Composite material

Composite materials are engineered materials made from two or more materials that remain separate and distinct on a macroscopic level while forming a composite. The most primitive composite materials comprised straw and mud in the form of bricks for building construction. Concrete is a slightly more complex composite of stone mixed with cement. Graphite epoxy, a strong and lightweight carbon-reinforced polymer capable of withstanding heavy loads, is widely used in the bridge repair. Polymer sheets used to reinforce bridge beams have increased load capacity 30 and 65 percent and have proved durable on bridge spans as long at 26 feet.

Natural composites like bone and wood are formed by the processes of nature. The most advanced composites are used in the aerospace industry. Many jets and airplanes are made of composite materials that are stronger and lighter. The new Boeing 787 uses 50 percent composite materials dropping its overall weight by 12 percent, enhancing strength several fold and use less fuel. One of the best examples of a composite in the flying world is the B-2 or Stealth bomber; the body and parts of the wings are covered with a radar absorbing composite material, making it virtually undetectable to radar.

Fiberglass, a composite of glass fibers and polymer resins, was one of the earliest composites of the modern age. In 1950s, it was used as a lightweight alternative to steel and wood. Most cars today have fiberglass bumpers covering a steel frame and are used over wheel wells and other cosmetic parts of a car or truck. Fiberglass has become the standard material in recreational boats, from stern to bow. It has limited but useful applications for military and commercial boat use. While fiberglass can be molded into car, boat, plane and other hardened materials it can also be used as insulation when strands of fiber are interwoven with glass "wool." Fiberglass wool is a thick, fluffy material used for thermal insulation and sound absorption. Its versatility allows it to be used for home and building insulation, automobile engine compartments, ship and submarine bulkheads and hulls, acoustical paneling, and furnace and air conditioning units.

Composites have shown remarkable resilience in ballistics protection for lightweight vehicles. Composite armor uses materials of varying hardness and elasticity for heat and shock absorption and protect against both kinetic and chemical weapons. While passive armor is designed to absorb impacts and penetration of ammunition, active and reactive materials are designed to deflect or destroy incoming ammunition.

Components of a composite:

All the composites have two components: matrix and reinforcement. The matrix surrounds and supports the reinforcement materials by maintaining their relative positions. The reinforcements impart their special mechanical, electrical and physical properties to the composite. Metals, non-metals, ceramics and polymers can be used as matrix materials and reinforcement materials thus enabling wide variety of materials resulting into incredible design potential for making composites.

Many commercially produced composites use a polymer matrix material. Polyester, vinyl ester, epoxy, phenolic, polyimide, polyamide, and others are used as matrix. Reinforcement is often a strong fibre such as fiberglass, quartz, kevlar, Dyneema or carbon fibre that gives the composite its tensile strength.

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Functions of Matrix: *matrix* is often a resin such as polyester, or epoxy that binds the fibres together, transferring load from broken fibers to unbroken ones and between fibers that are not oriented along lines of tension. Also, unless the matrix chosen is especially flexible, it prevents the fibers from buckling in compression. Some composites use an aggregate instead of, or in addition to, fibers.

Engineered composite materials must be formed to shape. This involves strategically placing the reinforcements while manipulating the matrix properties to achieve a melding event at or near the beginning of the component life cycle. A variety of methods are used according to the end item design requirements. These fabrication methods are commonly named molding or casting processes, as appropriate, and both have numerous variations. The principle factors impacting the methodology are the natures of the chosen matrix and reinforcement materials. Another important factor is the gross quantity of material to be produced. Large quantities can be used to justify high capital expenditures for rapid and automated manufacturing technology. Small production quantities are accommodated with lower capital expenditures but higher labor costs at a correspondingly slower rate.

In terms of stress, any fibers serve to resist tension, the matrix serves to resist shear, and all materials present serve to resist compression, including any aggregate.

Composite materials can be divided into two main categories normally referred to as short fiber reinforced materials and continous fiber reinforced materials. Continuous reinforced materials will often constitute a layered or laminated structure.

Shocks, impact, loadings or repeated cyclic stresses can cause the laminate to separate at the interface between two layers, a condition known as delamination. Individual fibers can separate from the matrix e.g. fiber pull-out.

1 Classification

Composite materials are commonly classified at following two distinct levels:

- The first level of classification is usually made with respect to the matrix constituent. The major composite classes include Organic Matrix Composites (OMCs), Metal Matrix Composites (MMCs) and Ceramic Matrix Composites (CMCs). The term organic matrix composite is generally assumed to include two classes of composites, namely Polymer Matrix Composites (PMCs) and carbon matrix composites commonly referred to as carbon-carbon composites.

- The second level of classification refers to the reinforcement form - fibre reinforced composites, laminar composites and particulate composites. Fibre reinforced composites can be further divided into those containing discontinuous or continuous fibres.

- Fibre Reinforced Composites are composed of fibres embedded in matrix material. Such a composite is considered to be a discontinuous fibre or short fibre composite if its properties vary with fibre length. On the other hand, when the length of the fibre is such that any further increase in length does not further increase, the elastic modulus of the composite, the composite is considered to be continuous fibre reinforced. Fibres are small in diameter and when pushed axially, they bend easily although they have very good tensile properties. These fibres must be supported to keep individual fibres from bending and buckling.

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- Laminar Composites are composed of layers of materials held together by matrix. Sandwich structures fall under this category.

- Particulate Composites are composed of particles distributed or embedded in a matrix body. The particles may be flakes or in powder form. Concrete and wood particle boards are examples of this category.

COMPARISON WITH METALS

Requirements governing the choice of materials apply to both metals and reinforced plastics. It is, therefore, imperative to briefly compare main characteristics of the two.

- Composites offer significant weight saving over existing metals. Composites can provide structures that are 25-45% lighter than the conventional aluminium structures designed to meet the same functional requirements. This is due to the lower density of the composites.

Depending on material form, composite densities range from 1260 to 1820 kg/in^3 (0.045 to 0.065 lb/in^3) as compared to 2800 kg/in^3 (0.10 lb/in^3) for aluminium. Some applications may require thicker composite sections to meet strength/stiffness requirements, however, weight savings will still result.

- Unidirectional fibre composites have specific tensile strength (ratio of material strength to density) about 4 to 6 times greater than that of steel and aluminium.
- Unidirectional composites have specific -modulus (ratio of the material stiffness to density) about 3 to 5 times greater than that of steel and aluminium.
- Fatigue endurance limit of composites may approach 60% of their ultimate tensile strength. For steel and aluminium, this value is considerably lower.
- Fibre composites are more versatile than metals, and can be tailored to meet performance needs and complex design requirements such as aero-elastic loading on the wings and the vertical & the horizontal stabilisers of aircraft.
- Fibre reinforced composites can be designed with excellent structural damping features. As such, they are less noisy and provide lower vibration transmission than metals.
- High corrosion resistance of fibre composites contributes to reduce life- cycle cost.
- Composites offer lower manufacturing cost principally by reducing significantly the number of detailed parts and expensive technical joints required to form large metal structural components. In other words, composite parts can eliminate joints/fasteners thereby providing parts simplification and integrated design.
- Long term service experience of composite material environment and durability behaviour is limited in comparison with metals.

ADVANTAGES AND DISADVANTAGE OF COMPOSITES

1 advantages

Summary of the advantages exhibited by composite materials, which are of significant use in aerospace industry are as follows:

- High resistance to fatigue and corrosion degradation.
- High 'strength or stiffness to weight' ratio. As enumerated above, weight savings are significant ranging from 25-45% of the weight of conventional metallic designs.
- Due to greater reliability, there are fewer inspections and structural repairs.
- Directional tailoring capabilities to meet the design requirements. The fibre pattern can be laid in a manner that will tailor the structure to efficiently sustain the applied loads.

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- Fibre to fibre redundant load path.
- Improved dent resistance is normally achieved. Composite panels do not sustain damage as easily as thin gage sheet metals.
- It is easier to achieve smooth aerodynamic profiles for drag reduction. Complex double-curvature parts with a smooth surface finish can be made in one manufacturing operation.
- Composites offer improved torsional stiffness. This implies high whirling speeds, reduced number of intermediate bearings and supporting structural elements. The overall part count and manufacturing & assembly costs are thus reduced.
- High resistance to impact damage.
- Thermoplastics have rapid process cycles, making them attractive for high volume commercial applications that traditionally have been the domain of sheet metals. Moreover, thermoplastics can also be reformed.
- Like metals, thermoplastics have indefinite shelf life.
- Composites are dimensionally stable i.e. they have low thermal conductivity and low coefficient of thermal expansion. Composite materials can be tailored to comply with a broad range of thermal expansion design requirements and to minimise thermal stresses.
- Manufacture and assembly are simplified because of part integration (joint/fastener reduction) thereby reducing cost.
- The improved weatherability of composites in a marine environment as well as their corrosion resistance and durability reduce the down time for maintenance.
- Close tolerances can be achieved without machining.
- Material is reduced because composite parts and structures are frequently built to shape rather than machined to the required configuration, as is common with metals.
- Excellent heat sink properties of composites, especially Carbon-Carbon, combined with their lightweight have extended their use for aircraft brakes.
- Improved friction and wear properties.
- The ability to tailor the basic material properties of a Laminate has allowed new approaches to the design of aeroelastic flight structures.

