
Materials Science and Engineering (BMEE209L)

by

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Content

☐ **Module: 7 Non-metallic and Composite Materials** covers the following:

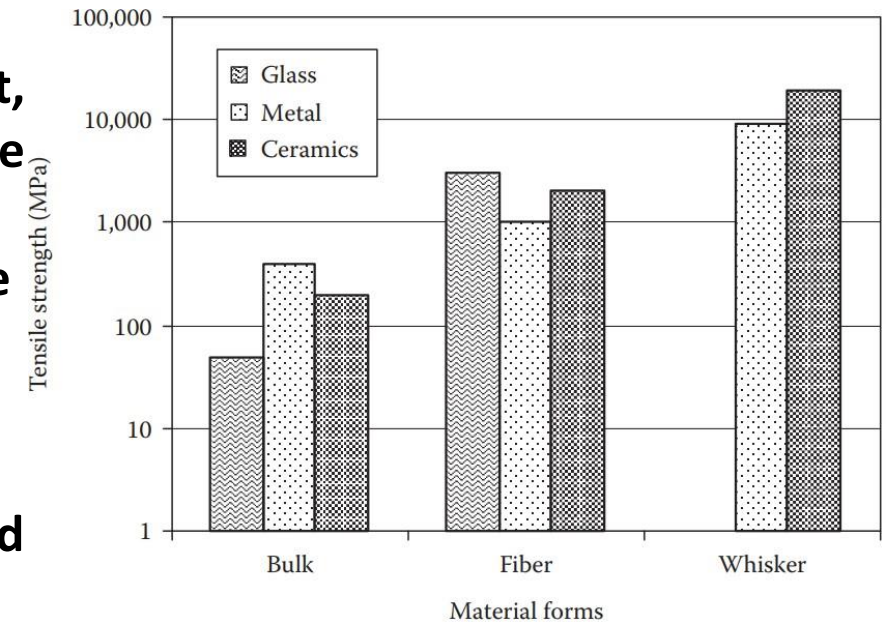
- **Fibers**
- **Natural Fibers and Synthetic Fibers**
- **Composite Materials**
- **Classification of Composite Materials**
- **Properties and Application of Composite Materials**

Raw Materials for Composite

- ❑ Composite materials are formed by the combination of two or more materials to achieve properties (physical, chemical, etc.) that are superior to those of its constituents.
- ❑ The main components of composite materials, or composites are:
 - Dispersed phase (Fibers)
 - Continuous phase (Matrix)
- ❑ The fibers provide most of the stiffness and strength.
- ❑ The matrix binds the fibers together thus providing load transfer between fibers and between the composite and the external loads and supports.
- ❑ Also, it protects the fibers from environmental attack.
- ❑ Other substances are used to improve specific properties.
- ❑ For example, fillers are used to reduce the cost and improve process-ability and dimensional stability.

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- ❑ The dispersed phase can be in the form of **long fibers**, **short fibers**, **whiskers**, **flakes**, **sheets**, or **particulates**.
- ❑ Among these forms, **fiber** forms are widely used in the composites because of their superior properties and load transfer characteristics.
- ❑ A **fiber** can be defined as an elongated material, mostly with a circular cross-section having a more or less uniform diameter of $<250\text{ }\mu\text{m}$ and an aspect ratio (length to diameter ratio) of >100 .
- ❑ Fiber form is stronger than bulk form due to the size effect, that is, the defect size in the fiber is restricted to the size (diameter) of fibers.
- ❑ Figure shows the strength of different material types in three forms, namely, **bulk**, **fiber**, and **whisker** forms.
- ❑ Whiskers are monocrystalline short fibers.
- ❑ The diameter of whiskers is 0.1 to a few micrometers and length can be up to a few millimeters.
- ❑ Silicon carbide whiskers are the common whisker materials used in composites.



Tensile strength of materials in different forms

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- ❑ The fibrous materials can be broadly classified into **two** types:
 - Natural
 - Synthetic fibers
- ❑ The plant kingdom is a rich source of **natural fibers**, and these fibers are mainly based on cellulose.
- ❑ Some of the natural fibers are cotton, flax, jute, hemp, sisal, coir, and ramie.
- ❑ Animal kingdom also supplies many natural fibers.
- ❑ These fibers are mainly based on proteins.
- ❑ Hair, wool, and silk are some of the natural fibers.
- ❑ The silk fibers produced by spider are considered as the toughest material.

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- ❑ Natural fibers are relatively cheap and produced from renewable sources, therefore, not widely used because of their poor mechanical properties compared to synthetic fibers.
- ❑ The other problems with natural fibers are poor moisture resistance, non-uniform dimensions and properties, incompatibility with polymer matrices, and poor weather resistance.
- ❑ Hence, natural fiber-reinforced polymer composites are used only in applications where the load-bearing capacity is not very critical.
- ❑ A major advantage of natural fibers is their biodegradability.
- ❑ Biodegradable composites can be made by using natural fibers with biodegradable polymer matrices.

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- ☐ **Synthetic fibers** are high-performance fibers.
- ☐ The modulus and strength values are very high for most of the synthetic fibers.
- ☐ Some of the common synthetic fibers include glass, boron, carbon, aramid, alumina, and silicon carbide.

- ☐ Glass fibers are the most widely used synthetic fibers.
- ☐ At present boron fibers are rarely used, since carbon fibers of equivalent properties with good flexibility are available at a cheaper rate.
- ☐ Most of the high-performance composites are made with carbon fibers.

- ☐ Aramid fibers are used only in polymer matrices, since they are based on organic polymers and cannot withstand the processing temperatures of metals and ceramics.
- ☐ The attractive property of aramid fiber is its high-damping characteristics.
- ☐ Because of this property, bullet proof vests are made with this fiber.

- ☐ Ceramic fibers are mainly used in metal matrix composites (MMCs) and ceramic matrix composites (CMCs).
- ☐ They are relatively expensive, but their high temperature resistance is very good.

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- ❑ Many **particulate** materials are derived from the natural minerals.
- ❑ Some particulate materials are also prepared using synthetic routes.
- ❑ Particulate materials are available from a few hundred micrometers to nanometer level.
- ❑ Particulates are added to polymers, mainly to reduce cost and to metal and ceramic matrices to improve some specific properties.
- ❑ Calcium carbonate, titanium oxide, and clays are the common **particulate materials** added to polymer.
- ❑ Alumina, silicon carbide, and zirconia are the common **particulate materials** used in metal and CMCs.
- ❑ Since the fibers are the most important type of reinforcements in composites, more emphasis is given for this type of reinforcement.

Characteristics of Fibers

❑ The important **characteristics** of fibers are:

- Small diameter
- High aspect ratio (length to diameter ratio)
- Good flexibility

❑ Most of the synthetic fibers have diameter in range of 5–15 μm .

❑ According to Griffith's theory, the fracture strength of brittle material can be related to the defect size by the following equation:

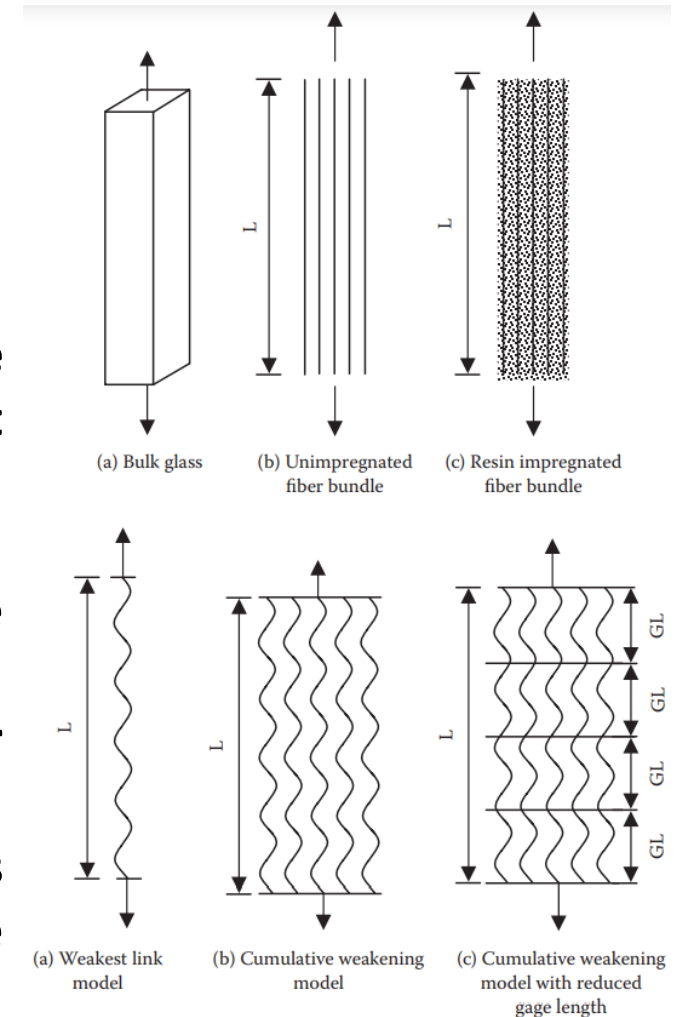
$$\sigma_c = \left(\frac{2 E \gamma}{\pi c} \right)^{1/2}$$

❑ Where,

- E is Young's modulus
- γ is the surface energy per unit area
- σ_c is the critical value of stress required for propagation of the flaw of length 2c (crack length)

Contd...

- ❑ There are **three models** available for the failure of materials as:
 - weakest link
 - cumulative weakening
 - cumulative weakening with reduced gage length
- ❑ Most bulk materials fail by the weakest link model, that is, the failure starts at the weakest location (the place where the largest defect exists), propagates, and finally leads to the failure.
- ❑ Fiber bundles fail by the cumulative weakening model.
- ❑ After the failure of any fiber in the bundle, the remaining fibers take the load.
- ❑ The load carried by this fiber will now be shared by all other filaments.
- ❑ Correspondingly, the stress on each fiber will increase. As the load is further increased, a few more fibers will break and the load will be redistributed.
- ❑ The process of redistribution continues until the remaining fibers can no longer take the load and the whole bundle fails at this stage.



Failure models (bulk material, fiber bundle, composite)

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- ❑ The **flexibility** of fibrous materials is also generally good.
- ❑ Flexibility is a function of modulus and size.
- ❑ For the same material available in different forms, the modulus value is the same.
- ❑ Hence, only the size factor controls the flexibility.
- ❑ The smaller the size the better will be the flexibility.
- ❑ The inverse of the product of bending moment and radius of curvature is a measure of flexibility.
- ❑ The single fiber can be assumed as a circular rod of diameter, d.
- ❑ When a circular rod is subjected to bending, according to bending theory:

$$\frac{M}{I} = \frac{E}{R}$$

- Where, M is the bending moment
- I is moment of inertia (for the circular rod, it is $\pi d^4/64$)
- E is Young's modulus
- R is radius of curvature
- ❑ Hence, the flexibility given as:
$$\frac{1}{MR} = \frac{64}{E\pi d^4}$$
- ❑ If the flexibility is good, then it is easy to bend the fiber to conform to the shape of the product.

Natural Fibers

- ☐ Nowadays environmental-friendly composites are the most sought-after composites because of growing environmental concerns.
- ☐ The synthetic fiber based composites are difficult to dispose after their utility.
- ☐ This has driven the use of natural fiber-reinforced composites (FRCs) for less critical loadbearing applications.
- ☐ Different kinds of natural fibers are available and processed in different countries.
- ☐ The separation of long fibers from the plants is a major issue.
- ☐ Typical use of natural fiber composites include interior parts, such as door trim, package trays, and rear shelves.
- ☐ Cellulose is the basic compound present in the fiber cells of plants. It is a natural polymer with high specific strength and stiffness. The fiber cells can be found in the stem, leaves, or seeds of plants.

Advantages of Natural Fibers

- ❑ The cost of the natural fibers is low (approximately 30% lower than glass fibers).
- ❑ The density values of natural fibers are roughly one-half of the density of glass fiber.
- ❑ Hence, the specific strength and modulus values are comparable to glass fibers.
- ❑ It is a renewable resource and the production requires little energy.
- ❑ Unlike synthetic fiber production, the natural fiber plants release oxygen to the environment by absorbing CO₂.
- ❑ Moreover, these materials are biodegradable.
- ❑ Hence, the natural fibers are environmental-friendly materials.
- ❑ The polymer composites made using natural fibers can be thermally decomposed easily, whereas glass fiber causes problem in combustion furnaces.

Disadvantages of Natural Fibers

- ☐ There is a wide variation in dimensions and properties and the quality of the fibers depends on the **place of cultivation** and **weather conditions**.
- ☐ The price of the fiber depends on the harvest results and agricultural policies.
- ☐ Even though the specific strength and stiffness of natural fibers are comparable to glass fibers, the actual mechanical properties are lower.
- ☐ Moisture absorption is another major problem for the natural fibers and the fibers swell on moisture absorption.
- ☐ This affects the durability of composites. Hence, the natural FRCs are only suitable for indoor applications.
- ☐ The maximum processing temperature of composites is limited due to the degradation of natural fibers.
- ☐ Hence, the natural fibers are suitable for only certain organic polymer matrices.

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☐ Bast Fibers

- The bast of plants like flax, hemp, jute, kenaf, and ramie contains the fiber bundles.

☐ Leaf Fibers

- The leaf fibers are coarser than the bast fibers.
- Some of the leaf fibers are sisal and palm.

☐ Seed Fibers

- Cotton, coir, and kapok are the common seed fibers.
- Coir fiber is derived from coconut husk.
- It is a coarse fiber with good flexibility.
- Kapok fiber is a hollow fiber with a sealed tail.
- It is a short fiber with a smooth, silky surface.

Properties of Natural Fibers

Typical Properties of Commonly Used Natural Fibers and Glass Fiber

Properties	Fiber								
	E-Glass	Flax	Hemp	Jute	Ramie	Coir	Sisal	Abaca	Cotton
Density (g cm ⁻³)	2.5–2.59	1.4–1.5	1.4–1.5	1.3–1.5	1.0–1.5	1.15–1.46	1.3–1.5	1.5	1.5–1.6
Diameter (μm)	<17	12–600	25–500	20–200	20–80	10–460	8–200	—	10–45
Length (mm)	—	5–900	5–55	1.5–120	900–1200	20–150	900	—	10–60
Tensile strength (MPa)	2000–3500	345–2000	270–900	320–800	400–1000	95–230	360–700	400–980	290–800
Specific strength (MPa/ρ)	770–1400	230–1430	180–640	210–615	265–1000	65–200	240–540	265–650	180–530
Young's modulus (GPa)	70–76	27.6–103.0	23.5–90.0	8–78	25–128	2.8–6.0	9–38	6–20	5.5–12.6
Specific modulus (GPa/ρ)	~29	~45	~40	~30	~60	~4	~17	~9	~6
Elongation (%)	1.8–4.8	1.2–3.3	1.0–1.8	1.5–1.8	1.2–4.0	15–51	2–7	1–10	3–10
Moisture absorption (wt.%)	—	8–12	6–12	12–14	8–17	8	10–22	5–10	7.9–8.5

Source: Data from Dittenber, D.B. and GangaRao, H.V.S., *Composites*, A43, 1419, 2012.

