Polymer Composites

❖ What is a composite?

- A composite is a structural material that consists of two or more combined constituents that are combined at a macroscopic level and are not soluble in each other. One constituent is called the *reinforcing phase* and the one in which it is embedded is called the *matrix.*

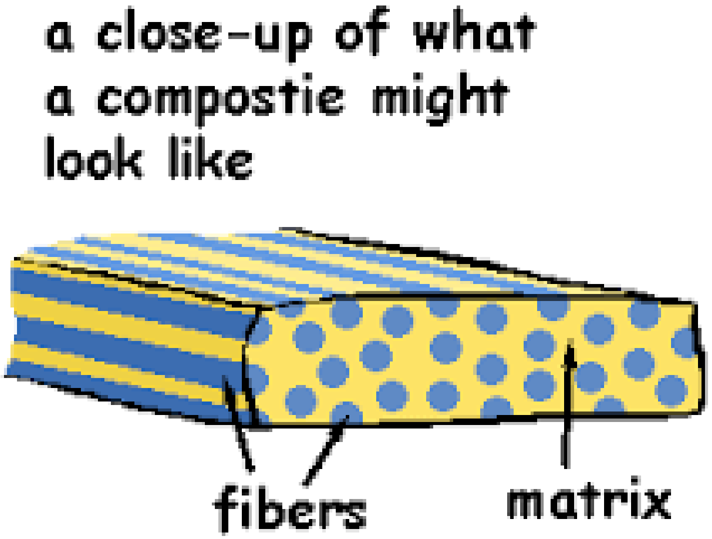
Reinforcing phase

(fibers, particles, flakes)

+

Matrix (Continuous)

Composite



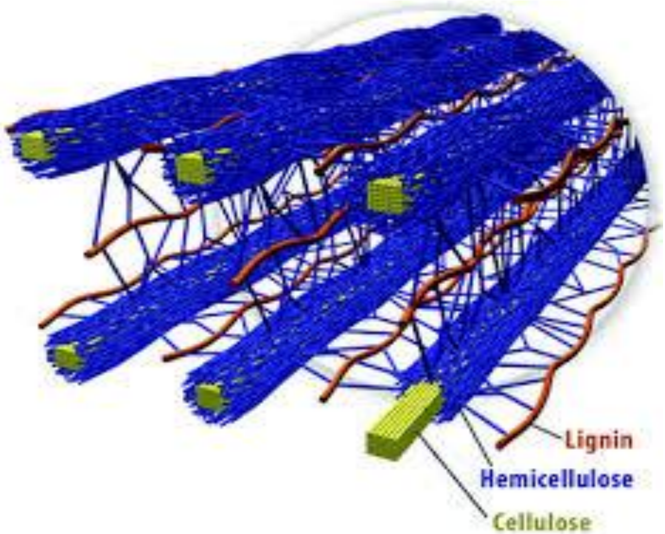
Examples: Concrete reinforced with steel

Epoxy reinforced with graphite

Naturally found composites

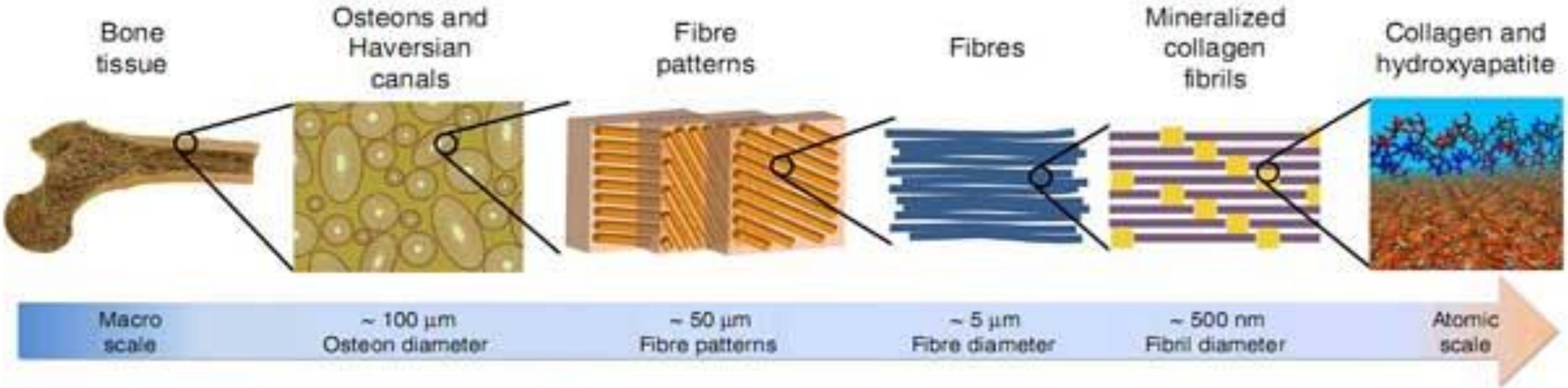
Wood

(Cellulose + Lignin)



Bone

(Hydroxyapatite + Collagen)

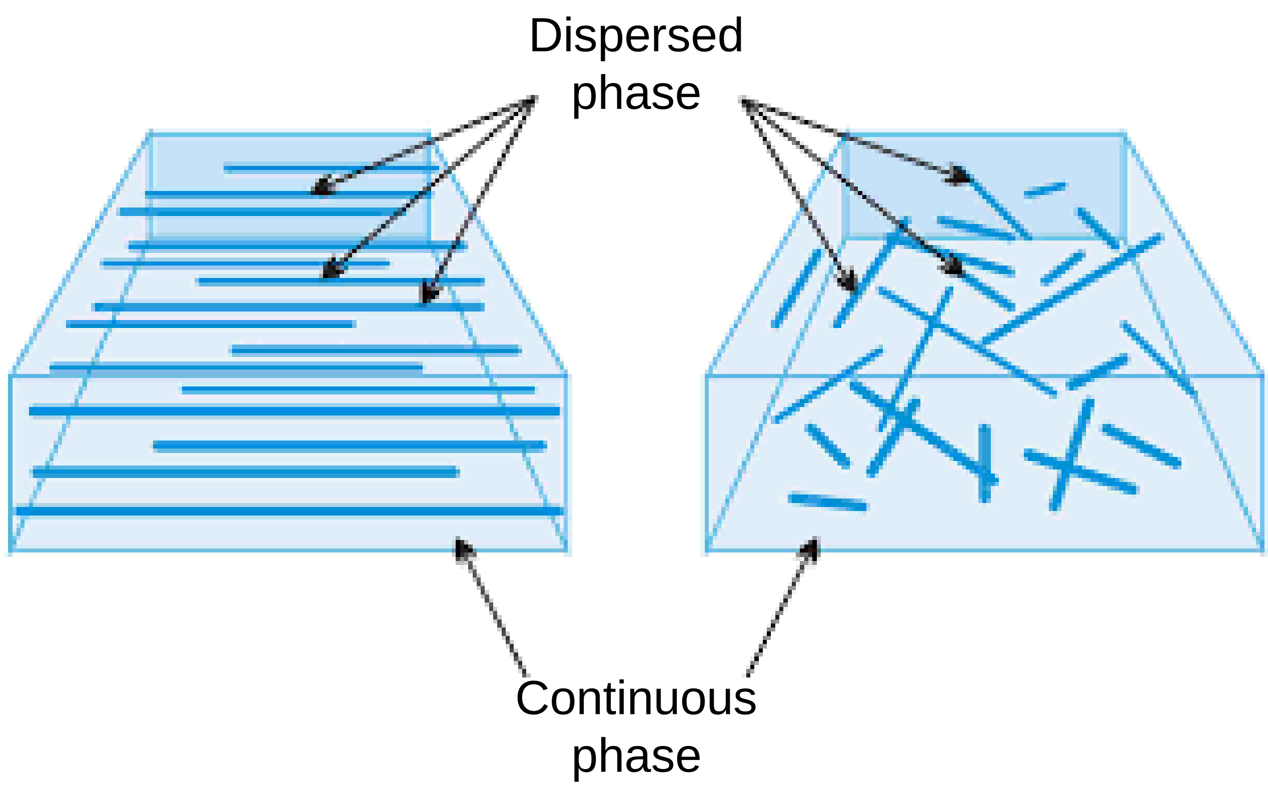


Advanced composites

❖ **Materials having high performance reinforcements of a thin diameter in a matrix material.**

❖ **Examples:**

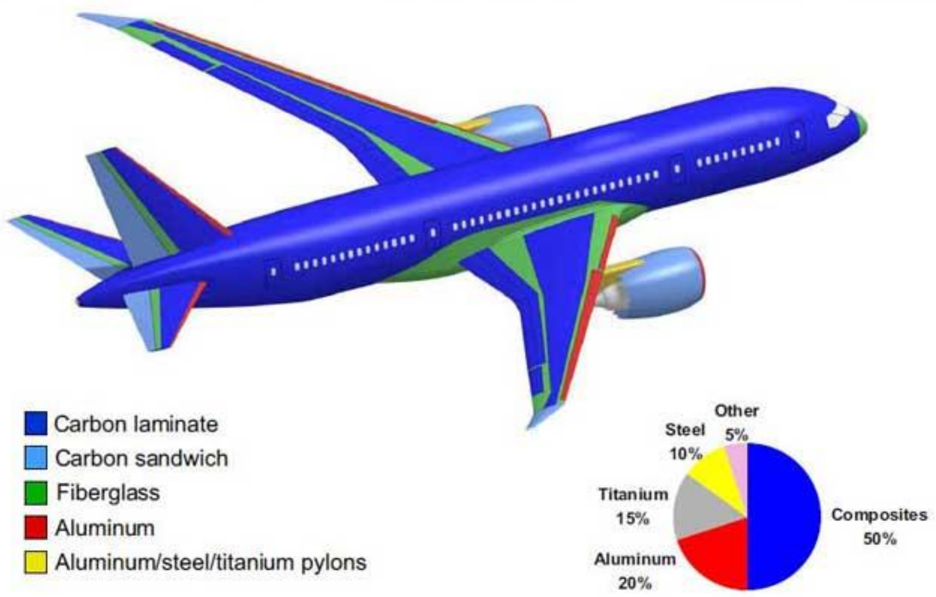
- Graphite/Epoxy
- Kevlar/Epoxy
- Boron/Aluminium



Advantages of composites over metals

- Overall mass of aircraft is lowered without decreasing the strength and stiffness of its components.
- Cost of material is higher but the number of parts in the assembly are reduced.
- Savings in the fuel cost.
- Reduction in 1 lb of mass in an aircraft saves 30 gal of fuel per year.

- Other advantages:
  - Improved strength, fatigue, stiffness, impact resistance, thermal conductivity, corrosion resistance



Mechanical advantage of composite

Axial Deflection,

$$u = \frac{PL}{AE}$$

L = length of the rod

E = Young's modulus of elasticity of the material of the rod

P=Axial Load

Cont.

Mass of the rod, M=ρAL

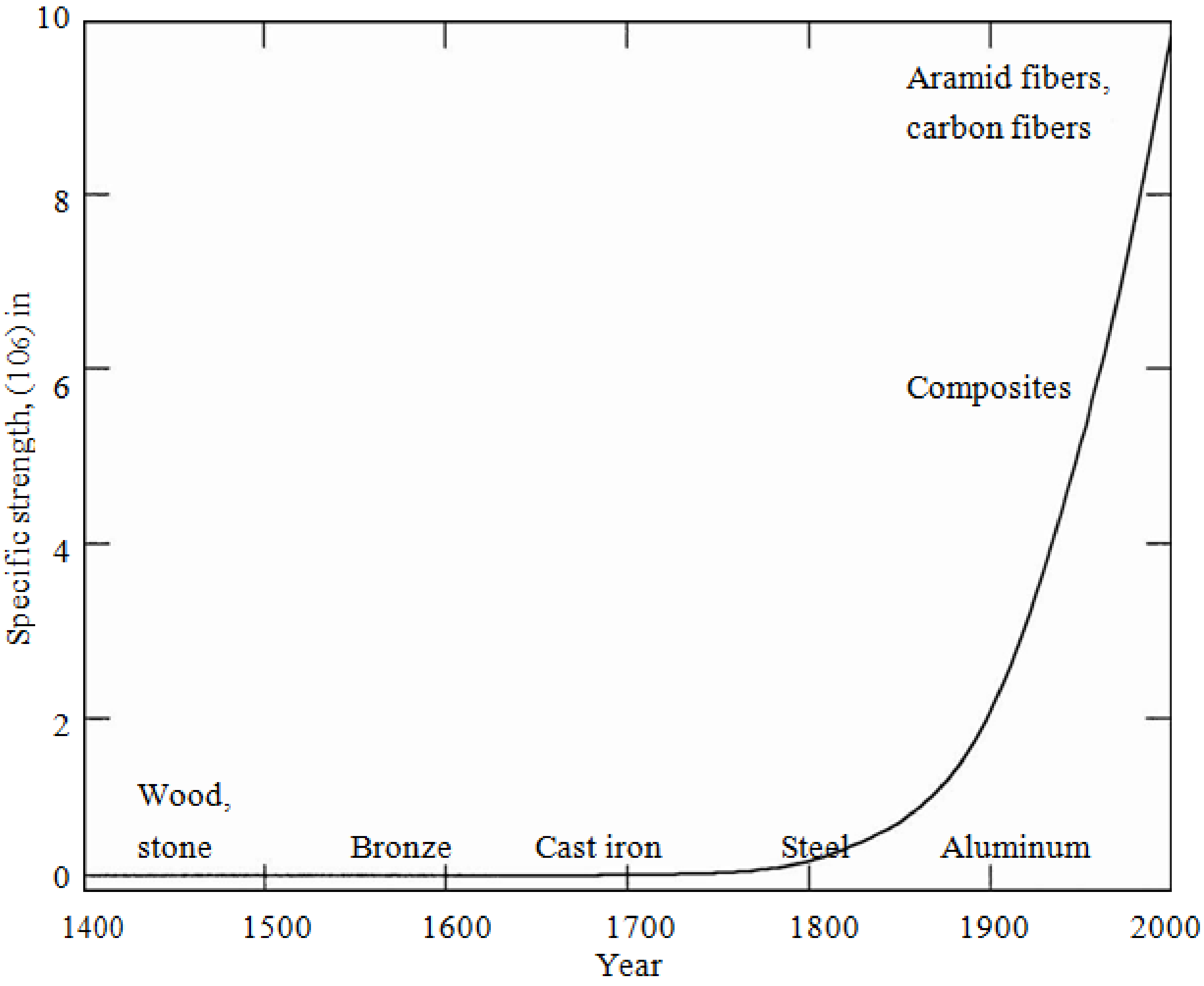
ρ=Density of material of the rod

$$M = \frac{PL^2}{4} \, \frac{1}{(E)/(\rho)}$$

Specific modulus = E/ρ

Specific strength = σ_{ult} / ρ

Specific strength as a function of time of use of materials



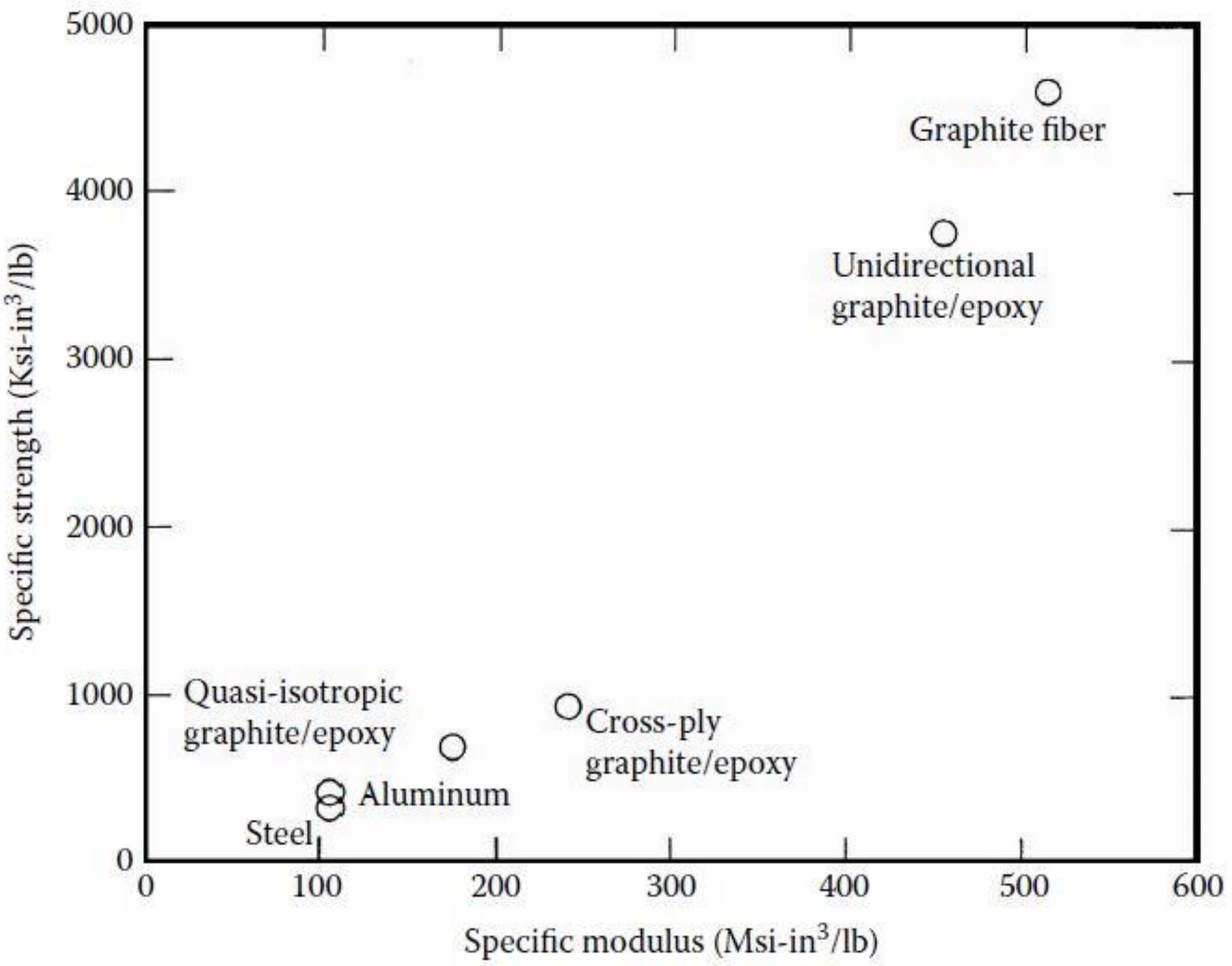
(Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

Contd..

Material units	Specific gravity	Young's modulus (GPa)	Ultimate strength (MPa)	Specific modulus (Gpa-m^3/kg)	Specific strength (Mpa-m^3/kg)
Graphite fiber	1.8	230.00	2067	0.1278	1.148
Aramid fiber	1.4	124.00	1379	0.8857	0.9850
Glass fiber	2.5	85.00	1550	0.0340	0.6200
Unidirectional graphite/epoxy	1.6	181.00	1500	0.1131	0.9377
Unidirectional glass/epoxy	1.8	38.60	1062	0.02144	0.5900
Cross-ply graphite/epoxy	1.6	95.98	373.0	0.06000	0.2331
Cross-ply graphite/epoxy	1.8	23.58	88.25	0.01310	0.0490
Quasi-isotropic graphite/epoxy	1.6	69.64	276.48	0.04353	0.1728
Quasi-isotropic glass/epoxy	1.8	18.96	73.08	0.01053	0.0406
Steel	7.8	206.84	648.1	0.02652	0.08309
Aluminium	2.6	68.95	275.8	0.02652	0.1061

System of units: SI

Specific strength as a function of specific modulus for metals, fibers and composites



Mechanical parameters for measuring relative advantage of composites over metals

Euler buckling formula

$$P_{cr} = \frac{\pi^2 EI}{L^2}$$

P_{cr} = critical buckling load (lb or N)

E = Young's modulus of column (lb/in.^{2} or N/m^2)

I = second moment of area (in.^{4} or m^4)

L = length of beam (in. or m)

Second moment of area

$$I = \frac{\pi d^4}{64}$$

Mass of the rod

$$M = \rho \frac{\pi d^2 L}{4}$$

M = mass of the beam (lb or kg)

ρ = density of beam (lb/in.^{3} or kg/m^3)

d = diameter of beam (in. or m)

Cont.

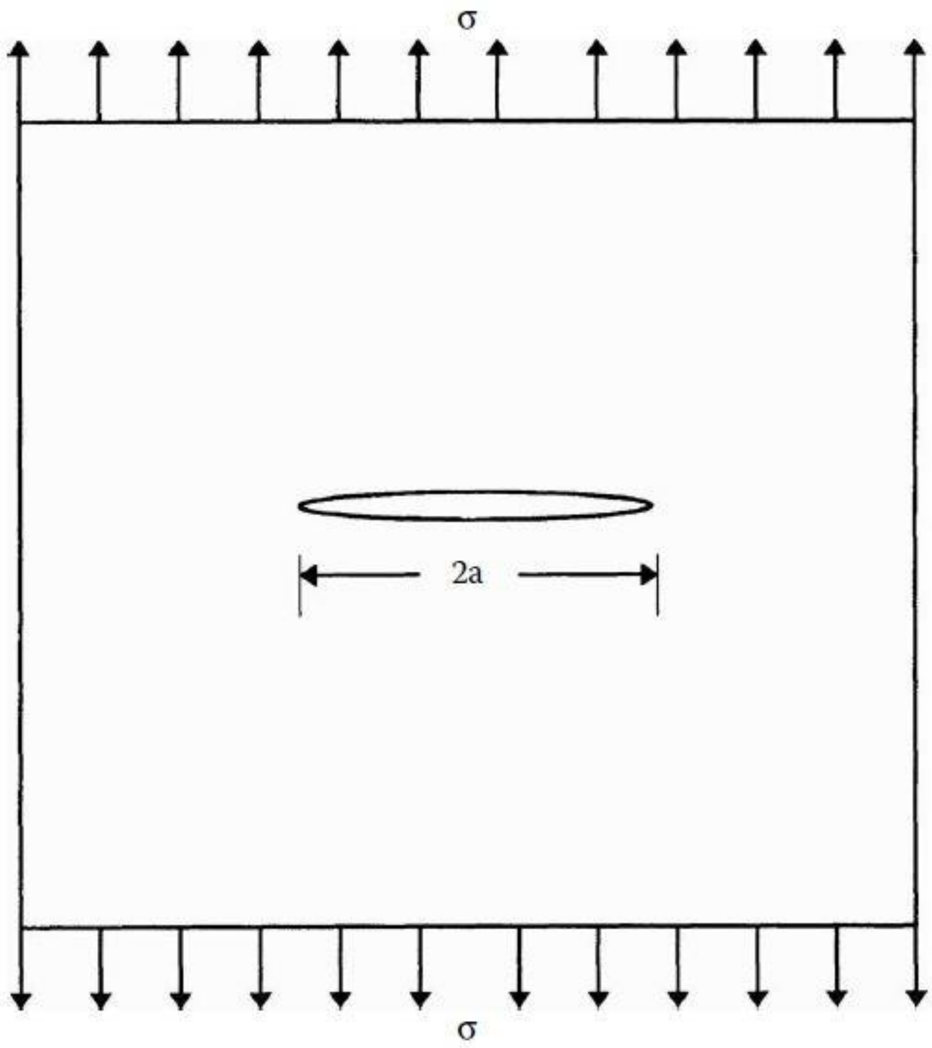
$$M = 2L^2 \frac{\sqrt{Pcr}}{\sqrt{\pi}} \frac{1}{E^{1/2}/\rho}$$

Lightest beam for specified stiffness is the one having highest value of $E^{1/2}/\rho$.