The above advantages translate not only into airplane, but also into common implements and equipment such as a graphite racquet that has inherent damping, and causes less fatigue and pain to the user.

2. <u>Disadvantage of Composites</u>

Some of the associated disadvantages of advanced composites are as follows:

a). High cost of raw materials and fabrication.

b). Composites are more brittle than wrought metals and thus are more easily damaged.

c). Transverse properties may be weak.

d). Matrix is weak, therefore, low toughness.

e). Reuse and disposal may be difficult.

f). Difficult to attach.

g). Repair introduces new problems, for the following reasons:

- Materials require refrigerated transport and storage and have limited shelf life.
- Hot curing is necessary in many cases requiring special tooling.
- Hot or cold curing takes time.

h). Analysis is difficult.

i). Matrix is subject to environmental degradation.

However, proper design and material selection can circumvent many of the above disadvantages.

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New technology has provided a variety of reinforcing fibres and matrices those can be combined to form composites having a wide range of exceptional properties. Since the advanced composites are capable of providing structural efficiency at lower weights as compared to equivalent metallic structures, they have emerged as the primary materials for future use.
In aircraft application, advanced fibre reinforced composites are now being used in many structural applications, viz. floor beams, engine cowlings, flight control surfaces, landing gear doors, wing-to-body fairings, etc., and also major load carrying structures including the vertical and horizontal stabiliser main torque boxes.

Composites are also being considered for use in improvements to civil infrastructures, viz., earthquake proof highway supports, power generating wind mills, long span bridges, etc

Functions of a Matrix

In a composite material, the matrix material serves the following functions:

- Holds the fibres together.
- Protects the fibres from environment.
- Distributes the loads evenly between fibres so that all fibres are subjected to the same amount of strain.
- Enhances transverse properties of a laminate.
- Improves impact and fracture resistance of a component.
- Helps to avoid propagation of crack growth through the fibres by providing alternate failure path along the interface between the fibres and the matrix.
- Carry interlaminar shear.

The matrix plays a minor role in the tensile load-carrying capacity of a composite structure. However, selection of a matrix has a major influence on the interlaminar shear as well as in-plane shear properties of the composite material. The interlaminar shear strength is an important design consideration for structures under bending loads, whereas the in-plane shear strength is important under torsion loads. The matrix provides lateral support against the possibility of fibre buckling under compression loading, thus influencing to some extent the compressive strength of the composite material. The interaction between fibres and matrix is also important in designing damage tolerant structures.

Finally, the processability and defects.in a composite material depend strongly on the physical and thermal characteristics, such as viscosity, melting point, and curing temperature of the matrix.

Properties of a Matrix

The needs or desired properties of the matrix which are important for a composite structure are as follows:

- Reduced moisture absorption.
- Low shrinkage.
- Low coefficient of thermal expansion.
- Good flow characteristics so that it penetrates the fibre bundles completely and eliminates voids during the compacting/curing process.
- Reasonable strength, modulus and elongation (elongation should be greater than fibre).
- Must be elastic to transfer load to fibres.
- Strength at elevated temperature (depending on application).
- Low temperature capability (depending on application).
- Excellent chemical resistance (depending on application).
- Should be easily processable into the final composite shape.
- Dimensional stability (maintains its shape).

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As stated above, the matrix causes the stress to be distributed more evenly between all fibres by causing the fibres to suffer the same strain. The stress is transmitted by shear process, which requires good bonding between fibre and matrix and also high shear strength and modulus for the matrix itself. One of the important properties of cured matrix system is its glass transition temperature (T_g) at which the matrix begins to soften and exhibits a decrease in mechanical properties. The glass transition temperature is not only an important parameter for dimensional stability of a composite part under influence of heat, but it also has effect on most of the physical properties of the matrix system at ambient temperature.

As the load is primarily carried by the fibres, the overall elongation of a composite material is governed by the elongation to failure of the fibres that is usually 1-1.5%. A significant property of the matrix is that it should not crack. The function of the matrix in a composite material will vary depending on how the composite is stressed. For example, in case of compressive loading, the matrix prevents the fibres from buckling and is, therefore, a very critical part of the composite since without it, the reinforcement could carry no load. On the contrary, a bundle of fibres could sustain high tensile loads in the direction of the filaments without a matrix. Some of the *physical properties* of the matrix which influence the behaviour of composites are:

- Shrinkage during cure,
- Modulus of elasticity,
- Ultimate elongation,
- Strength (tensile, compressive and shear), and
- Fracture toughness.

Factors considered for Selection of Matrix

In selecting matrix material, following factors may be taken into consideration:

- The matrix must have a mechanical strength commensurate with that of the reinforcement i.e. both should be compatible. Thus, if a high strength fibre is used as the reinforcement, there is no point using a low strength matrix, which will not transmit stresses efficiently to the reinforcement.
- The matrix must stand up to the service conditions, viz., temperature, humidity, exposure to ultra-violet environment, exposure to chemic3l atmosphere, abrasion by dust particles, etc.
- The matrix must be easy to use in the selected fabrication process.
- Smoke requirements.
- Life expectancy.
- The resultant composite should be cost effective.

The fibres are saturated with a liquid resin before it cures to a solid. The solid resin is then said to be the matrix for the fibres.

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Manufacturing Processes

Manufacturing of composite materials involves distinct operations that may vary depending upon available technology, existing facilities and personnel skill. The manufacturing process may also vary due to wide variety of composite materials and their application. Each of the fabrication processes has characteristics that define the type of products to be produced. This is advantageous because this expertise allows the manufacturer to provide the best solution for the customer. *Factors considered for selection of most efficient manufacturing process* are as follows:

- User needs
- Total production volume
- Performai l ce requirements
- Economic targets
- Size of the product
- Labour
- Surface complexity
- Materials
- Appearance
- Tooling/assembly
- Production rate
- Equipment

The goals of the composite manufacturing process are to:

- Achieve a consistent product by controlling
    - Fibre thickness
    - Fibre volume
    - Fibre direction
- Minimise voids
- Reduce internal residual stresses
- Process in the least costly manner

The procedure to achieve these goals involves series of actions to select the three key components, viz.-

- Composite material and its configuration
- Tooling
- Process

As reinforcement for composite material, the choice between unidirectional tape and woven fabric is made on the basis of the greater strength and modulus attainable with the tape particularly in applications in which compression strength is important. Salient advantages and disadvantages of tape and fabric for their selection are given below:

Tape Advantages

- Best modulus and strength efficiency
- High fibre volume achievable
- Low scrap rate
- Less tendency to trap volatiles
- Automated lay-up possible
- No discontinuities
- Available in thin plies

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Tape Disadvantages

- Poor drape on complex shapes
- Cured composite more difficult to machine
- Lower impact resistance
- Multiple plies required for balance and symmetry
- Higher labour cost for-hand lay-up

Fabric Advantages

- Better drape for complex shapes
- Single ply is balanced and may be essentially symmetric
- Can be laid up without resin
- Plies stay in line better during cure
- Cured parts easier to machine
- Better impact resistance
- Many forms available

Fabric Disadvantages

- Fibre discontinuities (splices)
- Less strength and modulus
- Lower fibre volume than tape
- More costly than tape
- Greater scrap rates
- Warp and fill properties differ
- Fabric distortion can cause part warping

Another aspect considered important for composite fabrication is appropriate lay-up techniques along with composite cure control. Some of the considerations for choosing lay-up techniques are given below:

Classification of Manufacturing Processes

Most widely used manufacturing methods for laminated fibre composites are as follows:

1 Open Mold Process

- Spray lay-up - Chopped roving and resin sprayed simultaneously, rolled.
- Hand lay-up - Lay-up of fibres or woven cloth, impregnate, no heat or pressure.
- Filament winding.
- Sheet molding compound.
- Expansion tool molding.
- Contact molding.

2 Closed Mold Process

- Compression molding – Load with raw material, press into shape.
- Vacuum bag, pressure bag, autoclave - Prepreg laid up, bagged, cured.
- Injection molding – Mold injected under pressure.
- Resin Transfer – Fibres in place, resin injected at low temperature.

3 Continuous Process

- Pultrusion.
- Braiding.

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1 Open Mold Processes

Open molding offers a number of process and product advantage over other high volume and complex application methods. These include:.

- Freedom of design
- Easy to change design
- Low mold and/or tooling cost
- Tailored properties possible
- High strength large parts possible
- On-site production possible

Disadvantages associated with the open molding process include:

- Low to medium number of parts
- Long cycle times per molding
- Not the cleanest application process
- Only one surface has aesthetic appearance
- Operator skill dependent

Spray Lay-up

In a spray lay-up method, the fibre is chopped in a hand held gun and fed into a spray of catalysed liquid resin directed at the mold (Fig 10.1). The sprayed, catalysed liquid resin will wet the reinforcement fibres, which are simultaneously chopped in the same spray gun. The deposited materials are left to cure under standard atmospheric conditions.