Synthetic Fibers

- ❑ The majority of the composites produced today are based on **synthetic fibers**, since there are many drawbacks with the natural fibers.
- ❑ The properties of a particular type of natural fiber vary from place to place.
- ❑ Hence, it may not be possible to produce a natural FRC with the desired properties.
- ❑ Moreover, the natural fibers degrade rapidly under normal environmental conditions.
- ❑ However, the synthetic fibers have narrow range of properties and also they are more resistant to normal environmental conditions.
- ❑ Some of the commonly used synthetic fibers are **glass, carbon, aramid, polyethylene, aluminum oxide, aluminum silicates, and silicon carbide**.

Glass Fibers

- ☐ Glass fibers are the most widely used fiber reinforcements in composites, especially in polymer matrix composites.
- ☐ Bulk glass has high hardness, moderate stiffness, transparency, and chemical resistance.
- ☐ In addition to that, glass in the fiber form has high strength and good flexibility.
- ☐ Many structural composites, printed circuit boards, and wide range special products are manufactured using glass fibers as reinforcement.
- ☐ Glass is an amorphous material and originally the amorphous compounds formed from silica-based compounds are called glass.
- ☐ The major constituent of any inorganic glass forming material is silica.
- ☐ Apart from silica, oxides of aluminum, boron, calcium, etc. are also present in varying quantities depending on the type of glass.
- ☐ The glass fibers used in composites are made from the silica-based inorganic compounds.

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- ❑ There are a variety of glass fibers available with **varying chemical composition** and the chemical compositions of commonly used glass fibers are given as:
- ❑ The glass fiber varieties are designated with English alphabets implying special properties.

Chemical composition of different types of glass fibers

Fiber Type	Composition (wt.%)												
	SiO ₂	Al ₂ O ₃	B ₂ O ₃	MgO	CaO	Na ₂ O/K ₂ O	Fe ₂ O ₃	ZnO	BeO	TiO ₂	ZrO ₂	Li ₂ O	Other Oxides
E	52.4–53.2	14.4–14.8	8.0–10.0	4.5	17.5	0.5	0.4	—	—	—	—	—	—
E Boron free	59.0–60.0	12.1–13.2	—	3.1–3.4	22.1–22.6	0.8–0.9	0.2	—	—	0.5–1.5	—	—	—
C	64.4	4.1	4.7	3.3	13.2	9.4	—	—	—	—	—	—	BaO: 0.9
S	64.2	24.8	0.01	10.27	0.01	0.24	0.21	—	—	—	—	—	BaO: 0.2
Z	68	0.7	—	—	—	12.3	—	—	—	1.5	16.5	1.0	—
M	53.7	—	—	9.0	12.9	—	0.5	—	8.0	7.9	2.0	3.0	CeO ₂ : 3.0
ECR	58.0	11.6	—	2.0	21.7	1.2	0.1	2.9	—	2.5	—	—	—
D	55.7–74.5	0.3–13.7	22.0–26.5	0–1.0	0.5–2.8	0.2–2.3	—	—	—	—	—	—	—
Silica	99.99	—	—	—	—	—	—	—	—	—	—	—	—

Source: Data mainly from Wallenberger, F.T. et al., *ASM Handbook*, Vol. 21, *Composites*, ASM International, Materials Park, OH, 2001, p. 28.

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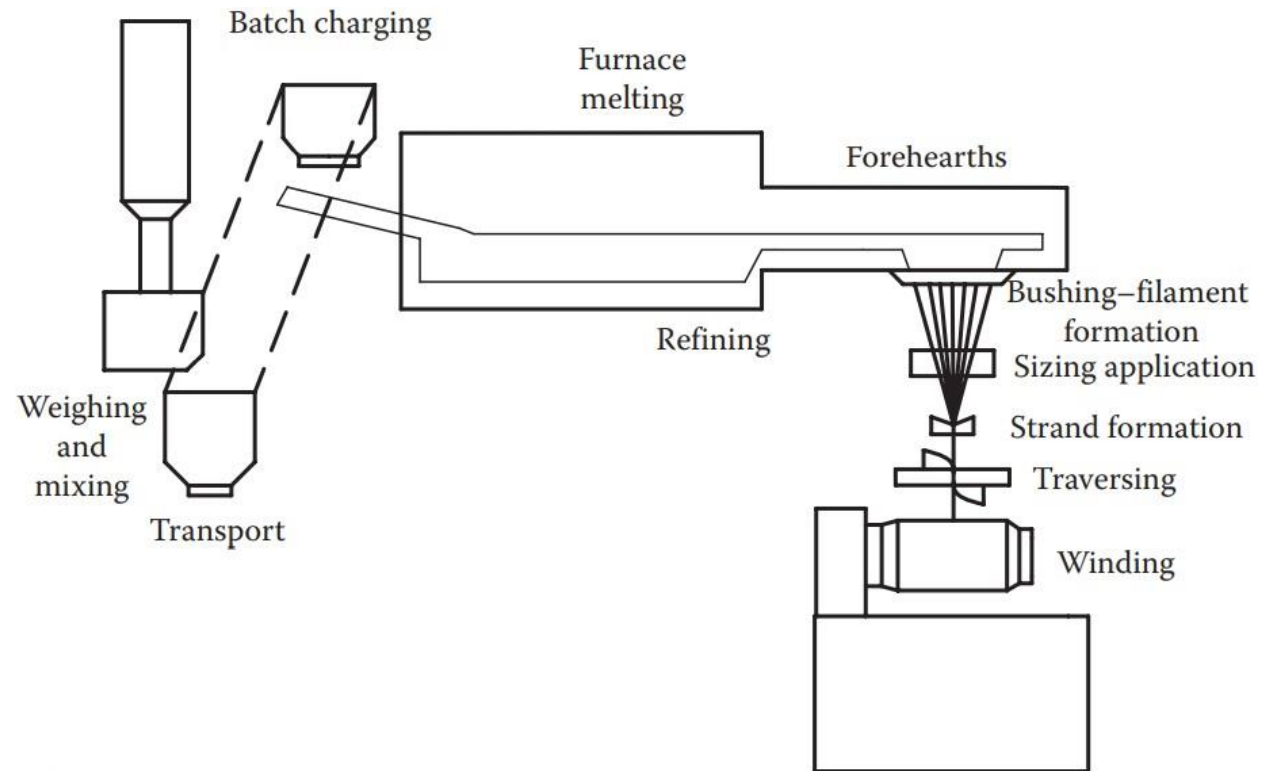
- ❑ There are **two** categories of glass fibers and they are low-cost:
 - General-purpose fibers
 - Premium special-purpose fibers
- ❑ The **general-purpose fibers** constitute more than 90% of the glass fibers used, mainly the E-glass variety.
- ❑ E-glass is the most preferred fiber type for the composite industries because of the cost and processing advantages.
- ❑ Originally this type was developed for electrical applications because of its better electrical insulating properties.
- ❑ The **general-purpose E-glass fiber** is also produced as **two** variants:
 - with boron
 - without boron
- ❑ Boron-free E-glass has about 5% higher elastic modulus than boron-containing glass fiber, but the filament strengths of both types of glass fibers are almost the same.
- ❑ The corrosion resistance of boron-free fiber is found to be seven times higher than that of boron-containing fiber when tested in 10% sulfuric acid.

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- ❑ The **special-purpose glass fibers** include S-glass, C-glass, Z-glass, D-glass, M-glass, ECR-glass, and silica fibers.
- ❑ Among the special-purpose glass fibers, ECR fibers offer better long-term acid resistance and short-term alkali resistance.
- ❑ C-glass provides better corrosion resistance to acids compared to E-glass.
- ❑ High-strength glass fibers such as S-glass fibers have 10%–15% higher strength than E-glass, but the real importance of these fibers is their stability at high temperatures.
- ❑ The tensile strength of glass fibers is generally determined by the silicate network connectivity.
- ❑ The other important constituent of glass fiber is boron oxide.
- ❑ Although it can become part of the network, it is weaker than silica.
- ❑ Hence, the high-strength glass fibers are made with less alkali and boron contents.
- ❑ M-glass is a high-modulus glass fiber with modulus value higher than E-glass.
- ❑ Z-glass has a high resistance to alkaline environment and is mainly used in chemical applications.
- ❑ Printed circuit boards are generally made using E-glass fibers.
- ❑ The D-glass fibers contain high levels of B_2O_3 (20–26 wt.%) and therefore have much lower dielectric constants than that of E-glass fibers.
- ❑ However, the cost of these fibers is high because of the necessity to use special processing methods to overcome the problem of high boron content.

Glass Fiber Manufacturing Process

- ❑ Glass fiber is produced by **melt-spinning process**.
- ❑ The required amount of natural minerals conforming to the final glass composition is melted in a furnace.
- ❑ This melt is allowed to flow through a platinum alloy bushing containing several hundred individual orifices of diameter 0.793–3.175 mm.
- ❑ The molten glass is coming out as a continuous stream.
- ❑ Fibers are rapidly drawn from this highly viscous melt and then cooled.
- ❑ The **final diameter** of the fiber depends on the **platinum orifice diameter** and **viscosity of molten glass**.
- ❑ The viscosity is in turn controlled by the chemical composition.
- ❑ The diameter of glass fibers typically range from 3 to 20 μm .
- ❑ The fibers are drawn at velocities up to 61 m/s.



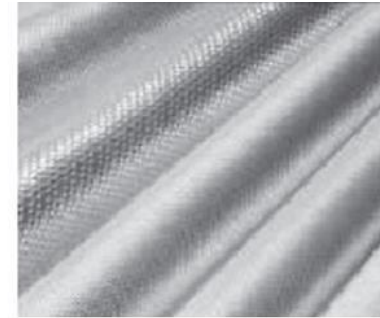
Schematic of glass fiber manufacturing process

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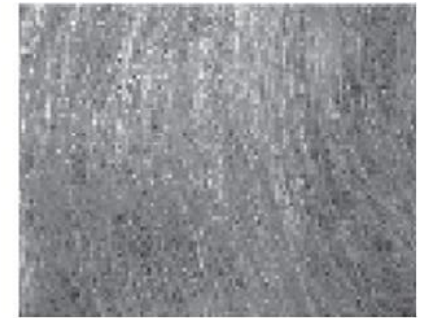
- ❑ Individual filaments are gathered into multifilament strands after applying a size coating.
- ❑ The size coating performs several functions, such as a lubricant, protective agent, binder, and coupling agent to the polymer being reinforced.
- ❑ A collection of strands is either wound on a tube as continuous roving or used to produce various glass fiber forms.
- ❑ Some special glass fibers are produced by **marble melt process**.
- ❑ In this process, the raw materials are melted and solid glass marbles of 20–30 mm in diameter are formed.



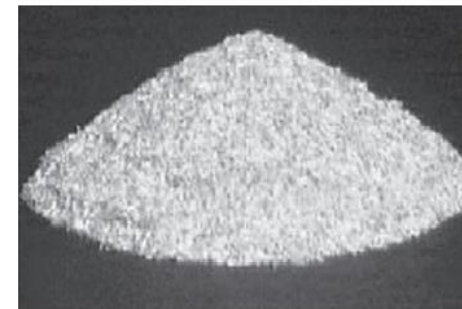
Rovings



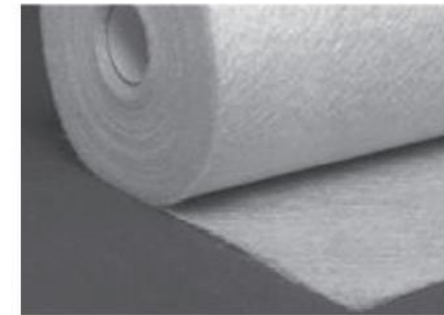
Woven rovings



Continuous fiber mat



Chopped strands



Chopped strand mat

Various forms of glass fiber

Carbon Fibers

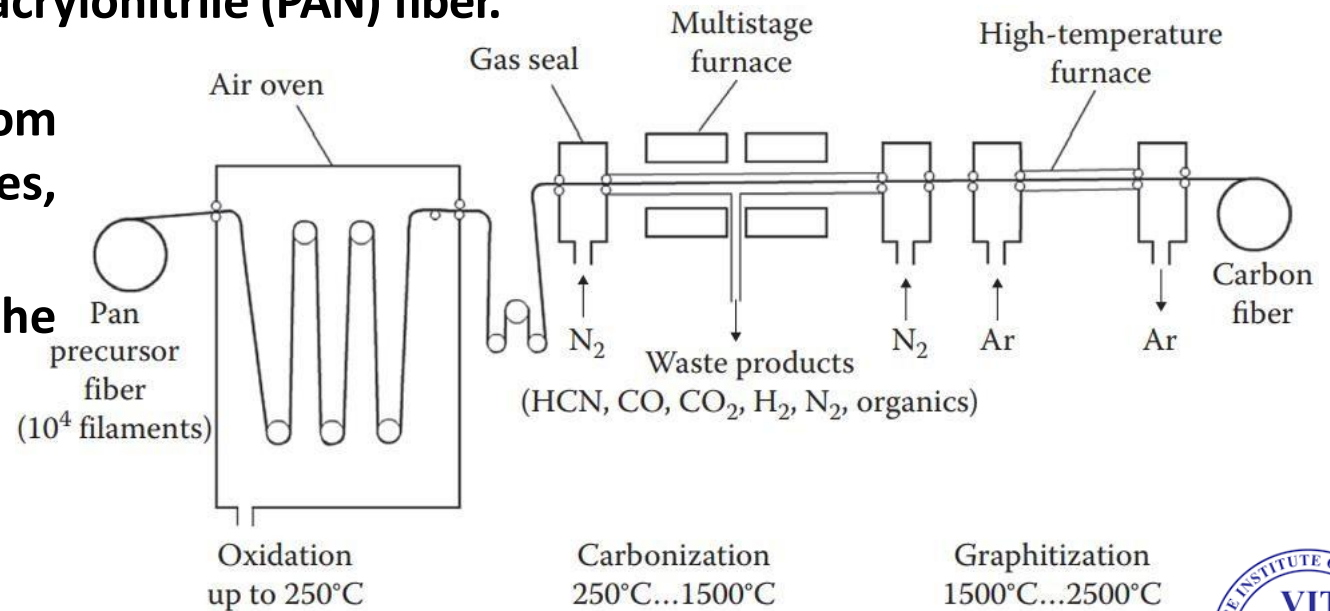
❑ Carbon exists in various allotropic forms.