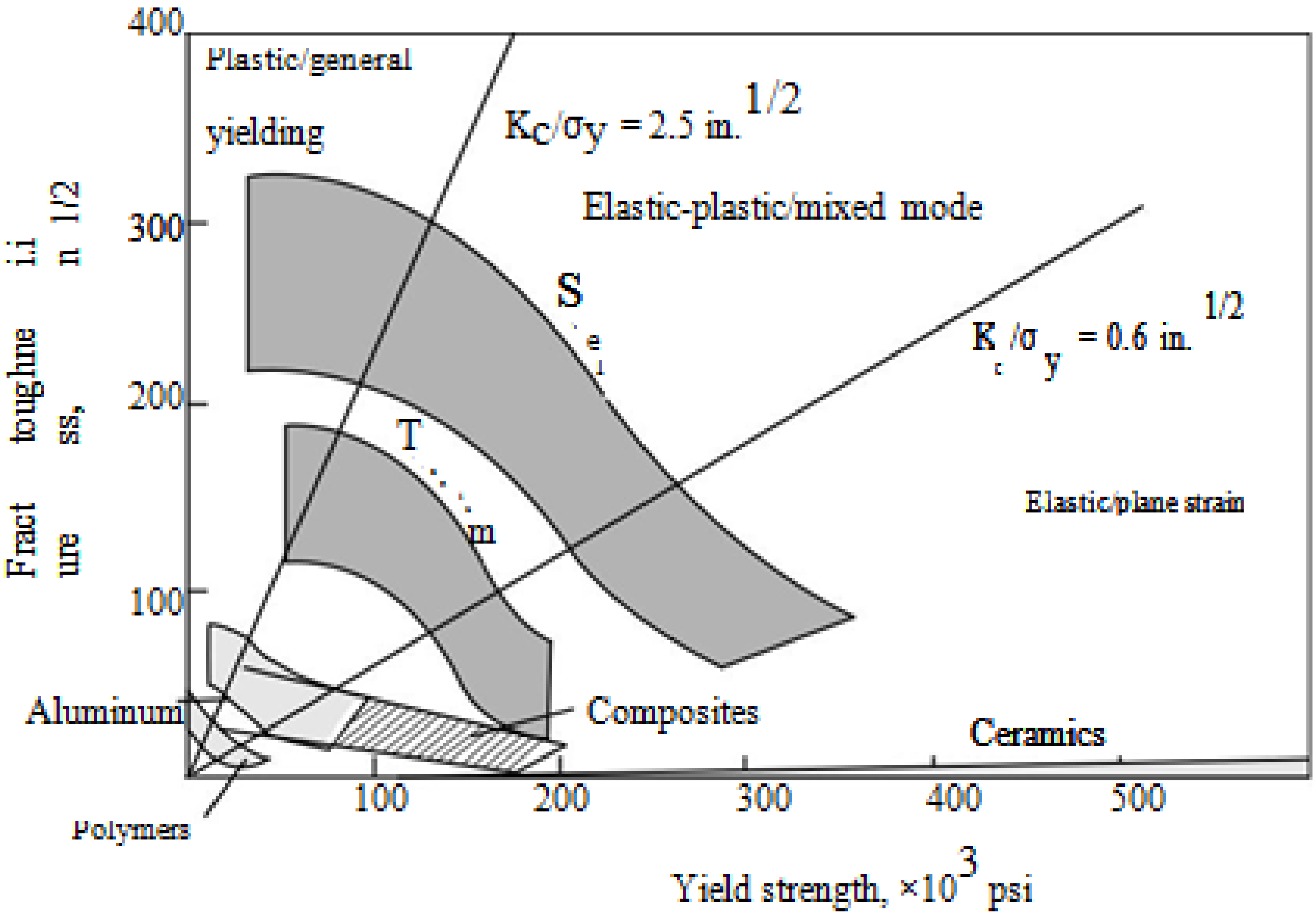
Drawbacks and Limitations in use of composites

- High fabrication cost
- Mechanical characterization of composite is more complex than metal
- Repairing composites is not as simple as that of metals
- As compared to metals, composites do not have high combination of fracture and toughness
- Composites do not necessarily give higher performance in all the properties used for material selection

A uniformly loaded plate with a crack

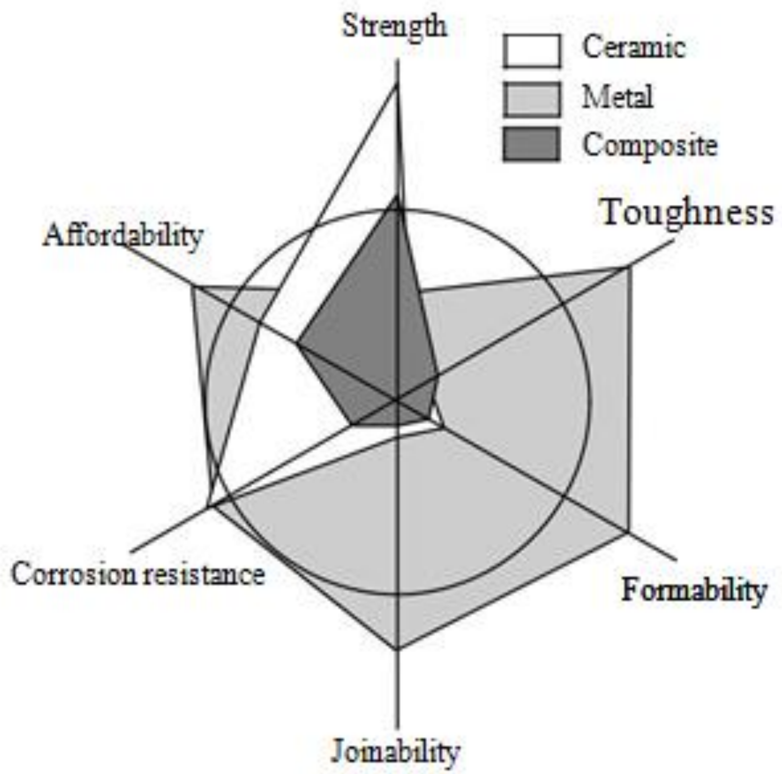


Fracture toughness as a function of yield strength for monolithic metals, ceramics, and metal–ceramic composites



(Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

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



(Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

Specific modulus parameters for typical materials

Material units	Specific gravity	Young's modulus (Msi)	E/ρ (Msi-in.^{3}/lb)	$E^{1/2}/\rho$ (psi$^{1/2}$-in.^{3}/lb)	$E^{1/3}/\rho$ (psi$^{1/3}$-in.^{3}/lb)
Graphite fiber	1.8	33.35	512.8	88,806	4,950
Kevlar fiber	1.4	17.98	355.5	83,836	5,180
Glass fiber	2.5	12.33	136.5	38,878	2,558
Unidirectional graphite/epoxy	1.6	26.25	454.1	88,636	5,141
Unidirectional glass/epoxy	1.8	5.598	86.09	36,384	2,730
Cross-ply graphite/epoxy	1.6	13.92	240.8	64,545	4,162
Cross-ply graphite/epoxy	1.8	3.420	52.59	28,438	2,317
Quasi-isotropic graphite/epoxy	1.6	10.10	174.7	54,980	3,740
Quasi-isotropic glass/epoxy	1.8	2.750	42.29	25,501	2,154
Steel	7.8	30.00	106.5	19,437	1,103
Aluminium	2.6	10.00	106.5	33,666	2,294

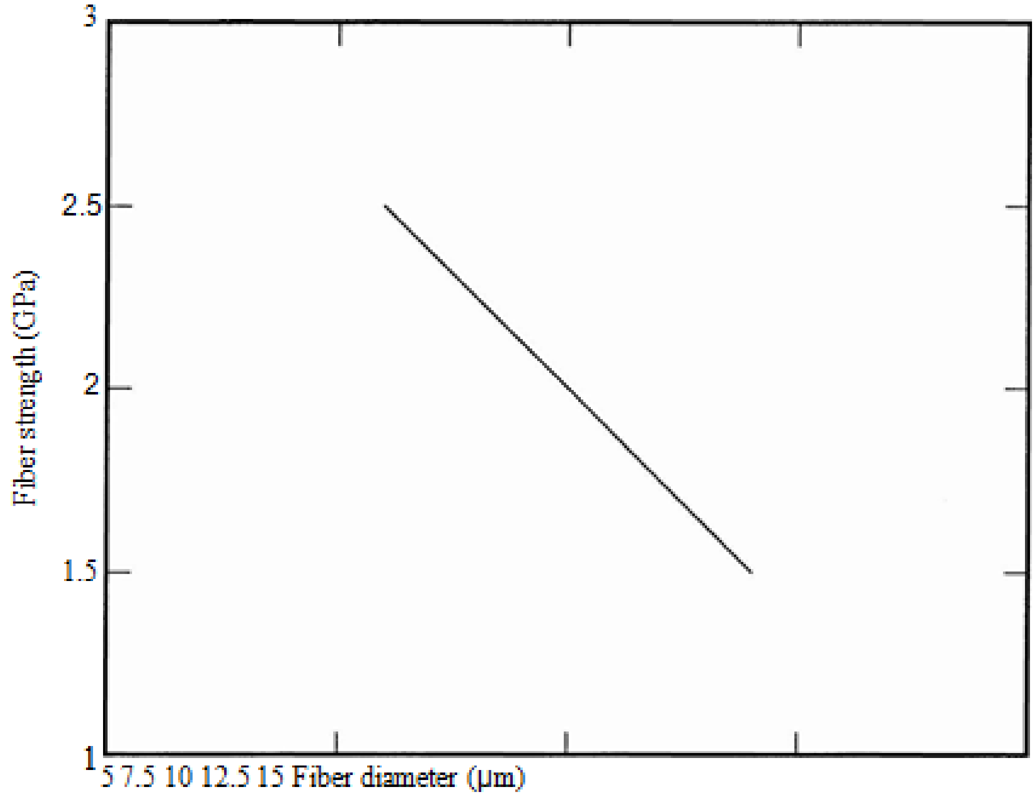
System of units: USCS

Specific modulus parameters for typical materials

Material units	Specific gravity	Young's modulus (GPa)	E/ρ (GPa-m^3/kg)	$E^{1/2}/\rho$ (Pa-m^3/kg)	$E^{1/3}/\rho$ ($Pa^{1/3}$-m^3/kg)
Graphite fiber	1.8	230.00	0.1278	266.4	3.404
Kevlar fiber	1.4	124.00	0.08857	251.5	3.562
Glass fiber	2.5	85.00	0.034	116.6	1.759
Unidirectional graphite/epoxy	1.6	181.00	0.1131	265.9	3.535
Unidirectional glass/epoxy	1.8	38.60	0.02144	109.1	1.878
Cross-ply graphite/epoxy	1.6	95.98	0.060	193.6	2.862
Cross-ply graphite/epoxy	1.8	23.58	0.0131	85.31	1.593
Quasi-isotropic graphite/epoxy	1.6	69.64	0.04353	164.9	2.571
Quasi-isotropic glass/epoxy	1.8	18.96	0.01053	76.50	1.481
Steel	7.8	206.84	0.02652	58.3	0.7582
Aluminium	2.6	68.95	0.02662	101.0	1.577

System of units: SI

Fiber strength as a function of fiber diameter for carbon fibers.



(Reprinted from Lamotte, E. De, and Perry, A.J., Fibre Sci. Technol., 3, 159, 1970. With permission from Elsevier.)

Fiber reinforcements of a thin diameter

Assume a lamina consisting of N fibers of diameter D.

The fibre–matrix interface area in this lamina is

$$A_I = N \pi D L$$

If the fibres of diameter D is replaced by fibres of diameter, d, then the number of fibres(n) to keep the fibre volume the same would be

$$n = N\left(\frac{D}{d}\right)^2$$

Then, the fibre–matrix interface area in the resulting lamina would be

$$A_{II} = n \pi d L$$

$$= \frac{N \pi D^2 L}{d}$$

$$= \frac{4(\text{Volume of fibres})}{d}$$

The area of the fiber–matrix interface is inversely proportional to the diameter of the fiber.

Bending stiffness is the resistance to bending moments.
If a beam is subjected to a pure bending moment, M,

$$\frac{d^2v}{dx^2} = \frac{M}{EI}$$

v= deflection of centroidal line
E= Young's modulus of the beam (psi or Pa)
I = second moment of area (in.4 or m4)
x = coordinate along the length of beam

Bending stiffness is EI &
Flexibility is simply the inverse of EI.

Cont.

Second moment of area of a cylindrical beam of diameter d is

$$I = \frac{\pi d^4}{64}$$

$$\text{Flexibility} \propto \frac{1}{E d^4}$$

Fiber: Towards mechanical performance of a composite

❖Length

- Long, continuous fibers are easy to orient and process, but short fibers cannot be controlled fully for proper orientation.
- Long fibers provide many benefits over short fibers such as impact resistance, low shrinkage, improved surface finish, and dimensional stability.
- Short fibers provide low cost, are easy to work with, and have fast cycle time fabrication procedures.
- Short fibers have fewer flaws and therefore have higher strength.

❖Orientation

- Fibers oriented in one direction give very high stiffness and strength in that direction.
- If the fibers are oriented in more than one direction, such as in a mat, there will be high stiffness and strength in the directions of the fiber orientations.
- For the same volume of fibers per unit volume of the composite, it cannot match the stiffness and strength of unidirectional composites.

Contd.

❖ Shape

- ➢ The most common shape of fibers is circular because handling and manufacturing them is easy.
- ➢ Hexagon and squareshaped fibers are possible, but their advantages of strength and high packing factors do not outweigh the difficulty in handling and processing.

❖ Material

- ➢ The material of the fiber directly influences the mechanical performance of a composite.
- ➢ Fibers are generally expected to have high elastic moduli and strengths.

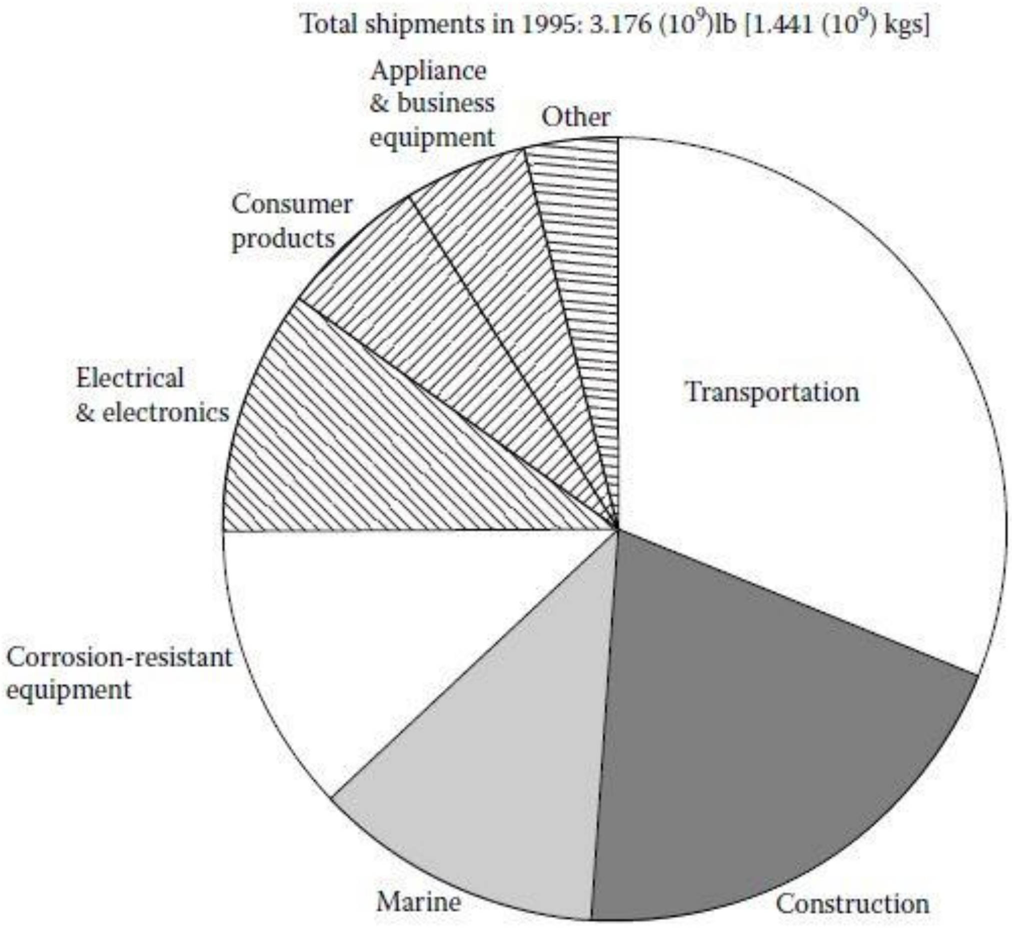
Matrix Affects the mechanical performance of composites

- The matrix functions include binding the fibers together, protecting fibers from the environment, shielding from damage due to handling, and distributing the load to fibers.
- The properties that are influenced by matrix are:
  - transverse modulus and strength
  - shear modulus and strength
  - compressive strength
  - interlaminar shear strength
  - thermal expansion coefficient
  - thermal resistance
  - fatigue strength.

Other factors influencing the mechanical performance of a composite

- ❖Chemical bonding
- ❖Mechanical bonding
- ❖Reaction bonding

Approximate shipments of polymer-based composites in 1995.



Source: Data used in figure published with permission of the SPI, Inc.; http://www.socplas.org.)

Classification of Composites

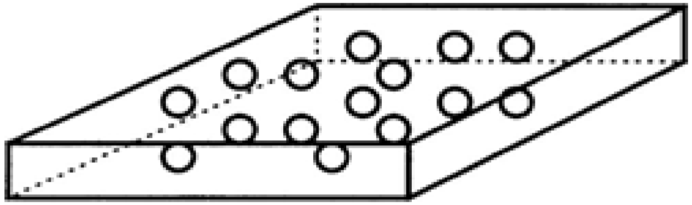
❖Composites are classified by the geometry of the reinforcement — particulate, flake, and fibers or by the type of matrix — polymer, metal, ceramic, and carbon.

❖*Particulate* composites

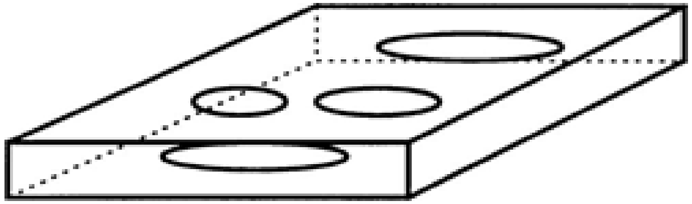
❖*Flake* composites

❖*Fiber* composites

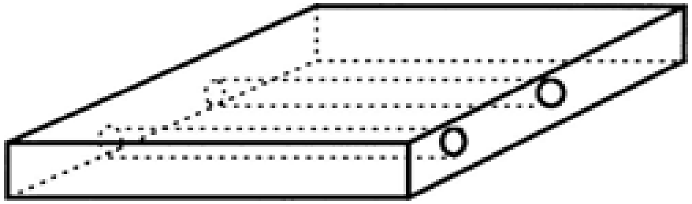
❖*Nanocomposites*



Particulate composites



Flake composites



Fiber composites

Most common advanced composites

- ❖Polymer matrix composites (PMCs) consisting of a polymer (e.g., epoxy, polyester, urethane) reinforced by thin diameter fibers (e.g., graphite, aramids, boron).
- ❖Graphite/ epoxy composites are approximately five times stronger than steel on a weight-for- weight basis.
- ❖The reasons why they are the most common composites include their low cost, high strength, and simple manufacturing principles.

What are the drawbacks of polymer matrix composites

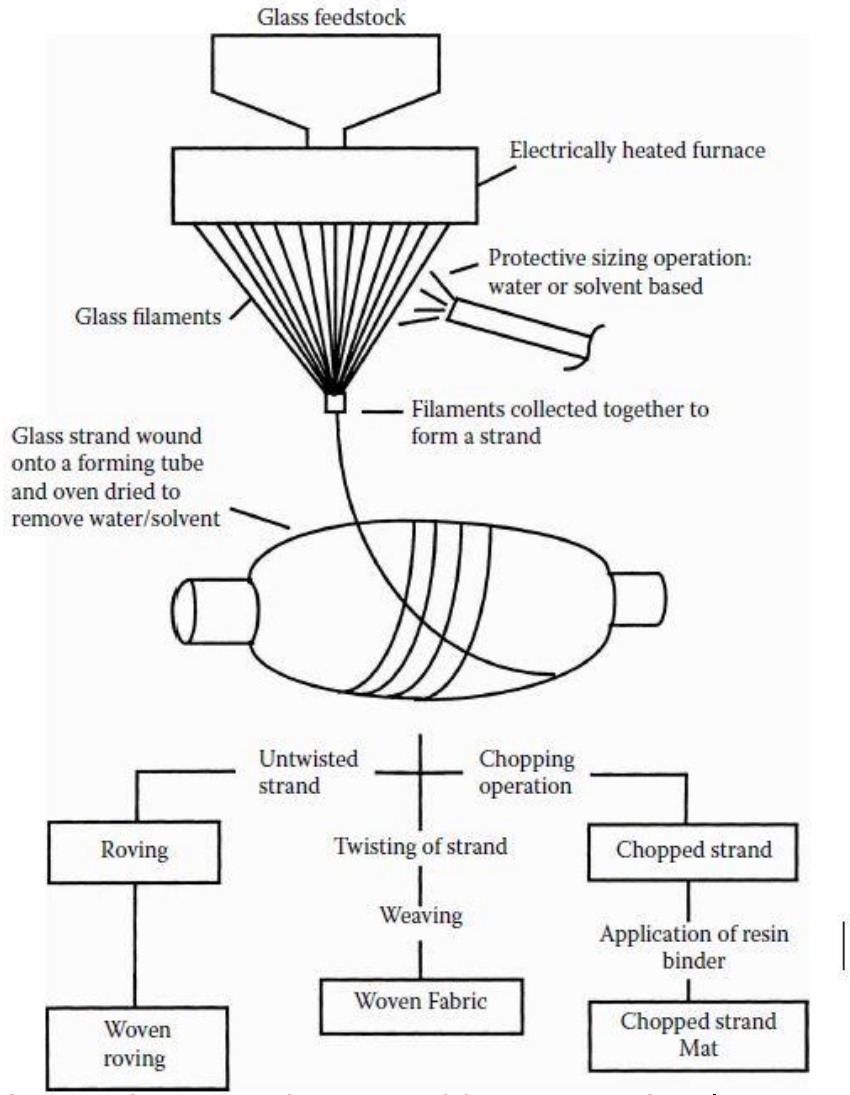
- Low operating temperatures
- High coefficients of thermal and moisture expansion
- Low elastic properties in certain directions

Fibers used in advanced polymer composites

❖Glass

- most common fiber used in polymer matrix composites
- high strength, low cost, high chemical resistance, and good insulating properties.
- low elastic modulus, poor adhesion to polymers, high specific gravity, sensitivity to abrasion and low fatigue strength.
- Main types are E-glass (also called "fiberglass") and S-glass
  - "E" in E-glass stands for electrical because it was designed for electrical applications
  - S" in S-glass stands for higher content of silica.

Manufacturing of glass fibers



From Bishop, W., in *Advanced Composites*, Partridge, I.K., Ed., Kluwer Academic Publishers, London, 1990, Figure 4, p. 177. Reproduced with kind permission of Springer.)

Cont.

❖Graphite

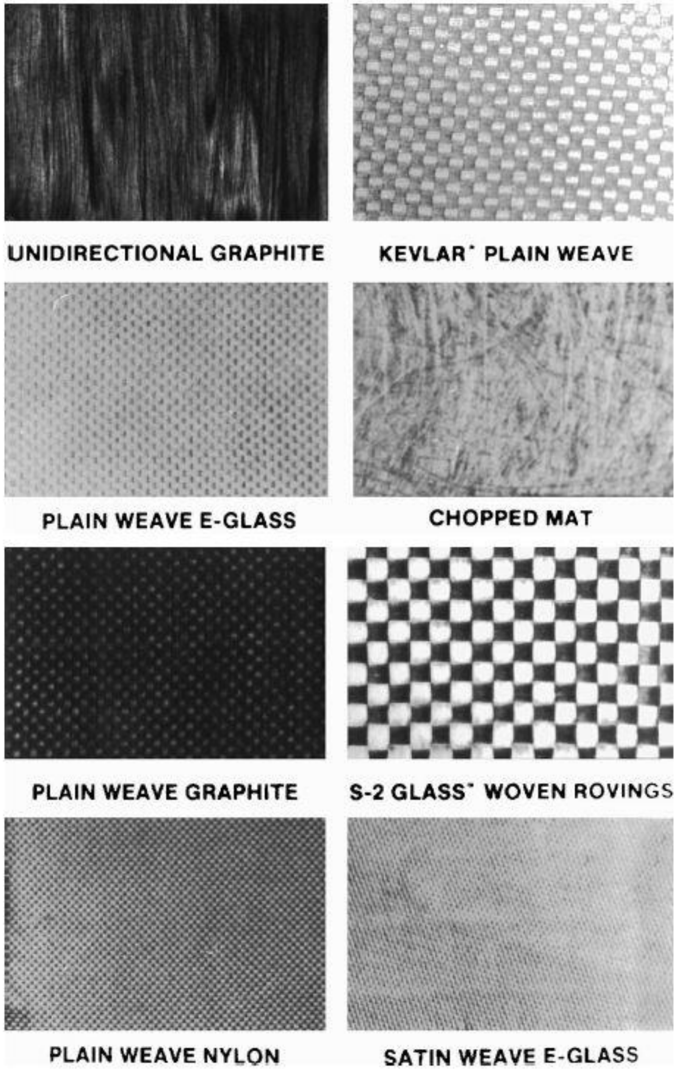
- very common in high-modulus and high-strength applications such as aircraft components
- high specific strength and modulus, low coefficient of thermal expansion, and high fatigue strength.
- high cost, low impact resistance, and high electrical conductivity.

Cont.

❖ Aramid

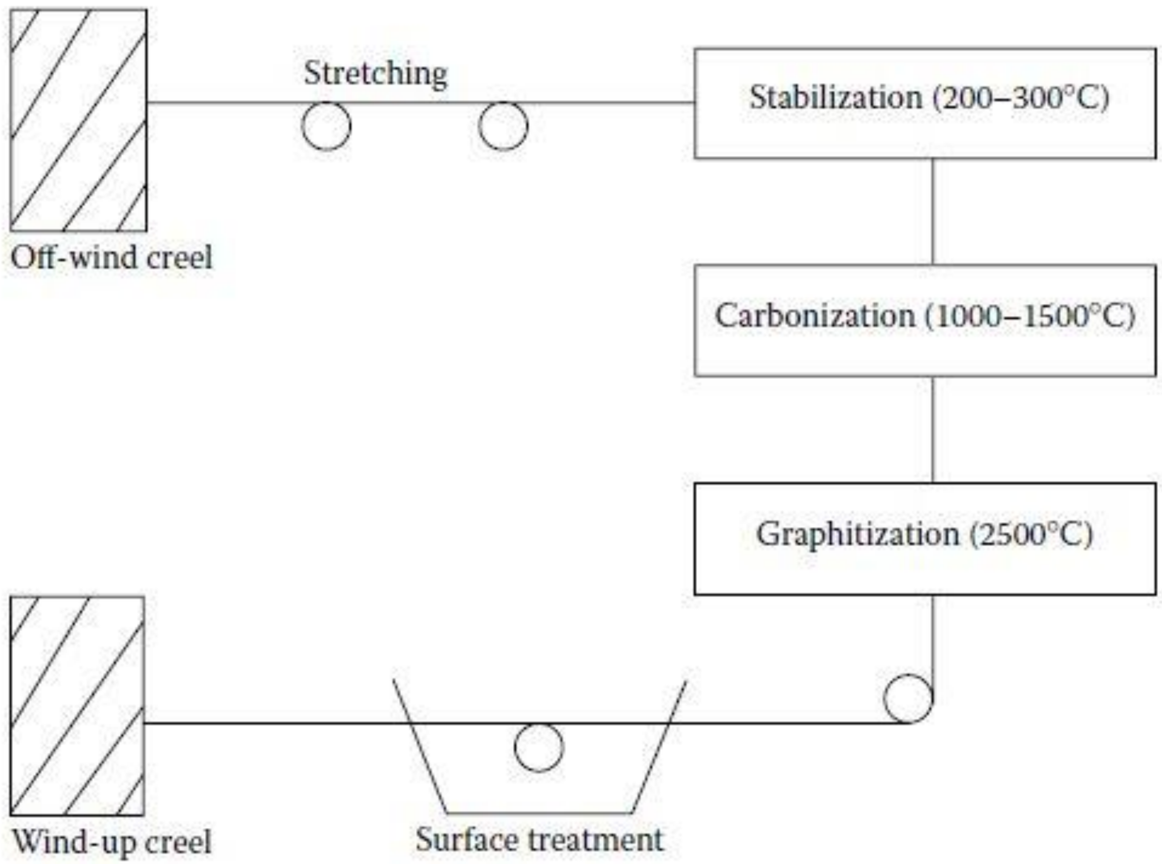
- Aromatic organic compound made of carbon, hydrogen, oxygen, and nitrogen.
- Low density, high tensile strength, low cost and high impact resistance.
- Two main types of aramid fibers are Kevlar 29®* and Kevlar49®†
- Kevlar 29 is mainly used in bulletproof vests, ropes, and cables and high performance aircraft applications

Forms of available fibres



(Graphic courtesy of M.C. Gill Corporation, http://www. mcgillcorp.com.)

