compared with low pressure molding and mechanical mixing the reaction injection molding offers the following advantages.

Since the mixing head is self cleaning, no solvent flush is required, as it is in low pressure molding. Since there is no mechanical mixing, outputs are higher and faster-reacting urethane mixes can be used. Since reaction time is faster, mold residence time is reduced because the material cures more rapidly, in turn reducing mold cycle time by as much as 75%. Since high pressure impingement mixing reduces air entrapment in the reaction mixture, part appearance is improved and surface defects eliminated.

Vacuum Bag Molding

Vacuum bag molding, a refinement of hand lay-up, uses a vacuum to eliminate entrapped air and excess resin. After the lay-up is fabricated on either a male or female mold from precut plies of glass mat or fabric and resin, a non adhering film of polyvinyl alcohol or nylon is placed over the lay-up and sealed at the mold flange. A vacuum is drawn on the bag formed by the film while the composite is cured at room or elevated temperatures. Compared to hand lay-up, the vacuum method provides higher reinforcement concentrations, better adhesion between layers, and more control over resin/glass ratios. Advanced composite parts utilize this method with preimpregnated fabrics rather than wet lay-up materials and require oven or autoclave cures.

Pultrusion



Pultrusion is a continuous method of manufacturing various reinforced plastic shapes of uniform cross sections. Glass reinforcements, such as unidirectional rovings or multi-directional glass fiber mat, are guided through a liquid resin bath to thoroughly wet every fiber. The reinforcements are then guided and formed, or shaped, into the profile to be produced before entering a die. As the material progresses through the heated die, which is shaped to match the design profile, the resin changes from a liquid to a gel, and finally, into a cured, rigid plastic.

A pulling device grips the cured material and literally pulls the material through the die. Hence, the name pultrusion. It is the power source for the process. After the product passes through the puller, it is sawed into desired lengths. Although pultrusion is ideally suited for custom shapes, some standard products include rods, bars, angles, channels, and I-beams.

Summary

Composite materials (or composites for short) are engineered materials made from two or more constituent materials with significantly different physical or chemical properties and which remain separate and distinct on a macroscopic level and are not soluble to each other. One constituent is called the MATRIX and the other is called the REINFORCING phase. Based on reinforcement they are classified as Particle Reinforced composites Fiber reinforced composites. Based on matrix they are classified as PMC, MMC and CMC. Composites have the following advantages over metals such as specific strength, specific weight, design tailorability, use of existing manufacturing process.

Self assessment questions

1) Define composite material and give the classification of composite briefly?
2) Describe the features of fibrous composite, laminated composite and particulate composite?
3) Using neat sketches, explain the process of preparation of MMC?

4) Discuss the role of matrix and reinforcement in a composite material. Write a short note on FRP?
5) Explain autoclave & filament winding methods for production of FRP.
6) Compare MMC's with PMC's.
7) How the mechanical advantage of composite is measured. What are the limitations of composite materials?
8) What are the applications of composite material?
9) What are FRP's? Give at least four examples.
10) Discuss briefly advantages and applications of MMC's and FRP's.
11) Compare MMC's with PMC's.
12) Why and how are composite superior to conventional materials.
13) What are the main types of synthetic fiber used in FRP's?
14) List at least three commonly used matrix material and reinforcement fibers used in the production of FRP's.
15) Discuss the role of FRP's in space, naval and aeronautical engineering

TEXT BOOKS:

1. Smith, Foundations of Materials Science and Engineering, 4th Edition, McGraw Hill, 2009.

2. William D. Callister, Material science and Engineering and Introduction, Wiley, 2006.

REFERENCES

1. V.Raghavan, Materials Science and Engineering, , PHI, 2002
2. Donald R. Askland and Pradeep.P. Phule, The Science and Engineering of Materials, Cengage Learning, 4lh Ed., 2003.
3. George Ellwood Dieter, Mechanical Metallurgy, McGraw-Hill.
4. ASM Handbooks, American Society of Metals.