❑ The **three** important forms are:

- **Graphite** – Carbon atoms are arranged in a hexagonal fashion in the graphite structure. It has a layer structure with closely packed and strongly bonded carbon atoms in the layer and weak van der Waals forces between the layers. Graphite is a highly anisotropic material, because of this structure. The modulus value along the plane is close to 1000 GPa and across the plane is only about 35 GPa. This is the form that exists in carbon fibers.
- **Diamond** – Diamond has a cubic structure with strong covalent bonding in all the three directions.
- **Fullerenes** – Fullerenes are made of 60 or 70 carbon atoms. They are also known as **buckyballs**.

Carbon Fiber Production

- ❑ Carbon is one of the light elements with a density of 2.27 g/cm^3 .
- ❑ Carbon fibers have density ranging from 1.6 to 2.20 g/cm^3 depending on the processing conditions.
- ❑ They are made from organic precursor fibers.
- ❑ The organic precursor fibers are special-grade polymeric fibers, which undergo large amount of plastic deformation before fracture.
- ❑ These fibers are converted to carbon fibers on **pyrolysis** (thermal decomposition of materials at elevated temperatures in an inert atmosphere).
- ❑ The widely used precursor fiber is **polyacrylonitrile (PAN)** fiber.
- ❑ Other precursor fibers are derived from rayon, pitch, polyvinyl alcohol, polyimides, and phenolics.
- ❑ There are **four** essential steps in the carbon fiber preparation:
 - Fiberization
 - Stabilization
 - Carbonization
 - Graphitization



Schematic of carbon fiber production

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- ❑ **Fiberization** is the preparation of precursor fiber from the organic material by melt, wet, or dry-spinning method. The selection of appropriate polymer is very important. It is based on the carbon yield, molecular weight, fiber forming ability, etc.
- ❑ **Stabilization** treatment is to make the precursor fiber non-melting during the subsequent high-temperature treatments. This is carried out at 250 °C under normal atmospheric conditions. Wherever possible, stretching is applied during this treatment so that there is some molecular alignment along the fiber axis.
- ❑ **Carbonization** treatment is to drive out the non-carbon elements from the precursor fiber. It is normally carried out under inert atmospheric conditions between 1000 – 1500 °C with a very slow heating rate. After this treatment, the fiber has a network of hexagonal carbon ribbons. However, all the ribbons are not aligned to the fiber axis. Hence, the mechanical properties of the fibers after carbonization are poor.
- ❑ **Graphitization** treatment is carried out between 1500 – 2500 °C under inert atmospheric condition with some stretching. The ribbons get aligned due to plastic deformation and the axis decides final properties of fiber. Better the orientation, better will be the modulus of carbon fibers.

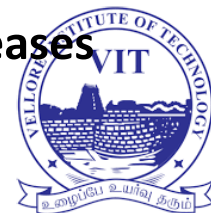
Properties of Carbon Fibers

Commercially Carbon Fibers Properties

Manufacturer	Product Name	Precursor	Filament Count	Density (g cm ⁻³)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Strain-to-Failure (%)
Amoco (United States)	Thornel 75	Rayon	10K	1.9	2520	517	1.5
	T300	PAN	1, 3, 6, 15K	1.75	3310	228	1.4
	P55	Pitch	1, 2, 4K	2.0	1730	379	0.5
	P75	Pitch	0.5, 1, 2K	2.0	2070	517	0.4
HEXEL (United States)	P100	Pitch	0.5, 1, 2K	2.15	2240	724	0.31
	AS-4	PAN	6, 12K	1.78	4000	235	1.6
	IM-6	PAN	6, 12K	1.74	4880	296	1.73
	IM-7	PAN	12K	1.77	5300	276	1.81
Toray (Japan)	UHMS	PAN	3, 6, 12K	1.87	3447	441	0.81
	T300	PAN	1, 3, 6, 12K	1.76	3530	230	1.5
	T800H	PAN	6, 12K	1.81	5490	294	1.9
	T1000G	PAN	12K	1.80	6370	294	2.1
	T1000	PAN	12K	1.82	7060	294	2.4
	M46J	PAN	6, 12K	1.84	4210	436	1.0
	M40	PAN	1, 3, 6, 12K	1.81	2740	392	0.6
	M55J	PAN	6K	1.93	3920	540	0.7
	M60J	PAN	3, 6K	1.94	3920	588	0.7
	T700	PAN	6, 12K	1.82	4800	230	2.1
Toho Rayon (Japan)	Besfight HTA	PAN	3, 6, 12, 24K	1.77	3800	235	1.6
	Besfight IM 60	PAN	12, 24K	1.8	5790	285	2.0
Nippon Graphite Fiber Corp. (Japan)	CN60	Pitch	3, 6K	2.12	3430	620	0.6
	CN90	Pitch	6K	2.19	3430	860	0.4
	XN15	Pitch	3K	1.85	2400	155	1.5
BASF	GY-80	PAN	—	1.96	1860	572	0.32
	GY-70	PAN	—	1.90	1860	517	0.36
	G40-700	PAN	—	1.77	4960	300	1.65

Source: Data from Krenkel, W., *Ceramic Matrix Composites*, Wiley-VCH, Weinheim, Germany, 2008, p. 71. With permission.

- ❑ The width of the ribbons, the number of graphene layers in a set (thickness of a group), and the length of the ribbons determine the **mechanical**, **electrical**, and **thermal** properties of the carbon fiber.
- ❑ Larger and more oriented graphene planes result in higher modulus and thermal and electrical conductivity.
- ❑ One of the important advantages of using carbon fibers in composites is **superior fatigue resistance**.
- ❑ Carbon fiber is its **negative coefficient of thermal expansion** (CTE) in axial direction at room temperature. However, the CTE becomes **positive above 700 °C**.
- ❑ The purity of low-modulus carbon fibers is less than 99%, mainly because of **retained nitrogen**. This nitrogen can be removed by subjecting the fiber to **higher heat treatment temperature**, which also improves **density** and **crystalline perfection**.
- ❑ Increase in purity and crystalline perfection increases **electrical** and **thermal conductivities** of carbon fibers.



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- ❑ As an inert inorganic material, carbon fibers are **not affected** by moisture, air, solvents, bases, and weak acids at room temperature.
- ❑ However, they undergo **oxidation** at elevated temperatures. The threshold temperatures for oxidation on exposure to long duration in air are 350 °C and 450 °C for low-modulus PAN-based fibers and high-modulus (pitch and PAN) fibers.
- ❑ Impurities present in the fibers tend to **catalyze oxidation** at these low temperatures and the oxidation resistance can be increased by **increasing the purity of fibers**.
- ❑ Polymer resins and molten metals do not easily wet carbon fibers, because of the relatively **inert** and **nonpolar nature** of the fiber.
- ❑ Surface treatments given by fiber manufacturers introduce active chemical groups such as hydroxyls, carbonyls, and carboxyls on the fiber surface.
- ❑ These groups can facilitate the formation of chemical bonding with the polymer matrix.
- ❑ However, the bonding is not strong and the interface bond strength mainly depends on the number of links.
- ❑ In addition to this, some **mechanical bonding** also helps to improve the **bond strength**.

Organic Fibers

- ☐ Synthetic organic fibers are made from organic polymers having linear molecular chains.
- ☐ Molecular chains in polymeric materials are neither arranged in a regular order nor fully stretched.
- ☐ The molecular chains are held together by very weak secondary bonds.
- ☐ This type of random coil structure is responsible for the poor mechanical properties of polymers.
- ☐ The polymer molecules undergo stretching and orientation during load application.
- ☐ It is possible to **improve the modulus values** of polymers by **stretching** and **aligning the polymer molecules** in a particular direction.
- ☐ **Drawing** is a process used to align and stretch the polymer molecules.
- ☐ The **higher the draw ratio** (ratio of original diameter to final diameter), the better will be the **stretching** and **orientation**.
- ☐ However, the maximum draw ratio depends on the **nature of polymer**.
- ☐ For a particular polymer, the maximum draw ratio is controlled by **molecular weight**, **molecular weight distribution**, and **processing conditions**, such as temperature and strain rate.
- ☐ At **very high temperatures**, there will be bulk flow of material; hence, there will not be any stretching or orientation of molecules.
- ☐ At **very low temperatures**, void formation will lead to the premature failure of material.

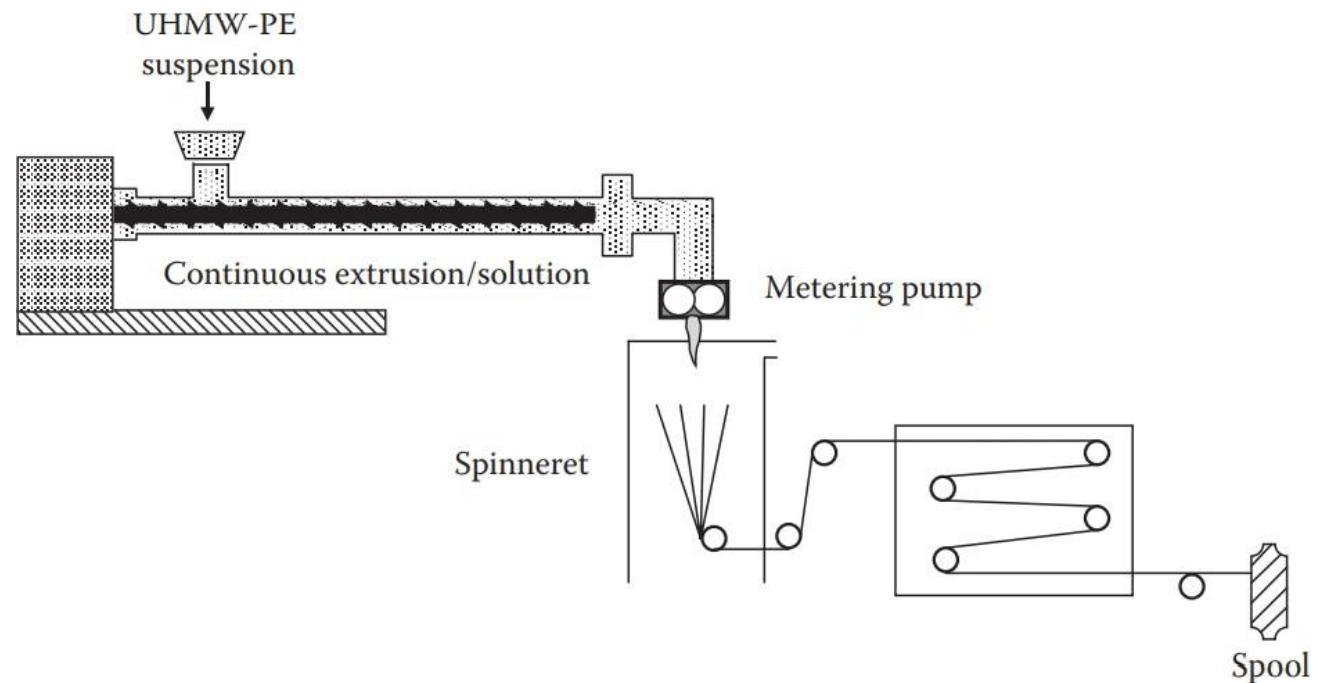
Polyethylene Fiber Manufacturing

- ❑ Polyethylene is a simple polymer with $-\text{CH}_2-\text{CH}_2-$ repeating units.
- ❑ Generally the molecules in bulk polyethylene material assume the random coil configuration; hence, the **mechanical properties are poor**.
- ❑ Once the polymer chains are **aligned with full extension**, then it is possible to get better properties in this polymer.
- ❑ The van der Waals forces existing between molecular chains in this polymer are very weak.
- ❑ Hence, significant overlap of chains is required to get better properties.
- ❑ That means the **molecular chain length should be very high**.
- ❑ In other words, the **molecular weight of the polymer should be high**.

- ❑ By careful control of the processing conditions, now it is possible to prepare polyethylene with molecular weight in the order of millions.
- ❑ Since there are large number of entanglements at this high molecular weight, **melt spinning may not be useful** to produce high-modulus fibers.
- ❑ The entanglements are less when the **material is dissolved in a suitable solvent at low concentrations**.
- ❑ Currently the commercial polyethylene fibers are produced from the solutions and the process is called **gel-spinning process**.

Contd...

- ❑ The solvent is selected in such a way that the high solubility of polyethylene at high temperature is drastically reduced when the temperature decreased by a few degrees.
- ❑ Thus, the polymer crystallizes from the solution when the temperature is lowed.
- ❑ This can happen when the solution at high temperature is allowed to pass through a spinneret.
- ❑ The gelled fiber coming out of the spinneret is passed through a low-temperature liquid bath, where most of the solvent is removed.
- ❑ At this stage, it has a swollen network structure with the presence of crystalline regions at the network junctions.
- ❑ With this structure, it is possible to draw the fiber to very high draw ratios of the order of 200.



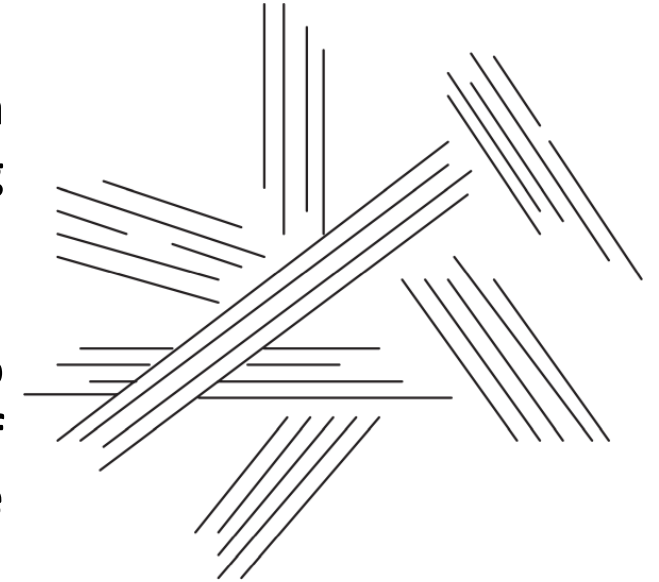
Schematic of gel-spinning process to produce polyethylene fiber

Aramid Fibers

- ☐ **Aramid** is the short form of aromatic polyamide.
- ☐ Aromatic polyamides contain rigid rodlike polymer molecules.
- ☐ The presence of aromatic rings in the para-aramid is responsible for the rigid rodlike structure.
- ☐ The rodlike molecules are highly oriented along the fiber axis; hence, the fiber has very high modulus values.
- ☐ Under certain conditions of concentration in a suitable solvent, these rodlike molecules form liquid crystal structure.
- ☐ This is the structure, in which a group of rodlike molecules aligns in a particular direction, but the orientation of each group is different.
- ☐ During fiber spinning, the groups are aligned in a particular direction.
- ☐ The fiber consists of highly crystalline and oriented polymer molecules.
- ☐ This type of structure is responsible for the high modulus and strength values of the aramid fiber.