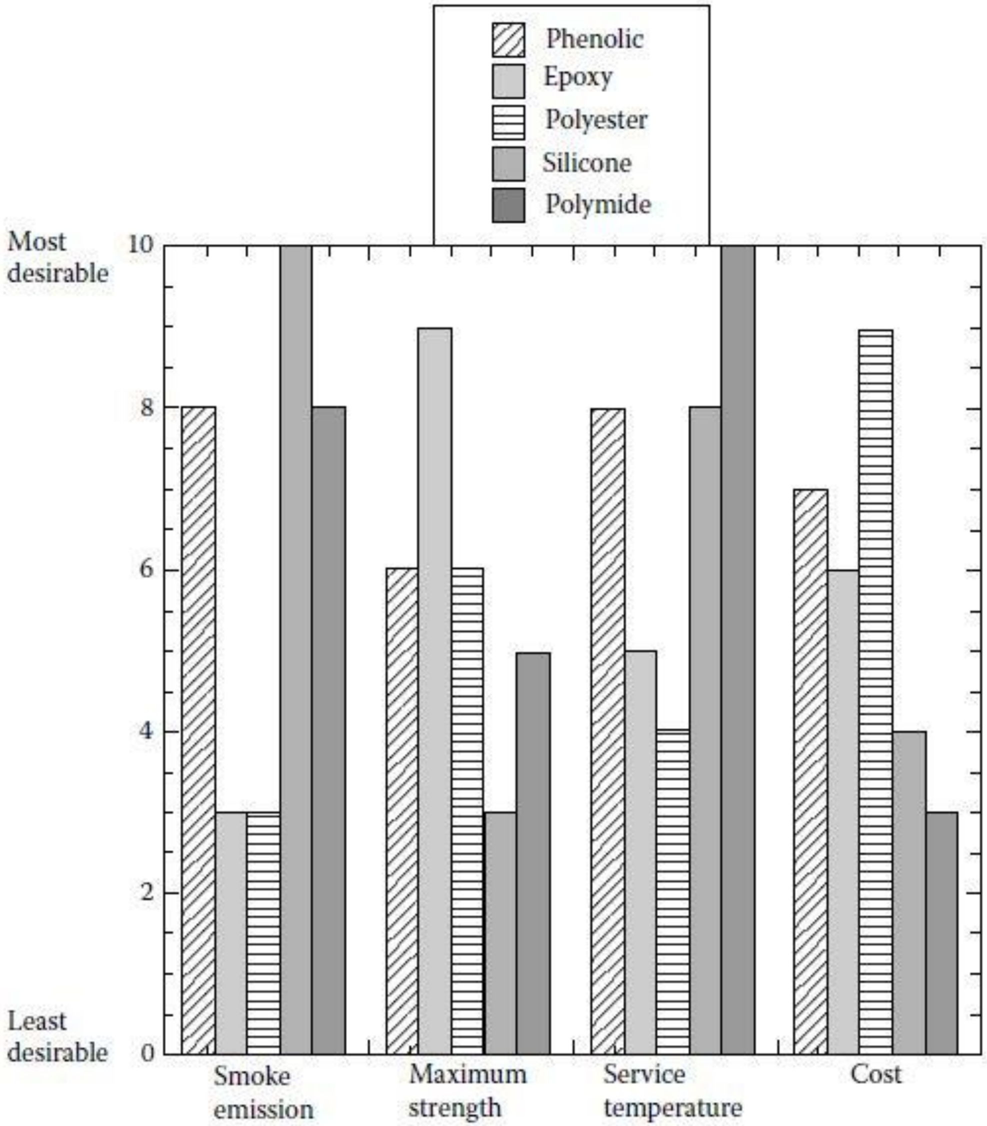
Stages of manufacturing a carbon fiber from PAN-based precursors.



Various polymers used in advanced polymer composites

- **Polyesters**
  - low cost and the ability to be made translucent
  - Service temperatures below 170°F (77°C),
  - Brittle
  - high shrinkage of as much as 8% during curing.
- **Phenolics**
  - low cost and high mechanical strength
  - high void content.
- **Epoxies**
  - high mechanical strength
  - Good adherence to metals and glasses
  - high cost and difficulty in processing.
- **Acrylic**
- **Urethane**
- **Polyamide**

Comparison of performance of several common matrices used in polymer matrix composites



(Graphic courtesy of M.C. Gill Corporation, http://www.mcgillcorp.com.)

Most common matrix material

❖ Epoxy

- More than two-thirds of the polymer matrices used in aerospace applications are epoxy based. The main reasons why epoxy is the most used polymer matrix material are:
- High strength
- Low viscosity and low flow rates, which allow good wetting of fibers and prevent misalignment of fibers during processing
- Low volatility during cure
- Low shrink rates
- Available in more than 20 grades to meet specific property and processing requirements

Room Temperature Properties of a Typical Epoxy

Property	Units	Value
Specific gravity	-	1.28
Young's modulus	GPa	3.792
Ultimate tensile strength	MPa	3.792

Polymers: Thermostes and Thermoplastics

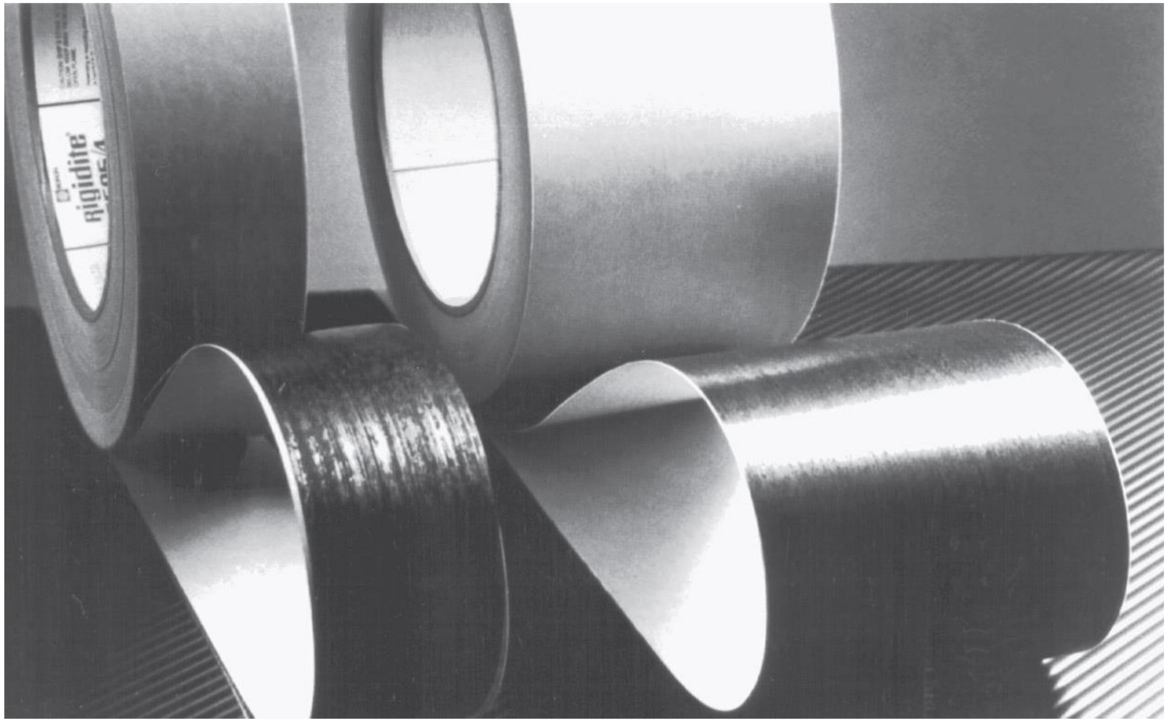
- ❖Thermoset polymers are insoluble and infusible after cure because the chains are rigidly joined with strong covalent bonds
- ❖Thermoplastics are formable at high temperatures and pressure because the bonds are weak and of the van der Waals type
- ❖Thermosets: epoxies, polyesters, phenolics, and polyamide
- ❖Thermoplastics : polyethylene, polystyrene, polyether–ether–ketone (PEEK) and polyphenylene sulfide (PPS).

Cont.

Thermoplastics	**Thermosets**
Soften on heating and pressure, and thus easy to repair	Decompose on heating
High strains to failure	Low strains to failure
Indefinite shelf life	Definite shelf life
Not tacky and easy to handle	Tacky
Higher fabrication temperature and viscosities have made it difficult to process	Lower fabrication temperature
Excellent solvent resistance	Fair solvent resistance

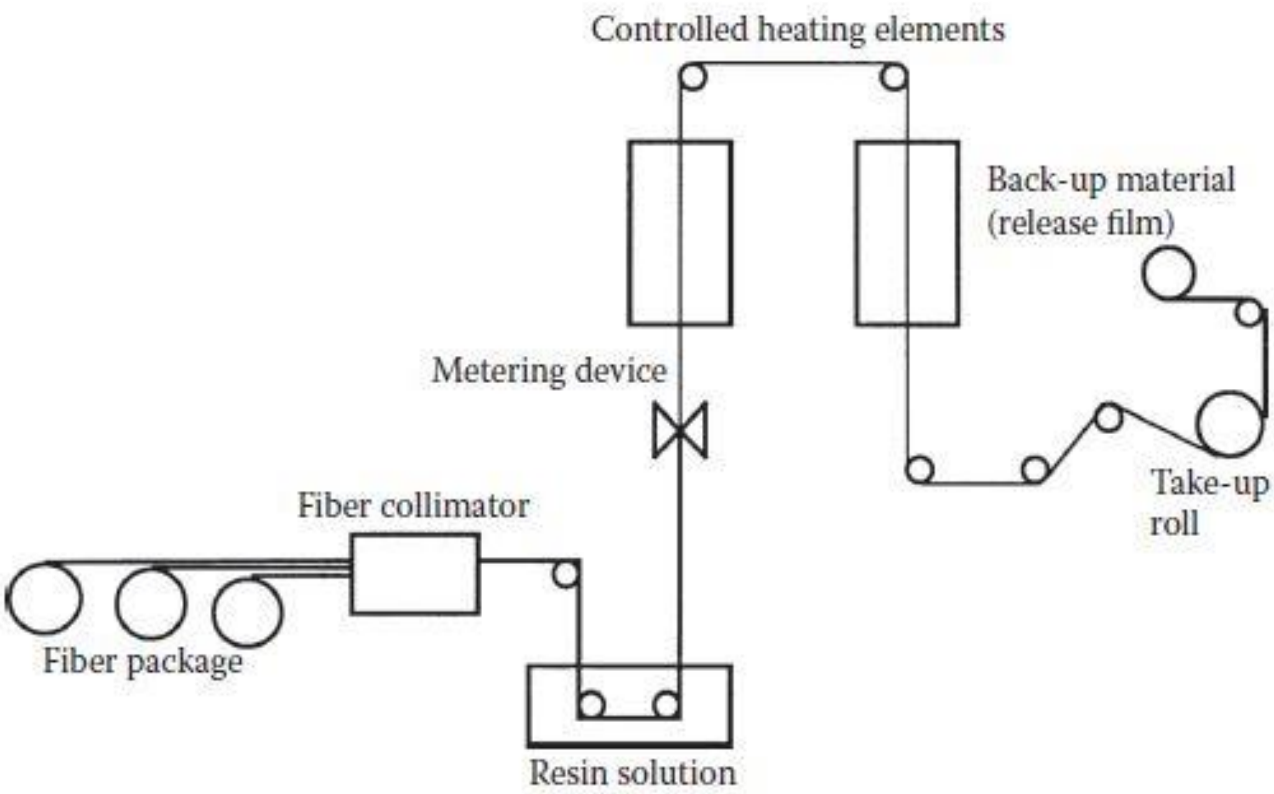
Prepregs

- Prepregs are a ready-made tape composed of fibers in a polymer matrix
- They are available in standard widths from 3 to 50 in. (76 to 1270 mm).

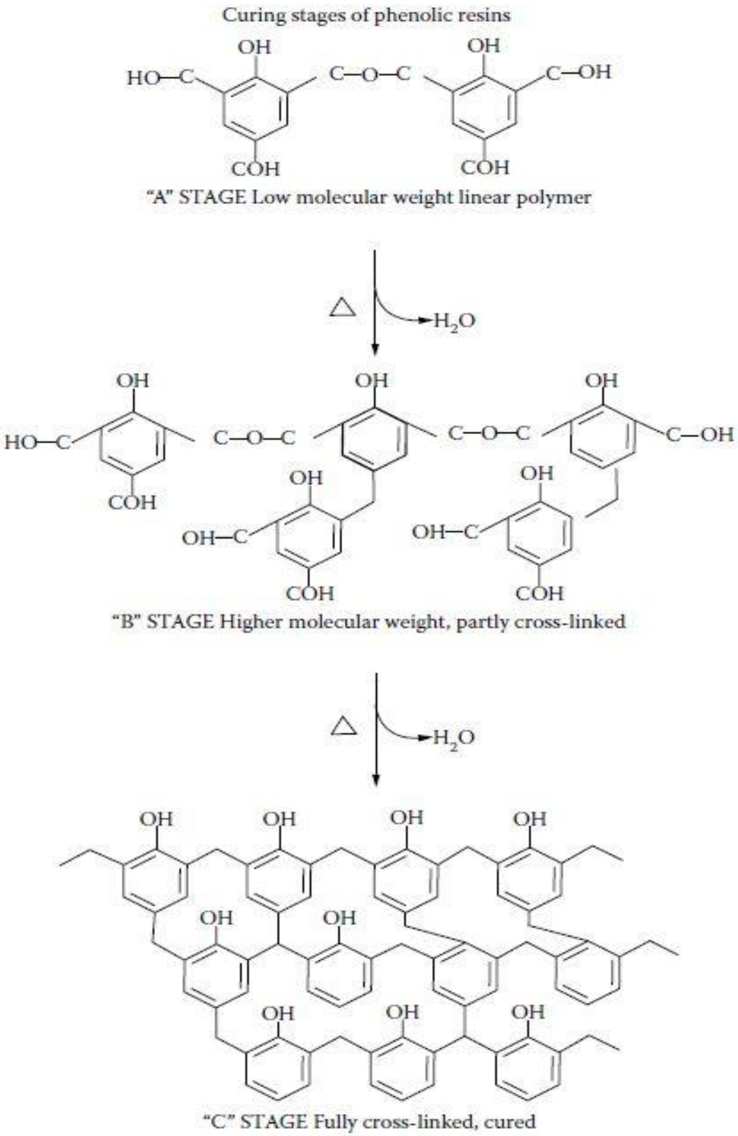


Boron/epoxy prepreg tape.

Prepreg manufacturing



Curing stages of phenolic resins



Filament winding process

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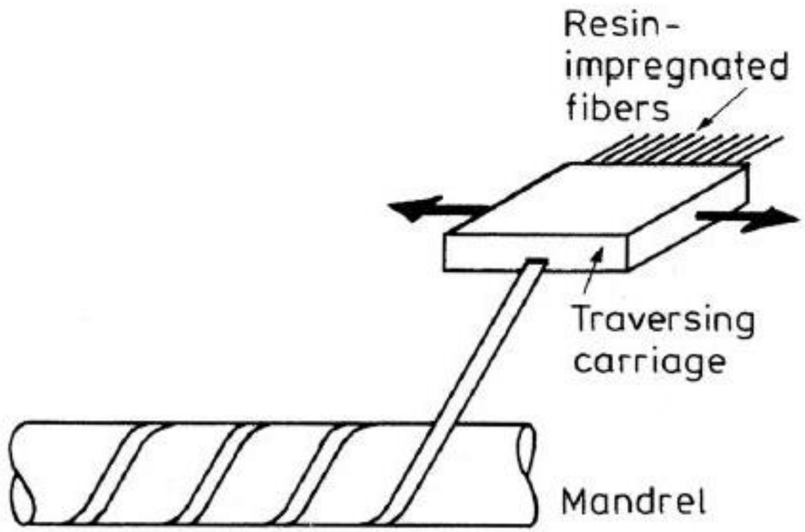
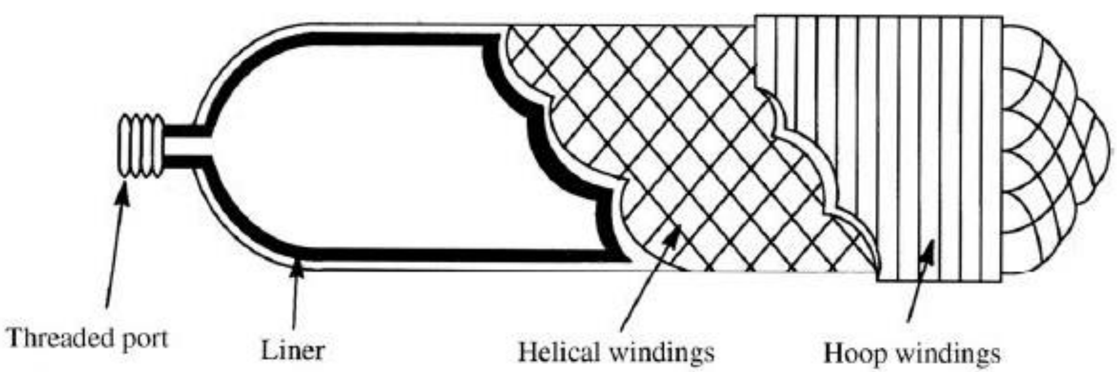




Human-powered submarine and its mold

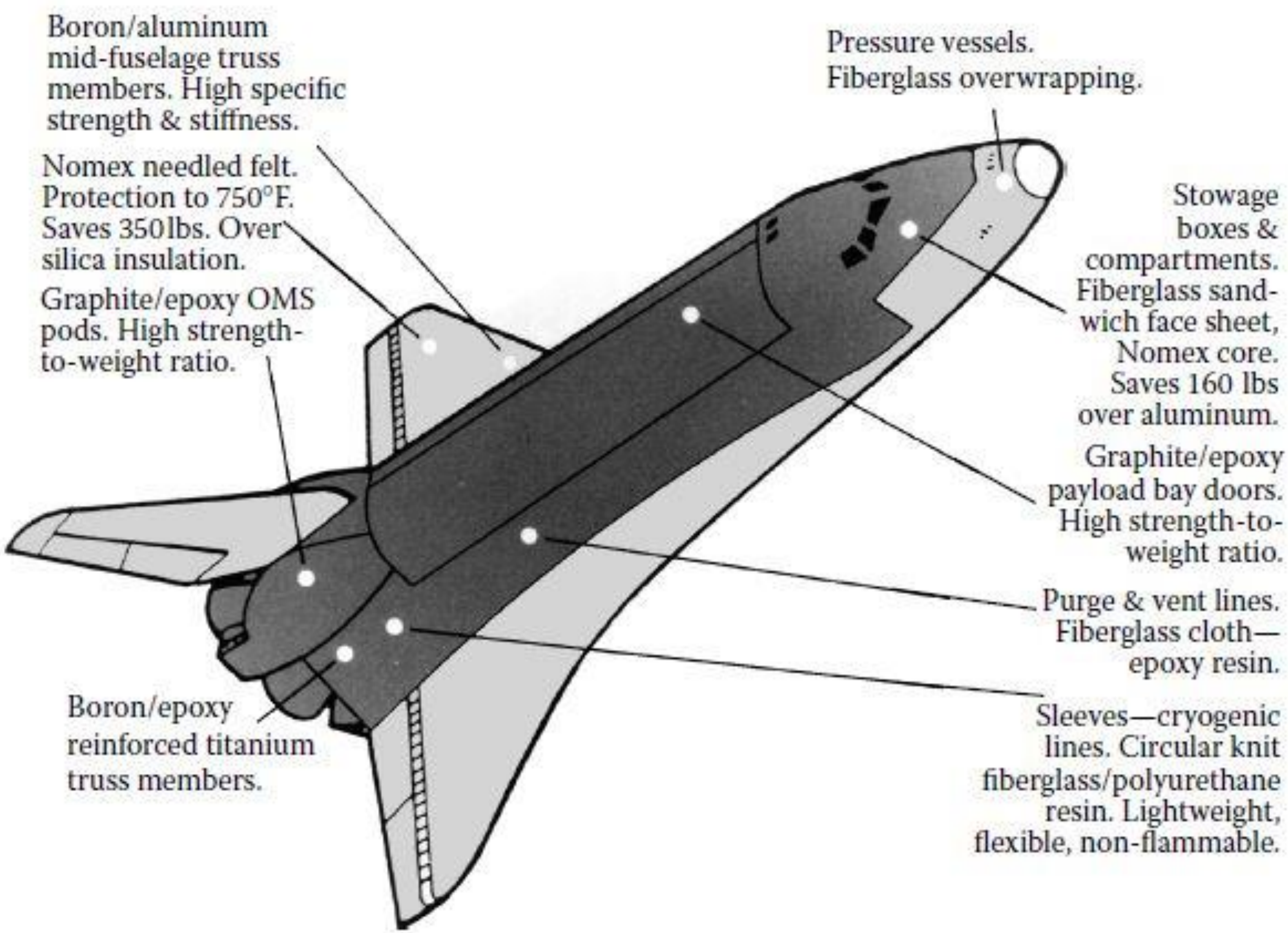
Autoclave used for processing polymer matrix composites

Applications of polymer matrix composites

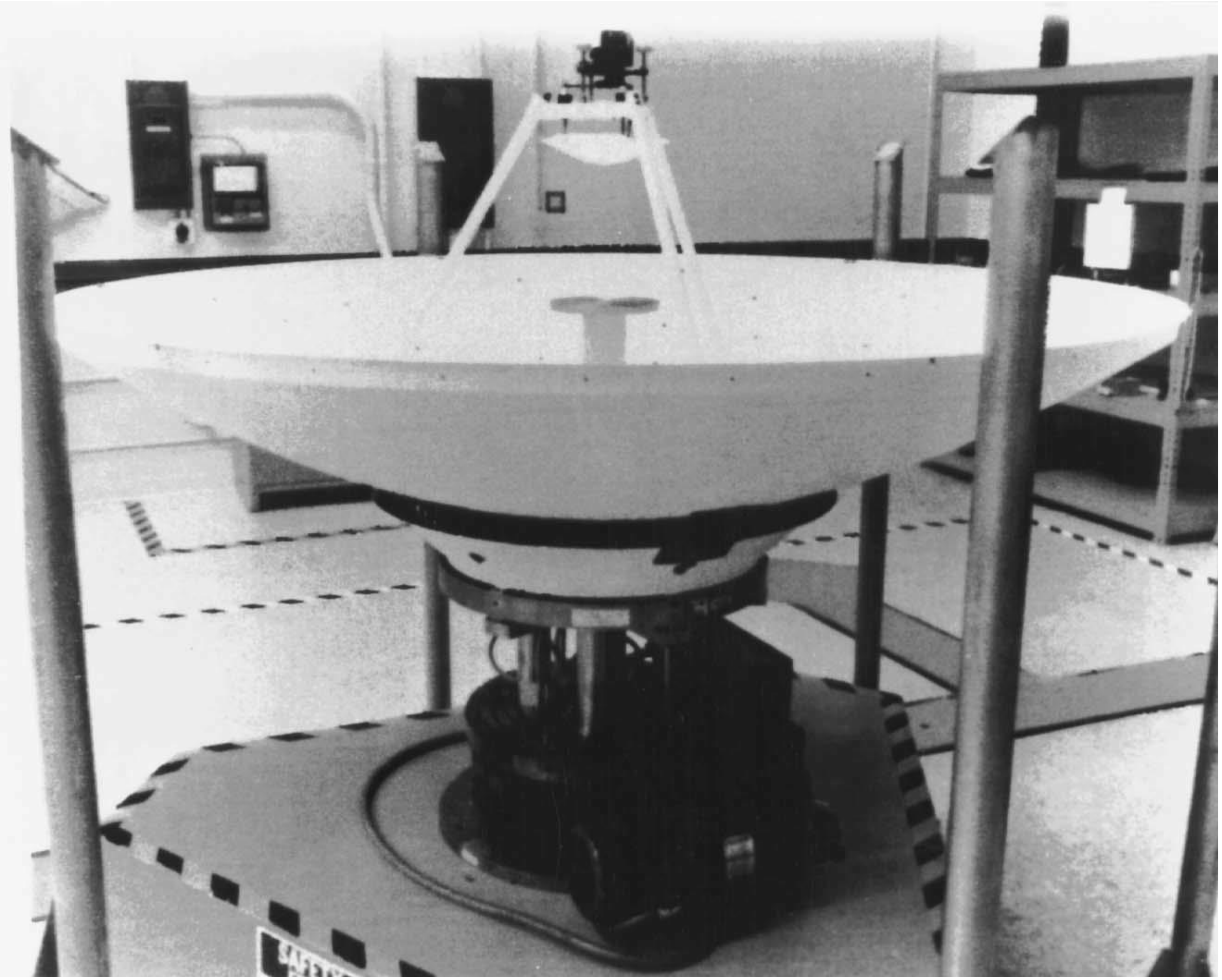
- Aircraft
- Space
- Sporting goods
- Medical devices
- Marine
- Automotive
- Commercial

The BELL™ V-22 Osprey in combat configuration

Space shuttle



High-gain antenna for space station



First privately manned vehicle to go beyond Earth's atmosphere

Rear fiberglass monosprings for Corvettes

Metal matrix composites

- ❖Metal matrix composites (MMCs) have a metal matrix.
- ❖Examples of matrices in composites include aluminum, magnesium and titanium.
- ❖Typical fibers include carbon and silicon carbide.
- ❖Mainly reinforced to increase or decrease their properties to suit the needs of design

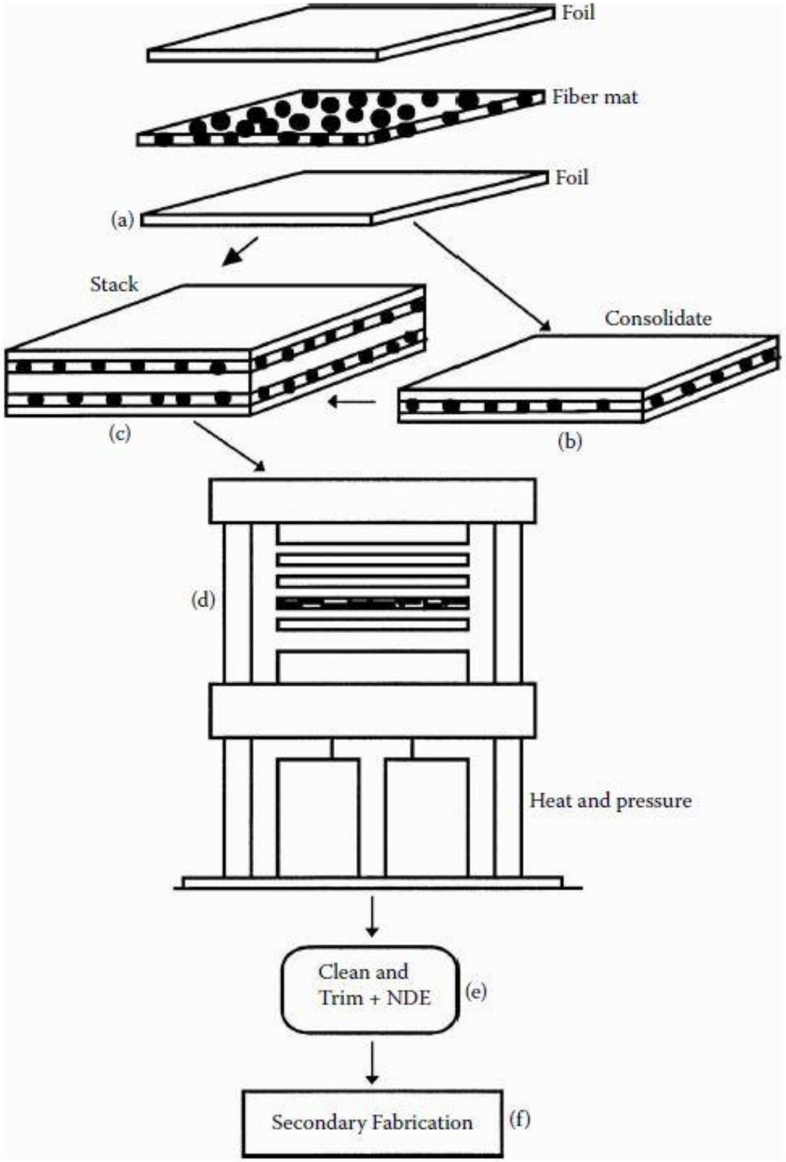
Advantages of metal matrix composites

- ❖higher specific strength and modulus by reinforcing low-density metals such as aluminum and titanium
- ❖lower coefficients of thermal expansion by reinforcing with fibers with low coefficients of thermal expansion, such as graphite.
- ❖Higher elastic properties
- ❖Higher service temperature
- ❖Insensitive to moisture