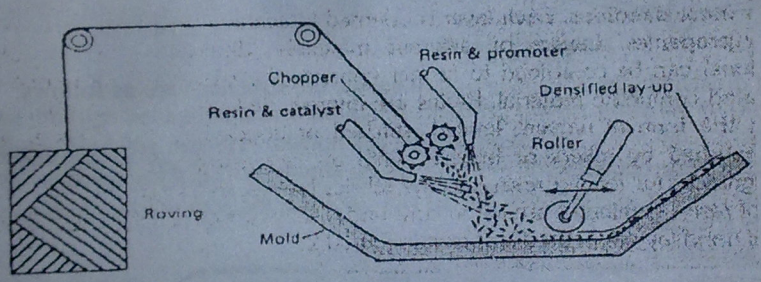

Fig 10.1

Advantages

- Widely used form any years.
- Low cost way of quickly depositing fibre and resin.
- Low cost tooling.

Disadvantages

- Laminates tend to be very resin-rich and, therefore, excessively heavy.
- Only short fibres are incorporated, which severely limits the mechanical properties of the laminate.
- Resins need to be low in viscosity to be sprayable. This generally compromises their mechanical/thermal properties.
- The high styrene content of spray lay-up resins generally means that they have the potential to be more harmful and their lower viscosity means that they have an increased tendency to penetrate clothing etc.

Applications

Simple enclosures, lightly loaded structural panels, e.g. caravan bodies, truck fairings, bathtubs, shower trays, some small dinghies.

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Wet Lay-up/Hand Lay-up

The hand (wet) lay-up is one of the oldest and most commonly used methods for manufacture of composite parts. Hand lay-up composites are a case of continuous fibre reinforced composites. Layers of unidirectional or woven composites are combined to result in a material exhibiting desirable properties in one or more directions. Each layer is oriented to achieve the maximum utilisation of its properties. Layers of different materials (different fibres in different directions) can be combined to further enhance the overall performance of the laminated composite material. Resins are impregnated by hand into fibres, which are in the form of woven, knitted, stitched or bonded fabrics. This is usually accomplished by rollers or brushes, with an increasing use of nip-roller type impregnators for forcing resin into the fabrics by means of rotating rollers and a bath of resin. Laminates are left to cure under standard atmospheric conditions. A typical hand lay-up method is shown in Fig10.2.

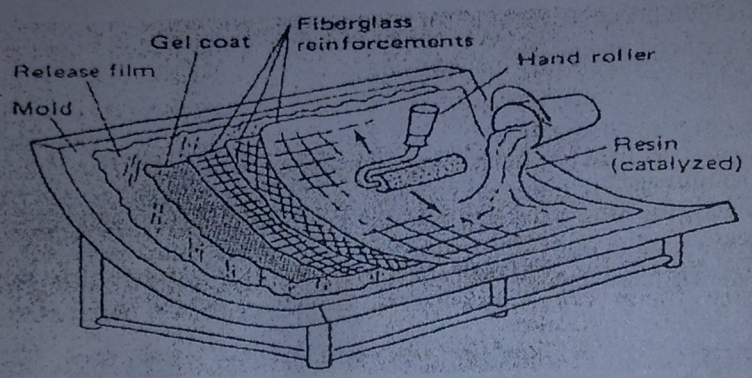

Fig 10.2

Some of the advantages and disadvantages of hand lay-up of composite structures are as follows:

Advantages

- Design flexibility.
- Large and complex items can be produced.
- Tooling cost is low.
- Design changes are easily effected.
- Sandwich constructions are possible.
- Semi-skilled workers are needed.
- Higher fibre content and longer fibres than with spray lay-up.

Disadvantages

- Only one molded surface is obtained.
- Quality is related to the skill of the operator.
- Low volume process.
- Longer cure times required.
- Resins need to be low in viscosity to be workable by hand. This generally compromises their mechanical/thermal properties.
- The waste factor can be high.

Applications

- Standard wind-turbine blades, production boats, architectural moldings.

3 Filament Winding

Filament winding is automated processes for creating parts of simple geometry wherein continuous resin impregnated fibres are wound over a rotating male tool called mandrel. Fig 10.3 depicts a filament winding process where a continuous fibre roving passes through a shuttle, which rotates and the roving is wrapped around a revolving or stationary mandrel. Two basic

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types of filament winding are in use - (i) the polar or planer method, and (ii) the high helical pattern winding.

The polar or planer method of winding utilizes a fixed mandrel and a shuttle that revolves around the longitudinal axis of the part to form longitudinal winding patterns. This type of winding is used if the longitudinal fibres are required with angle less than 25° to the mandrel axis. The polar winding schematic is shown in Fig 10.4.

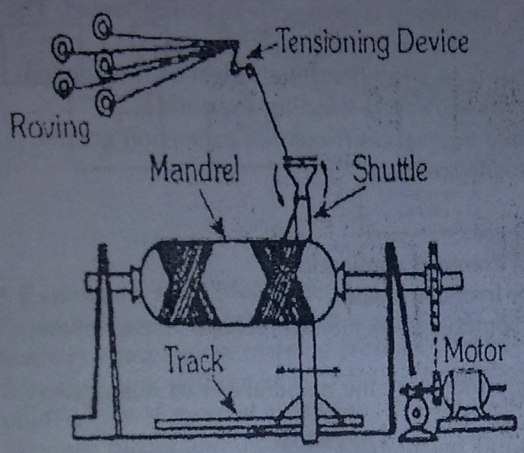

Fig10.3 Fig 10.4

In the high helical pattern winding, the mandrel rotates while the shuttle transverses back and forth. Both the mandrel rotation and shuttle movement are in the horizontal plane. By controlling the mandrel rotation and shuttle speed, the fibre angle can be controlled. Angles of 25°-85° to the mandrel rotation axis are possible. The helical winding schematic is shown in Fig 10.5.

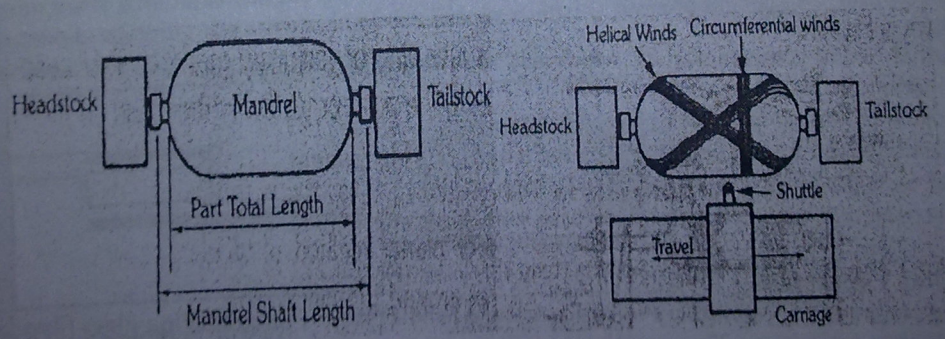

Fig 10.5

After completion of the winding, the filament wound structure is cured at room temperature or in an oven. The mandrel is removed after the curing. The mandrel, which determines accurate internal geometry for the component, is generally the only major tool. Low cost mandrel materials such as cardboard or wood can be used for winding low cost routine parts. For critical parts requiring close tolerances, expensive mandrels designed for long term use may be required. For high temperature cure 315°C (600°F), graphite mandrels with low thermal expansion may be advantageous. However, attention should be paid for potential difficulties for mandrel removal.

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Mandrels are either removable or non-removable. Removable mandrels are classified according to the removal techniques as:

- Entirely removed.
- Collapsible.
- Breakable or soluble.

The selection of mandrel involves several considerations. These include part size and complexity, size of openings, resin system and its curing and the number of components to be fabricated. The requirements for a mandrel are:

- It must be stiff and strong enough to support its own weight and the weight of the applied composite while resisting the fibre tension pressure from winding and curing.
- It must be dimensionally stable and should have thermal coefficient of expansion greater than the transverse coefficient of the composite structure.

Different materials used for construction of mandrel are:

- Low melting temperature alloys used for small diameter applications.
- Sand, soluble plaster and eutectic salts used for irregular shapes.
- Inflatable material used in applications where sometimes the mandrel remains a part of the structure.
- Segmented metal used for high production rates, and where the mandrel can be withdrawn through a small hole in the part.

Segmented metal and inflatable mandrel are the reusable mandrels.

Advantages

- . Excellent mechanical properties due to use of continuous fibres.
- High degree of design flexibility due to controlled fibre orientation and lower cost of large number of composites.
- This is a very fast and economic method of laying down material.
- Resin content can be controlled by metering the resin onto each fibre tow through nips or dies.

Disadvantages

- Difficulty to wind complex shapes, which may require complex equipment.
- Poor external finish.
- The process is limited to convex shaped components.
- Fibre cannot easily be laid exactly along the length of a component.
- Mandrel costs for large components can be high.
- Low viscosity resins usually need to be used with lower mechanical properties.