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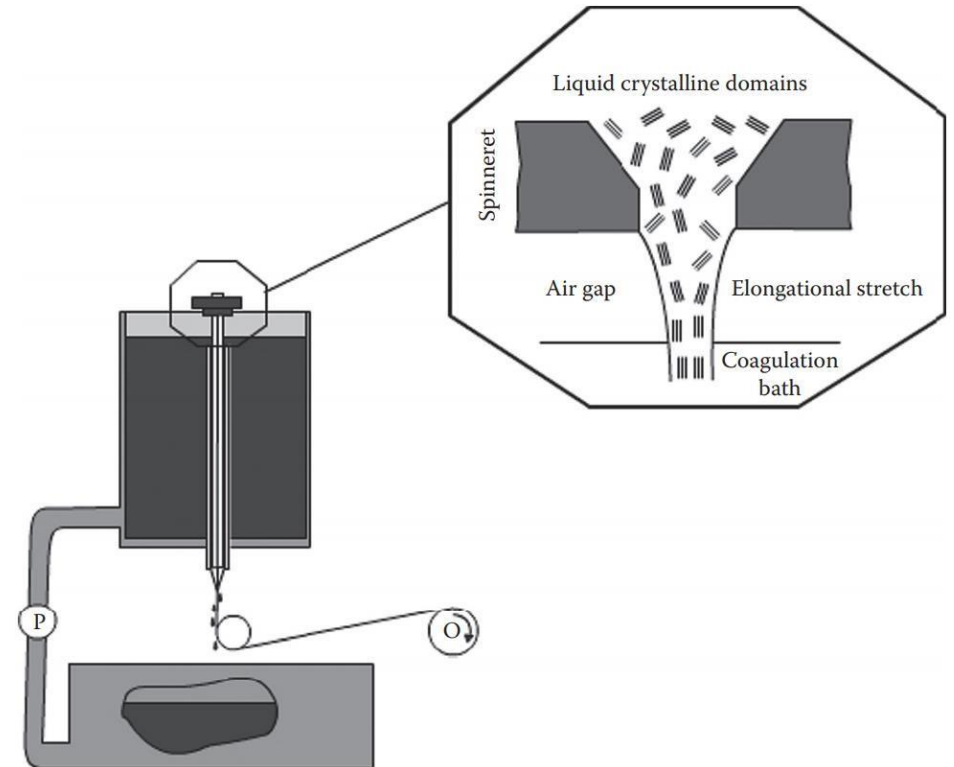
- ❑ **Fiber spinning** from the aramid polymer is very difficult because of the **rigid rodlike** molecular structure.
- ❑ This kind of structure in aramid is responsible for its **high glass transition temperature** and **poor solubility** in many solvents. For para-aramid, 100% sulfuric acid is used as a solvent.
- ❑ When the polymer content is more than the solubility limit, usually a saturated solution is formed with the undissolved polymer remaining in the liquid.
- ❑ The incorporation of diamines with wider distances between the two amino groups would be favorable to a lower spatial density of hydrogen bonding and rate of crystallization. Moreover, it improves the fiber **drawability**.
- ❑ Para-aramid fibers are produced from the liquid crystal solutions by **dry- jet wet-spinning** method.



Arrangement of
molecular rods in the
liquid crystalline state

Aramid Fiber Production

- ❑ The solution is made with 100% sulfuric acid and maintained at 80 °C and the liquid bath is maintained at 0 – 4 °C.
- ❑ A gap of 1 cm is maintained between the spinneret and coagulating bath while extruded through the spinneret.
- ❑ The crystal domains become elongated and oriented along the fiber axis because of shear forces acting in the spinneret and air gap.
- ❑ Another advantage of air gap is the possibility to maintain the solution at a higher temperature, since the spinneret is separated from the low-temperature bath.
- ❑ The concentration can be increased at high temperature, and hence, the fiber yield will increase.
- ❑ The fibers are spun at the rate of several hundred m/min.



Schematic of dry-jet wet-spinning process to produce aramid fibers



Contd...

- ❑ There is strong covalent bonding in the fiber direction and weak hydrogen bonding in the transverse direction. Therefore, the fiber is highly anisotropic.
- ❑ Another important characteristic of aramid fiber is its good vibration damping property.
- ❑ Aramid fiber is sensitive to ultraviolet radiation. The original yellow color of the fiber turns into brown color on exposure to ultraviolet radiation. The color change is also an indicator for the degradation of the fiber. After the color change, there will be significant loss in mechanical properties. It is advisable to store the aramid fiber in a place where there is no ultraviolet radiation.
- ❑ Para-aramid has better resistance to fatigue. Creep rate is low and similar to that of glass fiber but less susceptible to creep rupture. Although para-aramid fiber exhibits brittle behavior in tension, it exhibits nonlinear, ductile behavior under compression. At a compressive strain of 0.3%–0.5%, yield is observed due to the formation of kink bands. As a result of this behavior, the use of para-aramid fibers in applications that are subjected to high compressive or flexural loads is restricted.

Ceramic Fibers

- ❑ The operating conditions of components are becoming more severe as the technology develops.
- ❑ One of the severe operating conditions is high temperature.
- ❑ Apart from the matrix materials, the fiber should also withstand this condition.
- ❑ Ceramic fibers are the suitable candidates for this type of environment.
- ❑ They usually have high modulus and high strength values and retain them at high temperatures.
- ❑ There are **two** classes of ceramic fibers are commercially available:
 - Oxide fibers based on alumina–silica system
 - Non-oxide fibers, primarily SiC

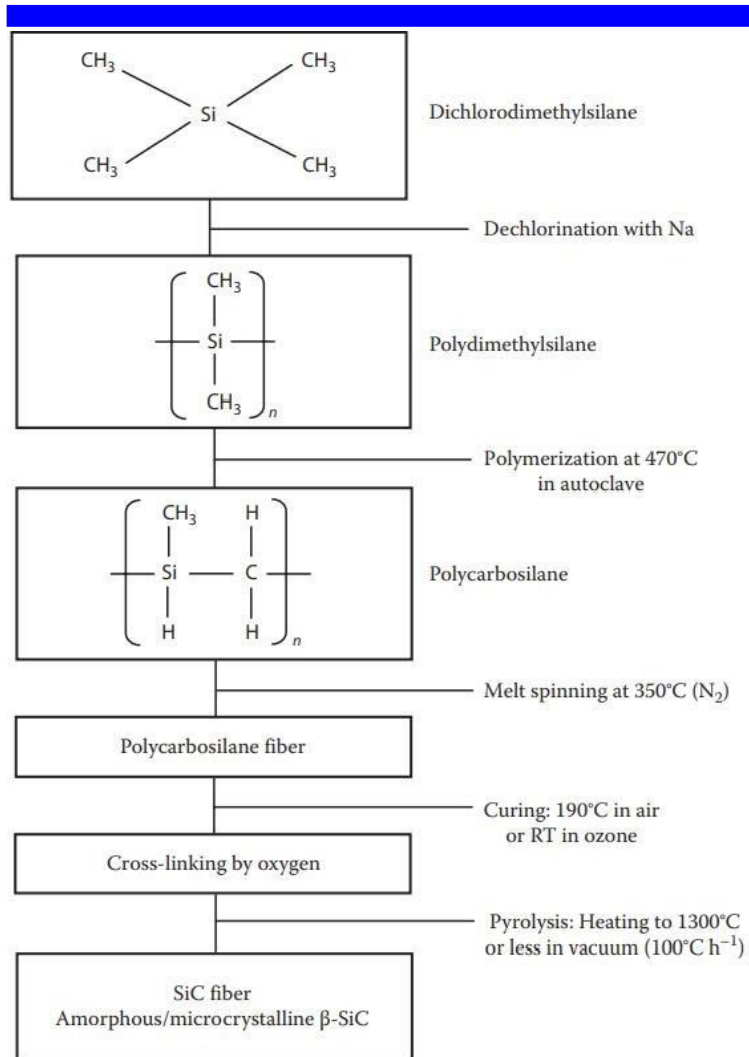
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- ❑ There are **three** commonly used fabrication methods available for the manufacture of high-temperature ceramic fibers as:
 - Sol-gel method
 - Polymer pyrolysis method
 - Chemical vapor deposition (CVD) method
- ❑ The most common approach for producing polycrystalline ceramic fibers is spinning from the chemically derived precursors and heat treating to get the final ceramic fibers.
- ❑ **Sol-gel** processing is generally used for **oxide fibers**, while non-oxide fibers are prepared using **organometallic polymer precursors**.
- ❑ An important characteristic of these ceramic fibers is their ultrafine microstructure with grain sizes sometimes in the nanometer scale.
- ❑ Fine-grain sizes are preferred for better tensile strength but can be detrimental to creep resistance.

Silicon Carbide Fiber

- ❑ Among the non-oxide fibers, SiC fibers are the widely used fibers.
- ❑ The SiC fibers are available in various types, which range from fibers with **very high oxygen content** and **excess carbon to the near-stoichiometric fibers**.
- ❑ These large compositional differences affect the **chemical** and **thermo-mechanical** properties of SiC fibers and their **composites**.
- ❑ The SiC fibers are not commercially used as the oxide fibers, because of high production costs and the need to protect from oxidizing environments.
- ❑ **Polymer pyrolysis** and **CVD** methods are used to produce SiC fibers.
- ❑ SiC fibers with small diameters (50 μm) fibers are produced by CVD.
- ❑ The selection of appropriate polymer is very important for the polymer pyrolysis process.
- ❑ Organosilane polymers are generally used, which contain C and Si atoms on their backbone chain.

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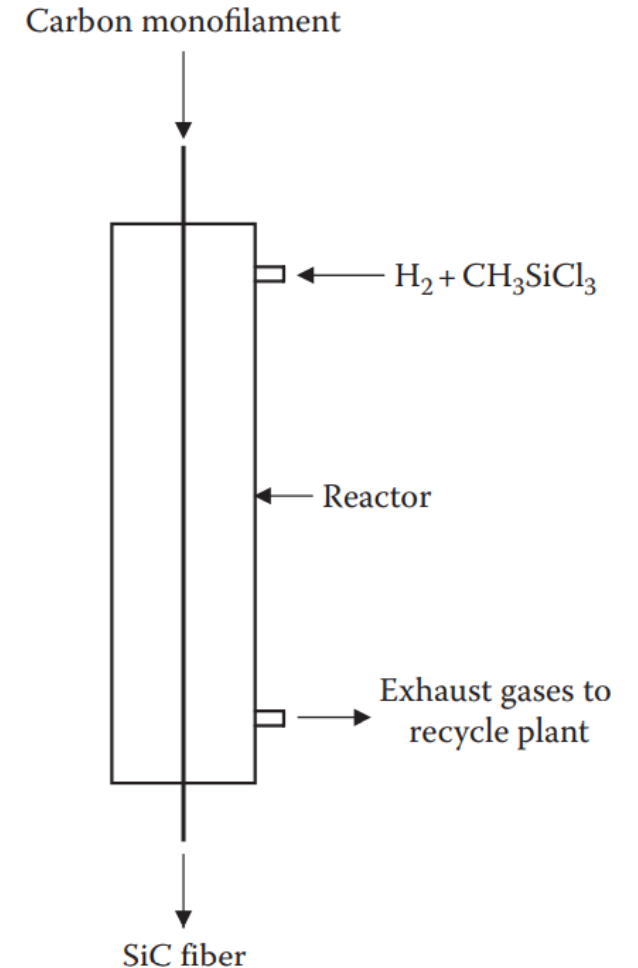
Flow diagram for the preparation of SiC fibers

- ❑ Molecular weight, yield, and purity are important parameters to be considered during the selection of polymer.
- ❑ Polycarbosilane is an ideal polymer for the preparation of SiC.
- ❑ The production of SiC fiber from polycarbosilane is almost similar to the production of carbon fiber.
- ❑ The precursor fiber is produced from the organic polymer by melt spinning.
- ❑ It is then stabilized by heating in air at 190 °C.
- ❑ After the stabilization, it is pyrolyzed at 1000 °C under N₂ atmosphere to form SiC fiber.
- ❑ This fiber is further heated to 1200 °C in N₂ under stretch for better crystallization.



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- ❑ In another method, the oxide-based impurities are allowed to decompose at high temperatures, and the resulting porous fibers are sintered at very high temperatures to form **dense, oxygen-free**, and nearly **stoichiometric** SiC fibers.
- ❑ To accelerate densification, sintering aids such as **aluminum** and **boron** are introduced in the polymer.
- ❑ Although the grain size of these sintered the fibers is larger than the pyrolyzed fibers, it is beneficial for improved creep resistance and thermal conductivity.
- ❑ Stoichiometric SiC fibers with better creep resistance can also be produced by **CVD route**.
- ❑ A substrate fiber is passed through a chamber, where the gases required for the formation of SiC are present with the help of Trichloromethyl silane gas and undergoes reduction reaction in presence of H_2 at high temperature.
- ❑ Mercury seals are used at both the ends of reaction chamber, which act as contact electrodes for the fiber heating.
- ❑ By controlling the current and frequency, it can be heated the filament to a particular temperature.



Schematic for the preparation of SiC fibers by CVD process

Alumina Based Fibers

- ☐ There are some applications where the component is exposed to oxidizing atmosphere at a temperature of above 1400 °C.
 - ☐ Oxide fibers with high melting points are more suitable for these kinds of applications.
 - ☐ Among the oxide fibers, α -alumina fiber is widely used because of its good refractory properties.
 - ☐ Other fibers are made with alumina and varying amounts of silica.
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- ☐ These alumina-based fibers are mainly produced by the **sol-gel process**.
 - ☐ In this process, precursor materials are reacted to form a sol, which is then polymerized into an inorganic polymeric gel.
 - ☐ The main advantages of this process are compositional and microstructure control, wide variety of shapes, and low processing temperatures.
 - ☐ Sol-gel processing involves the formation of sol and gel.
 - ☐ Sol is a **colloid**, in which fine solid particles are dispersed in a liquid.
-
- ☐ The sol is reasonably stable for long time because of very fine nature of solid particles in the sol.
 - ☐ The sol can be converted into gel by evaporation of liquid or by introducing a coagulating liquid.
 - ☐ The gel is an interconnected network of solid particles in a liquid medium.
 - ☐ Fibers can be prepared either from the sol or gel by wet-/dry-spinning process.