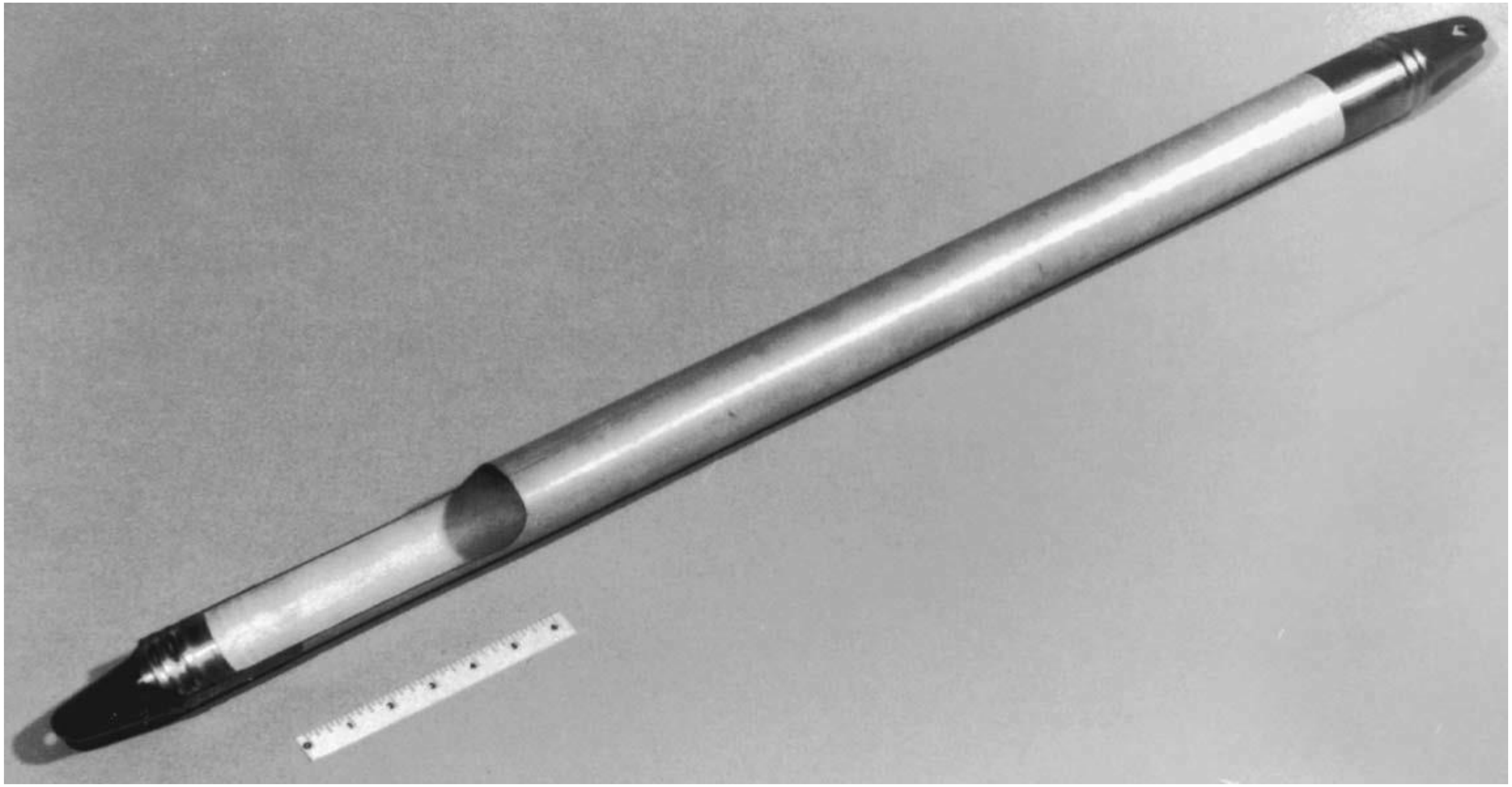
Applications of MMCs

- Space
- Military
- Transportation

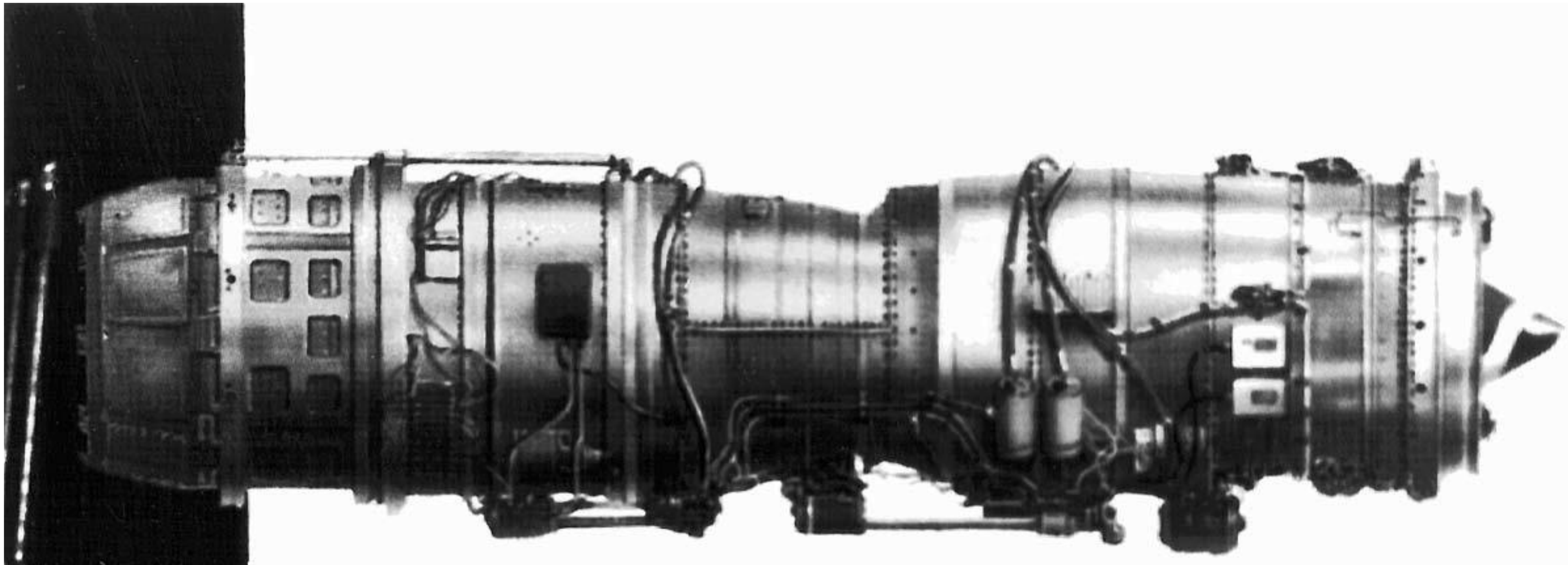
Schematic of diffusion bonding for metal matrix composites



Boron/aluminum component made from diffusion bonding



Gas turbine engine components made of metal matrix composites



High strength, low weight and the ability to perform at high temperatures make metal matrix composites the material of choice for gas turbine engine components

Ceramic matrix composites

- Ceramic matrix composites (CMCs) have a ceramic matrix such as alumina calcium alumino silicate reinforced by fibers such as carbon or silicon carbide.

- Advantages:
  - high strength, hardness, high service temperature limits for ceramics, chemical inertness, and low density.
  - Low fracture toughness

- Applications:
  - High temperature areas

Carbon–carbon composites

- Carbon–carbon composites use carbon fibers in a carbon matrix.
- These composites are used in very high-temperature environments of up to 6000°F (3315°C), and are 20 times stronger and 30% lighter than graphite fibers.

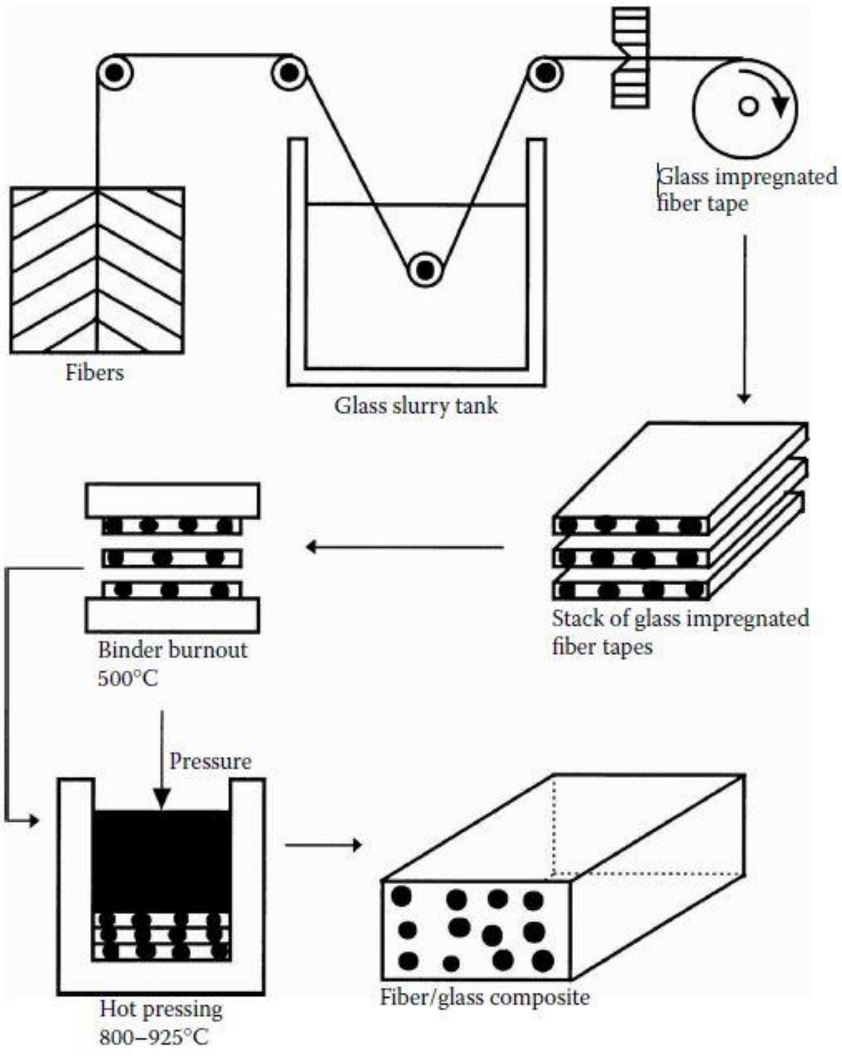
- Advantages:
  - ability to withstand high temperatures
  - low creep at high temperatures
  - low density
  - good tensile and compressive strengths
  - high fatigue resistance
  - high thermal conductivity
  - high coefficient of friction

Cont.

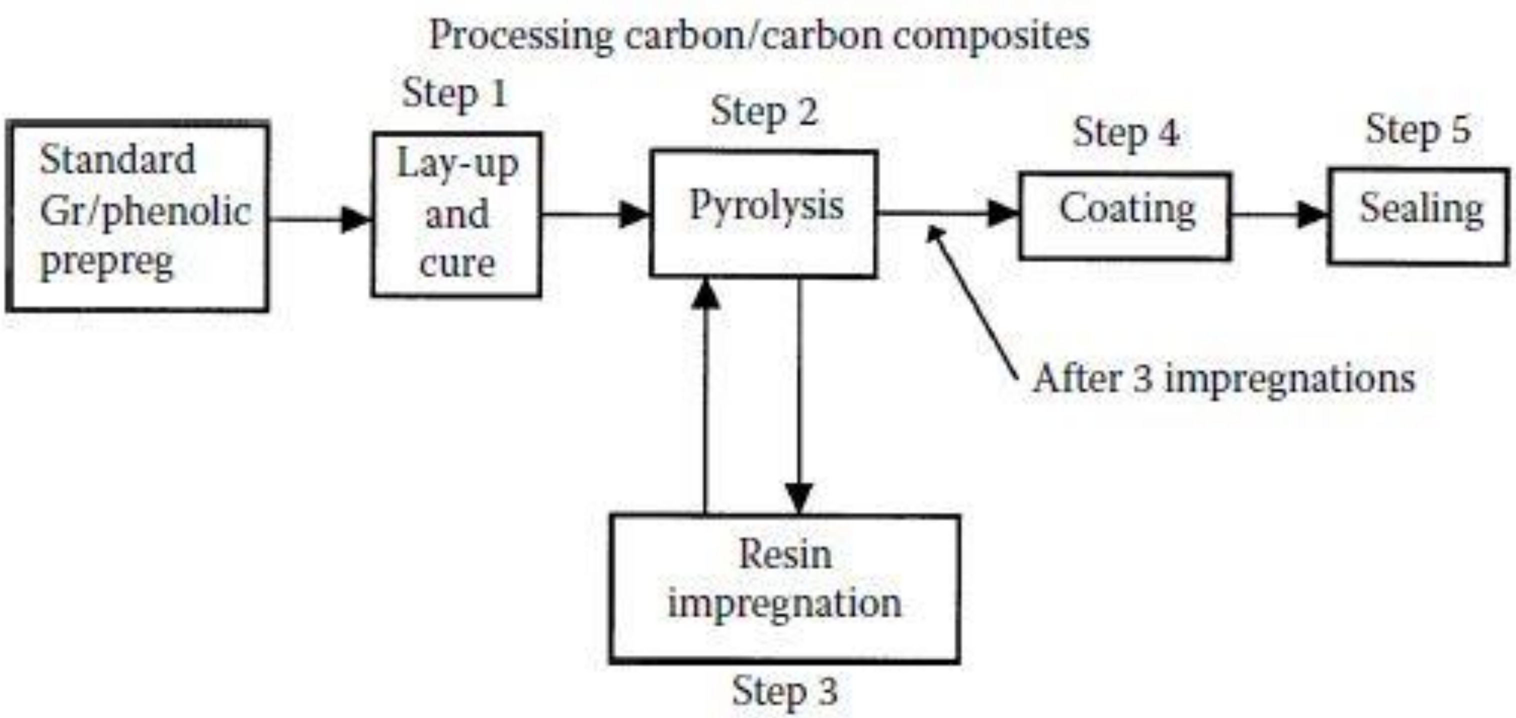
❖ Drawbacks

- ➢ High cost
- ➢ Low shear strength
- ➢ Susceptibility to oxidation at high temperature

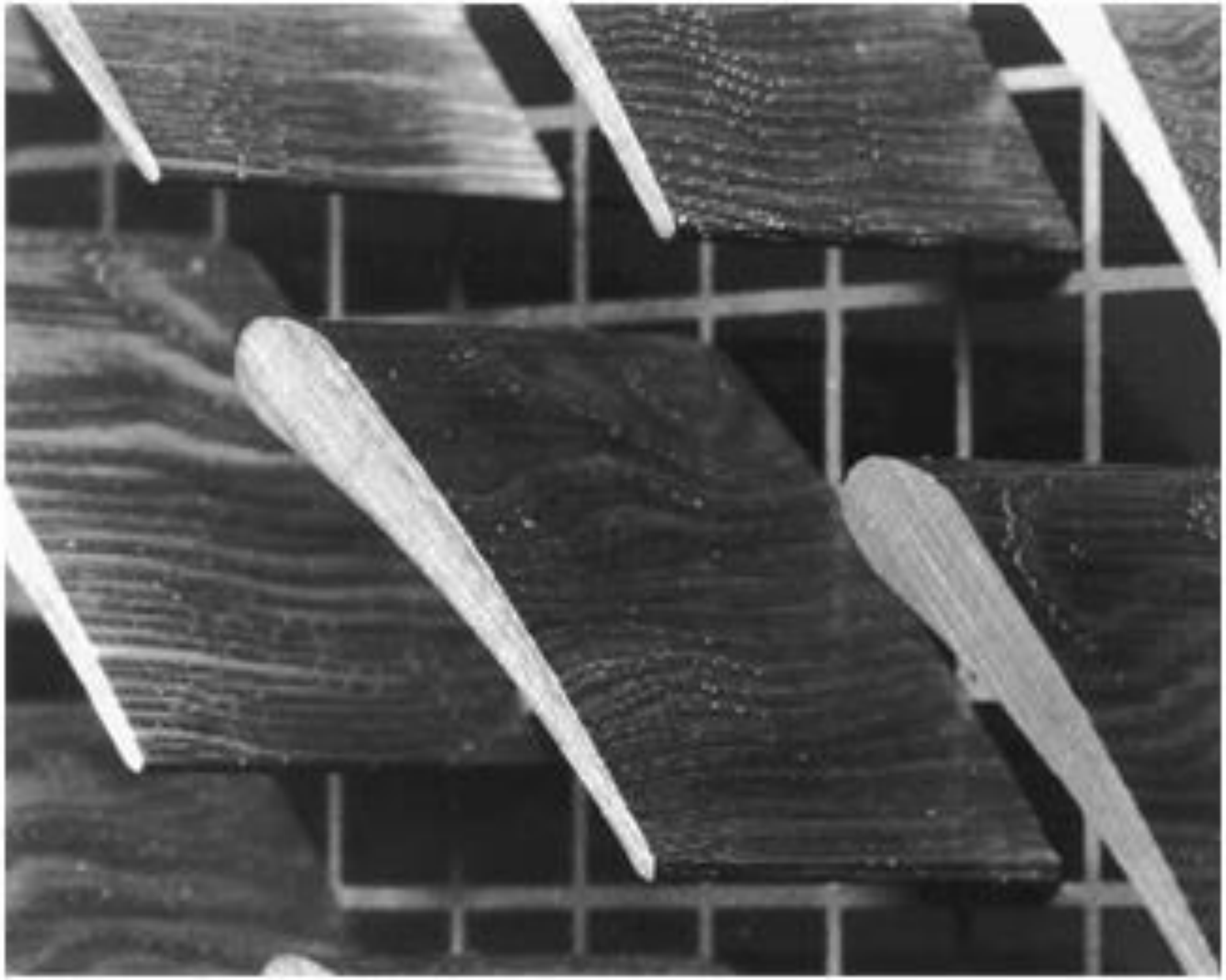
Slurry infiltration process for ceramic matrix composites



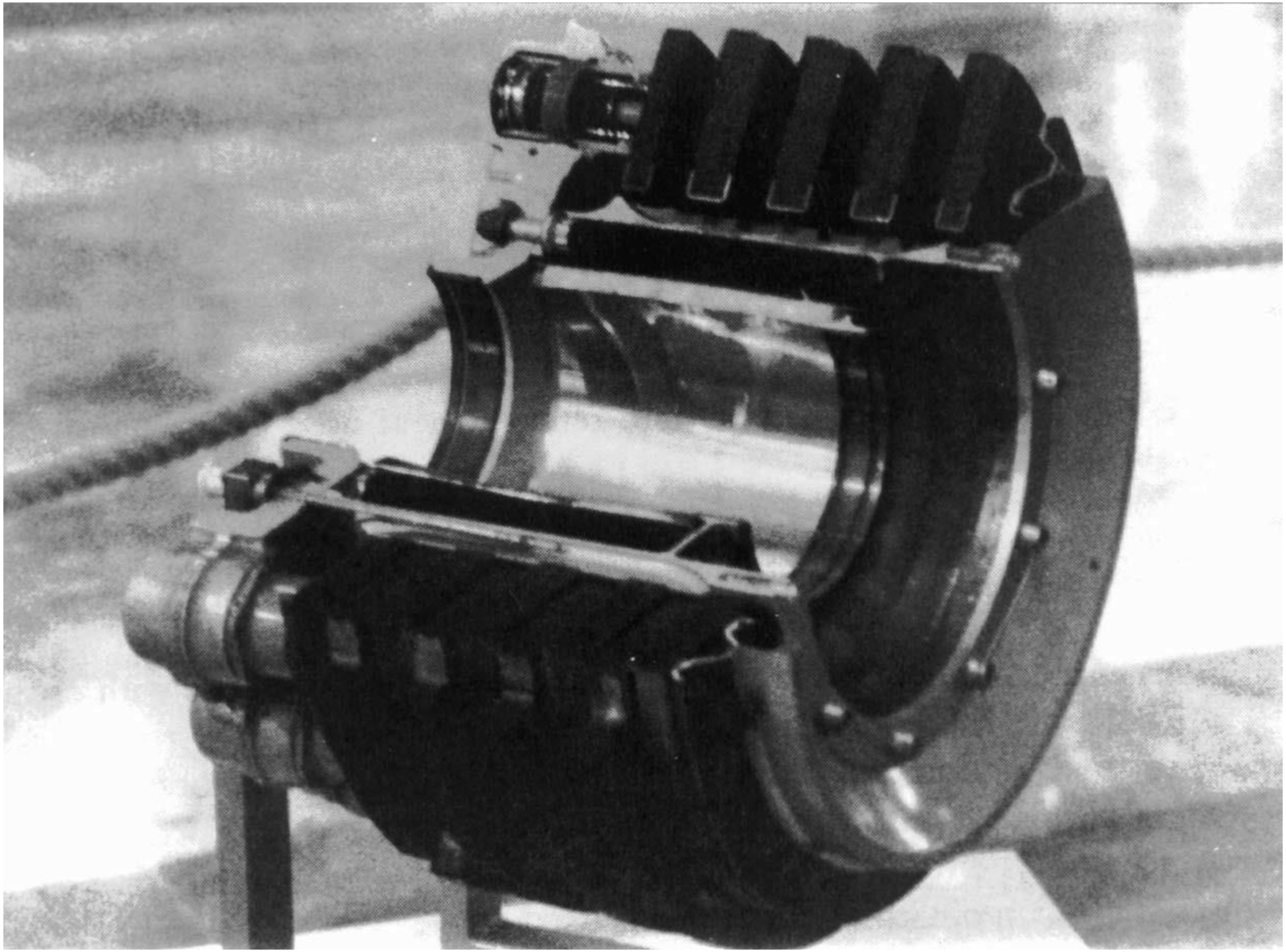
Processing of carbon–carbon composites



Ceramic matrix composites for high temperature and oxidation resistant application



Sectioned carbon–carbon brake from Airbus A320



Recycling of Fiber-reinforced composites

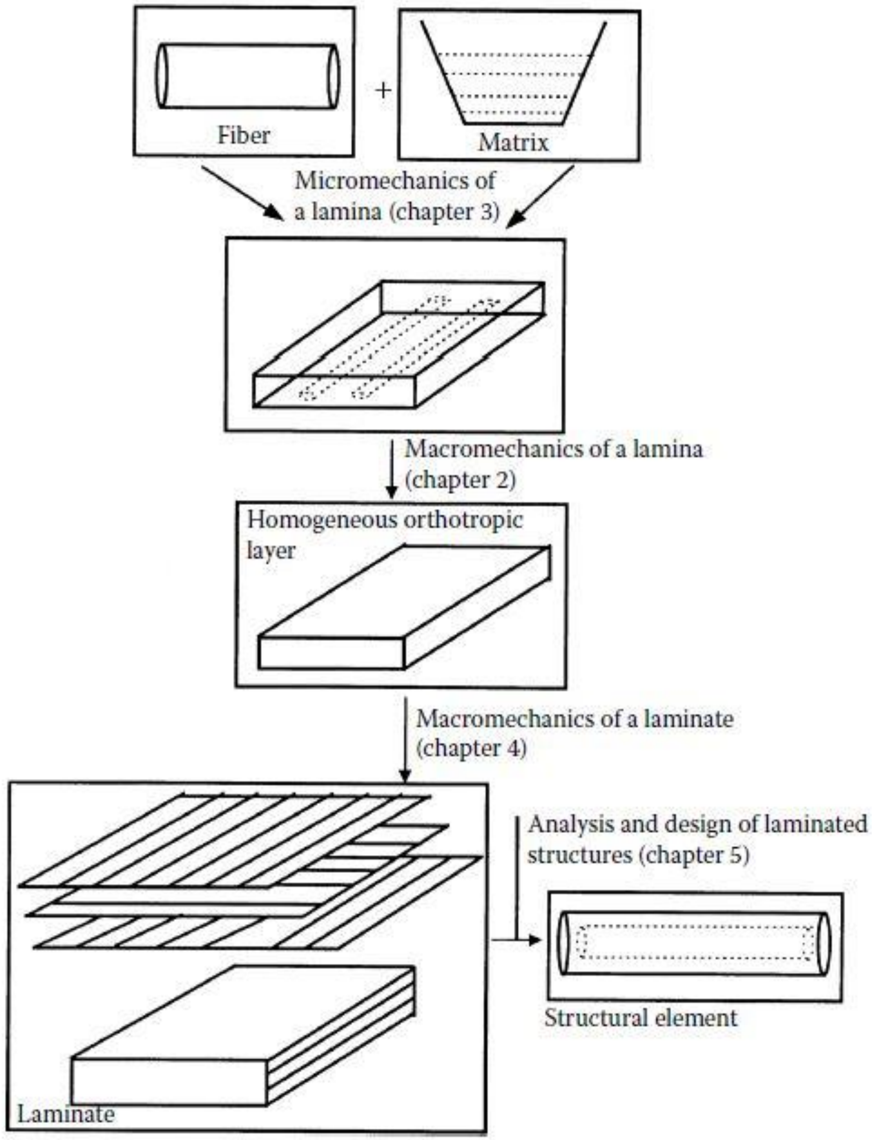
❖ Chemical process

- Pyrolysis

❖ Mechanical process

- Shredding
- Separation
- Washing
- Grinding
- Drying
- Extrusion

Analysis of laminated composites



Isotropic body

- An isotropic material has properties that are the same in all directions.
- Example: Young’s modulus of steel is the same in all directions.

Homogeneous body

- A homogeneous body has properties that are the same at all points in the body.
- Example: Steel rod
- On heating this rod at one end, the temperature at various points on the rod would be different because Young's modulus of steel varies with temperature
- The body is still isotropic because the properties at a particular point are still identical in all directions but not homogenous.

- Most composite materials are neither isotropic nor homogeneous

Cont.

❖Anisotropic material

- At a point in an anisotropic material, material properties are different in all directions.

❖Nonhomogenous body

- A nonhomogeneous or inhomogeneous body has material properties that are a function of the position on the body.

❖Lamina

- A lamina (also called a ply or layer) is a single flat layer of unidirectional fibers or woven fibers arranged in a matrix.

❖Laminate

- A laminate is a stack of plies of composites.
- Each layer can be laid at various orientations and can be made up of different material systems.