4 Sheet Molding Compound

Sheet molding compound (SMC) refers to both a material and a process for producing glass fibre reinforced polyester resin items. The material is typically composed of a filled, thermosetting resin and a chopped or continuous strand reinforcement of glass fibre. A SMC processing machine, (Fig 10.6) produces molding compound in sheet form. The glass fibre is added to a resin mixture that is carried onto a plastic carrier film. After partial cure, the carrier films are removed. The sheet molding material is cut into lengths and placed onto matched metal dies under heat and pressure. Salient advantages of SMC molding process are as follows:

- High volume production.
- Excellent part reproducibility.
- Minimum material scrap.
- Excellent design flexibility.
- Parts consolidation.

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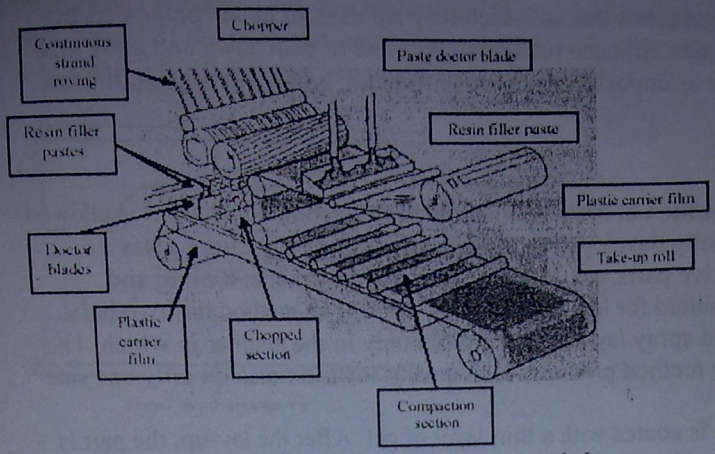

Fig 10.6

5 Expansion Tool Molding:

Expansion tool molding makes use of rubber inserts in a metal or epoxy tool that expands when heated to provide the molding pressure. The advantage of expansion tool molding is its ability to fabricate parts without an autoclave. The method is dependent upon materials with high coefficients of thermal expansion. It is designed to utilize the difference in thermal expansion between rubber and the tooling material. The female areas of the mold are made of a material with a low coefficient of thermal expansion. The male plug is made of a silicon rubber or other rubber type tool material having comparatively high coefficient of thermal expansion. When the tool is heated, the rubber male plug expands at a much greater rate than the surrounding female tool. Pressure up to 14 MPa (2000 psi) can be achieved at 175°C (350°F), which acts in all directions. The molding pressure can be controlled by controlling the temperature, rubber composition, rubber thickness and the ratio of rubber volume to the female mold volume. Thermal expansion molding techniques are utilised for special applications of small complex composite structures and composite tubing with critical outside surfaces. Fig 10.7 illustrates the methods allowing the expansion of the silicone rubber to provide the required pressure for compacting of the composite materials.

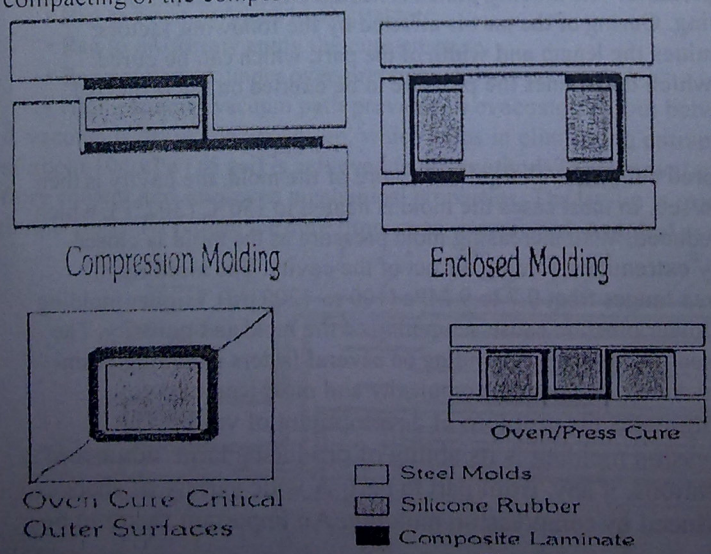

Fig 10.7

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1.3.2 Disadvantage of Composites

Some of the associated disadvantages of advanced composites are as follows:

a). High cost of raw materials and fabrication.
b). Composites are more brittle than wrought metals and thus are more easily damaged.
c). Transverse properties may be weak.
d). Matrix is weak, therefore, low toughness.
e). Reuse and disposal may be difficult.
f). Difficult to attach.
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1.3: ADVANTAGES AND DISADVANTAGE OF COMPOSITES

1.3.1 advantages

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- High resistance to fatigue and corrosion degradation.
- High 'strength or stiffness to weight' ratio. As enumerated, above, weight savings are significant ranging from 25-45% of the weight of conventional metallic designs.
- Due to greater reliability, there are fewer inspections and structural repairs.
- Directional tailoring capabilities to meet the design requirements. The fibre pattern can be laid in a manner that will tailor the structure to efficiently sustain the applied loads.
- Fibre to fibre redundant load path.
- Improved dent resistance is normally achieved. Composite panels do not sustain damage as easily as thin gage sheet metals.
- It is easier to achieve smooth aerodynamic profiles for drag reduction. Complex double-curvature parts with a smooth surface finish can be made in one manufacturing operation.
- Composites offer improved torsional stiffness. This implies high whirling speeds, reduced number of intermediate bearings and supporting structural elements. The overall part count and manufacturing & assembly costs are thus reduced.
- High resistance to impact damage.
- Thermoplastics have rapid process cycles, making them attractive for high volume commercial applications that traditionally have been the domain of sheet metals. Moreover, thermoplastics can also be reformed.
- Like metals, thermoplastics have indefinite shelf life.
- Composites are dimensionally stable i.e. they have low thermal conductivity and low coefficient of thermal expansion. Composite materials can be tailored to comply with a broad range of thermal expansion design requirements and to minimise thermal stresses.
- Manufacture and assembly are simplified because of part integration (joint/fastener reduction) thereby reducing cost.
- The improved weatherability of composites in a marine environment as well as their corrosion resistance and durability reduce the down time for maintenance.
- Close tolerances can be achieved without machining.
- Material is reduced because composite parts and structures are frequently built to shape rather than machined to the required configuration, as is common with metals.
- Excellent heat sink properties of composites, especially Carbon-Carbon, combined with their lightweight have extended their use for aircraft brakes.
- Improved friction and wear properties.
- The ability to tailor the basic material properties of a Laminate has allowed new approaches to the design of aeroelastic flight structures.

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2.3.3 Factors considered for Selection of Matrix

In selecting matrix material, following factors may be taken into consideration:

- The matrix must have a mechanical strength commensurate with that of the reinforcement i.e. both should be compatible. Thus, if a high strength fibre is used as the reinforcement, there is no point using a low strength matrix, which will not transmit stresses efficiently to the reinforcement.
- The matrix must stand up to the service conditions, viz., temperature, humidity, exposure to ultra-violet environment, exposure to chemic3l atmosphere, abrasion by dust particles, etc.
- The matrix must be easy to use in the selected fabrication process.
- Smoke requirements.
- Life expectancy.
- The resultant composite should be cost effective.

The fibres are saturated with a liquid resin before it cures to a solid. The solid resin is then said to be the matrix for the fibres.

2.3.4 General types of Matrix Materials

In general, following general following types of matrix materials are available:

- Thermosetting material;
- Thermoplastic material;
- Carbon;
- Metals;
- Ceramics;
- Glass Matrix.

A thermosetting material is the one which when cured by heat or chemical reaction is changed into an infusible and insoluble material. Thermosetting resins undergo irreversible chemical cross-linking reaction upon application of heat. On the other hand, thermoplastics do not undergo a chemical reaction on application of heat. They simply melt on application of heat and pressure to form a component. Thermoplastics can be softened and they undergo large and rapid change in viscosity with variation in temperature. Thermoplastics can be repeatedly softened by heating and hardened by cooling.

Some of the significant *differences* between thermosets and thermoplastics are given below:

Thermosets	Thermoplastics
• Resin cost is low.	• Resin cost is slightly higher.
• Thermosets exhibit moderate shrinkage.	• Shrinkage of thermoplastics is low
• Interlaminar fracture toughness is low.	• Interlaminar fracture toughness is high.
• Thermosets exhibit good resistance	• Thermoplastics exhibit poor resistance

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d composite material depend strongly on the physical and thermal characteristics, such as viscosity, melting point, and curing temperature of the matrix.

2.3.2 Properties of a Matrix

The needs or desired properties of the matrix which are important for a composite structure are as follows:

- Reduced moisture absorption.
- Low shrinkage.
- Low coefficient of thermal expansion.
- Good flow characteristics so that it penetrates the fibre bundles completely and eliminates voids during the compacting/curing process.
- Reasonable strength, modulus and elongation (elongation should be greater than fibre).
- Must be elastic to transfer load to fibres.
- Strength at elevated temperature (depending on application).
- Low temperature capability (depending on application).
- Excellent chemical resistance (depending on application).
- Should be easily processable into the final composite shape.
- Dimensional stability (maintains its shape).