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- ☐ Metallo-organic and inorganic compounds are used to prepare the sol.
- ☐ For example, aluminum isopropoxide or aluminum secondary butoxide is used as a precursor for the alumina fiber.
- ☐ The metal alkoxide precursors used in the sol–gel process give better homogeneity and high-purity metal oxide products.
- ☐ However, the alkoxides are highly moisture sensitive and expensive.
- ☐ Chloride and nitrate salts of aluminum can also be used.
- ☐ Aluminum alkoxides form sol on hydrolysis reaction in the presence of acid/base catalyst.
- ☐ To form sol from inorganic salts, the salts are first dissolved in water and then small quantity of base solution is introduced so that very fine precipitates of the respective hydroxides are formed.
- ☐ Short fibers are produced from the sol by dry spinning.
- ☐ Continuous fibers are usually produced from the gel by dry spinning.
- ☐ A large volume of volatile materials are going out during the conversion from gel to oxide fiber.
- ☐ Hence, a careful control of temperature is very important. Otherwise the fiber will either break or have large amount of porosity.

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- ❑ Another important alumina-based fiber is **mullite fiber**.
- ❑ Mullite has a chemical composition of 72 wt.% Al_2O_3 and 28 wt.% SiO_2 . With this composition, mullite crystallizes before the formation of α -alumina.
- ❑ Sometimes a small amount of boria is also added to this composition.
- ❑ This boria addition lowers the mullite formation temperature and helps in sintering; hence, the strength of the fiber is increased.
- ❑ Although boria addition improves the room temperature mechanical properties, the high-temperature properties are affected due to the evaporation of boron compounds above 1100°C .
- ❑ The fiber also shows poor creep resistance due to the presence of glassy borosilicate intergranular phase.

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- ❑ Apart from SiC fiber, other **non-oxide fibers** such as silicon nitride, boron carbide, and boron nitride are also promising high-temperature fibers.
- ❑ Silicon nitride fibers can be produced by CVD or polymer pyrolysis process, similar to SiC fiber production.
- ❑ The only difference is that the starting chemical compound is different.
- ❑ For the CVD fiber, the reactants are SiCl_4 and NH_3 .
- ❑ In the polymer pyrolysis process, organosilazane polymers containing methyl groups on Si and N are used.
- ❑ It is very difficult to produce 100% Si_3N_4 fiber by polymer pyrolysis, since carbon in the polymer reacts with Si and form SiC.
- ❑ Hence, the fiber is not strictly a Si_3N_4 fiber, but it is a carbonitride fiber.
- ❑ Similar processing methods can also be used for the preparation of **boron carbide** and **boron nitride** fibers.

Applications of Ceramic Fibers

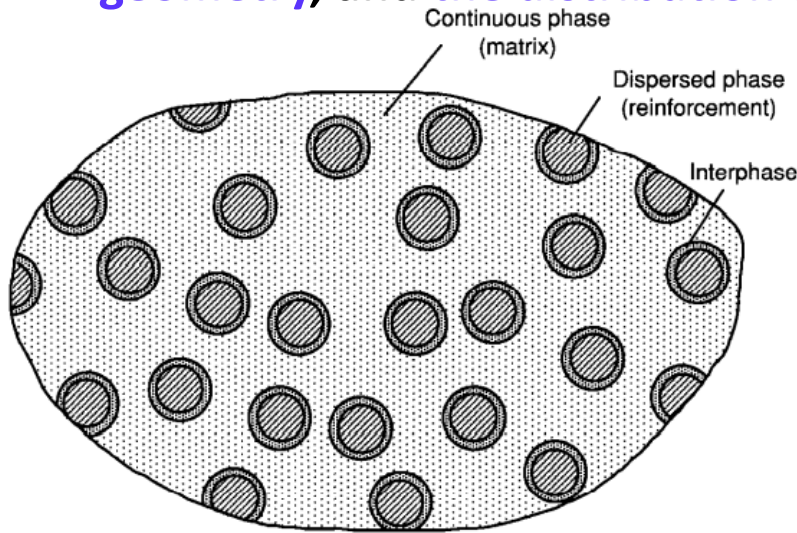
- ❑ **Oxide-based ceramic fibers** are preferred for applications up to 1100 °C in which high-temperature chemical resistance is an important criterion.
- ❑ Although they are very sensitive to surface flaws, oxide ceramic fibers are used in reactive environments such as waste incineration, hot gas filtration, and metal–matrix composites (especially aluminum-based composites).
- ❑ These fibers are also used in fiber form in high-temperature thermal insulation applications, such as sleeves for pipes and electrical cables, high temperature shielding blankets and gasket seals.
- ❑ The cost of most small diameter oxide ceramic fibers is higher than that of glass and carbon fibers but lower than that of SiC fibers.
- ❑ **Non-oxide fibers** such as SiC_f are useful for high-temperature structural applications (>1100 °C).
- ❑ They have better creep resistance and lower grain growth rate compared to oxide fibers, which allow better dimensional stability and strength retention.
- ❑ The SiC fiber can also provide greater thermal and electrical conductivity. However, the non-oxide fibers will oxidize slowly at high temperature under oxygen-containing environment.
- ❑ Silica is one among the most protective scales and it protects SiC from further oxidation.
- ❑ Hence, SiC fiber in general has very good oxidation resistance, and SiC-based fibers are generally preferred for applications that require long term service under mild oxidizing conditions at temperatures higher than possible with oxide fibers.

SiC Whiskers

- ❑ **Whiskers** are mono-crystalline short fibers having very high strength, approaching theoretical strength because of the absence of crystalline imperfections, such as dislocations.
- ❑ However, the spread in the properties is high due to the non-uniform dimensions of the whiskers.
- ❑ The diameter of the whiskers varies from less than a micrometer to a few micrometers and the length varies from a few micrometers to a few millimeters.
- ❑ Hence, the aspect ratio varies from 50 to 10,000.
- ❑ The handling and alignment of whiskers in a matrix are difficult because of their fine nature.
- ❑ SiC whiskers were initially produced from **rice husks**.
- ❑ Rice husks are the waste by-products obtained during polishing of rice grains.
- ❑ In the rice husk, very fine silica particles are embedded in the cellulose network.
- ❑ Rice husks are heated at 700 °C with inert atmospheric conditions to decompose organic materials.
- ❑ After this coking treatment, the residue contains only silica and carbon.
- ❑ This residue is taken in a graphite crucible and then heated to 1500 – 1600 °C.
- ❑ At this high temperature, the carbon reacts with silica and forms SiC whiskers as well as powders.
- ❑ Some residual carbon also remain with SiC and this can be removed by heating at 700 °C under oxidizing atmosphere.
- ❑ SiC whiskers are separated from the particles by dispersing in a liquid with some surface active agents.

Composite Materials – Introduction

- ❑ A structural composite is a material system consisting of two or more phases on a macroscopic scale, whose mechanical performance and properties are designed to be superior to those of the constituent materials acting independently.
- ❑ One of the phases is usually discontinuous, stiffer, and stronger and is called the **reinforcement**, whereas the less stiff and weaker phase is continuous and is called the **matrix**.
- ❑ Sometimes, because of chemical interactions or other processing effects, an additional distinct phase called an **interphase** exists between the reinforcement and the matrix.
- ❑ The properties of a composite material depend on the **properties of the constituents, their geometry, and the distribution of the phases.**



Phases of a composite material

- ❑ One of the most important parameters is the **volume (or weight) fraction of reinforcement** or fiber volume ratio.
- ❑ The distribution of the reinforcement determines the **homogeneity** or uniformity of the material system.
- ❑ The more non-uniform the reinforcement distribution, the more heterogeneous the material, and the higher the scatter in properties and the probability of failure in the weakest areas.
- ❑ The geometry and orientation of the reinforcement affect the anisotropy of the system.

Role of the Phases

- ❑ The phases of the composite system play different roles, which depend on the **type** and **application** of the composite material.
- ❑ In the case of low- to medium-performance composite materials, the **reinforcement**, usually in the form of short fibers or particles, may provide some stiffening but only limited strengthening of the material.
- ❑ The **matrix** is the main load-bearing constituent governing the mechanical properties of material.
- ❑ In case of high-performance structural composites, the normally continuous fiber reinforcement is the backbone of the material, which determines its stiffness and strength in the fiber direction.
- ❑ The matrix phase provides protection for the sensitive fibers, bonding, support, and local stress transfer from one fiber to another.
- ❑ The **interphase**, although small in dimensions, can play an important role in controlling the failure mechanisms, failure propagation, fracture toughness and the overall stress-strain behavior to failure of the material.

History of Composites

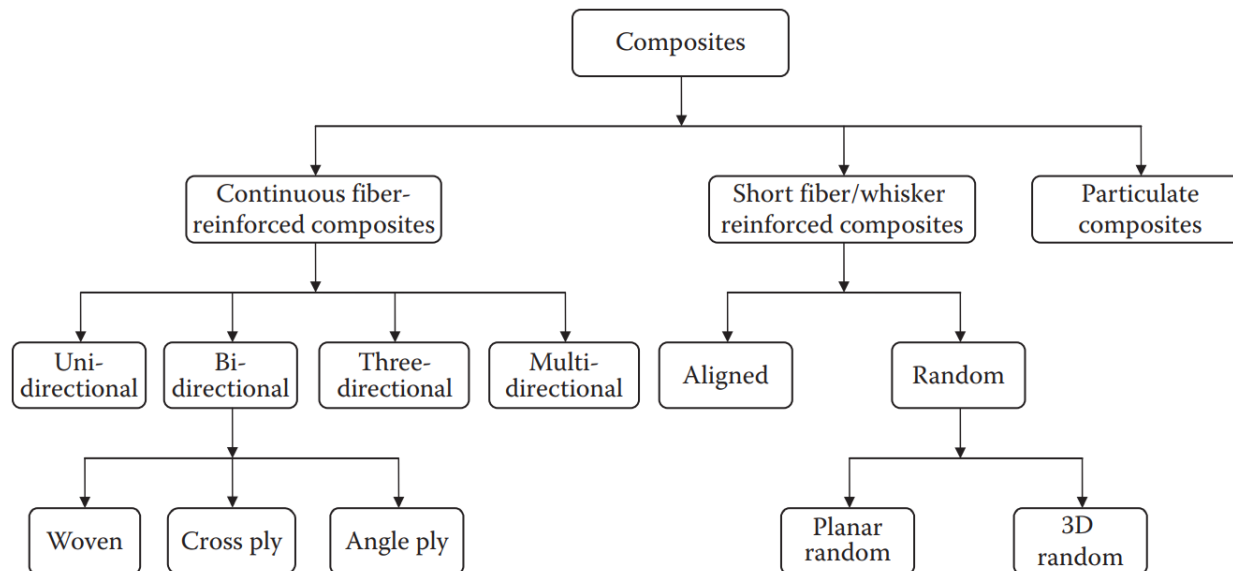
- ☐ Israelites made bricks using clay and plant straw, which are the earliest examples for the man-made composites.
- ☐ The Samurais of Japan made swords using laminated metals during the fifteenth century.
- ☐ Concrete, filled rubber, and phenolic resins were developed during the early twentieth century.
- ☐ The development of a process to manufacture glass fibers has led to the development of composites during the Second World War.
- ☐ The combination of glass fiber and plastics resulted in an incredibly strong material called FRPs. This material is used for making radomes of aircrafts during the early stages of development.
- ☐ The military applications of polymer matrix composites (PMCs) during the Second World War led to large-scale commercial exploitation after the war, especially in the marine industry, during the late 1940s and early 1950s.
- ☐ The first commercial boat hull (watertight body) was introduced in 1946.

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- ☐ The rapid growth in composite science and technology happened during the 1950s in the United States and Europe.
- ☐ The composites industry began to mature in 1970s. During this period DuPont introduced the aramid fiber in the name of Kevlar. Carbon fiber production also started during this time. Many high-performance composites have been produced with these fibers.
- ☐ At present, the aircraft, automobile, marine, sports, electronic, chemical, and medical industries are quite dependent on FRPs.
- ☐ The major concern of the today's world is energy conservation. The operating efficiency of any machinery can be increased when the light materials are used.
- ☐ At present, wind energy is one of the main sources of energy in many countries. Huge windmill blades are being made from polymer composites.
- ☐ There is no doubt that the composites will continue to play a major role in the modern world for energy conservation/generation.

Classification of Composites Based on Dispersed Phase

- ❑ Composites can be broadly classified into **natural composites** and **synthetic composites**.
- ❑ Some of the examples of **natural composites** are wood, bone, etc. Wood is a composite made of strong and flexible cellulose fibers in lignin (complex organic polymers) matrix.
- ❑ The **synthetic composites** are man-made composites.
- ❑ In synthetic composites, there is sufficient flexibility of selecting a suitable reinforcement and a matrix from the wide variety of reinforcements and matrices so that composites with the desired properties can be made.
- ❑ Based on the dispersed phase, the composites can be classified as **fiber reinforced composites (FRCs)** and **particulate composites**.



- ❑ The FRCs can be fabricated as **single layer** or as **multilayer composites**.
- ❑ When the layers in a multilayered composite are made with the same type of fiber reinforcement, then it is called a **laminate**.
- ❑ If two or more types of fiber reinforcements are used in different layers, then it is a **hybrid composite**.

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- ☐ Long or short fibers are used as reinforcements in single-layer composites.
- ☐ Better load transfer is possible with the fiber reinforcements and hence high mechanical properties are realized.
- ☐ However, the properties are not same in all the directions.
- ☐ Usually, the mechanical properties are high along the fiber direction.
- ☐ Isotropic composites can be easily made with short fibers.
- ☐ During processing, the fibers may align in a particular direction in some of the processing methods and then the composites become anisotropic.
- ☐ However, the composites are isotropic in most of the cases when the short fibers are used as the reinforcement.