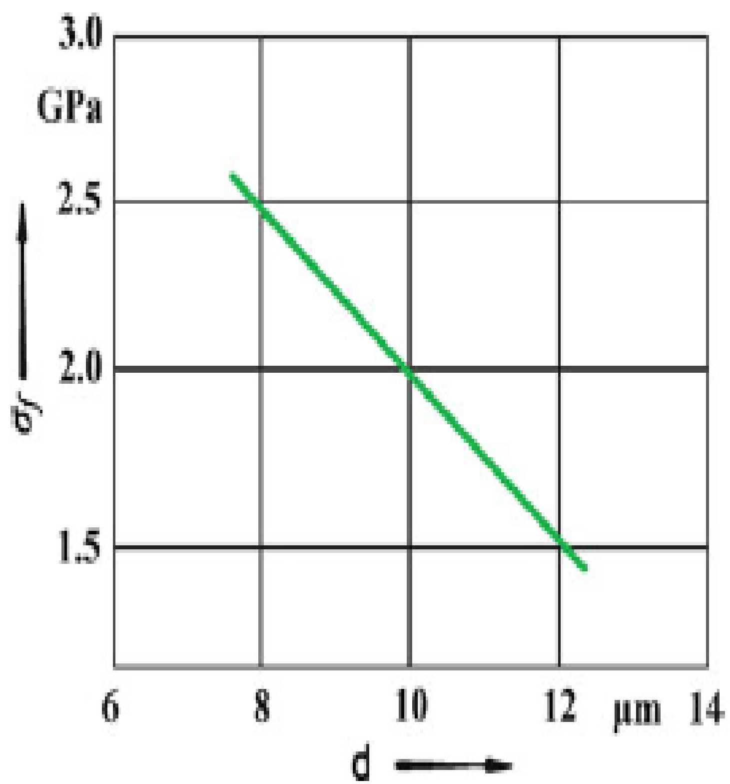
❖Hybrid laminate

- Hybrid composites contain more than one fiber or one matrix system in a laminate.
  - Interply hybrid laminates
  - Intraply hybrid composites
  - Interply-intraply hybrid
  - Resin hybrid laminates

Reinforcements

Introduction

Fig. 2.1 Decrease in strength (σ_f) of a carbon fiber with increase in diameter [from de Lamotte and Perry (1970), used with permission]



Flexibility

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

$$MR = EI \ ,$$

E= Young’s Modulus

I=Second Moment of Area

R=Radius

M=Bending Moment

$$MR = EI = \frac{E\pi \, d^4}{64} ,$$

Flexibility

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

$$MR = EI \ ,$$

E= Young’s Modulus

I=Second Moment of Area

R=Radius

M=Bending Moment

$$MR = EI = \frac{E\pi\, d^4}{64},$$

$$\text{Flexibility} = \frac{1}{MR} = \frac{64}{E\pi d^4},$$

Fiber Spinning Processes

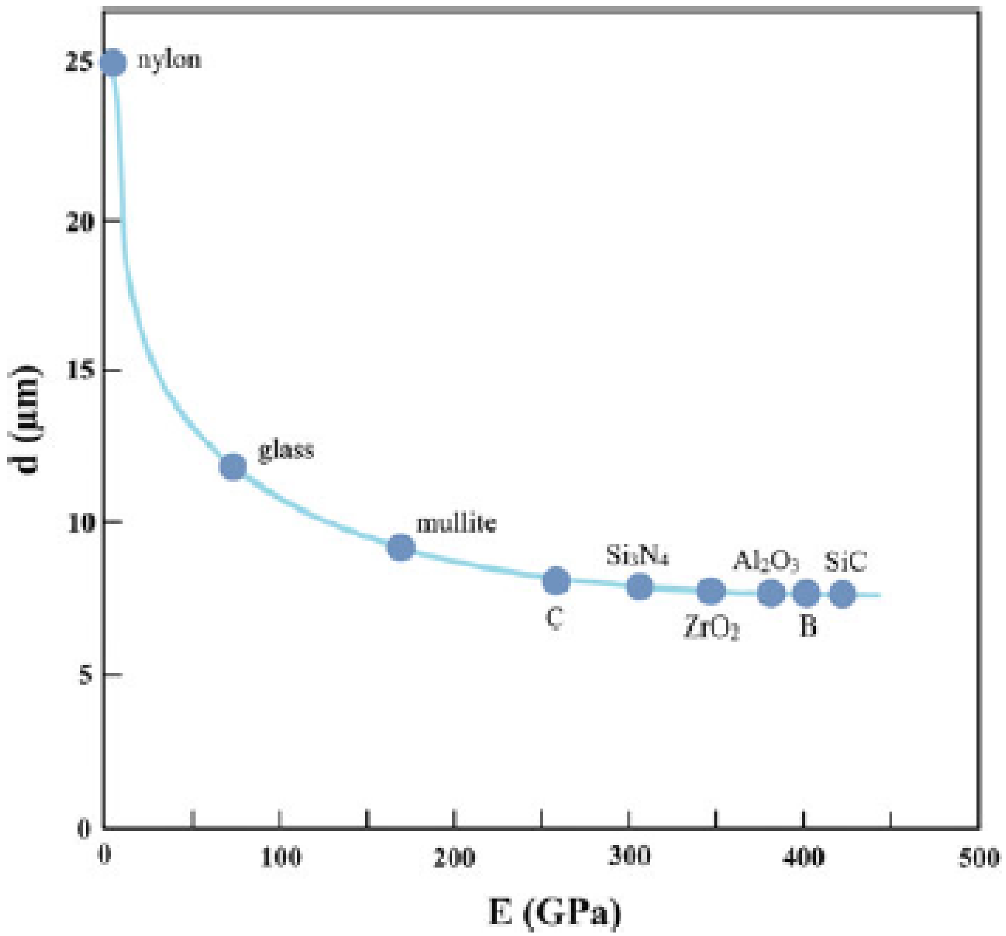


Fig. 2.2 Fiber diameter of different materials with flexibility equal to that of a nylon fiber of diameter equal to 25 µm. Note that one can make very flexible fibers out of brittle materials such as glass, silicon carbide, alumina, etc., provided one can process them into a small diameter

Stretching and Orientation

भारतीय प्रौद्योगिकी संस्थान गुवाहाटी • Indian Institute of Technology Guwahati •

Glass Fibres

Table 2.1 Approximate chemical compositions of some glass fibers (wt.%)

Composition	E glass	C glass	S glass
SiO_2	55.2	65.0	65.0
Al_2O_3	8.0	4.0	25.0
CaO	18.7	14.0	–
MgO	4.6	3.0	10.0
Na_2O	0.3	8.5	0.3
K_2O	0.2	–	–
B_2O_3	7.3	5.0	–

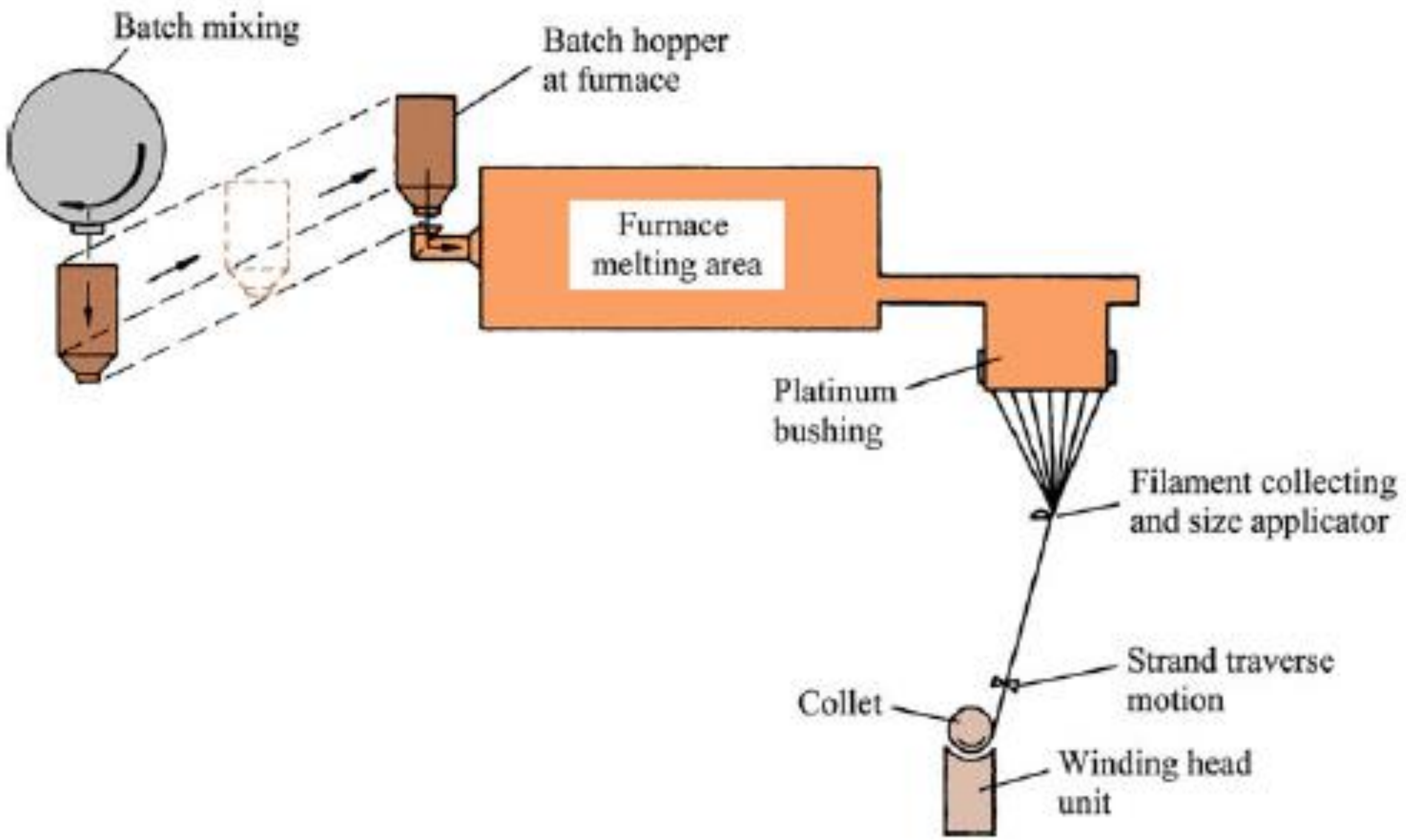


Fig. 2.3 Schematic of glass fiber manufacture

Fabrication

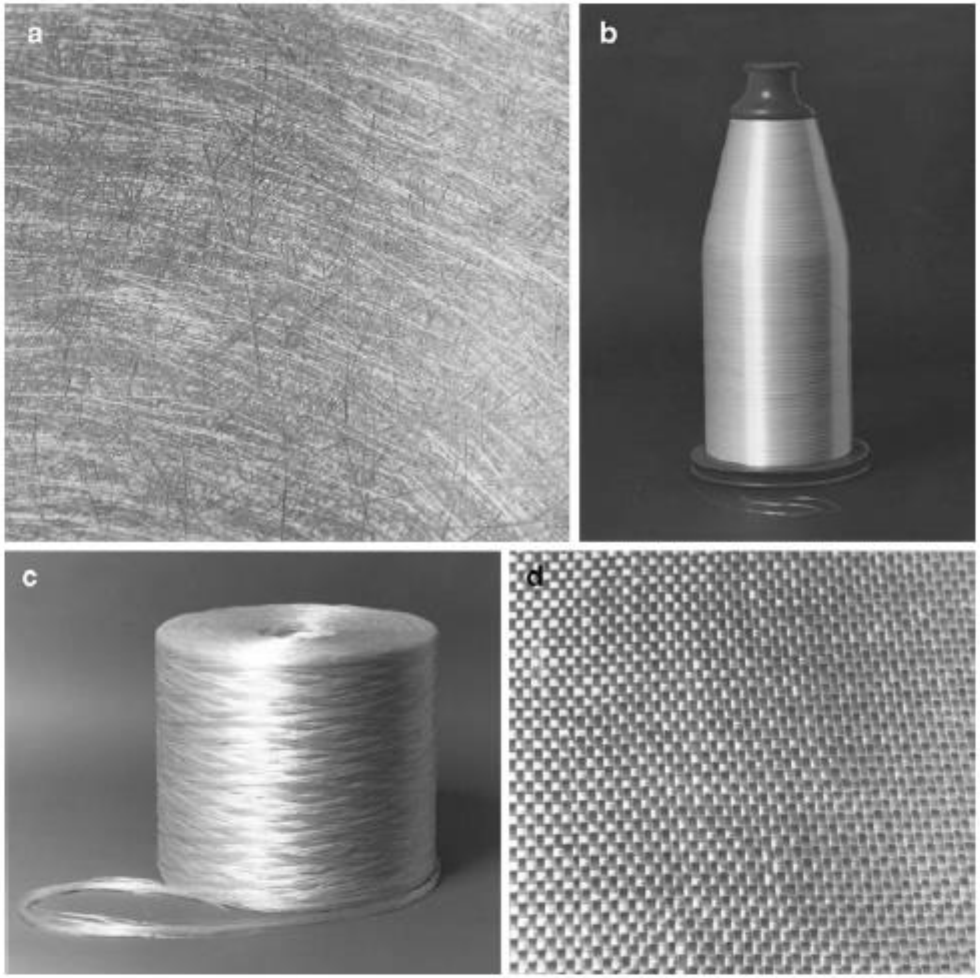


Fig. 2.4 Glass fiber is available in a variety of forms: (**a**) chopped strand, (**b**) continuous yarn, (**c**) roving, (**d**) fabric [courtesy of Morrison Molded Fiber Glass Company]

Fig. 2.5 Continuous glass fibers (cut from a spool) obtained by the sol–gel technique [from Sakka (1985), used with permission]

Structure

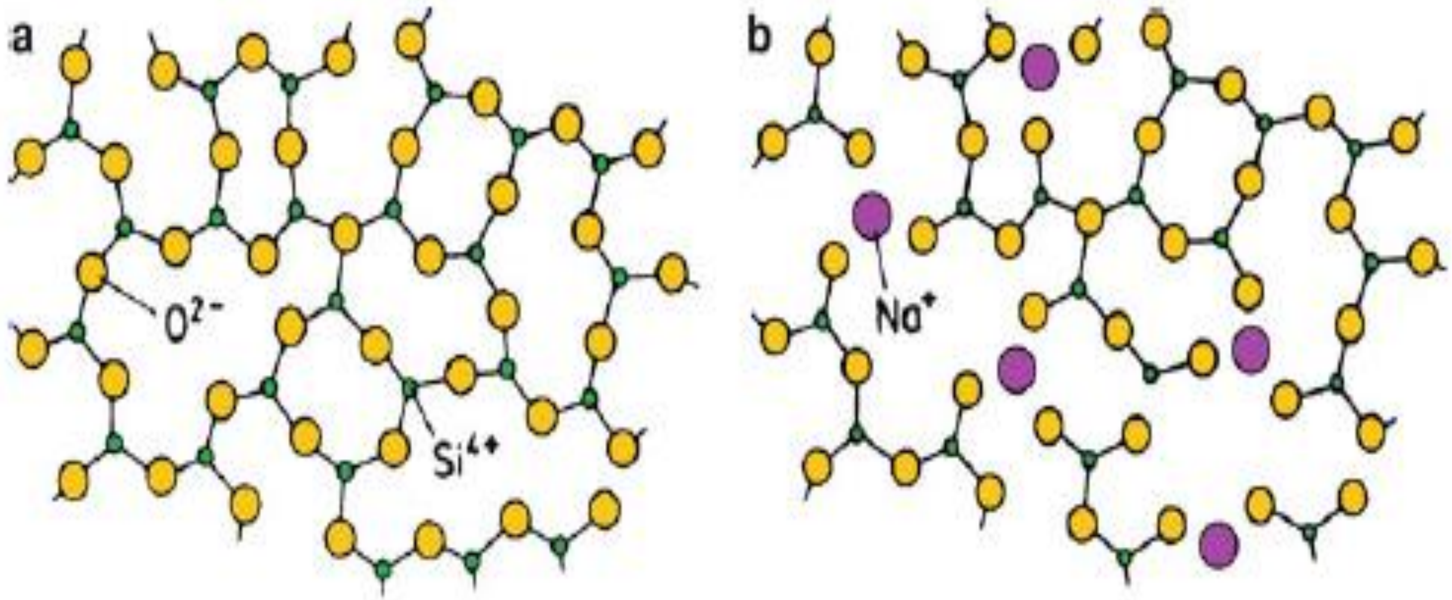


Fig. 2.6 Amorphous structure of glass: (**a**) a two-dimensional representation of silica glass network and (**b**) a modified network that results when Na_2O is added to (**a**). Note that Na^+ is ionically linked with O^{2-} but does not join the network directly

Properties and Applications

Table 2.2 Typical properties of E glass fibers

Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Coefficient of thermal expansion (K^{-1})
2.55	1,750	70	4.7×10^{-6}

Boron Fibers: Fabrication

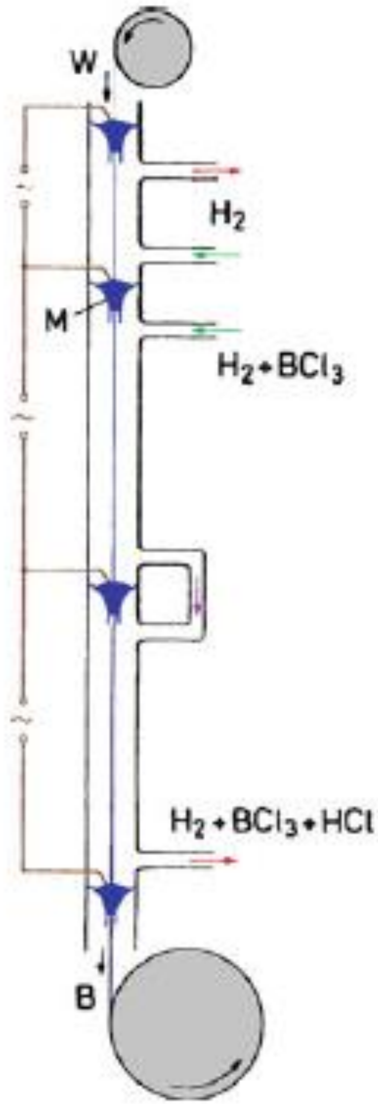


Fig. 2.7 Schematic of boron (B) fiber production by halide decomposition on a tungsten (W) substrate [from van Maaren et al. (1975), used with permission]

Fig. 2.8 A boron filament production facility (courtesy of AVCO Specialty Materials Co.)

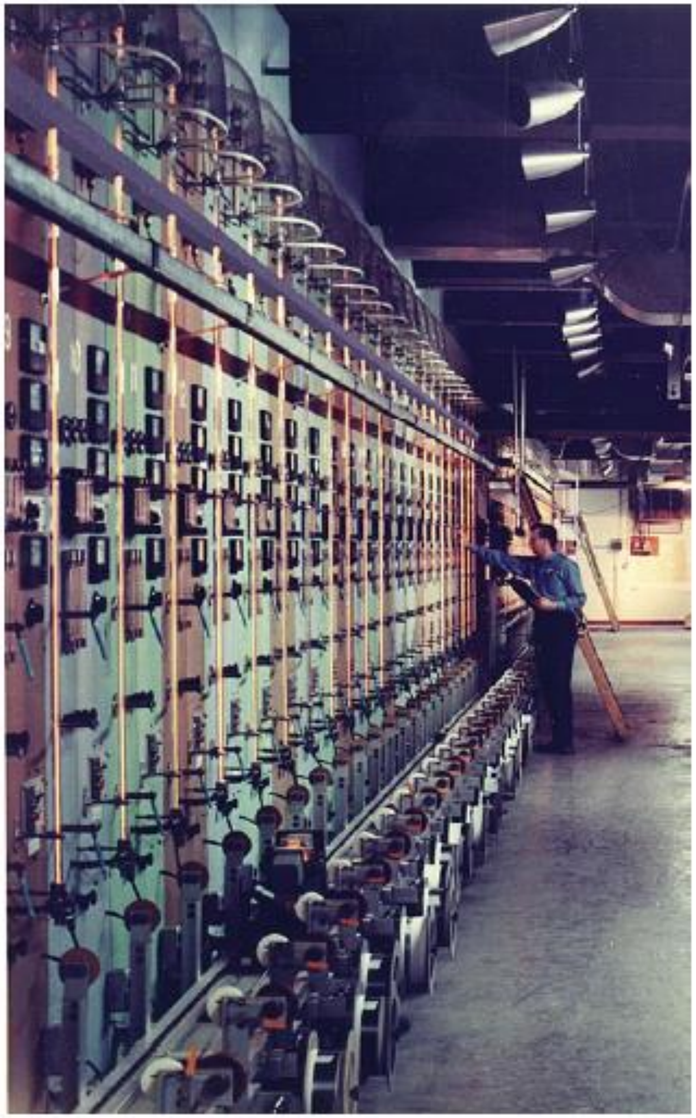
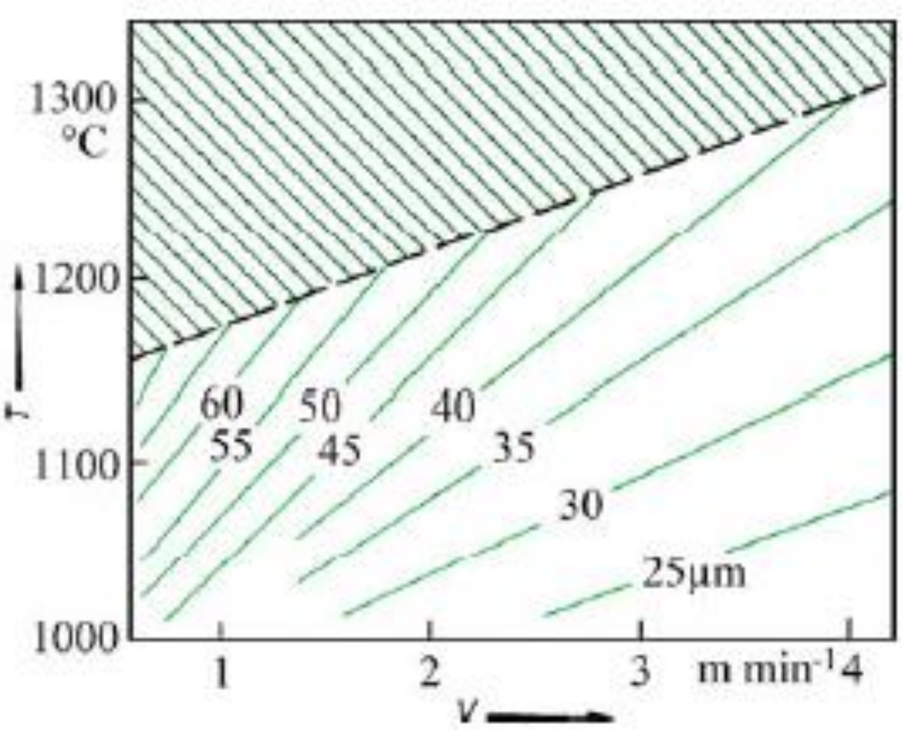


Fig. 2.9 Temperature (T) vs. wire speed (V) for a series of boron filament diameters. Filaments formed in the gray region (above the *dashed line*) contain crystalline regions and are undesirable [from van Maaren et al. (1975), used with permission]



Structure and Morphology

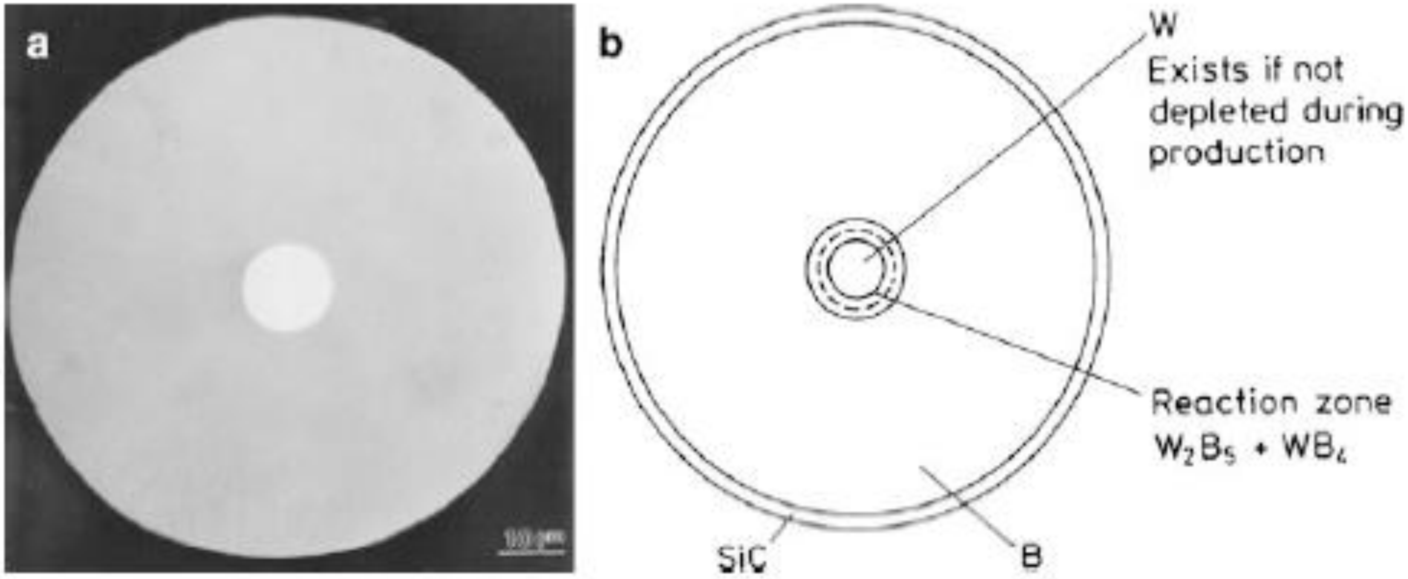


Fig. 2.10 (**a**) Cross-section of a 100-μm-diameter boron fiber. (**b**) Schematic of the cross-section of a boron fiber with SiC barrier layer