As stated above, the matrix causes the stress to be distributed more evenly between all fibres by causing the fibres to suffer the same strain. The stress is transmitted by shear process, which requires good bonding between fibre and matrix and also high shear strength and modulus for the matrix itself. One of the important properties of cured matrix system is its glass transition temperature (T_g) at which the matrix begins to soften and exhibits a decrease in mechanical properties. The glass transition temperature is not only an important parameter for dimensional stability of a composite part under influence of heat, but it also has effect on most of the physical properties of the matrix system at ambient temperature.

As the load is primarily carried by the fibres, the overall elongation of a composite material is governed by the elongation to failure of the fibres that is usually 1-1.5%. A significant property of the matrix is that it should not crack. The function of the matrix in a composite material will vary depending on how the composite is stressed. For example, in case of compressive loading, the matrix prevents the fibres from buckling and is, therefore, a very critical part of the composite since without it, the reinforcement could carry no load. On the contrary, a bundle of fibres could sustain high tensile loads in the direction of the filaments without a matrix. Some of the *physical properties* of the matrix which influence the behaviour of composites are:

- Shrinkage during cure,
- Modulus of elasticity,
- Ultimate elongation,
- Strength (tensile, compressive and shear), and
- Fracture toughness.

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Learning unit-3

2.3 Matrix Materials

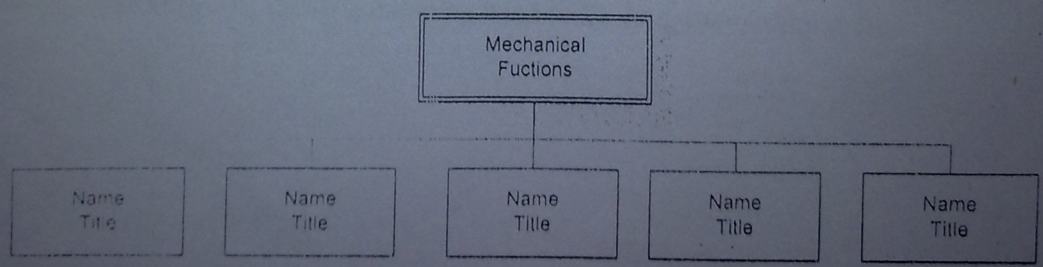
2.3.0 Introduction

Although it is undoubtedly true that the high strength of composites is largely due to the fibre reinforcement, the importance of matrix material cannot be underestimated as it provides support for the fibres and assists the fibres in carrying the loads. It also provides stability to the composite material. Resin matrix system acts as a binding agent in a structural component in which the fibres are embedded. When too much resin is used, the part is classified as resin rich. On the other hand if there is too little resin, the part is called resin starved. A resin rich part is more susceptible to cracking due to lack of fibre support, whereas a resin starved part is weaker because of void areas and the fact that fibres are not held together and they are not well supported.

2.3.1 Functions of a Matrix

In a composite material, the matrix material serves the following functions:

- Holds the fibres together.
- Protects the fibres from environment.
- Distributes the loads evenly between fibres so that all fibres are subjected to the same amount of strain.
- Enhances transverse properties of a laminate.
- Improves impact and fracture resistance of a component.
- Helps to avoid propagation of crack growth through the fibres by providing alternate failure path along the interface between the fibres and the matrix.
- Carry interlaminar shear.



The matrix plays a minor role in the tensile load-carrying capacity of a composite structure. However, selection of a matrix has a major influence on the interlaminar shear as well as in-plane shear properties of the composite material. The interlaminar shear strength is an important design consideration for structures under bending loads, whereas the in-plane shear strength is important under torsion loads. The matrix provides lateral support against the possibility of fibre buckling under compression loading, thus influencing to some extent the compressive strength of the composite material. The interaction between fibres and matrix is also important in designing damage tolerant structures. Finally, the processability and defects

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XB9/CE/102

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Composite Materials

> *"We never reach our ideals, whether of mental or moral improvement, but the thought of them shows us our deficiencies and spurs us on to higher and better things"*

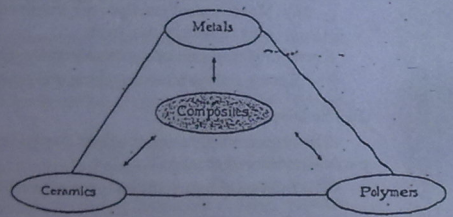
1 INTRODUCTION

For better overall performance we require unusual combinations of properties that cannot be provided by conventional materials like metals, ceramics or polymers. For example, structural materials required for aircraft must have high specific strength, stiffness and excellent resistance to corrosion, abrasion, impact and heat. This is rather unusual combination of properties since strong materials are generally dense and also increase in strength and stiffness usually results in decrease in impact strength.

The great and diverse demands made on materials for better overall performance led to the concept of composite materials.

A *composite* may be defined *as any multiphase material which consists of two or more physically and/or chemically distinct phases with an interface separating them.*

(As per this definition most of the metallic alloys, ceramic materials etc., are not considered as composite materials.)



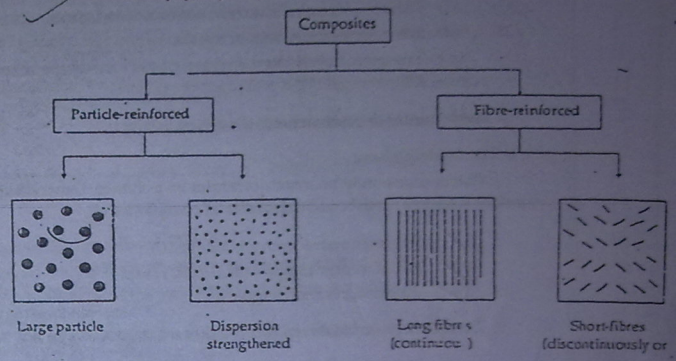
Newer materials "composites" are obtained from conventional materials like Metals, Ceramics & Polymers by adding fibers, particles etc. to them.

The composite materials shows properties distinctively different from those of the individual materials of the composite. In fact, composites show extraordinary combination of properties like toughness and strength with low weights and high temperature resistance. For instance, compared to steel and aluminium, composites are lighter, have low coefficient of thermal expansion and have superior strength, stiffness and fatigue resistance.

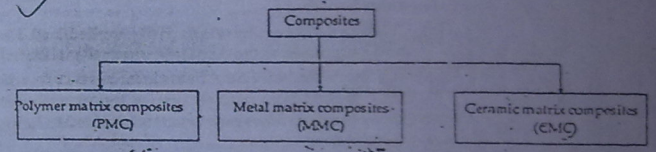
2 CLASSIFICATION OF COMPOSITE MATERIALS

Composite materials can be broadly classified into following types :

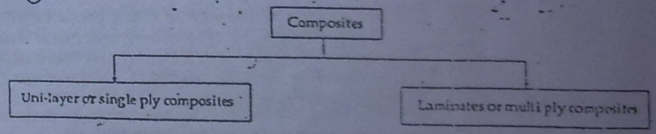
1. *On the basis of type of reinforcement used in the matrix*



2. *On the basis of type of matrix*



3. *On the basis of number of ply or lamina's or layers*



3 CONSTITUENTS OF COMPOSITES

Composites, in general, consist of body constituents and structural constituents. The *body constituent* enclose the composite and give it its bulk form. The continuous *matrix phase* is the body constituent. The *structural constituents* determine the internal structure of the composite. This is also known as *dispersed phase.*

The surface forming the common boundary between the matrix and dispersed phase is known as *interphase.*

Properties of the composites depends upon :

(i) The properties of the constituent materials ;

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(ii) Their relative amounts (*i.e.*, concentration of constituents) ;
(iii) Their distribution and orientation ; and
(iv) The geometry of the dispersed phase namely the shape, size and size distribution

These constituents are briefly discussed below :

(A) The Matrix phase

Matrix phase may be metal, ceramics or polymer. Depending on the type of matrix we have three broad categories of composites *viz.*

(i) Polymer matrix composites (PMC) ;
(ii) Metal matrix composites (MMC) ; and
(iii) Ceramic matrix composites (CMC)

The matrix phase has several important functions viz. :

(i) It binds the fibers together by virtue of its cohesive and adhesive characteristics ;
(ii) It acts as a medium by which an externally applied load is transmitted and distributed to the dispersed phase (generally a fiber) ;
(iii) It protects the individual fibers from chemical reaction with the environment and from surface damage due to mechanical abrasion. Otherwise surface flaws may result which lead to failure at low levels of tensile stress.
(iv) It keeps the reinforcing fibers in the proper position and orientation so that they can carry the intended loads ;
(v) It prevents the propagation of brittle cracks by virtue of its relative softness and plasticity. It provides interlaminar shear strength to the composite. Even if some of the individual fibers fail, total failure of the composite will not occur until large number of adjacent fibers fail and form a cluster of critical size.