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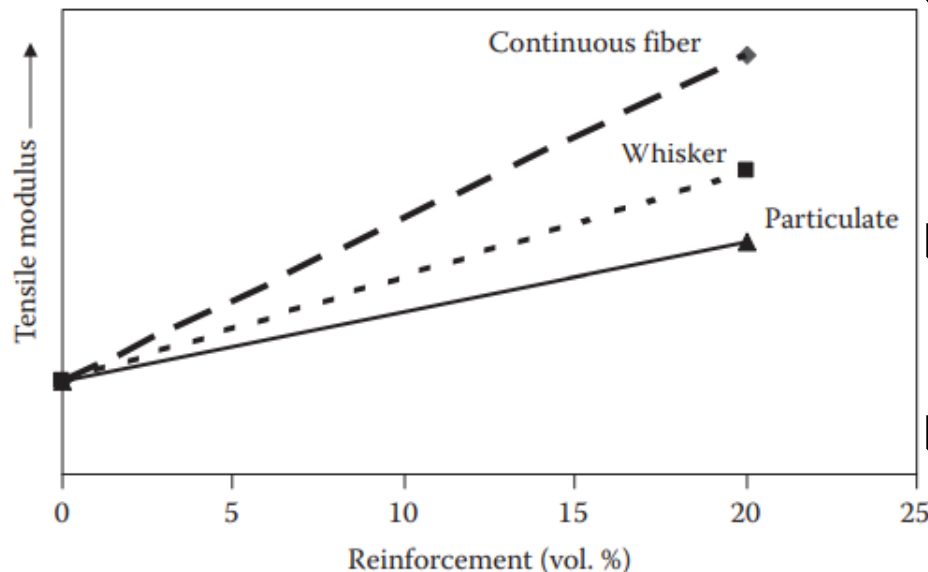
- ❑ **Hybrid composites** are made with two or more types of reinforcements.
- ❑ Commonly they are made with glass/carbon, glass/aramid (heat-resistant), and aramid/carbon fibers.
- ❑ A recent development is glass/natural fiber hybrid composites.
- ❑ Hybrid composites take advantage of the properties or features of each reinforcement type.
- ❑ For example, in the glass/carbon hybrid composite, the low cost of glass fiber and high modulus of carbon fiber are taken into consideration to form the low cost and high modulus composite.
- ❑ Hybrid composites can be made with alternate layers of the two types of fibers, one layer of the second type at middle plane, or by incorporating the second fiber type at selected areas.
- ❑ Similarly, carbon/aramid hybrid composites have increased modulus and compressive strength over an all-aramid composite and increased toughness over an all-carbon composite.

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- ☐ **Whiskers** are single crystal, short fibers with extremely high strength.
- ☐ The diameter of whiskers ranges from 0.1 to a few micrometers.
- ☐ The strength is almost close to the theoretical strength because of the absence of crystalline imperfections such as dislocations.
- ☐ Hence, it is possible to improve the strength of a matrix material significantly by using whiskers.
- ☐ However, most of the whiskers are expensive.
- ☐ The handling of whiskers is a problem because of their fine nature.
- ☐ Alignment in the matrix is another problem.
- ☐ Some of the whiskers are classified as carcinogenic materials.

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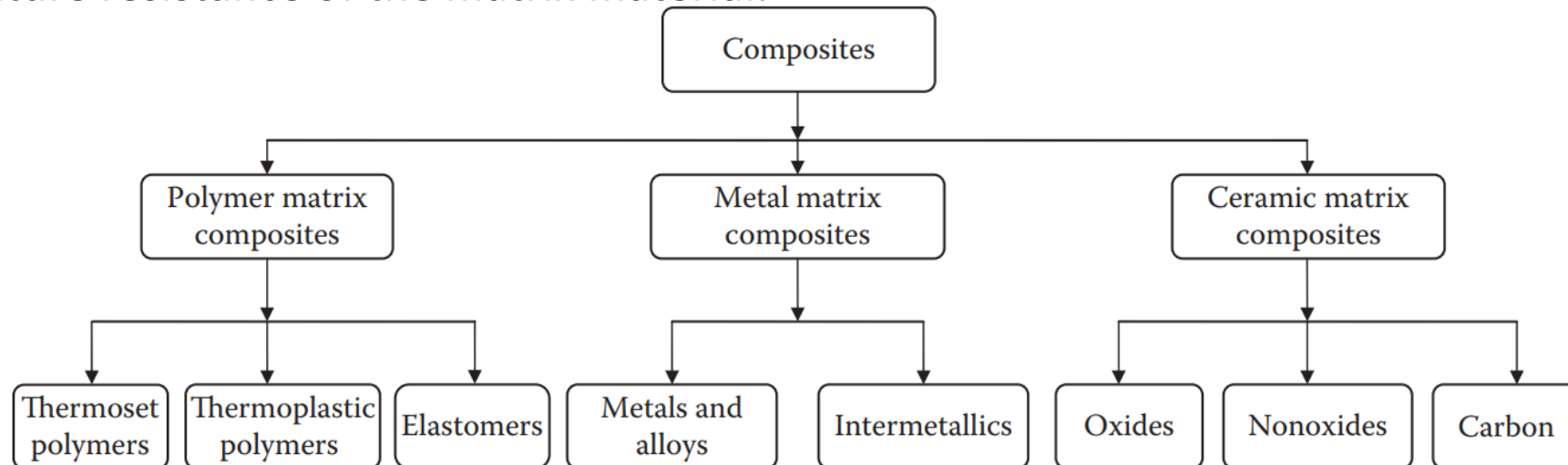
- ❑ **Particulates** are nearly equi-dimensional materials.
- ❑ They will not improve the strength of matrix in most of the particulate composites. Hence, it is not appropriate to call them as reinforcements.
- ❑ There are a few exceptions; very fine particles in a metal matrix can improve the strength by hindering dislocation motion and the tough particles can arrest the crack propagation and improve the strength of ceramics.



- ❑ Particulates are added mainly to modify certain physical properties of the matrix, such as **functional** or **thermal** properties.
- ❑ For example, particulates are added to polymers to reduce the cost of product and to increase the modulus.
- ❑ Figure shows Young's modulus of composites as a function of reinforcement volume fraction for different forms of reinforcement: continuous fiber, whisker, and particulate.

Classification of Composites Based on Matrix Materials

- ❑ Based on the matrix material, the composites are classified into **PMCs**, **MMCs**, and **CMCs**.
- ❑ The three types of composites differ in the **manufacturing method adopted**, **mechanical behaviors**, and **functional characteristics**.
- ❑ Since the matrix materials undergo physical or chemical change, the processing method to be used for making the composites has a direct bearing on the matrix system used.
- ❑ The temperature at which the matrix materials are processed determines the choice of the dispersed phase because the reinforcement should neither undergo any chemical reaction or physical change nor have any change in its properties.
- ❑ The temperature level at which a particular composite can be used is determined by the temperature resistance of the matrix material.



Polymer matrix composites (PMCs)

- ☐ The matrix material can be a **thermoset polymer**, a **thermoplastic polymer**, or an **elastomer** in the PMCs.
- ☐ Thermoset (Polyester, Phenolic, Epoxy resin) polymers are very commonly used because of the processing advantage.
- ☐ Currently thermoplastic (Polyethylene, Polystyrene, Polypropylene) polymers are gaining importance because of their relatively high toughness values and the possibility of post-processing.
- ☐ To meet the specific property requirements, a wide variety of thermoplastic polymers are available.
- ☐ PMCs are suitable for making products, which are used at ambient temperature.
- ☐ There are some special polymers, which can be used up to 250 °C.
- ☐ In any case, PMCs are not suitable for applications where service temperature is more than 350 °C.
- ☐ The success of PMCs, largely as replacement for metals, results from the much improved mechanical properties of the composites compared to the plastic matrix materials.
- ☐ The good mechanical properties of the composites are a consequence of utilizing the high-strength and high-modulus fiber reinforcement.
- ☐ Rubber is an example of elastomer.

Metal matrix composites (MMCs)

- ☐ Metals or metallic alloys are used as the matrix material in MMCs.
- ☐ Mainly lightweight metals and alloys such as, Al, Ti, and their alloys are used.
- ☐ In some special applications, heavy metals such as Cu and Co are used.
- ☐ MMCs can be suitable for applications where the service temperature is up to 1200 °C.
- ☐ At present, short fibers or particulates are mainly used as the dispersed phase because of the processing advantage.
- ☐ Metals and alloys are also reinforced with continuous fibers to improve modulus and strength significantly.
- ☐ A major problem for the MMCs is corrosion.
- ☐ Most of the MMCs are still under development and only a few components are made commercially.
- ☐ Recent interest on MMCs has concentrated on transport applications and consequently the light metal-based MMCs, particularly Al and its alloy-based MMCs, have received the most attention.
- ☐ The relatively low Young's modulus of Al and its alloys can be significantly improved by the incorporation of reinforcement.
- ☐ Metals and alloys inherently have good ductility and toughness.
- ☐ The reinforcements improve Young's modulus but at the expense of ductility.

Ceramic matrix composites (CMCs)

- ❑ Many oxide (Al_2O_3 , MgO) and nonoxide (Si_3N_4 , SiC) ceramic materials are used as matrix materials in CMCs.
- ❑ CMCs are useful for high-temperature applications, where the service temperatures are above 1200°C .
- ❑ These materials are very expensive because most of the CMCs are processed at high temperature.
- ❑ In some cases, there is a need to apply high pressure at that high temperature to get a quality product.
- ❑ Composites of carbon fibers with metallic and ceramic and glass matrix materials have also found applications.
- ❑ Special mention should be made of **carbon/carbon composites**, which can be treated as an important subclass of ceramic matrix composites.
- ❑ Carbon/carbon composites, carbon fiber-reinforced carbon matrix composites.
- ❑ The term 'carbon fibre's includes carbon fibres, carbon nanotubes and micro-carbon coils. Carbon matrices can contain fullerenes such as C_{60} , graphite, and composites of carbon with metals.
- ❑ Selected combinations of carbon fibres with carbon matrices produce high performance carbon/carbon composites.
- ❑ These composites are used in very high-temperature environments of up to 3315°C , and are 20 times stronger and 30% lighter than graphite fibers.

Classification of Composites Based on the Size of Dispersed Phase

- ☐ Based on the size of dispersed phase, the composites (multiscale) can be classified into **macrocomposites**, **microcomposites**, and **nanocomposites**.
- ☐ The size of dispersed phase in the **macrocomposites** is in the millimeter level.
- ☐ The best example for macrocomposite is concrete (made up of cement, sand, and gravel).

- ☐ **Microcomposites** consist of dispersed phase in the micrometer level.
- ☐ Most of the composites currently used are microcomposites.
- ☐ Glass FRPs (GFRPs) and carbon FRPs (CFRPs) are some of the common examples.

- ☐ At least one dimension of the dispersed phase is at the nanometer level in the **nanocomposites**.
- ☐ Carbon nanotube-reinforced plastics and nanoclay reinforced plastics are the typical examples for the nanocomposites.

- ☐ The micro and nanocomposite materials are inhomogeneous at the level of dispersed phase but homogeneous at the macro-level.
- ☐ That means they behave like a single component material at the macro level.

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- ☐ Irrespective of the type of composite material, the **interface** plays a major role in controlling the properties.
- ☐ The constituents of the composites are separated by well-defined interfaces.
- ☐ Interfacial bond strength is very important for the coherent behavior of the composites.
- ☐ Greater bond strength is ensured by the use of coupling agent and/or mechanical interlocking of the constituents.
- ☐ It is not necessary to have better interfacial bond strength always; sometimes a tailored interface is more beneficial than strong interface.
- ☐ A weak interface would be preferred for the energy-absorbing systems.
- ☐ Debonding followed by fiber pullout absorbs a lot of energy during fracture processes in those systems.
- ☐ Crack deflection by debonding is another major contributor for the improved fracture toughness.

Advantages of Composites

- ❑ The prime advantage of composites is their high specific stiffness and strength. Therefore, the component weight can be drastically reduced by using composites.
- ❑ Weight reduction is a major concern in aerospace and automobile sectors. Hence, the composite materials will have a clear edge over the other conventional materials in these sectors.
- ❑ Another advantage of composites is their **energy efficiency**.
- ❑ Most of the composites currently used are polymer-based composites. The polymer composites can be produced at ambient temperature or slightly above ambient temperature and may be a few hundred degrees above ambient temperature. Hence, very little energy is required for the production of composites. The extensive usage of polymer composites in aircrafts and automobiles will reduce the total weight and thus increase the fuel efficiency. **Composites are energy efficient because of these above reasons.**
- ❑ Generally polymers have better weather resistance than metallic materials. In PMCs, only the polymer matrix is exposed to the environment. Hence, the PMCs will also have good weather resistance.

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- ☐ It is possible to align the fibers in any particular direction in a FRC during manufacturing.
- ☐ The final composite will have directional properties and the mechanical properties will be high along the fiber direction.
- ☐ It is possible to make composites with desired properties.
- ☐ A suitable reinforcement, matrix, and processing method can be selected from the wide variety of reinforcements, matrices, and processing methods.
- ☐ A theoretical estimation of composite properties for any type of reinforcement and matrix with different fiber orientation is very easy, because of the availability of numerous software programs (Digimat/Femap/NX Nastran/Fibersim/HyperSizer etc.).

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- ☐ Complex shapes can be made very easily with composites.
- ☐ Processing methods of composites, at least polymer composites are matured enough to produce any complex shape.
- ☐ Most of the polymer composites are processed at ambient temperature or slightly above ambient temperature ($\sim 150^\circ\text{C}$).
- ☐ Hence, the processing equipment and tools need not be very critical.

- ☐ It is possible to produce composites with combination of desired properties.
- ☐ In some of the applications, like automobile body parts, it is necessary to have good mechanical properties with better thermal insulation and aesthetics.
- ☐ An automobile body part made with polymer composites will have all these properties.
- ☐ For the covers of electronic components, it is desirable to have some electrical conductivity to avoid static charge development.
- ☐ By incorporating a conducting material in the polymer, it is possible to produce a composite with some electrical conductivity.