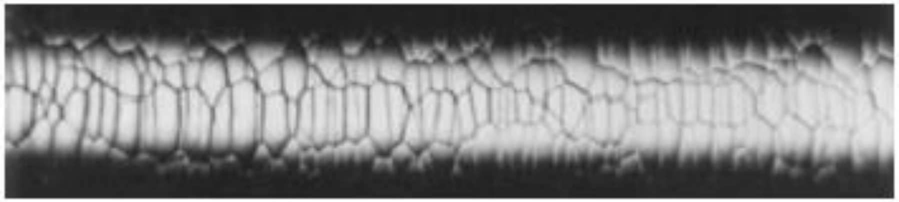
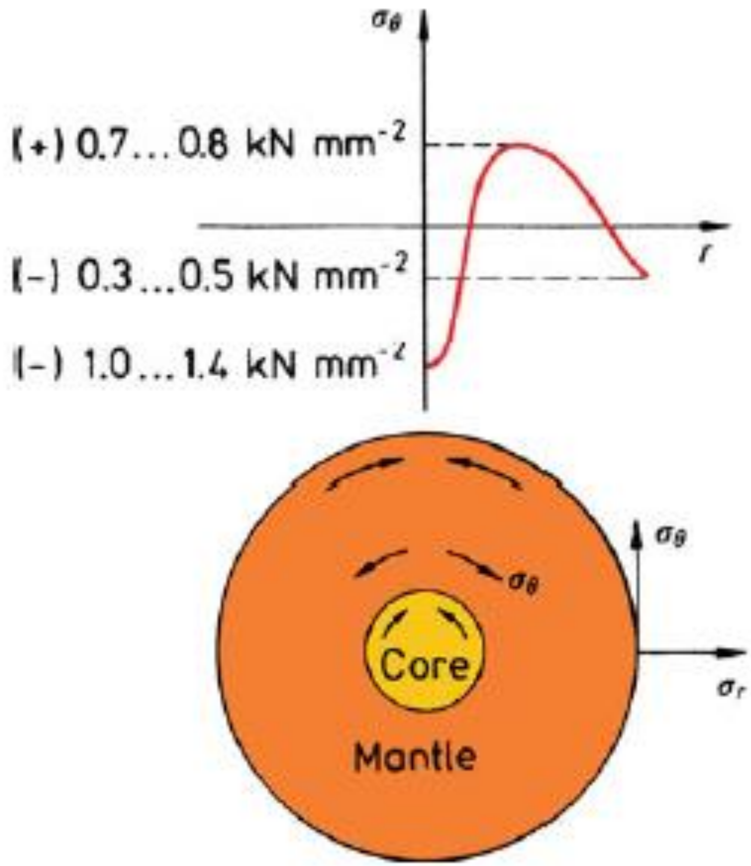


Fig. 2.11 Characteristic corncob structure of boron fiber [from van Maaren et al. (1975), used with permission]. The fiber diameter is 142 μm

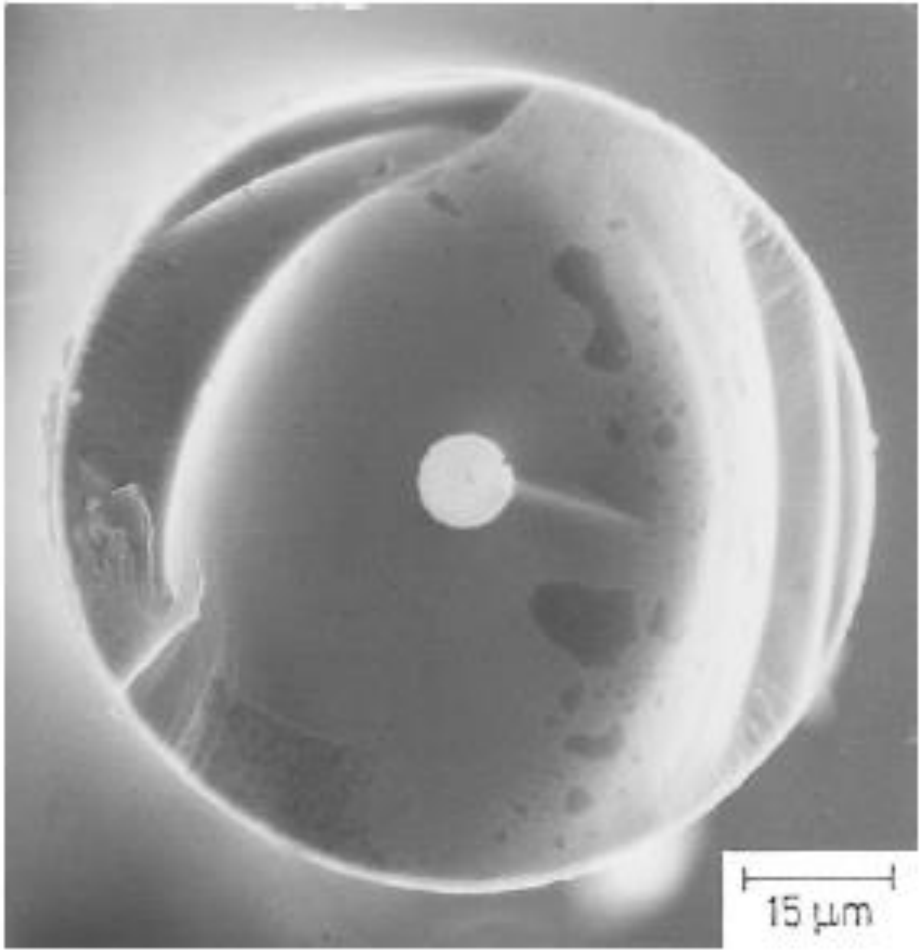
Fracture Characteristics

Fig. 2.12 Schematic of residual stress pattern across the transverse section of a boron fiber [from Vega-Boggio and Vingsbo (1978), used with permission]



Properties and Applications of Boron Fibers

Fig. 2.13 Fracture surface of a boron fiber showing a characteristically brittle fracture and a radial crack



Carbon Fibers

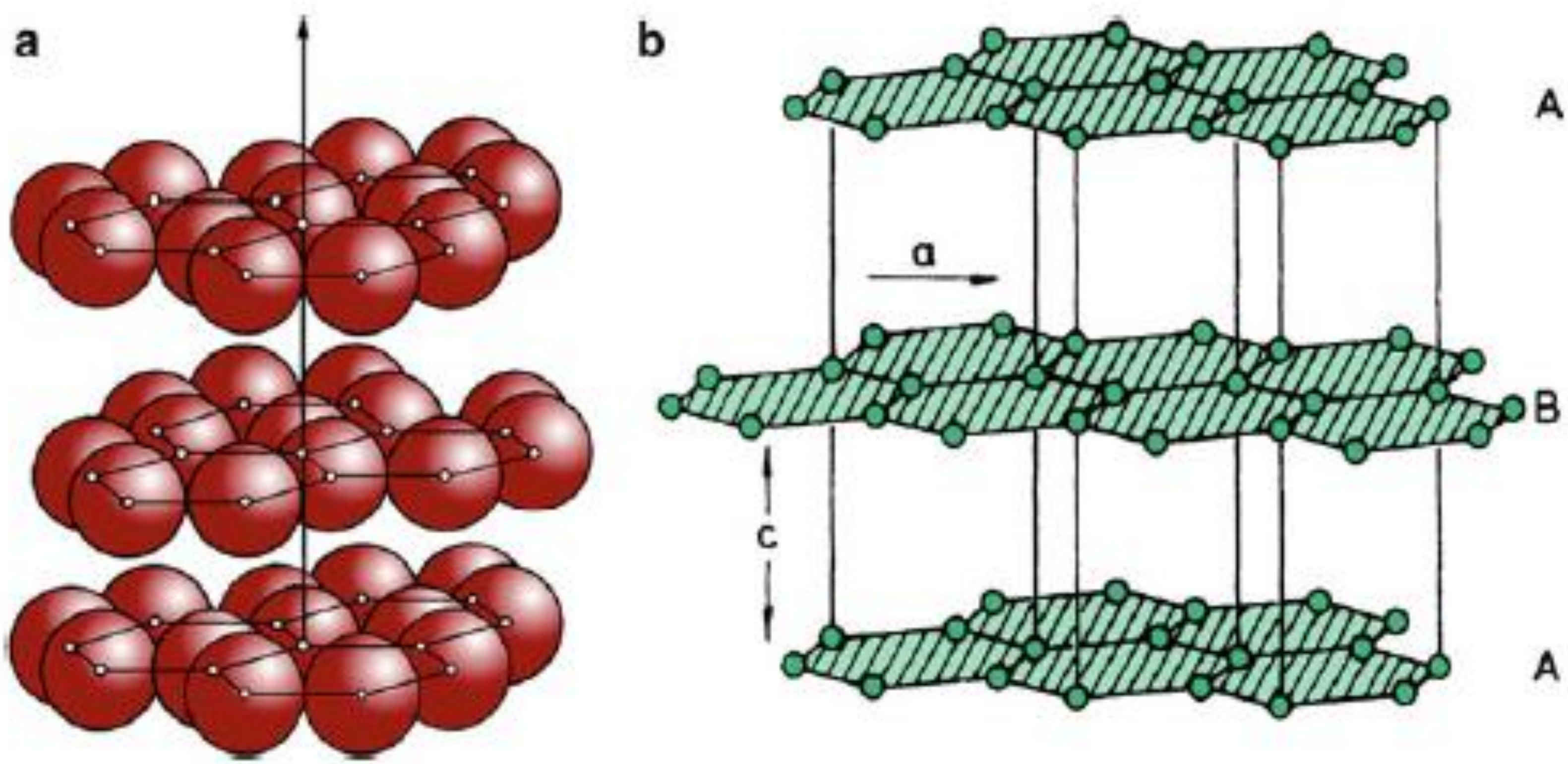


Fig. 2.14 (**a**) Graphitic layer structure. The layers are shown not in contact for visual ease. (**b**) The hexagonal lattice structure of graphite

Processing: Ex-PAN Carbon Fibers

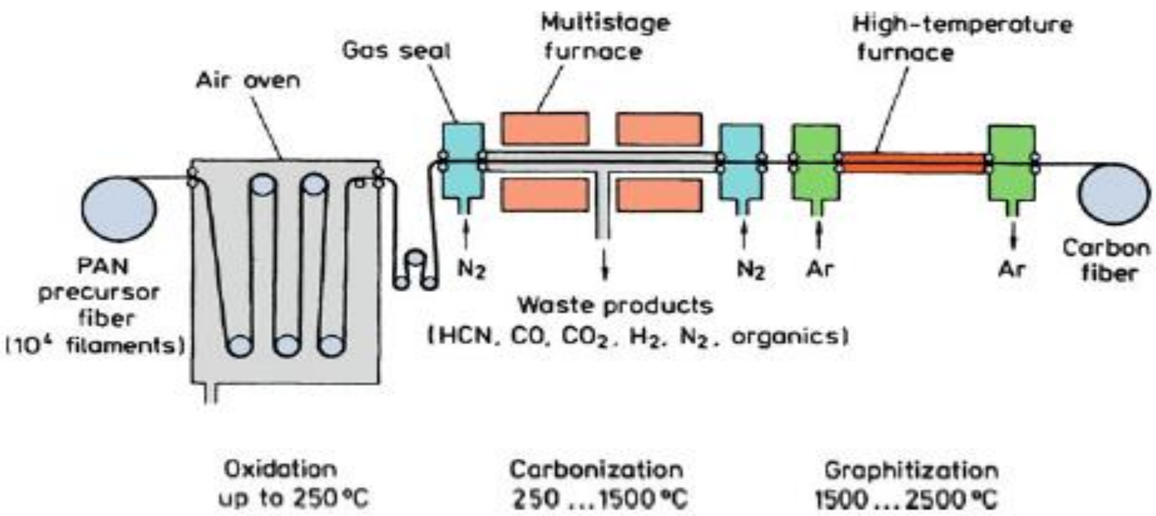


Fig. 2.15 Schematic of PAN-based carbon fiber production [reprinted with permission from Baker (1983)]

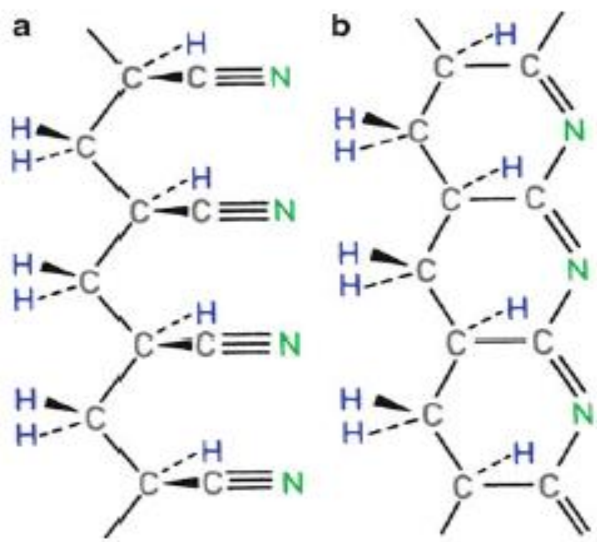


Fig. 2.16 (a) Flexible polyacrylonitrile molecule. (b) Rigid ladder (or oriented cyclic) molecule

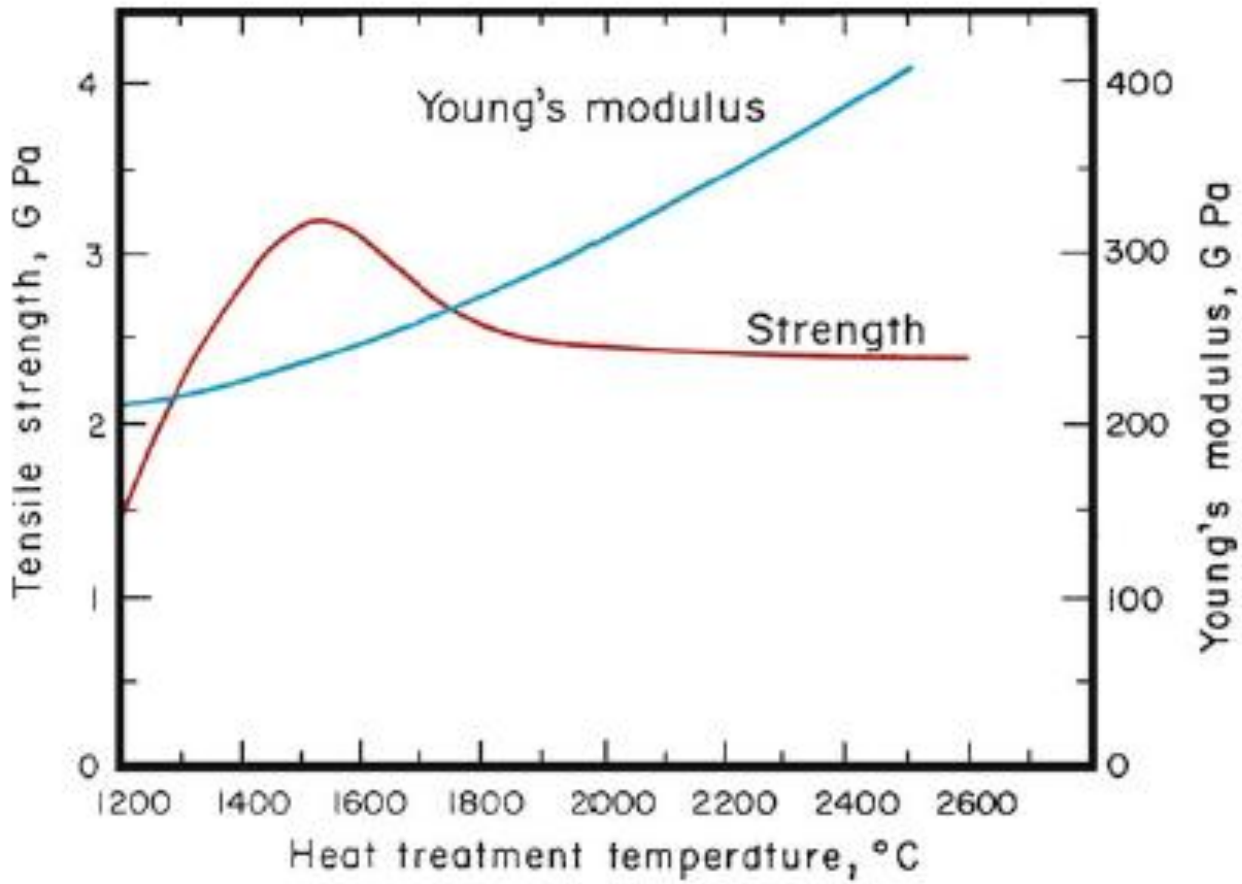
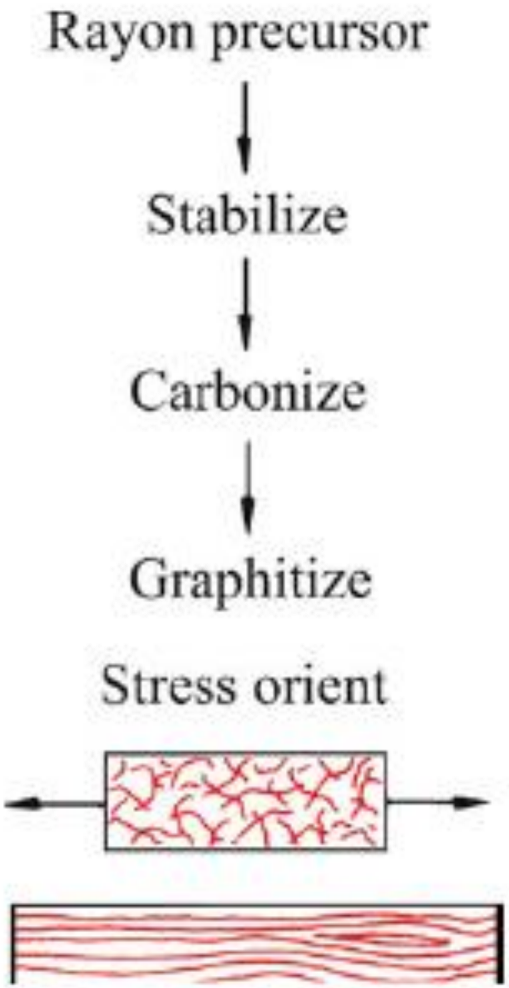


Fig. 2.17 Strength and elastic modulus of carbon fiber as a function of final heat treatment temperature [after Watt (1970), used with permission]

Ex-Cellulose Carbon Fibers

Fig. 2.18 Schematic of rayon-based carbon fiber production [after Diefendorf and Tokarsky (1975), used with permission]



Ex-Pitch Carbon Fibers

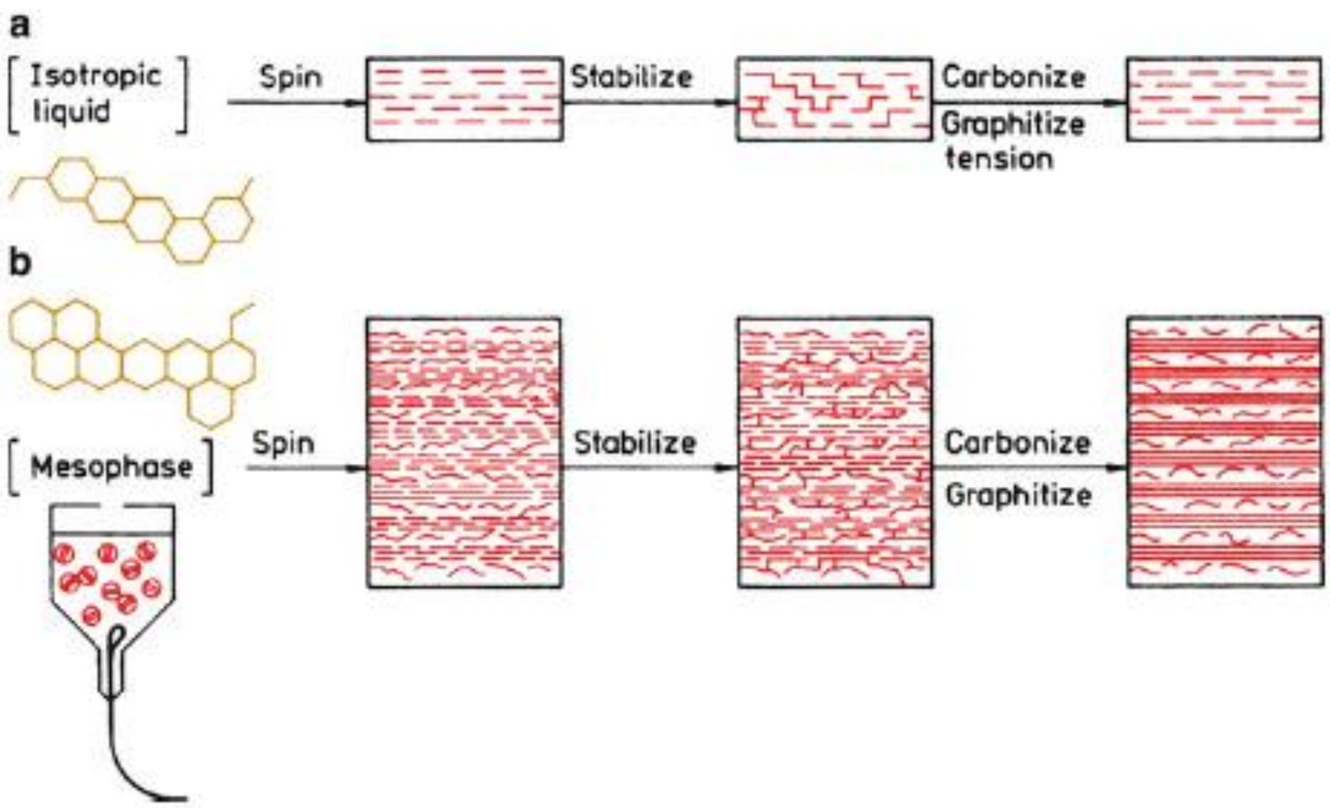


Fig. 2.19 Schematic of pitch-based carbon fiber production: (**a**) isotropic pitch process, (**b**) mesophase pitch process [with permission from Diefendorf and Tokarsky (1975)]

Structural Changes Occurring During Processing

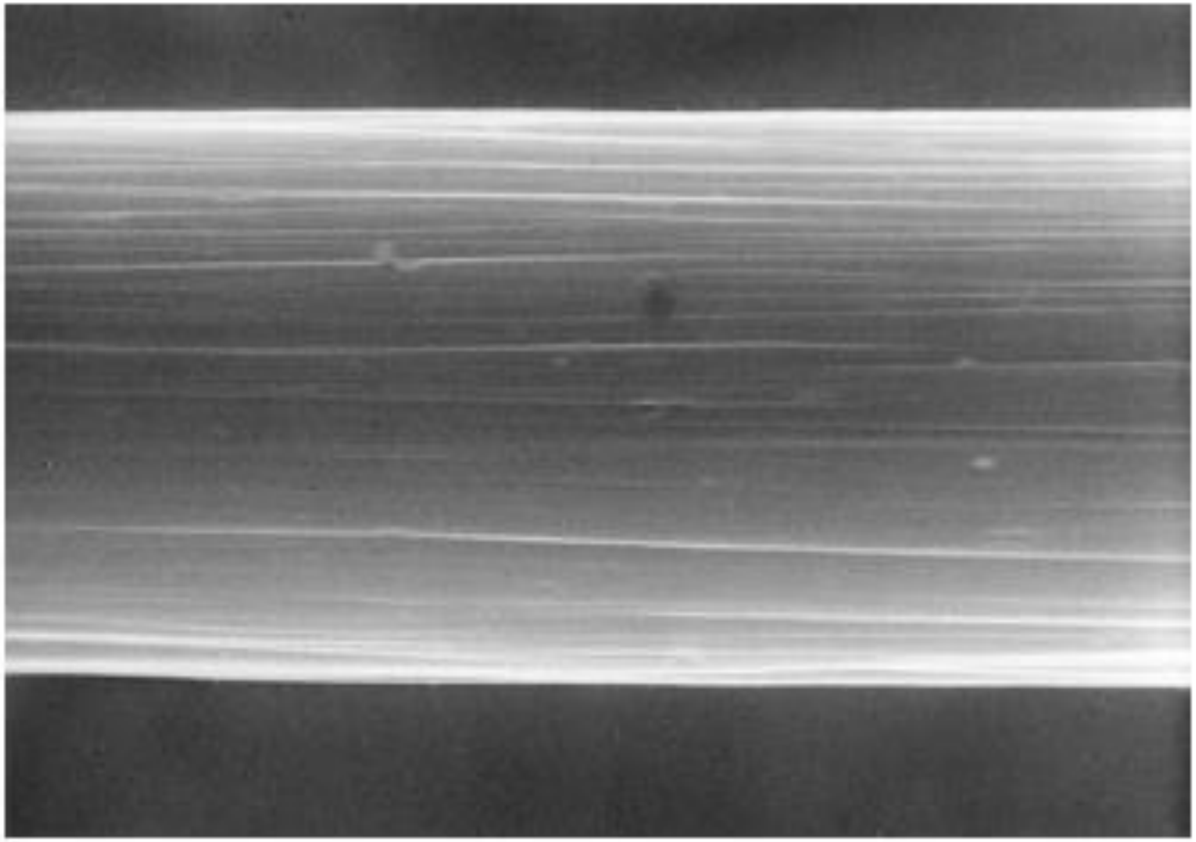


Fig. 2.20 Scanning electron micrograph of PAN-based carbon fiber (fiber diameter is 8 μm). Note the surface markings that stem from the fiber drawing process

Fig. 2.21 Two-dimensional representation of PAN-based carbon fiber [after Bennett and Johnson (1979), used with permission]

Properties and Applications

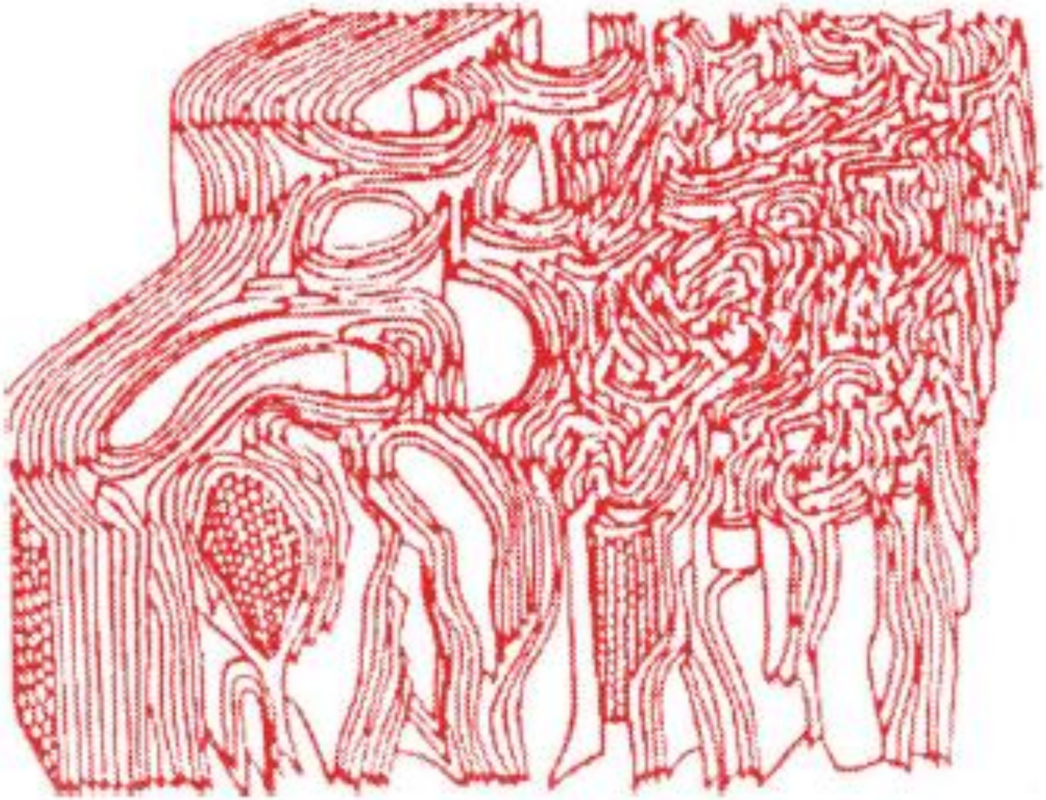


Fig. 2.22 Three-dimensional representation of PAN-based carbon fiber [from Bennett and Johnson (1978), used with permission]