The essential requirements of a good matrix materials are ;

(a) It should be ductile ;
(b) The bonding strength between the matrix and fibre must be high. This is essential to maximise the stress transmittance from the weak matrix to the strong fibers. Moreover, the ultimate strength of the composite depends on the strength of this bond ;
(c) It should have good corrosion resistance.

The properties governed by matrix phase :

Generally matrix determines the overall service temperature limitations of the composite. It also controls the environmental resistance of the composite. For example, composites based on polymers are limited to service temperatures below 300°C.

The pros and cons of different matrix phases are summarized below :

Matrix Phase	Pros	Cons
1. Metals	• Ductile • High moduli, • Resist thermal shock, • Easy to manufacture.	• High density, • Costly manufacturing & materials costs.
2. Ceramics	• Thermal stability, • Load bearing capacity, • Stiffness.	• Brittle, • Costly manufacturing & material costs, • Not stable against mechanical shock.
3. Polymers	• Low cost, • Light weight, • Corrosion resistant, • Tough, • Easily processible.	• Lower strength & Stiffness, • Low thermal stability, • Low load bearing capacity

In polymer matrix composites (PMC), both thermoplastic and thermosetting resins can be used. *Advantages of thermoplastic resins over thermosets are listed below* :

(i) They are tougher and have high strains to failure ;
(ii) They offer the potential of improved hot/wet resistance ; and
(iii) No chemical reactions are involved causing release of gaseous products or exothermal heat.

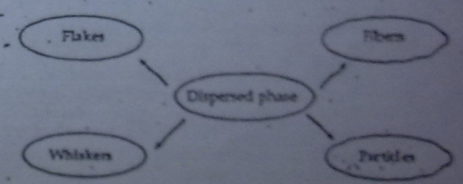
Examples of some representative polymeric matrix materials are :

Epoxy, polyetherether ketone, polyimide, polysulfone and phenolics.

(B) The Dispersed phase

The dispersed phase can be fiber, particle etc. On this basis we have fibre and particle reinforced composites.

The following figure shows types of reinforcement in composites :



The important characteristics of these structural constituents of composites are summarized below :

I. *Fibers.* Any polymer, metal or ceramic that has been drawn into long and thin filament, is termed as fiber. It is characterized by high aspect ratio (length to diameter ratio) and near crystal-sized diameter. They have high strength and

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ffness. This is due to the fact that the probability of the existence of a critical surface flaw that can lead to fracture diminishes with increasing aspect ratio. Effective transfer of load from one fiber to another requires the maintenance of characteristic aspect ratio. Orientation of fibers determine the property of fibrous composite. For example, in one dimensional fibrous composite, strength and modulus of the composite is maximum in the direction of fiber axis. The mechanical properties in any one direction are proportional to the amount of fibers by volume oriented in that direction.

Some of the fibers (used as reinforcements) are glass fibers, carbon fibers, aramide fibers, boron fibers and ceramic fibers.

The principal reinforcing fibers are briefly discussed below :

(i) Glass fibers. They are produced by extruding a glass melt through small orifices, rapidly pulling and subsequently cooling the emerging filaments. Individual fibers are called monofilaments and have diameter around 10 μm. Generally "size" is applied in liquid form (it contains chemical coupling agent, a binder and a lubricant) to glass monofilaments to help in the handling of strands, to protect them from deterimental abrasion and to promote subsequent adhesion of glass fibers to matrix.

Glass is popular as a fiber reinforcement material for several reasons :

(a) High strength glass fibers can be easily drawn from the molten state,

(b) It is readily available and is low in cost,

(c) Commonly available manufacturing techniques can be employed for the economic production of glass fiber-reinforced polymer composites,

(d) Composites, so produced, can be used in variety of corrosive environments since glass fibers when coupled with a plastic matrix exhibits chemical inertness, and

(e) Glass fiber-reinforced polymer composites have very high specific strength since glass fibers are relatively very strong.

Glass fibers have found very extensive use in plastics. Most commonly (1) *in continuous form* in catalyst activated thermo-setting resins and (2) *in short form* in thermoplastics.

(ii) Carbon fibers. They are prepared by preoxidation in the temperature range of 200–250° C under tension and controlled carbonisation (upto 1000° C) of an already formed organic carbon rich filamentary material. They are usually subjected to controlled surface treatments including oxidative etching, vapour deposition and polymer coating.

The monofilaments of carbon fibers have diameter in the range of 5 to 10 microns.

Carbon fibers are used as reinforcement in advanced polymer matrix composites due to :

(a) Their high specific strength and stiffness which is retained even at elevated temperatures ;

(b) Good resistance to moisture, acids, bases and wide variety of solvents ;

(c) Availability of relatively inexpensive and cost effective manufacturing processes for both fibers and composites.

(iii) Aramid fibers. They are basically aromatic polyamides (aramides) like Nomex and Kevlar. For instance, Kevlar is p-phenylene terephthalamide. It is spun from a nematic liquid crystalline solution using a dry jet wet spinning technique using sulphuric acid as the solvent and cold water as coagulant.

The characteristic properties of Kevlar fibers are :

(a) Higher tensile strengths and tensile moduli compared to other polymeric fiber materials.

(b) Excellent toughness, impact resistance and resistance to creep and fatigue failure.

(c) Resistant to combustion and stability even at relatively high temperatures.

(d) Retain mechanical properties over a temperature range of : −200 to + 200° C.

Limitations

(a) Weak in compression and

(b) Susceptible to degradation by strong bases and acids

Aramide fibers are commonly used in PMC's. The common matrix materials are polyesters and epoxies.

Specific strength and specific stiffness of few selected fiber materials are given in Table 1 below :

Table 1

Fiber	*Specific Strength (Tensile strength/density) (kN.m)*	*Specific stiffness (Tensile stiffness/density) (kN.m)*
Glass	136	29
Carbon	123	14
Aluminium	24	28

(II) *Particles.* Dispersed phase in particulate composites consist of particles. These particles can be metallic or non-metallic. Distribution of particles in a given matrix is generally random rather than controlled. Resulting composites are therefore usually isotropic. Because of their inherent hardness relative to the matrix material, the particles in a particulate composite place constraints on the plastic deformation of the plastic material. In essence the matrix transfers some of the applied stress to the particles, which bear a fraction of the load. There should be a good bond at the interface of matrix and particle for desired reinforcement in mechanical properties.

Particle-matrix interactions that lead to strengthening may or may not occur on the atomic or molecular level depending on size of the particles. Particulate fillers are accordingly classified as *large particle* and *dispersion strengthened* respectively.

The properties of matrix materials which are modified by adding particulate fillers are :

(a) Improved performance at elevated temperatures,

(b) Improved wear and abrasion resistance,

(c) Increase in surface hardness,

(d) Reduction in (cost, shrinkage and friction) and

(e) Modification in thermal and electrical conductivities.

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(III) *Flakes.* Thin flakes primarily have a two-dimensional geometry. They impart equal strength in all directions in their plane compared to fibers that are unidirectional reinforcements. Flakes can be packed more efficiently than fibers or spherical particles.

For example, mica flakes are used in electrical and heat insulating applications.

(IV) *Whiskers.* Whiskers are primarily very thin single crystals with high aspect ratio. They exhibit a high degree of crystalline perfection. They are associated with exceptionally high strengths because they are free from surface defects (flaws). Because of their high cost and difficulty in incorporating them in matrix, their extensive use is limited.

Important whisker materials are graphite, aluminium oxide, silicon carbide and silicon nitride.

ROLE OF INTERFACE IN COMPOSITE PERFORMANCE AND DURABILITY

The transmission of stress from matrix phase to reinforcement depends on the strength of interfacial bond. A strong interfacial bond resists failure.

For composites that have a good interfacial bond, the fracture mode is generally a sharp well-defined break.

For composites that have a poor interfacial bond, the fracture will be a progressive one-bond failure, followed by matrix failure and finally fibre failure.

The interface can act as a locus of chemical reaction, it can also serve as a nucleation site and a preferential adsorption site. It is because of (*i*) The difference between thermal expansion coefficients of the reinforcement and the matrix phases and (*ii*) Cure shrinkage in thermosets and crystallization in thermoplastics.

FIBER-REINFORCED COMPOSITES

When fibers are used as dispersed phase for the reinforcement of matrices, the resultant composites are known as fiber reinforced composites.

Fiber reinforced composites are characterized by :

(*i*) high specific strength (*i.e.* tensile strength/specific gravity)

(*ii*) high specific modulus (*i.e.* modulus of elasticity/specific gravity)

The properties of fiber-reinforced composites depend on

(*a*) Nature and properties of fibre and matrix materials ;

(*b*) Their relative volume fractions ;

(*c*) Orientation and distribution of fibers in matrix phase (superior properties are observed in the direction where fibers are oriented) ;

(*d*) Strength of the interfacial bond between the fiber and the matrix phases (high strength is generally desired) ;

(*e*) Length of the fibers or more appropriately aspect ratio (length / diameter ratio) of fibers.

For number of fiber-reinforced composites, aspect ratio has value in between 1 150. In fact, for effective strengthening and stiffening of the composite, some fibre length is must.