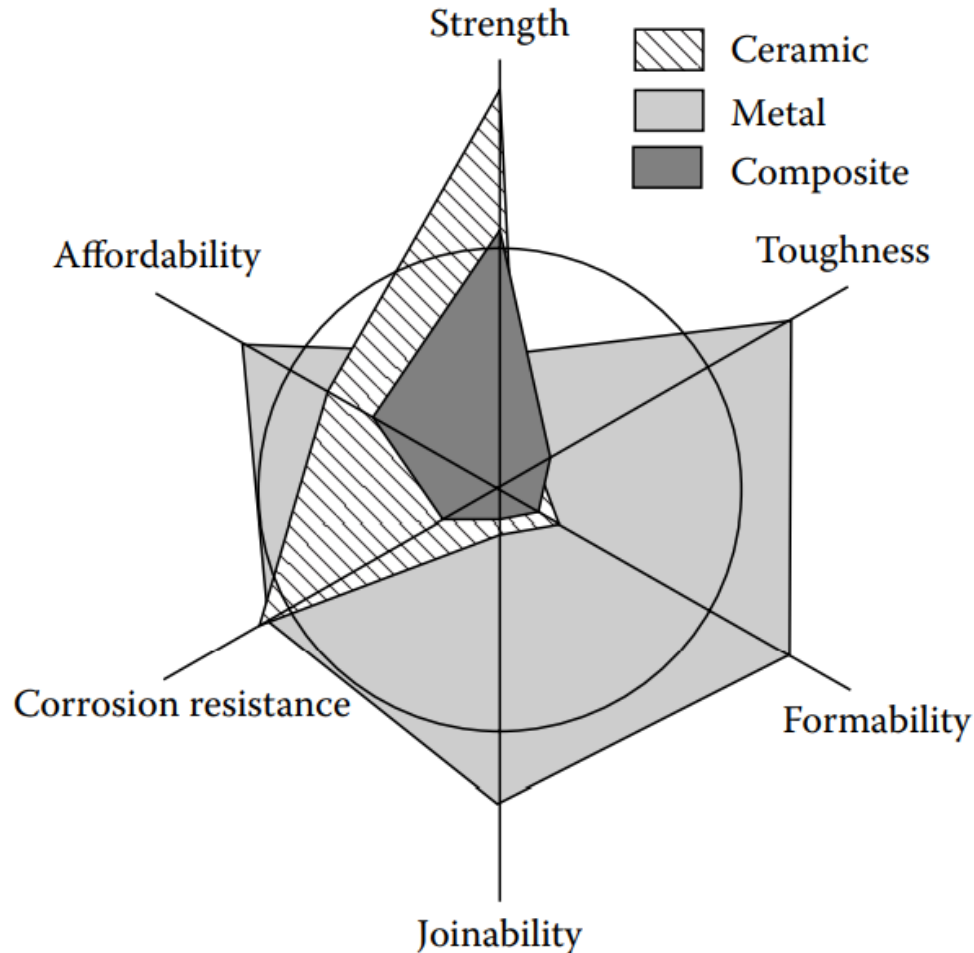
Disadvantages of Composites

- ☐ Composites are more expensive than conventional materials on a cost to cost basis.
- ☐ The composites are approximately 5 and 20 times costlier than aluminum and steel, respectively, on weight basis.
- ☐ However, the performance levels of composites are high.
- ☐ Composites find a place only when the high performance is a prime factor during the selection of material.
- ☐ The chances of formation of defects at the interface are high, since composites are made with entirely different kind of materials.
- ☐ Unless great care is exercised during processing, defects are inevitable.

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- ☐ Most of the FRCs are anisotropic in nature.
- ☐ Accidental high-stress application in the transverse direction to the fibers may damage the product.
- ☐ The production rate of composites is generally low.
- ☐ Composites may not be suitable for high volume production industries like automobile industries.
- ☐ The problem of slow production rate is overcome to some extent with the thermoplastic composites and molding compounds.
- ☐ Currently, FRC components can be made at rates comparable with conventional material components.
- ☐ The selection of suitable material among the conventional metallic materials is very easy because of the availability of widely accepted database on the properties. However, similar database on the properties of different composites is not available. This is another disadvantage for the composites.
- ☐ Recycling is another hurdle for the wide usage of composites. The recycling of composites is difficult compared to the conventional metallic materials.
- ☐ The good weather resistance of polymer matrix is a hindrance during recycling. At present various options are available for the recycling of composites but these options are little expensive.

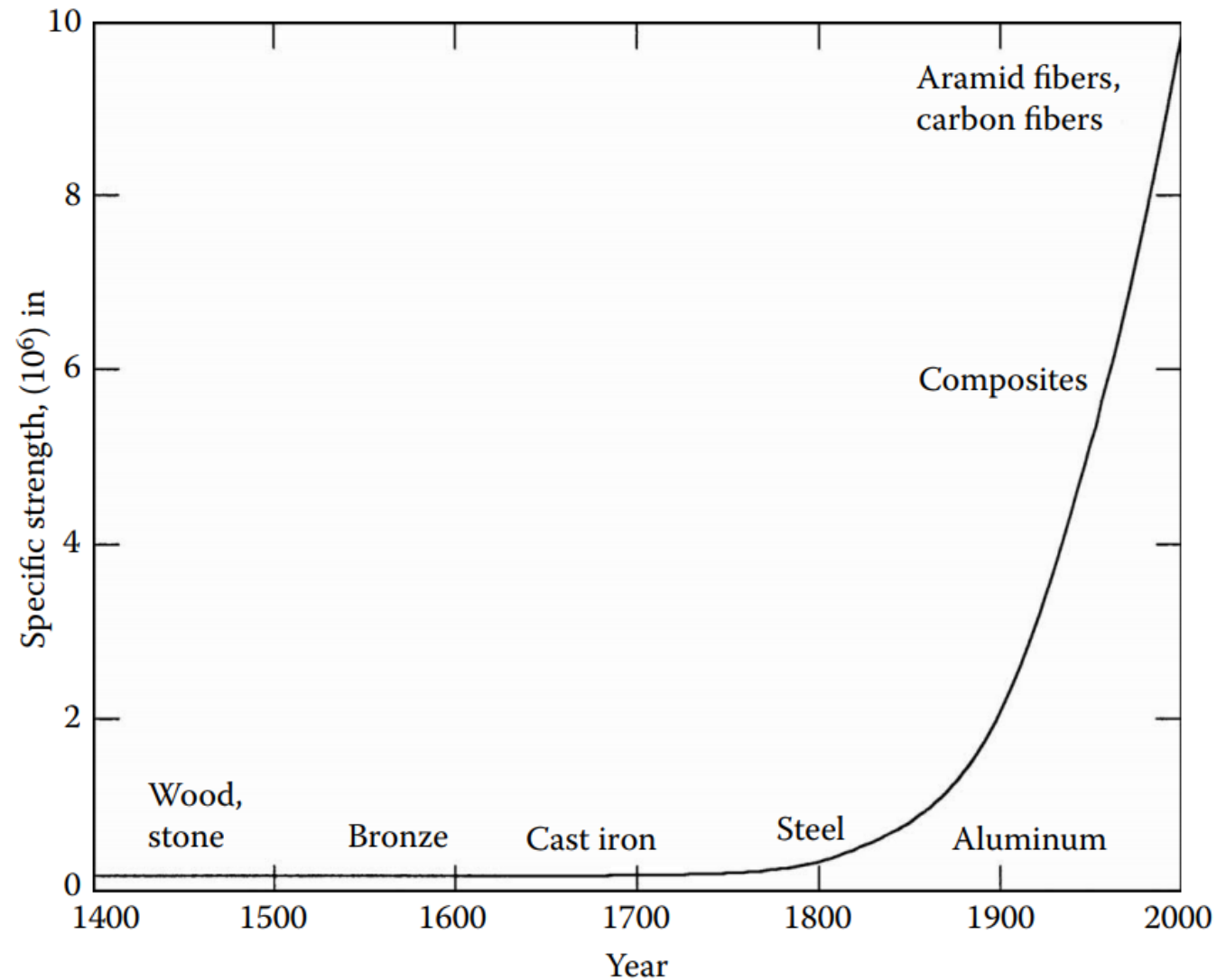
Properties of Composites



Primary material selection parameters for a hypothetical situation for metals, ceramics, and metal–ceramic composites

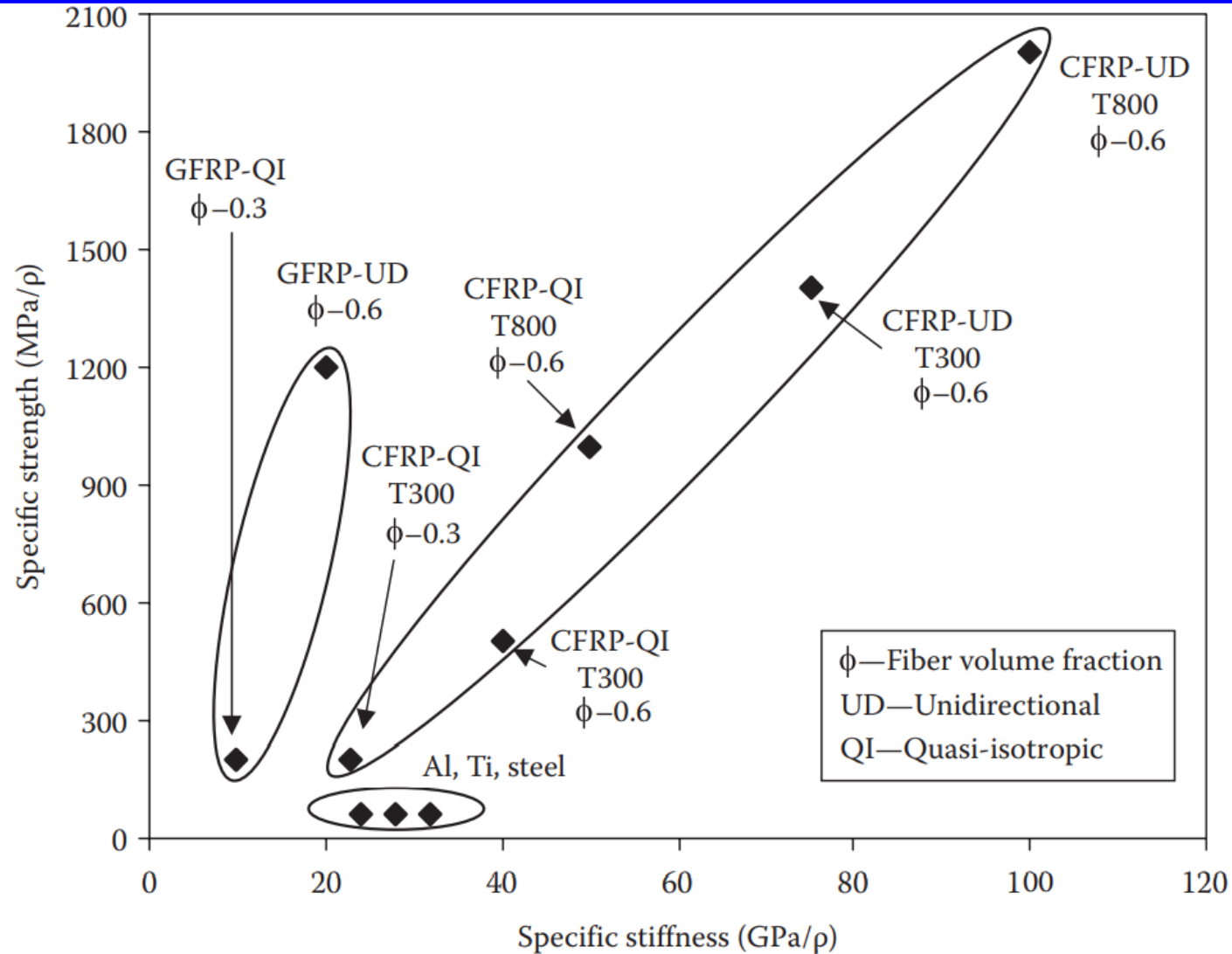
- ❑ Composites do not necessarily give higher performance in all the properties used for material selection.
- ❑ There are **six primary material selection parameters** — strength, toughness, formability, joinability, corrosion resistance, and affordability are plotted.
- ❑ If the values at the circumference are considered as the normalized required property level for a particular application, the shaded areas show values provided by ceramics, metals, and metal–ceramic composites.
- ❑ Clearly, composites show better strength than metals, but lower values for other material selection parameters.

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Specific strength as a function of time of use of materials

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Specific strength and stiffness values of conventional materials and composites

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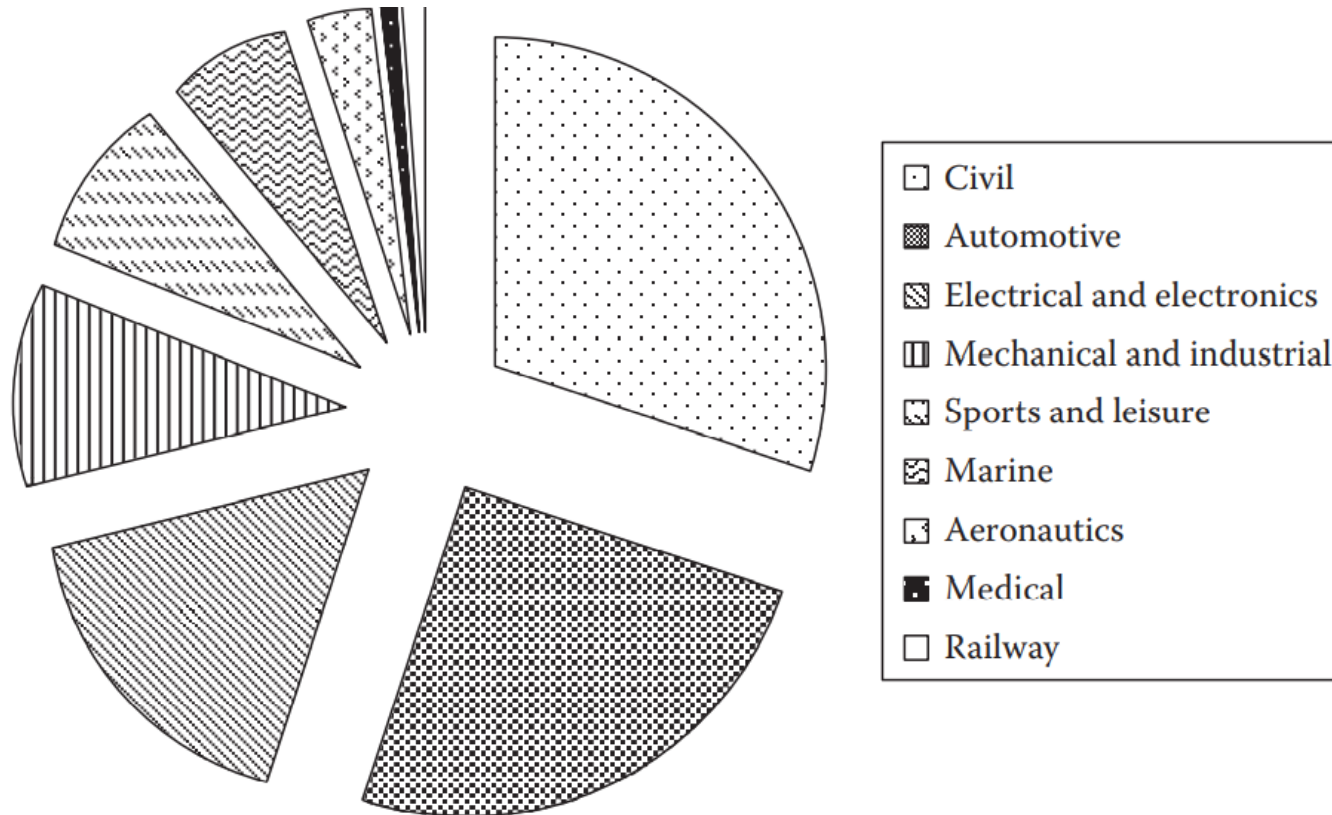
Specific Modulus and Specific Strength of Typical Fibers, Composites, and Bulk Metals

Material Units	Specific gravity ^a	Young's modulus (Msi)	Ultimate strength (ksi)	Specific modulus (Msi-in. ³ /lb)	Specific strength (ksi-in. ³ /lb)
<i>System of Units: USCS</i>					
Graphite fiber	1.8	33.35	299.8	512.9	4610
Aramid fiber	1.4	17.98	200.0	355.5	3959
Glass fiber	2.5	12.33	224.8	136.5	2489
Unidirectional graphite/epoxy	1.6	26.25	217.6	454.1	3764
Unidirectional glass/epoxy	1.8	5.598	154.0	86.09	2368
Cross-ply graphite/epoxy	1.6	13.92	54.10	240.8	935.9
Cross-ply glass/epoxy	1.8	3.420	12.80	52.59	196.8
Quasi-isotropic graphite/epoxy	1.6	10.10	40.10	174.7	693.7
Quasi-isotropic glass/epoxy	1.8	2.750	10.60	42.29	163.0
Steel	7.8	30.00	94.00	106.5	333.6
Aluminum	2.6	10.00	40.00	106.5	425.8

Composite consumption in the world

Composite consumption in the world

	North America	Europe	Asia
Composite consumption (million tons)	3.4	2.1	1.5
Share of global composite consumption (%)	48	30	22



Volume of composites used in different sectors

❑ A rough estimate indicates that there are more than 60,000 composite products available in the market.