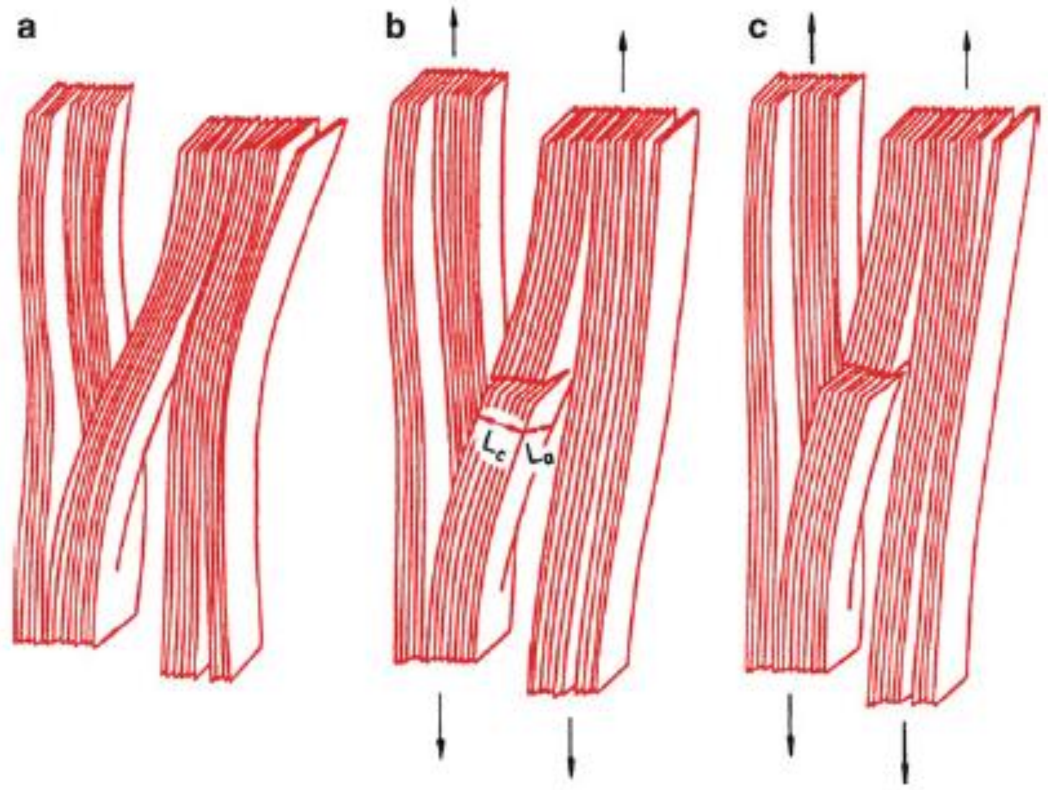
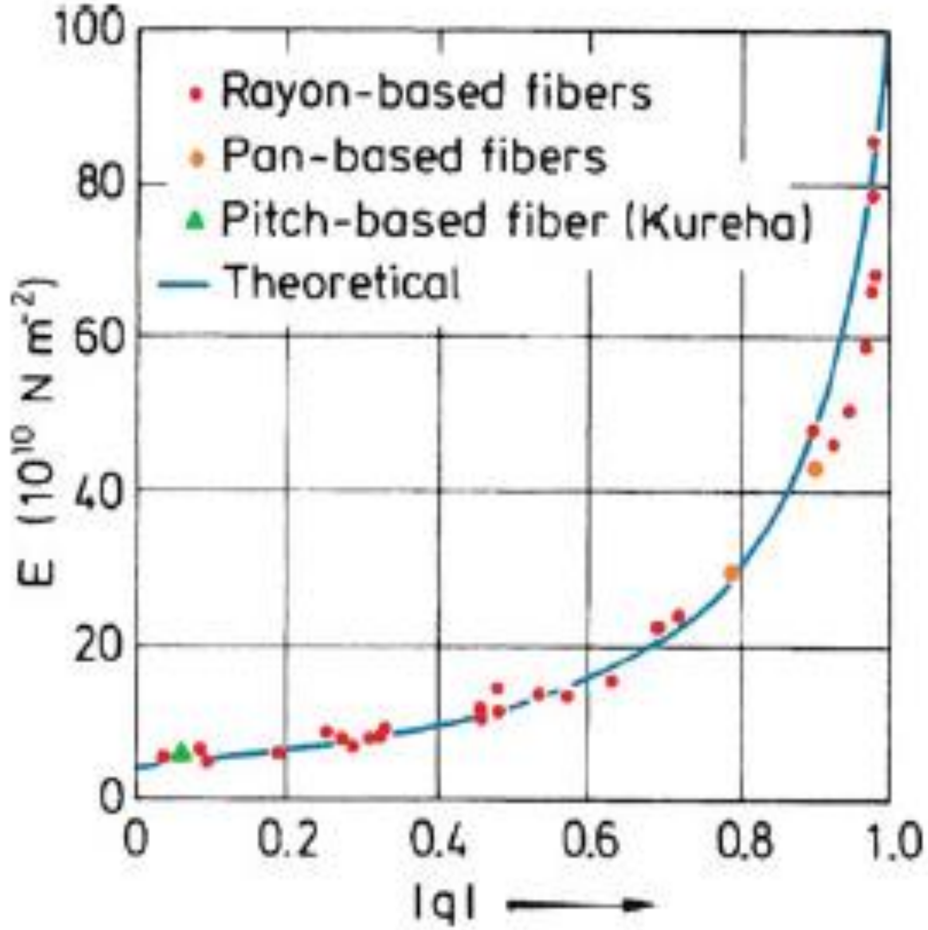


Fig. 2.23 Model for tensile failure of carbon fiber: (**a**) a misoriented crystallite linking two crystallites parallel to the fiber axis, (**b**) basal plane rupture under the action of applied stress, (**c**) complete failure of the misoriented crystallite [from Bennett et al. (1983), used with permission]

Fig. 2.24 Variation of longitudinal Young's modulus for various carbon fibers with the degree of preferred orientation. The value of the orientation parameter, q, is 1 for perfect orientation and zero for the isotropic case [from Fourdeux et al. (1971), used with permission]



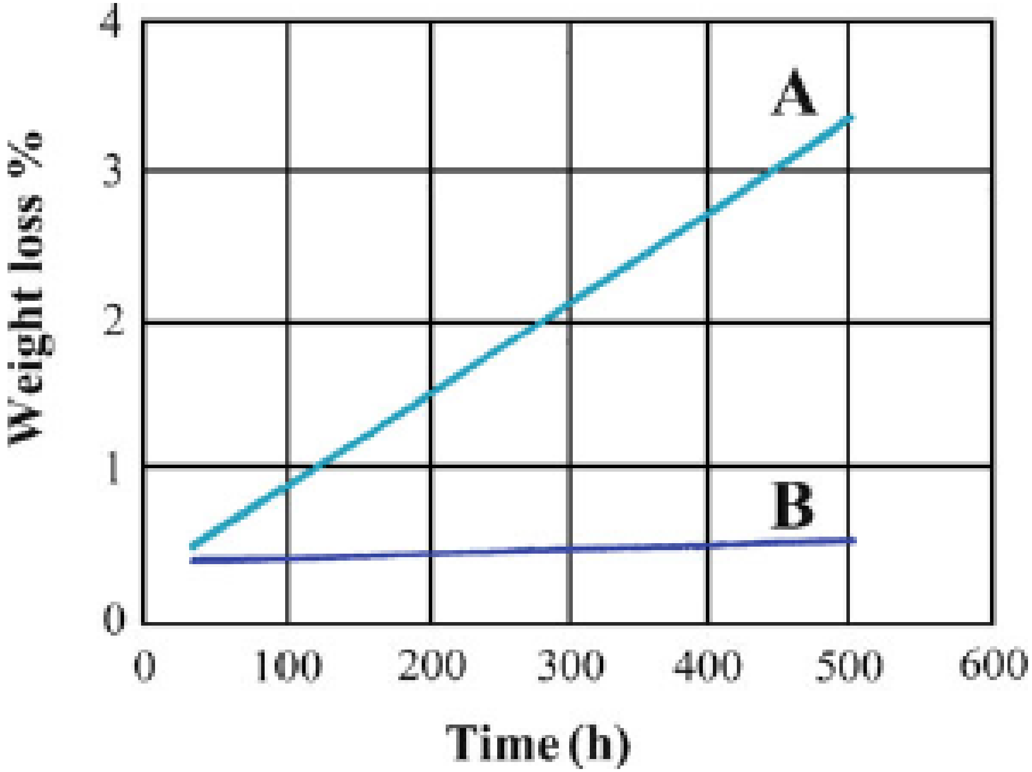


Fig. 2.25 Oxidation resistance, measured as weight loss in air at 350 °C, of carbon fibers having different moduli: (*A*) Low modulus Celion 3000 (240 GPa) and (*B*) High modulus Celion G-50 (345 GPa) [after Riggs JP (1985) Encyclopedia of polymer science and engineering, 2e, vol 2, John Wiley and Sons, New York, reprinted with permission]

Table 2.4 Comparison of properties of different carbon fibers

Precursor	Density (g/cm^3)	Young's modulus (GPa)	Electrical resistivity (10^{-4} Ω cm)
Rayon[a]	1.66	390	10
Polyacrylonitrile[b] (PAN)	1.74	230	18
Pitch (Kureha)			
LT[c]	1.6	41	100
HT[d]	1.6	41	50
Mesophase pitch[e]			
LT	2.1	340	9
HT	2.2	690	1.8
Single-crystal[f] graphite	2.25	1,000	0.40

[a]Union Carbide, Thornel 50
[b]Union Carbide, Thornel 300
[c]*LT* low-temperature heat-treated
[d]*HT* high-temperature heat-treated
[e]Union Carbide type P fibers
[f]Modulus and resistivity are in-plane values
Source: Adapted with permission from Singer (1979)

Organic Fibers

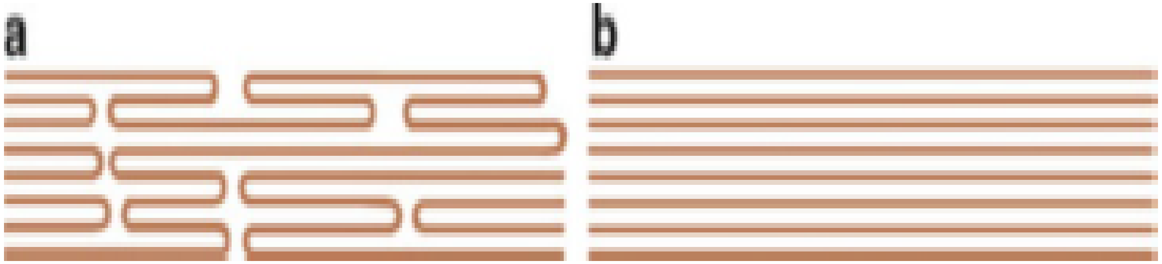


Fig. 2.26 Two types of molecular orientation: (**a**) oriented *without* high molecular extension and (**b**) oriented *with* high molecular extension [from Barham and Keller (1985), used with permission]

Oriented Polyethylene Fibers

Processing of Polyethylene Fibers

Gel Spinning of Polyethylene Fiber

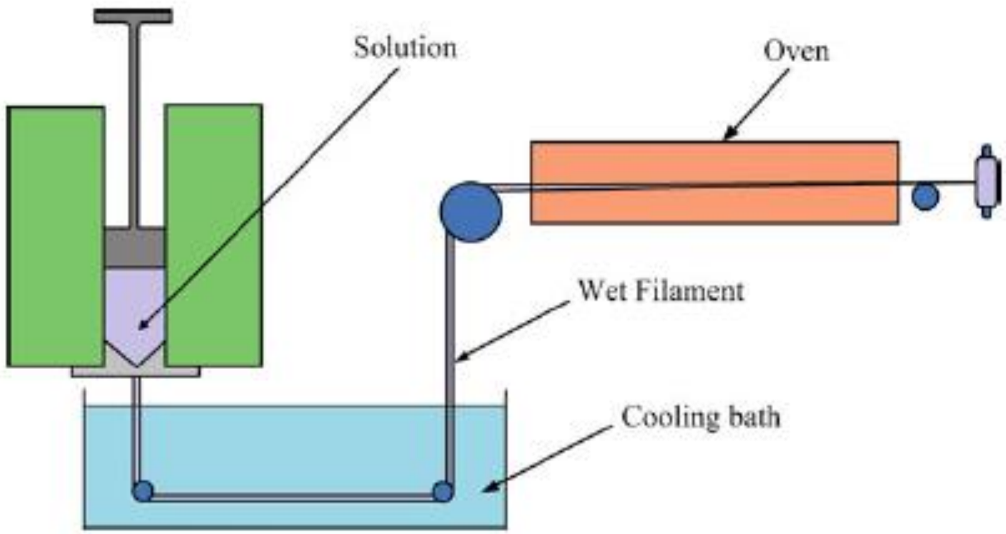


Fig. 2.27 Gel spinning process for making the high-modulus polyethylene fiber concentration

Table 2.5 Properties of polyethylene fibers[a]

Property	Spectra 900	Spectra 1000
Density (g/cm^3)	0.97	0.97
Diameter (μm)	38	27
Tensile strength (GPa)	2.7	3.0
Tensile modulus (GPa)	119	175
Tensile strain to fracture (%)	3.5	2.7

[a]Manufacturer's data; indicative values

Structure and Properties of Polyethylene Fiber

Table 2.5 Properties of polyethylene fibers[a]

Property	Spectra 900	Spectra 1000
Density (g/cm^3)	0.97	0.97
Diameter (μm)	38	27
Tensile strength (GPa)	2.7	3.0
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Tensile strain to fracture (%)	3.5	2.7

[a]Manufacturer's data; indicative values

Processing of Aramid Fibers

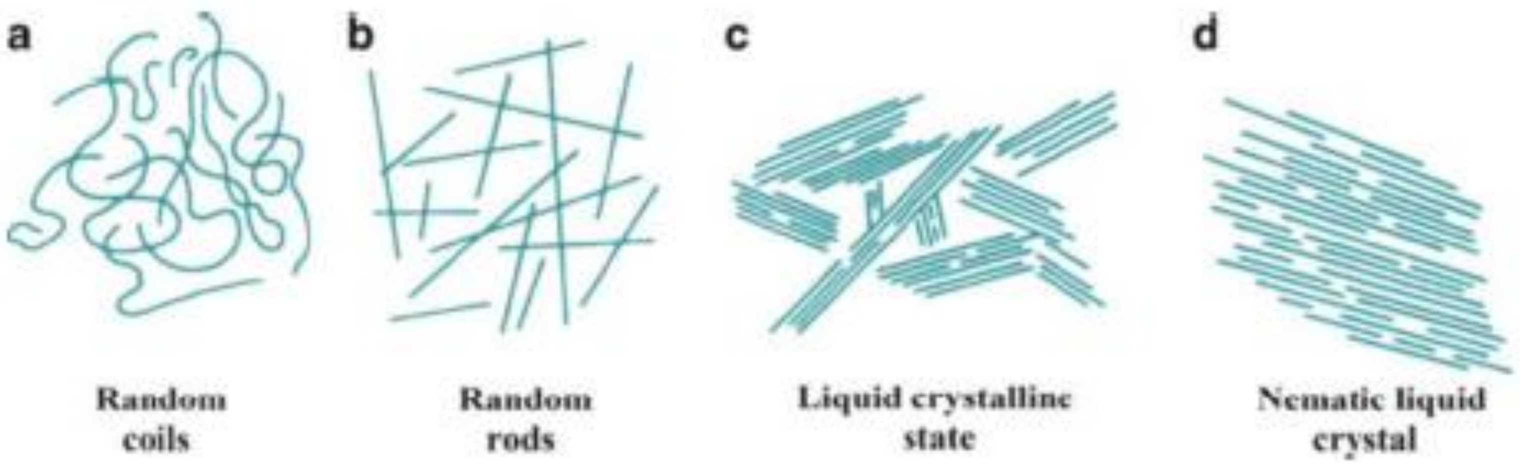


Fig. 2.28 Various states of polymer in solution: (**a**) two-dimensional, linear, flexible chains (random coils), (**b**) random array of rods, (**c**) partially ordered liquid crystalline state, and (**d**) nematic liquid crystal (randomly distributed parallel rods)

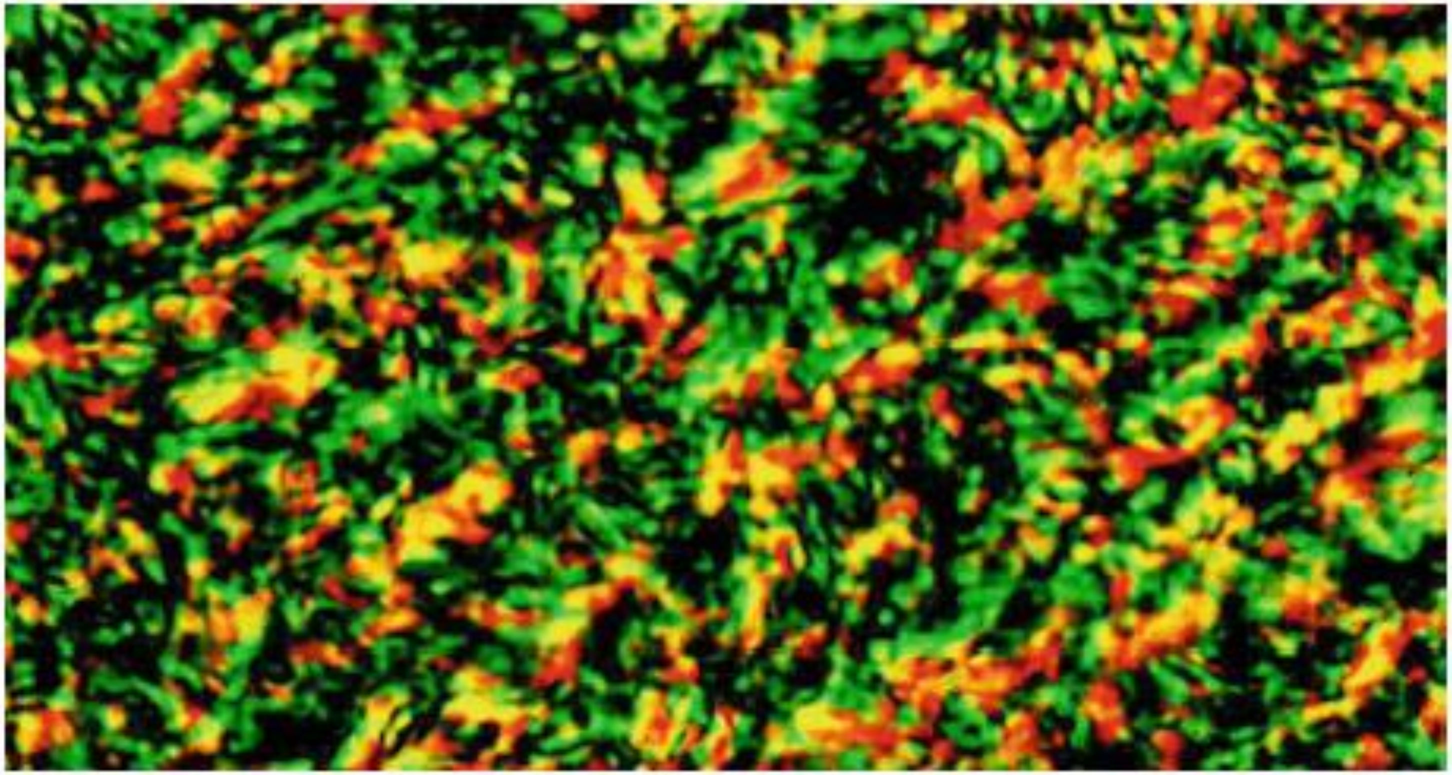


Fig. 2.29 Anisotropic Kevlar aramid and sulfuric acid solution at rest between crossed polarizers [courtesy of Du Pont Co.]

▪

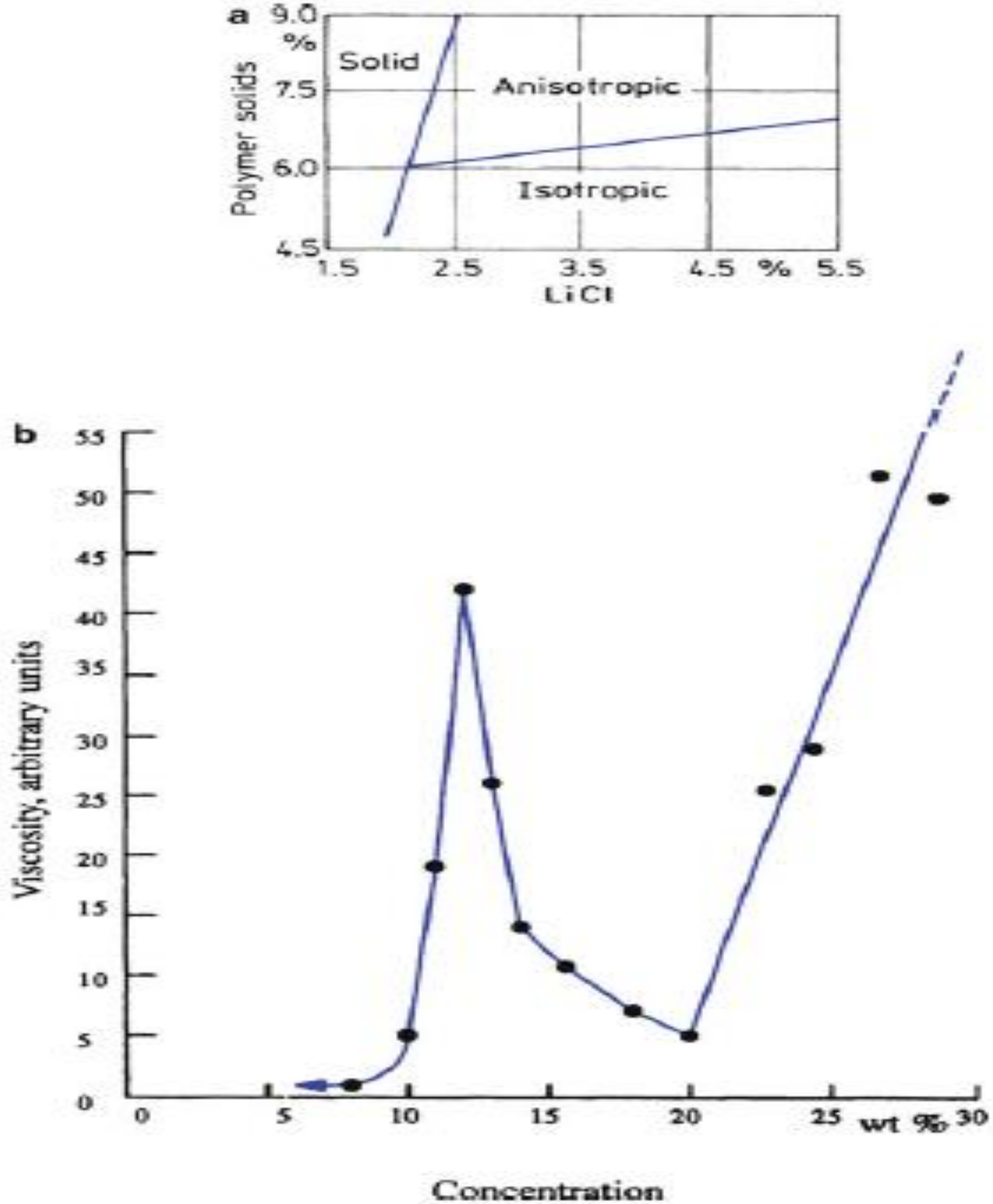
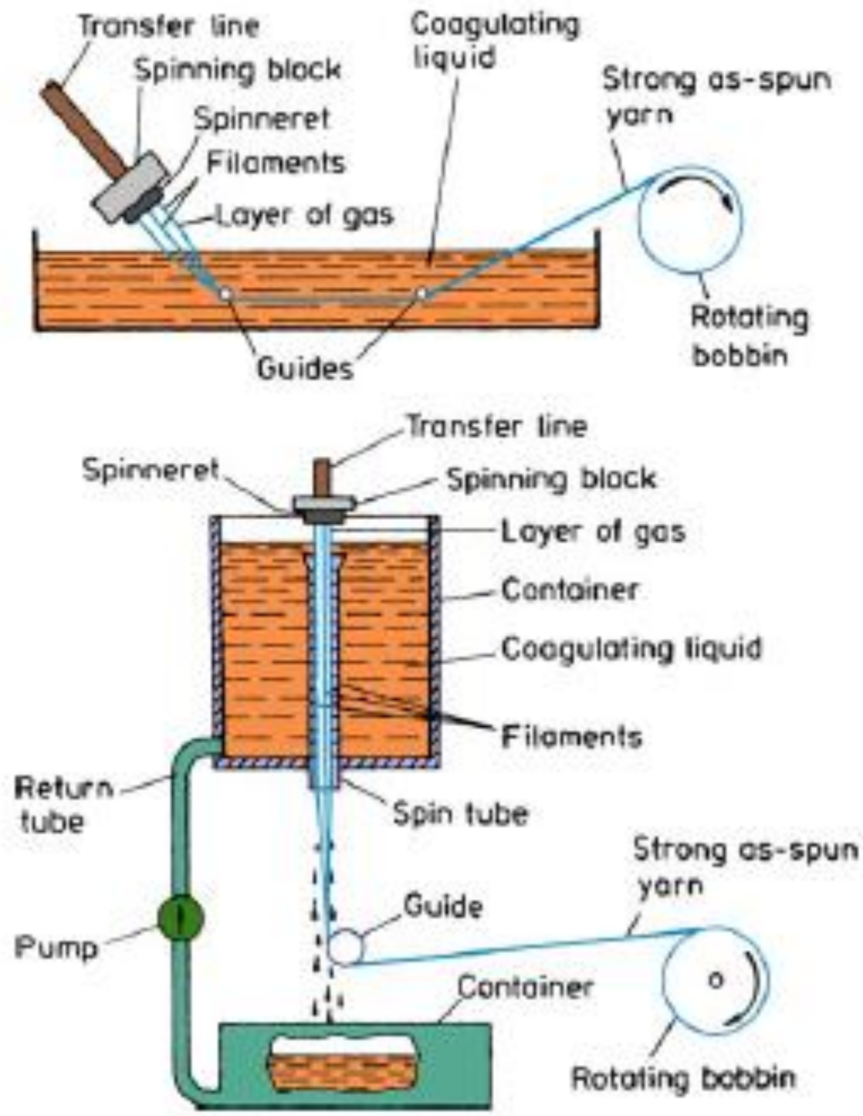


Fig. 2.30 (a) Phase diagram of poly-*p*-benzamide in tetramethylurea–LiCl solutions. Note that the anisotropic state is obtained under certain conditions [with permission from Magat (1980)] (b) Viscosity vs. polymer concentration in solution. A sharp drop in viscosity occurs when the solution starts becoming anisotropic liquid crystal [after Kwolek and Yang (1993)]

Fig. 2.31 The dry jet–wet spinning process of producing aramid fibers



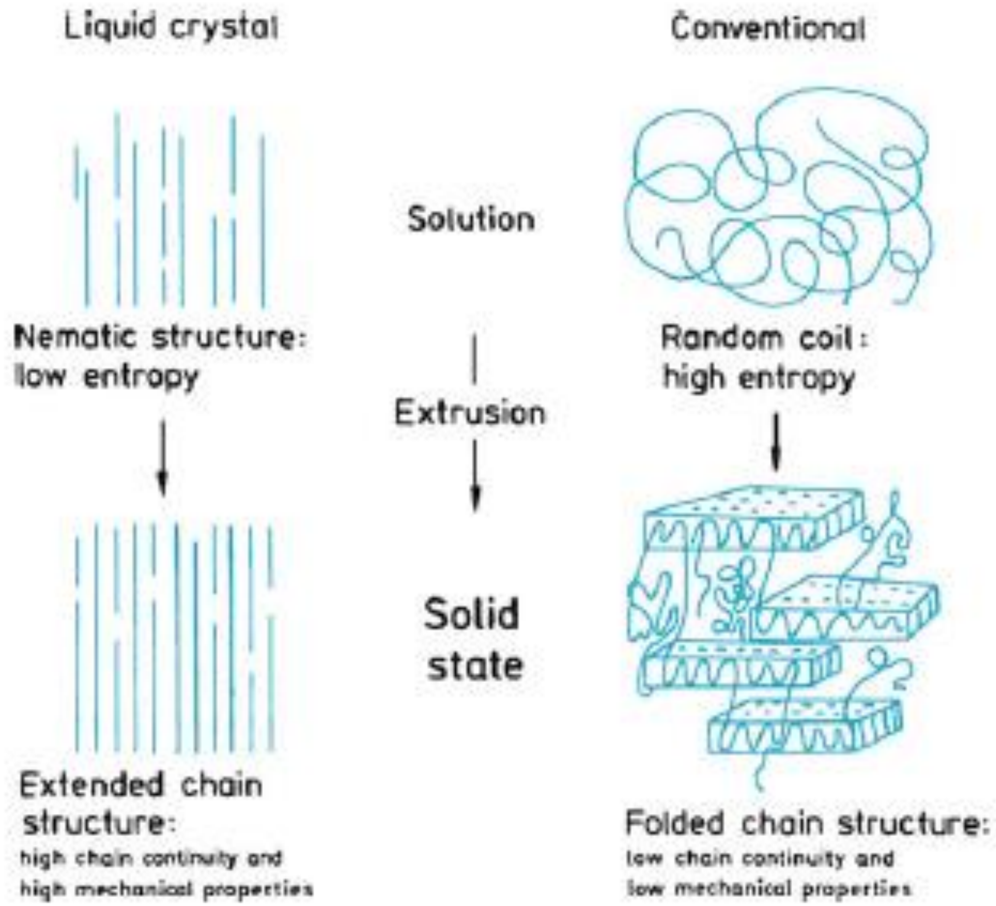


Fig. 2.32 Comparison of dry jet–wet spinning of nematic liquid crystalline solution and conventional spinning of a polymer [reprinted from Jaffe and Jones (1985), p 349, courtesy of Marcel Dekker, Inc.]