Critical fibre length (l_c) is defined as :

$$l_c = \sigma_f d / T_c$$

where σ_f is ultimate fibre strength of the fibers.

d is diameter of fibers, and

T_c is shear yield strength or fibre-matrix bond strength.

Long (or continuous) fibers have their lengths which are about 15 times greater than the critical length but in short (or discontinuous) fibers, the lengths of the fibers are considerably lower than their critical length. That's why the reinforcement efficiency of continuous fibers is higher than that for discontinuous fibers.

Some Important Types of Fiber-Reinforced Composites :

(A) **Class-fiber reinforced composites :** Glass fibers (both long and short) are generally used for improving the properties of polymeric matrices like polyesters, nylon etc.

These composites have the following characteristics :

(*i*) Lower densities,

(*ii*) Higher tensile strengths,

(*iii*) High impact resistance,

(*iv*) Excellent chemical and corrosion resistance.

But, these composites also have the following *limitations* :

(*i*) Limited service temperatures, because most polymeric matrices begin to deteriorate or flow at high temperatures.

(*ii*) These materials do not possess the desired stiffness and rigidity, particularly in their applications as structural components.

Some *typical applications* of these materials are in

Automotive parts, storage tanks, industrial floorings, plastic pipes and in transportation industries to reduce vehicle weight and boost fuel efficiency.

(B) **Carbon Fiber-Reinforced Polymer Composites :** High performance carbon fibers are now-a-days used as reinforcement in advanced polymer matrix composites, which requires retention of desired properties even at higher temperatures and excellent resistance to corrosion along with lighter weights.

Some *typical applications* of these materials are :

(*i*) Military and commercial aircraft structural components such as wing,

(*ii*) Wing, body and stabilizer components of helicopters,

(*iii*) Sports and recreational equipments like fishing rods, golf clubs.

The uses of these materials are limited because of their higher costs.

(C) **Aramid Fiber-Reinforced Polymer Composites :** These materials can be broadly classified into following categories :

(*i*) *Short fibre reinforced composites.* The short fibers of *p*-aramid have high aspect ratio and high surface area and hence they give effective reinforcement. Moreover, they have inherent toughness, strength and heat stability. They also have high wear resistance and are used in automotive brakes and clutches. In fact these composites perform better than asbestos at less than one-tenth the amount in brakes and clutches. Because asbestos causes serious health problems so its use is now-a-days

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(ii) *Long fibre reinforced composites.* These composites are metal-like in ductile energy absorption and respond to compressive stresses non-catastrophically. This is due to the fact that aramid fibres absorb energy in its accordian like compressive collapse. They are excellent advanced engineering and structural materials. The latest commercial aircrafts Boeing 767 and Airbus 320 contain about 3-5% of composites, much of which is *p*-aramid or hybrids of *p*-aramid and carbon.

The helicopter industry also utilises composites based on p-aramid in fuselage parts, motor housing and rotor blades. Even primary structures of small business air crafts are being made by using these composites.

These materials are also used for manufacturing protective apparel (thermal, cuts, ballistics).

(D) Alumina and/or carbon fibers reinforced metal-matrix composites : Fibre reinforcement in ductile metal matrix may improve specific strength & stiffness, resistance to abrasion & creep and dimensional stability.

The properties and application of two such composites are summarized below :

Matrix	*Reinforcement*	*Characteristic properties*	*Applications*
Aluminium alloy	Alumina or Carbon fibres	Light in weight, Resists wear and thermal distortion	Engine component of Automobiles.
Nickel and Cobalt based alloys	Alumina or refractory metals such as tungsten	Excellent high-temperature, creep and rupture resistance, Excellent impact strength	Turbine engines

6 UNIDIRECTIONAL FIBRE REINFORCED COMPOSITES

They are most widely used composite materials. They usually consist of several distinct layers of unidirectional composites. Unidirectional composites in turn, consist of parallel fibres embedded in a matrix. Each layer of a unidirectional composite is known as layer, ply or lamina. Each lamina is generally made of same constituent materials (*e.g.* matrix and fibre). But an individual lamina may differ from another lamina in

(*a*) relative volumes of the fibre and matrix,

(*b*) orientation of fibres with respect to common reference axes and

(*c*) form of the reinforcement used such as woven or non-woven reinforcement, continuous and discontinuous fibres.

There is also a possibility of *hybrid laminates* in which different layers consist of different fibres and/or matrix material. It is obvious that directional properties of the individual layers are different from each other. As complete knowledge of the properties of individual layers is required for the analysis and design of any structural element made from these fibre-reinforced composites. It is appropriate to first study the properties and behaviour of single layer composites which are basic building block for laminate constructions.

A typical undirectional composite is shown in Fig. 1.

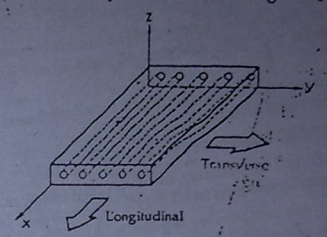

Fig. 1. Schematic diagram of unidirectional composite.

It consists of parallel fibers embedded is a matrix. The direction parallel to fibers is known as longitudinal direction (*x*-axis). The direction perpendicular to the fibers is called the transverse direction (any direction in the *y-z* plane).

A lamina has the strongest properties in the longitudinal direction.

The relative proportions of the matrix and reinforcing materials are largely responsible for the observed properties of the composites.

These proportions are expressed either as weight fractions or as volume fractions.

Let v_m = volume of the matrix material,

v_f = volume of the fibres and

v_c = volume of the composite material

Obviously, $v_c = v_m + v_f$ ...(1)

Then, volume fraction of the matrix $(V_m) = \frac{v_m}{v_m + v_f} = \frac{v_m}{v_c}$ ...(2)

Similarly, volume fraction of the fibres $(V_f) = \frac{v_f}{v_c}$ ...(3)

Moreover, $V_m + V_f = 1$

Now, if, w_m = weight of the matrix material,

w_f = weight of the fibres and

w_c = Weight of the composite material $= w_m + w_f$ ...(4)

then, Weight fraction of the matrix $(W_m) = \frac{w_m}{w_m + w_f} = \frac{w_m}{w_c}$ ...(5)

Similarly,

Weight fraction of the fibres $(W_f) = \frac{w_f}{w_m + w_f} = \frac{w_f}{w_c}$ ...(6)

Moreover, $W_m + W_f = 1$

Generally, *volume fractions* are used for the theoretical analysis of the composite materials. But *weight fractions* are easier to obtain during fabrication or by one of the experimental methods after fabrication.

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This can be explained as follows :

In ductile matrices, the triaxial restraint of the matrix between fibers limits the elongation of the matrix, and thus addition of rigid fibers greatly reduces the toughness.

But in brittle matrices addition of fibers increase toughness because of crack blunting, branching and arrest effects.

9 PARTICLE-REINFORCED COMPOSITES

In the particle-reinforced composites, the dispersed phase is a particle which generally has nearly same dimensions in all the directions (*i.e.*, it is equi-axed).

The behaviour of these composites is governed by :

(*i*) Distribution of particles throughout the matrix.
(For effective reinforcement, distribution should be uniform).

(*ii*) Relative volume fraction of the constituents (Greater the volume fraction of particulate reinforcement, more will be the improvement in the mechanical properties).

(*iii*) Strength of the bond at the interface of particles and matrix (stronger the bond, better will be the properties of composites).

Generally particulate phase can be divided into two categories *viz.* large particle and Dispersion-strengthened. The corresponding composites are briefly described below :

(*i*) *Large-Particle Composites.* In these composites the interactions between particle and matrix phases are not on the atomic or molecular level.

Elastic modulus of particle reinforced composite fall between

$$E_c(u) = E_m(1 - V_p) + E_l V_p$$

and

$$E_c(l) = \frac{E_m E_p}{(1 - V_p) E_p + V_p E_m}$$

where $E_c(u)$ and $E_c(l)$ represent upper and lower elastic modulus of composite.

E_m and E_p represents elastic modulus of matrix and particle phases and V_p represents volume fraction of particle phase.

Examples of large particle reinforced composites :

1. A composite in which vulcanized rubber (matrix) is reinforced by adding 15-30% by volume of carbon-black particles with 20-50 μm diameter.

The resulting composite has excellent tensile strength, toughness and abrasion resistance and is used for making *automobile tyres.*

2. *Cermets* (or ceramic-metal composite) in which ceramics like titanium carbide (TiC) and tungsten carbide (WC) are embedded in metals such as nickel or cobalt.

Cermets are used extensively as cutting tools. The cutting surface is being provided by hard ceramic carbide particles. They are not capable of withstanding the cutting stresses as they are brittle so they are not used alone. For enhancing the toughness, these particles need to be incorporated in ductile metal-matrix which

prevents particle to particle crack propagation by isolating them. As the cutting action generate high temperatures hence both the components (of composite used for cutting tools) should be refractory materials. In this case they are ceramics and metals.