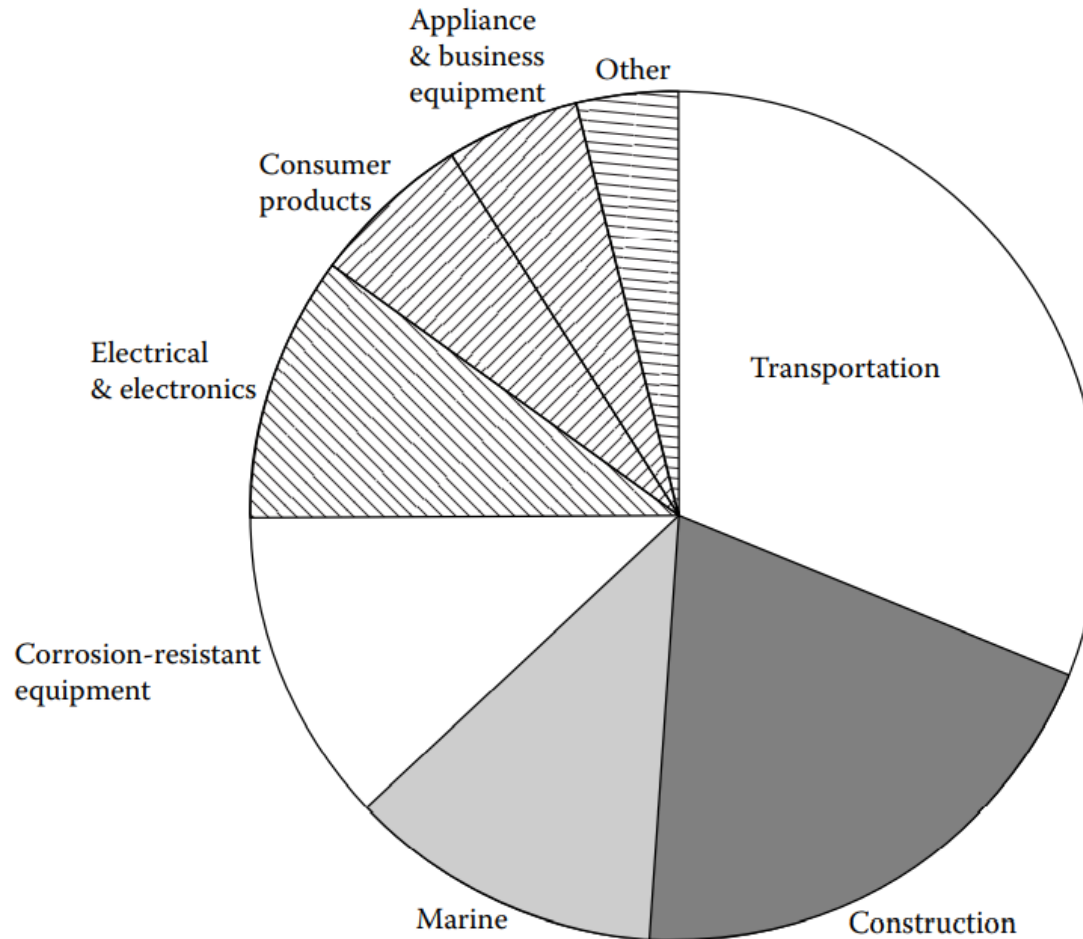
❑ A study made by DuPont predicts that in the year 2030, 50% of the engineering products will be made of composites.

❑ The annual growth rate of composites is 4%–7%.

❑ North America is the major consumer of composites, and Europe and Asia stand second and third, respectively.

USA Composites Shipment

Total shipments in 1995: 3.176 (10⁹)lb [1.441 (10⁹) kgs]



U.S. Composites Shipment in 106 lb, Including Reinforced Thermoset and Thermoplastic Resin Composites, Reinforcements, and Fillers

Markets	1990	1991	1992	1993	1994	1995
Aircraft/aerospace/military	39	38.7	32.3	25.4	24.2	24.0
Appliance/business equipment	153	135.2	143.2	147.5	160.7	166.5
Construction	468	420.0	483.0	530.0	596.9	626.9
Consumer products	165	148.7	162.2	165.7	174.8	183.6
Corrosion-resistant equipment	350	355.0	332.3	352.0	376.3	394.6
Electrical/electronic	241	231.1	260.0	274.9	299.3	315.1
Marine	375	275.0	304.4	319.3	363.5	375.1
Transportation	705	682.2	750.0	822.1	945.6	984.0
Other	79	73.8	83.4	89.3	101.8	106.6
TOTAL	2575	2360	2551	2726	3043.1	3176.4

Approximate shipments of polymer based composites in 1995



Applications of Composites

- ☐ Applications of composites abound and continue to expand.
- ☐ They include aerospace, aircraft, automotive, marine, energy, infrastructure, armor, biomedical, and recreational (sports) applications.
- ☐ Aerospace structures, such as space antennae, mirrors, and optical instrumentation, make use of lightweight and extremely stiff graphite composites.
- ☐ A very high degree of dimensional stability under severe environmental conditions can be achieved because these composites can be designed to have nearly zero coefficients of thermal and hygric expansion.
- ☐ The high-stiffness, high-strength, and low-density characteristics make composites highly desirable in primary and secondary structures of both military and civilian aircraft.

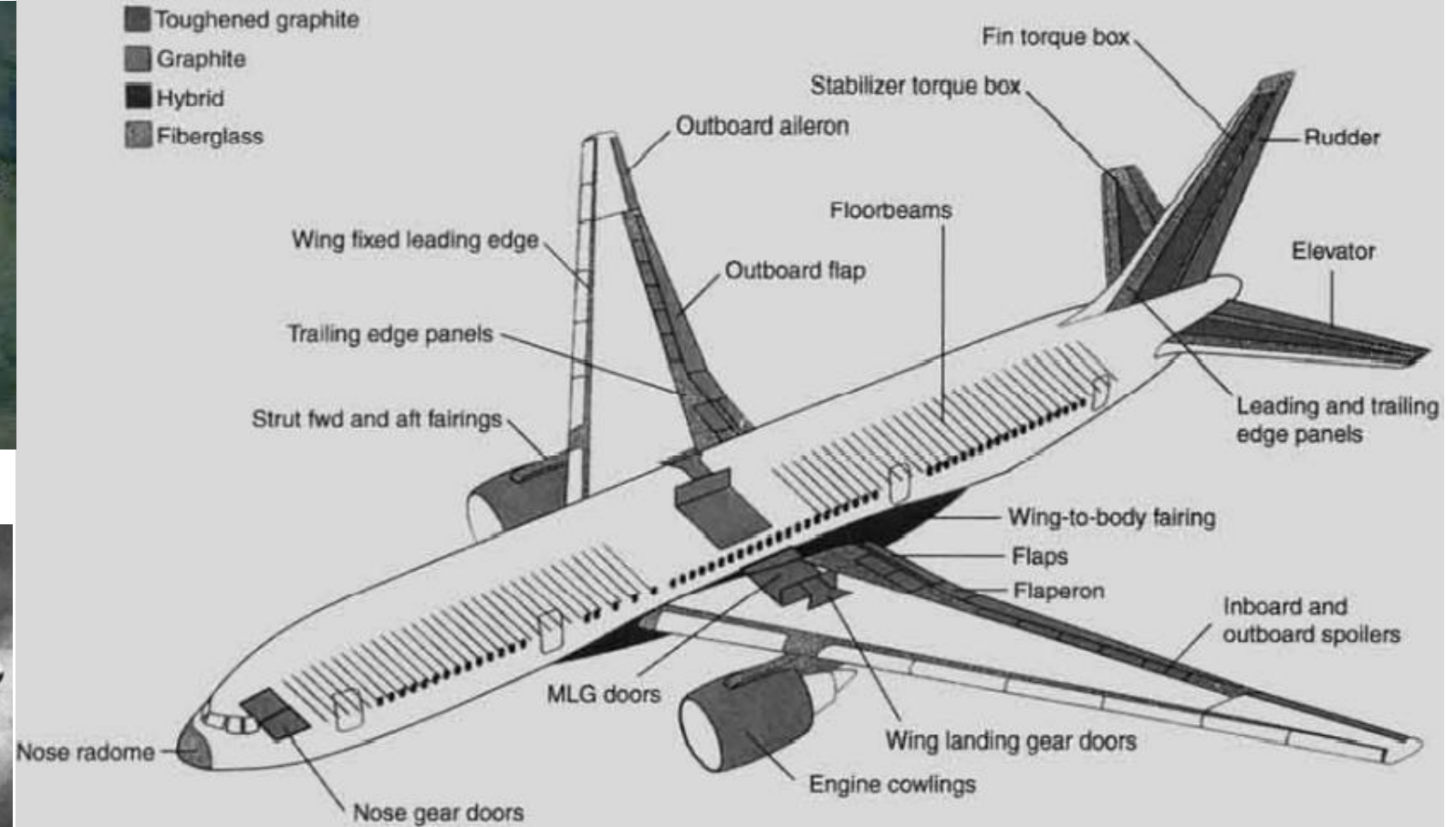
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Boeing 777 commercial aircraft



Boeing 787 "Dreamliner" with most of the fuselage (main body) and wings made of composite materials



Illustrating usage of composite materials in various components of the Boeing 777 aircraft

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Airbus A380 containing a substantial amount of composite materials including glass/epoxy/aluminum



Small aircraft with primary structure made of composite materials



Unmanned reconnaissance aircraft made of composite materials

- ☐ The Airbus A380 also uses a substantial amount of composites, including a hybrid glass/epoxy/aluminum laminate, which combines the advantages and mitigates the disadvantages of metals and composites.
- ☐ A recently certified small aircraft with the primary structure made almost entirely of composite (composite sandwich with glass fabric/epoxy skins and PVC foam core).
- ☐ Small unmanned air vehicles are also made almost entirely of composites.

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B-2 stealth bomber made almost entirely of composite materials



**Solar-powered flying wing
Helios**



Corvette rear leaf spring made of glass/epoxy composite weighing 3.6 kg (8 lb) compared to original steel spring weighing 18.6 kg (41 lb)

- ☐ The stealth characteristics of carbon/epoxy composites are highly desirable in military aircraft, such as the B-2 bomber.
- ☐ The solar-powered flying wing Helios, used by NASA for environmental research, was made of carbon and Kevlar fiber composites. It had a wing span of 75 m (246 ft) and weighed only 708 kg (1557 lb).
- ☐ A composite leaf spring, made of glass/epoxy composite and weighing one-fifth of the original steel spring.

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Cobra tram in Zurich, Switzerland, incorporating composite sandwich construction



Royal Danish Navy standard Flex 300 corvette: length, 55 m; displacement, 350 tons; materials, glass/polyester & PVC foam



Royal Swedish Navy Visby class corvette: length, 72 m; displacement, 600 tons; materials, carbon/ vinylester & PVC foam

- ☐ An example of an application to public transportation is the Cobra tram in Zurich.
- ☐ Ship structures incorporate composites in various forms, thick-section glass and carbon fiber composites and sandwich construction.
- ☐ Composite ship structures have many advantages such as insulation, lower manufacturing cost, low maintenance, and lack of corrosion.

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Composite wind turbine blade used for energy production



Composite drilling riser for offshore oil drilling



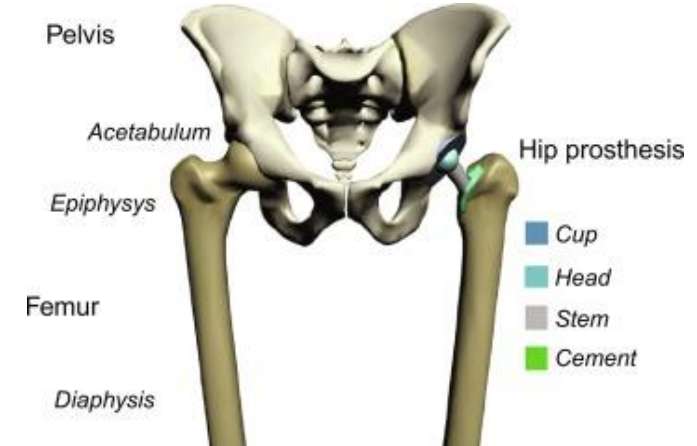
Composite pipe used for transport of drinking water: 80 cm (32 in) diameter glass/polyester pipe

- ☐ In the energy production field, carbon fiber composites have been used in the blades of wind turbine generators that significantly improve power output at a greatly reduced cost.
- ☐ In offshore oil drilling installations, composites are used in drilling risers like the one installed in the field in 2001.
- ☐ An 80 cm (32 in) composite pipeline, made of glass/polyester composite is used for infrastructure application.

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Foot and leg prostheses incorporating carbon/epoxy components



Carbon/polysulfone hip prosthesis components

- ☐ Composite materials also used in biomedical applications include prosthetic devices and artificial limb parts.

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Bicycle frame made of carbon/epoxy composite and weighing 1.36 kg, which is much less than the 5 kg weight of the corresponding steel frame



Footbridge in Aberfeldy, Scotland, using composite decking sections

- ☐ Leisure products include tennis rackets, golf clubs, fishing poles, skis, and bicycles.
- ☐ An example of a composite bicycle frame is shown.
- ☐ An example of a composite bridge is the 114 m (371 ft) long cable-stayed footbridge built in Aberfeldy, Scotland, in 1992.
- ☐ The deck structure rails and A-frame towers are made of glass/polyester, and the cables are Kevlar ropes.