(*ii*) *Dispersion-Strengthened composites.* Here reinforcement is done by the uniform dispersion of fine particles of very hard and inert material. These particles may be metallic or non-metallic. But because of their fine dimensions, interactions between them and matrix phase is on the atomic or molecular level. Generally, inert particles are chosen for reinforcement which do not react with the matrix phase hence strengthening is retained at elevated temperatures. Moreover, the resulting composites are durable.

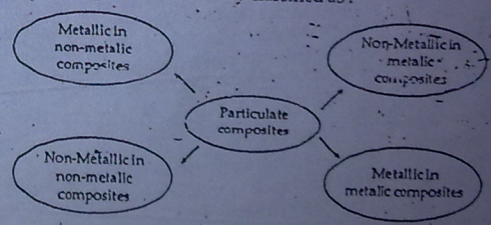
Examples of Dispersion strengthened composites : (1) Thoria-dispersed (or TD) nickel. In this composite, about 3 volume % of thoria (ThO_2) in the form of fine particles are uniformly dispersed in nickel matrix for improving the high-temperature strength of nickel alloys.

(2) Sintered aluminium powder : here aluminium metal matrix is reinforced by incorporating extremely fine (0.1 to 0.2 μm thick) particles of aluminium oxide. The resulting composites have excellent high temperature strength.

The four broad categories of particle reinforced composites are summarized below :

10 PARTICULATE COMPOSITES

Particulate composites are broadly classified as :



Types of Particulate composites

(*i*) *Non-metallic in metallic composites.* Examples of Non-metallic in metallic composites are :

- Ceramics particles suspended in a metal-matrix.
- Such composites are known as *cerments* and are of two types :

(a) *Oxide based cerments.* For example, Al_2O_3 with 72 vol. % dispersed in aluminium matrix has strength 30 GPa and also has very good thermal shock-resistance.

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(b) *Carbide based cements*

Carbide	Matrix	Applications
WC	Co	Wire-drawing die, valves and other machine parts requiring very high hardness
CrC	Co	Valves, pump parts & spray nozzles as it has very high resistance to corrosion and abrasion.

(ii) *Metallic in non-metallic composites.* Examples of metallic in non-metallic are :

Aluminium paint in which aluminium flakes suspended in paint.

(iii) *Metallic in metallic-composites.* Examples of metallic in metallic-composites are :

(a) Lead particles in copper alloys & steel, improves the machineability of the latter.

(b) Bearings made from Cu alloys utilize lead as a natural lubricant.

(iv) *Non-metallic in non-metallic composites.* Examples of non-metallic in non-metallic composites are :

(a) Flakes of mica or glass in glass or plastic matrix respectively.

(b) Concrete is another example of this class in which particles of sand and rock are dispersed in cement which then chemically react with water for hardening.

11 STRUCTURAL COMPOSITES

The composite materials which are used as structural components in demanding applications for better overall performance are known as "structural composites".

In general properties of structural composite depends on

(i) The properties of the constituent materials, and

(ii) Their geometrical design

Structural composites are broadly classified as:

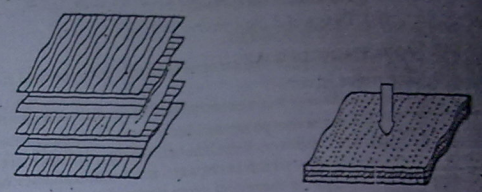
(a) Laminar and

(b) Sandwich composites.

These are briefly discussed below :

(a) *Laminar Composites* : They consists of number of two-dimensional sheets or layers that are stacked and subsequently cemented together (such that the orientation of reinforcement varies with each successive layer). This is shown in Fig. 5.

These layers possess relatively high strength in the direction of reinforcement and hence the resulting laminar composite has high strength in number of directions.



(a) Stacking of successively oriented fiber-reinforced layers (b) Fabricated laminar composite

Fig. 5. Successive stacking of oriented fiber reinforced layers for producing a laminar composite.

(b) Sandwich Panels : They consist of two stronger outer sheets (called "faces") separated by a layer of less-dense "core" material.

Core material should be light weight, able to transfer load from one facing to the other and should have high corrosion resistance.

The structural functions of the "core" is to resist any deformation perpendicular to the face plane by providing certain degree of shear rigidity. The "faces" bear most of the in-plane loading, as well as any transverse bending stresses.

The stiffness of the sandwich panels increases as the core thickness increases. For instance, if we increase the thickness of the core four times, relative stiffness increases by 39 times. As the core is generally of lighter material, so corresponding increase in weight is just 6%.

"Honeycomb" structure (made up of thin foils that have formed interlocked hexagonal cells with their axes oriented in a perpendicular direction to the "face" planes) is very popular type of "core material". It is shown below in fig 6.

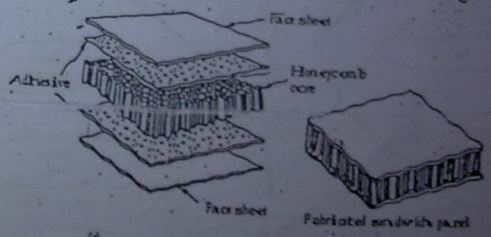


Fig. 6.

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Applications of Sandwich structures :

(i) For fabrication of wings of aircrafts,

(ii) For fabrication of roofs, floors and walls of building and

(iii) Design of ships, boat hulls etc.

12 ADVANTAGES OF COMPOSITES

The major advantages of the composites over conventional material are as follows :

(i) Composites are more economical than metals and ceramics.

(ii) Weight of the composite articles are approximately 25% to 50% of the weight of the conventional metallic design. Hence, there is significant weight savings which is required for minimization of fuel consumption that is why more and more parts of transportation industry are now-a-days made from composites.

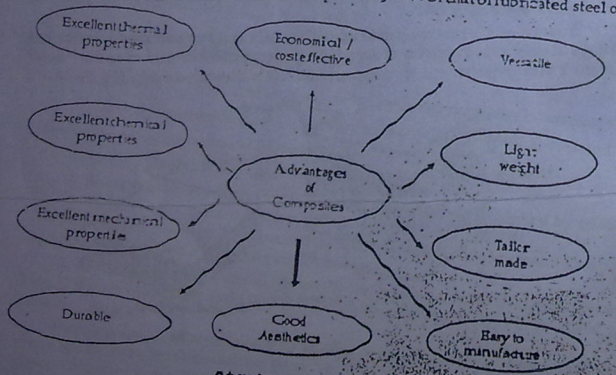
(iii) Composites show excellent mechanical properties *e.g.*

(a) Fibre-reinforced polymer composites show high strength and stiffness. They store more energy per unit weight and hence rotational components made out of them function significantly faster than those made of steel alloys.

(b) High modulus fiber reinforced composites show excellent torsional stiffness. This property is required by various high speed vehicles and aircrafts.

(c) Composites also show excellent impact and damage tolerance characteristics.

(d) Carbon fiber reinforced polymers shows outstanding friction and wear properties. For instance, the coefficient of friction of a carbon composite on steel is approximately 40% of that of lubricated steel on steel.



Advantages of composites

(iv) Composites also show excellent chemical properties, *e.g.*

(a) Glass fiber reinforced polymer composites show excellent corrosion resistance. (In fact, corrosion resistance of composite depends on the nature of matrix phase because dispersed phase (reinforcement) is basically embedded in matrix. Thus, any outside agent has to first interact with matrix. So, if matrix has better resistance to corrosion the corresponding composite also show better resistance to corrosion).

(b) In marine environments, fiber reinforced composites show improved weatherability and hence they are more durable so they require less maintenance compared to wood or metal.

(v) Composite materials can be tailored to comply with a broad range of thermal expansion design requirements and to minimize thermal stresses.

(vi) Better heat loss control is possible with composite structures compared to metallic one hence composites provide improved insulation.

(vii) Composites are also preferred compared to conventional materials due to selection flexibilities, changing of styling according to market needs and product aesthetic considerations.

13. APPLICATIONS OF COMPOSITES

The principal applications of composite are in

(i) *Transportation Industry.* (Generally Aramid reinforced composites are used) viz.

(a) Ground transportation : Automobile body and chassis part, racing vehicle component and engine components.

(b) Marine : spass for racing boats, propellers shaft and hulls for small crafts.

(c) Aerospace : Business and Military aircraft, Rocket components etc.

(ii) *Consumer products viz.* Sporting goods (*e.g.*, Lawn Tennis racket) and Musical instruments.

(iii) *Industrial and scientific Equipments viz.* Safety equipment including ballistic protection ; High speed machinery ; Communication antennae and electronic circuit boards, (*e.g.* printed circuit or wiring boards PCB or PWB) in which composites function primarily as an electrically insulating substrate on which various electrical or electronic components are mounted. PCB's eliminate bulky wiring, increase stability of circuitry and interconnections and provide miniaturisation advantages.

Note : High manufacturing costs associated with the high costs of the reinforcement fibers and highly labor intensive manufacturing processes hinder the extensive industrial use of these composites particularly continuously reinforced MMC's.

EXERCISES

1. Define 'composites'. Why they should be made ?
2. How are composite materials classified ?
3. Discuss the advantages and limitations of composite materials.
4. Enlist the general characteristics of composites.

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