Structure of Aramid Fibers

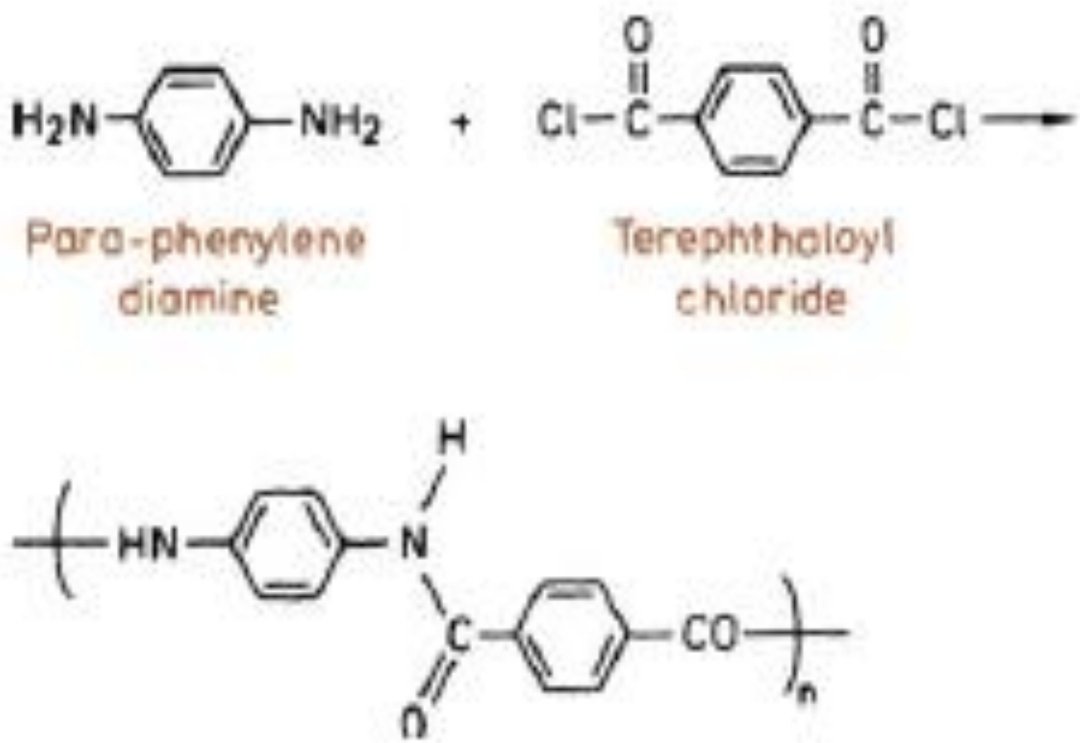


Fig. 2.33 Chemical structure of aramid fiber

Fig. 2.34 Strong covalent bonding in the fiber direction and weak hydrogen bonding (indicated by *H*) in the transverse direction

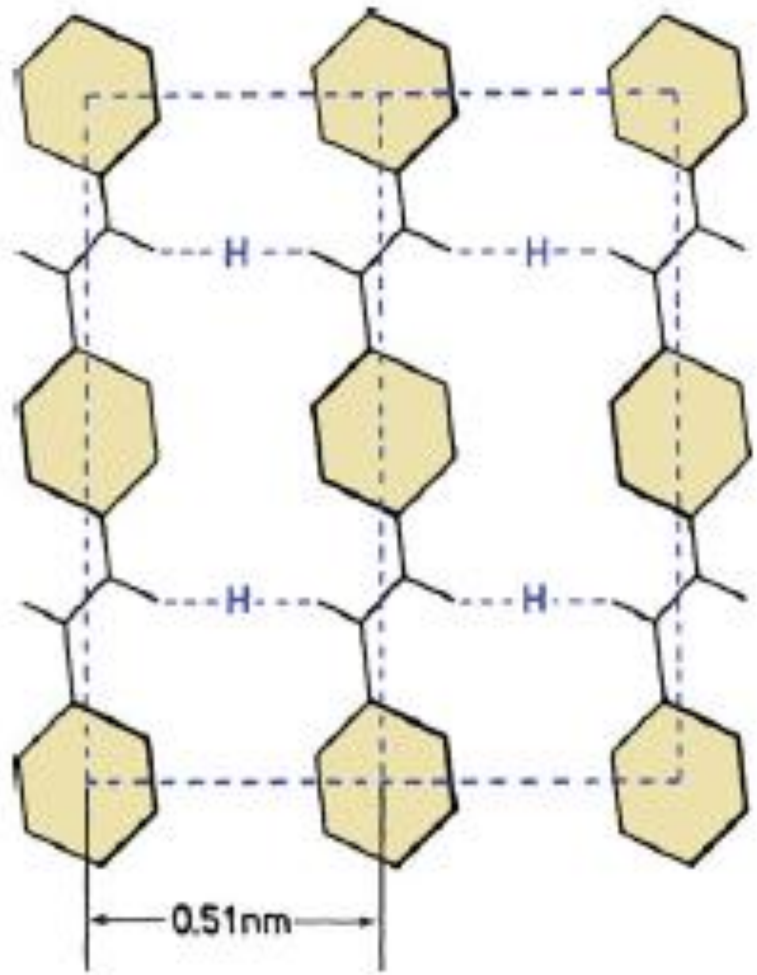
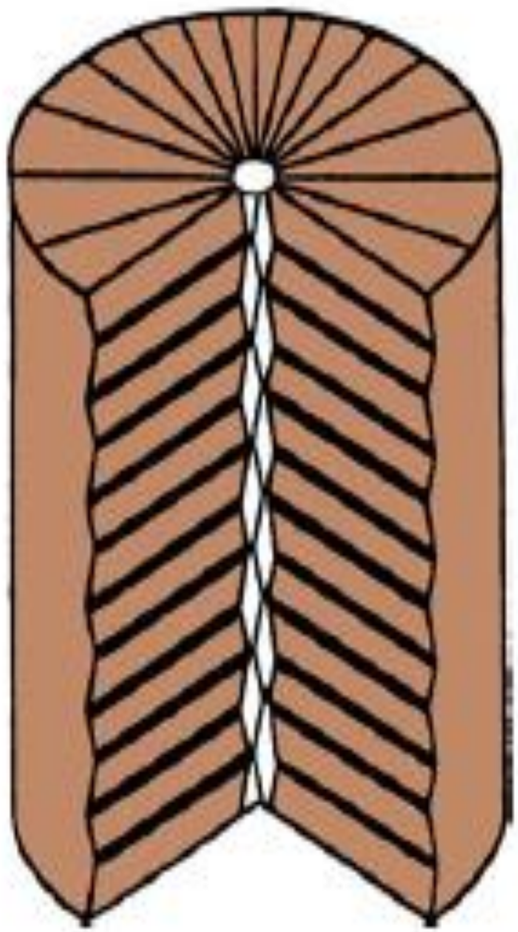


Fig. 2.35 Schematic representation of the supramolecular structure of aramid fiber, Kevlar 49. The structure consists of radially arranged, axially pleated crystalline sheets [from Dobb et al. (1980), used with permission]



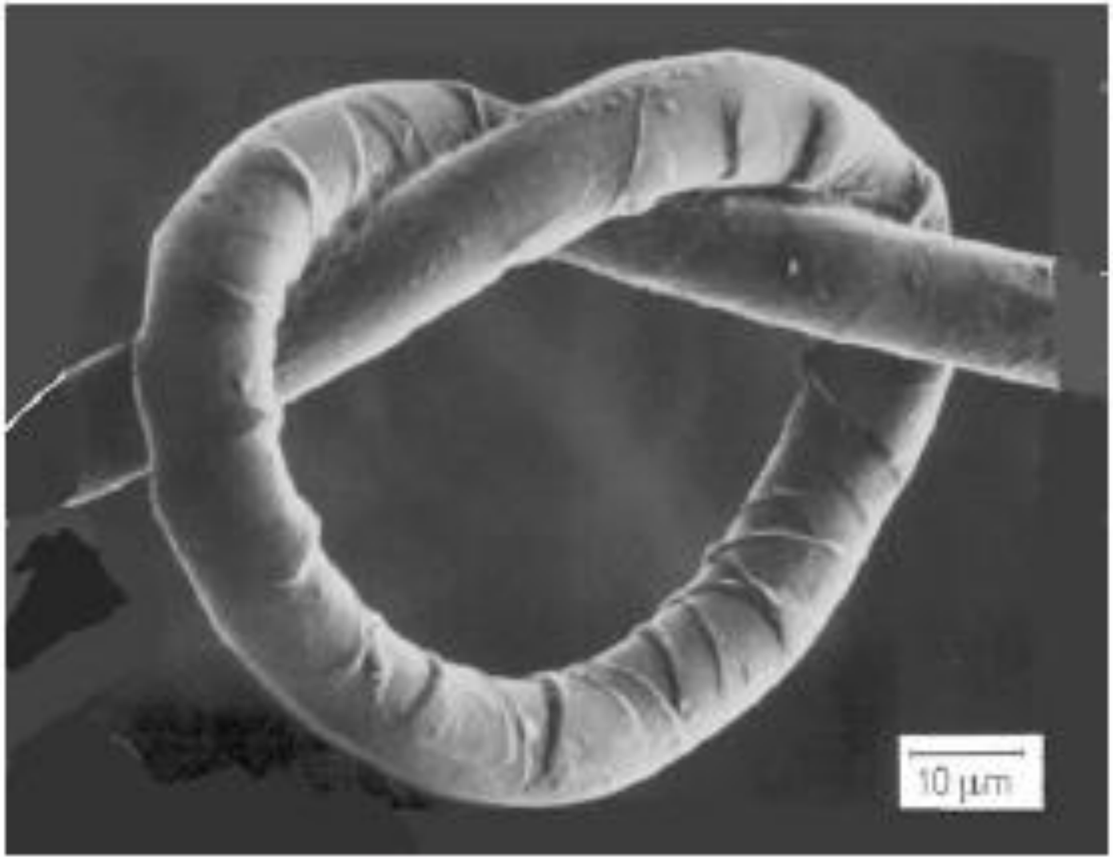


Fig. 2.36 Knotted Kevlar aramid fiber showing buckling marks on the compressive side. The tensile side is smooth [courtesy of Fabric Research Corp.]

Table 2.6 Properties of Kevlar aramid fiber yarns[a]

Property	K 29	K 49	K 119	K 129	K 149
Density (g/cm^3)	1.44	1.45	1.44	1.45	1.47
Diameter (μm)	12	12	12	12	12
Tensile strength (GPa)	2.8	2.8	3.0	3.4	2.4
Tensile strain to fracture (%)	3.5–4.0	2.8	4.4	3.3	1.5–1.9
Tensile modulus (GPa)	65	125	55	100	147
Moisture regain (%) at 25 °C, 65 % RH	6	4.3	–	–	1.5
Coefficient of expansion ($10^{-6}\ K^{-1}$)	−4.0	−4.9	–	–	–

[a] All data from Du Pont brochures. Indicative values only. 25-cm yarn length was used in tensile tests (ASTM D-885). *K* stands for Kevlar, a trademark of Du Pont

logarithmic decrement

$$\Delta = \ln \frac{\theta_n}{\theta_{n+1}},$$

At two successive amplitudes

Table 2.7 Properties of Technora fiber[a]

Density (g/cm^3)	Diameter (μm)	Tensile strength (GPa)	Tensile modulus (GPa)	Tensile strain to fracture (%)
1.39	12	3.1	71	4.4

[a]Manufacturer's data; indicative values only

Ceramic Fibers

Oxide Fibers

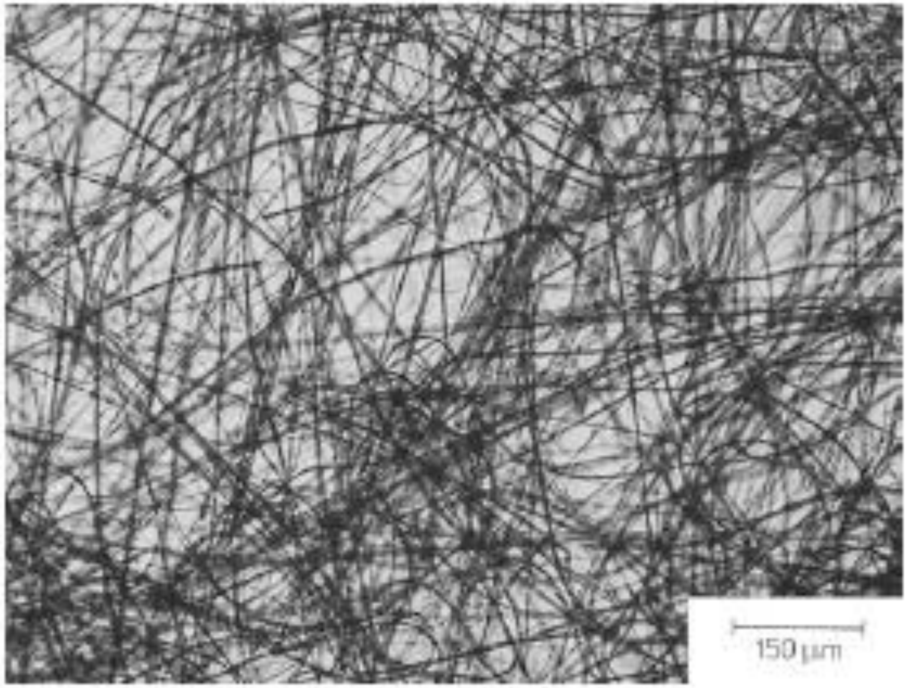


Fig. 2.37 Optical micrograph of Nextel 312 (Al_2O_3 + B_2O_3 + SiO_2) fiber

Table 2.8 Composition and properties of some oxide fibers[a]

Fiber type	Composition (wt.%)	Diameter (μm)	Density, (g/cm^3)	Tensile strength (GPa)	Young's modulus (GPa)
Nextel 312	Al_2O_3-62.5, SiO_2-24.5, B_2O_3-13	10–12	2.70	1.7	150
Nextel 440	Al_2O_3-70, SiO_2-28, B_2O_3-2	10–12	3.05	2.0	190
Nextel 550	Al_2O_3-73, SiO_2-27	10–12	3.03	2.0	193
Nextel 610	Al_2O_3-99+	10–12	3.9	3.1	370
Nextel 650	Al_2O_3-89, ZrO_2-10, Y_2O_3-1	10–12	4.10	2.5	358
Nextel 720	Al_2O_3-85, SiO_2-15	10–12	3.40	2.1	260
Saffil	Al_2O_3-96, SiO_2-4	3	2.3	1.0	100
Saphikon	Single Crystal Al_2O_3	75–250	3.8	3.1	380
Sumitomo	Al_2O_3-85, SiO_2-15	9	3.2	2.6	250

[a]Manufacturer's data

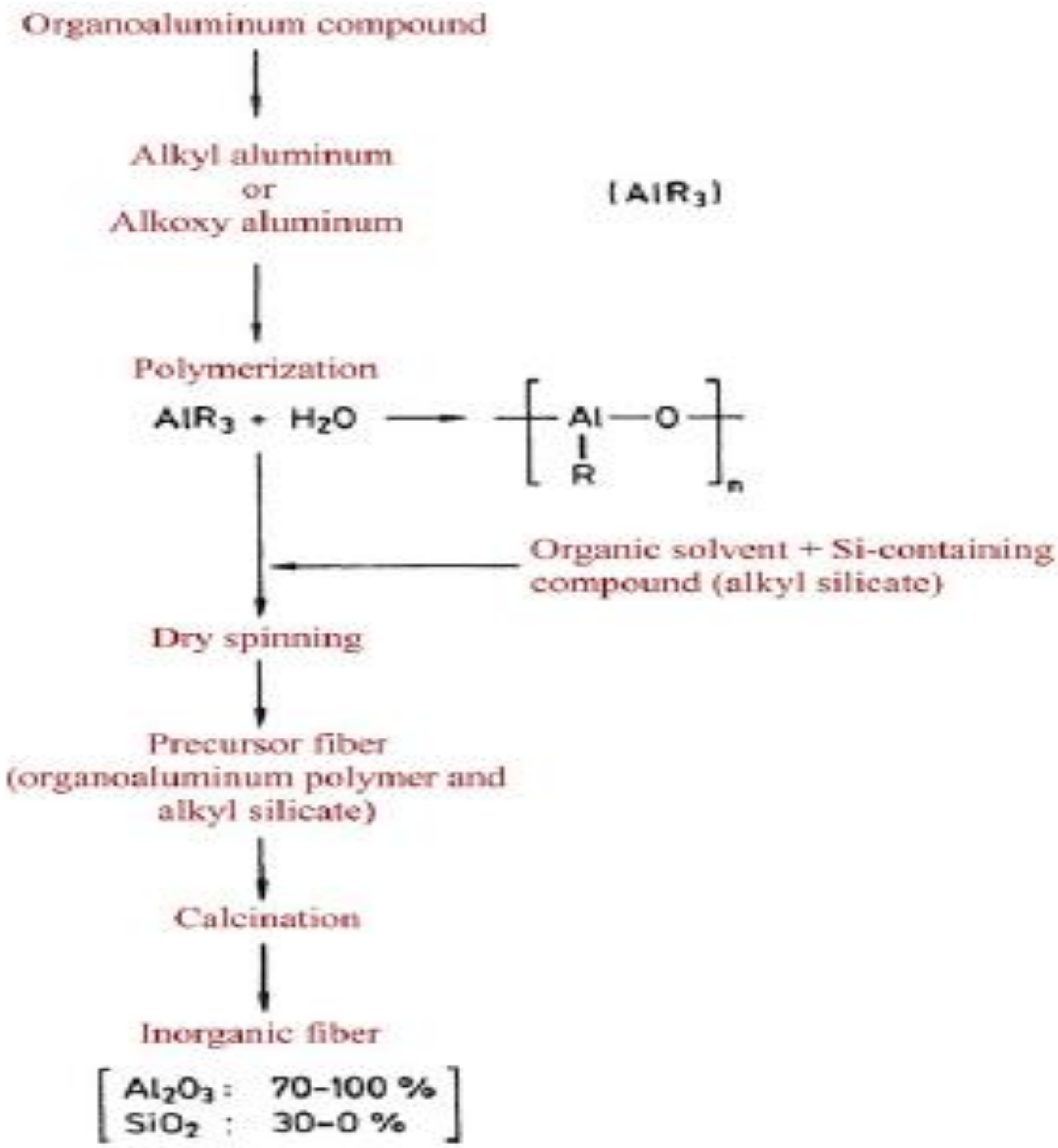
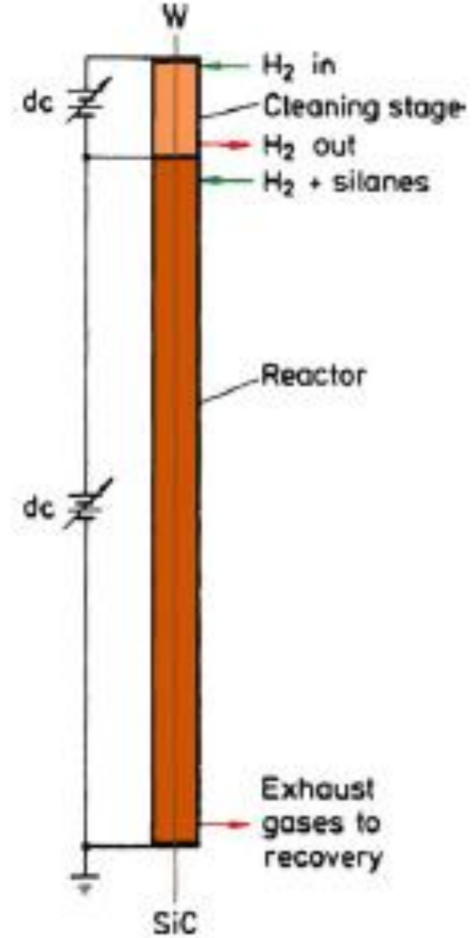


Fig. 2.38 Flow diagram of an alumina + silica fiber production

Nonoxide Fibers

Silicon Carbide Fibers by CVD

Fig. 2.39 CVD process for SiC monofilament fabrication [From J.V. Milewski et al. (1974), reproduced with permission]



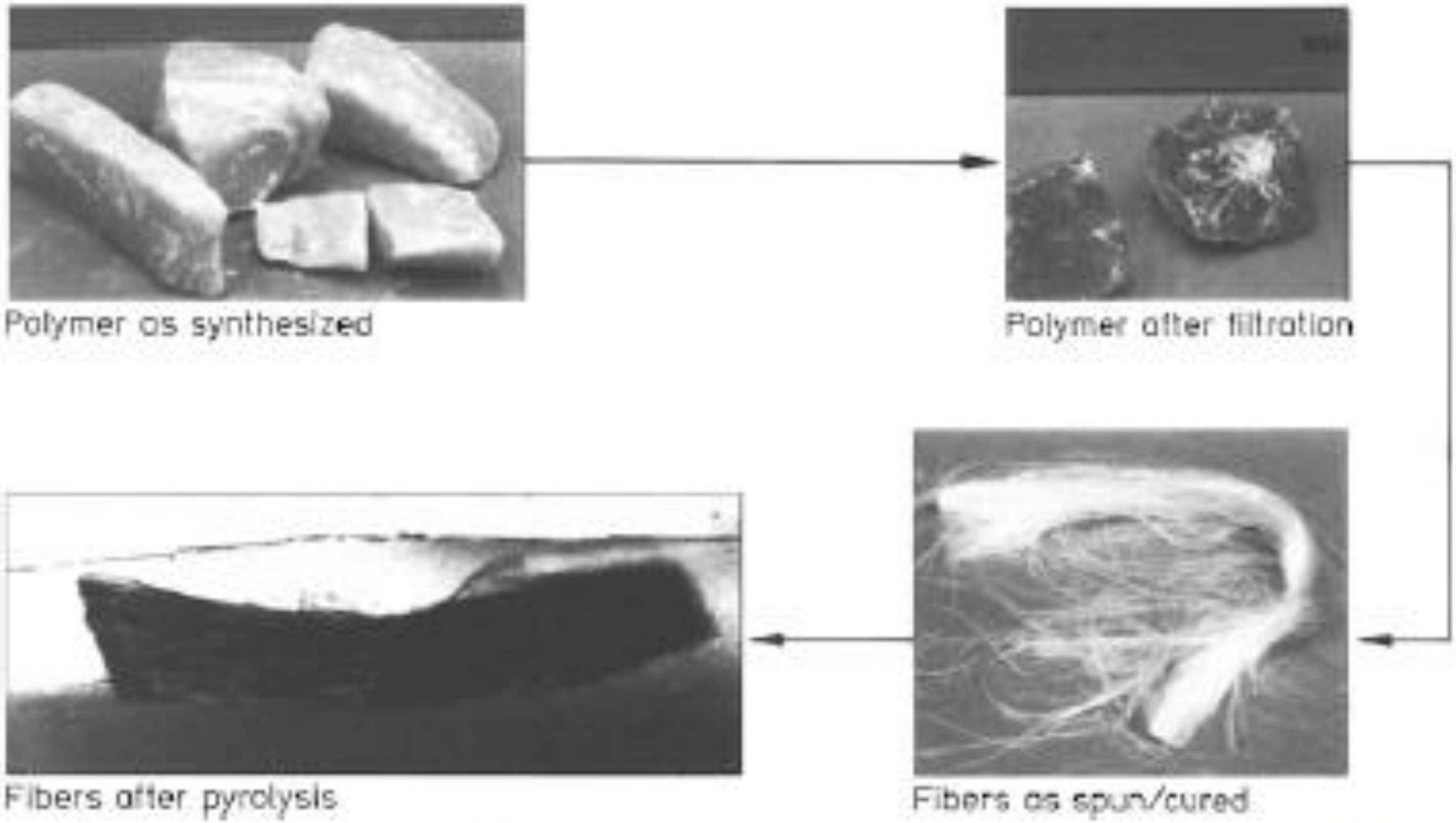
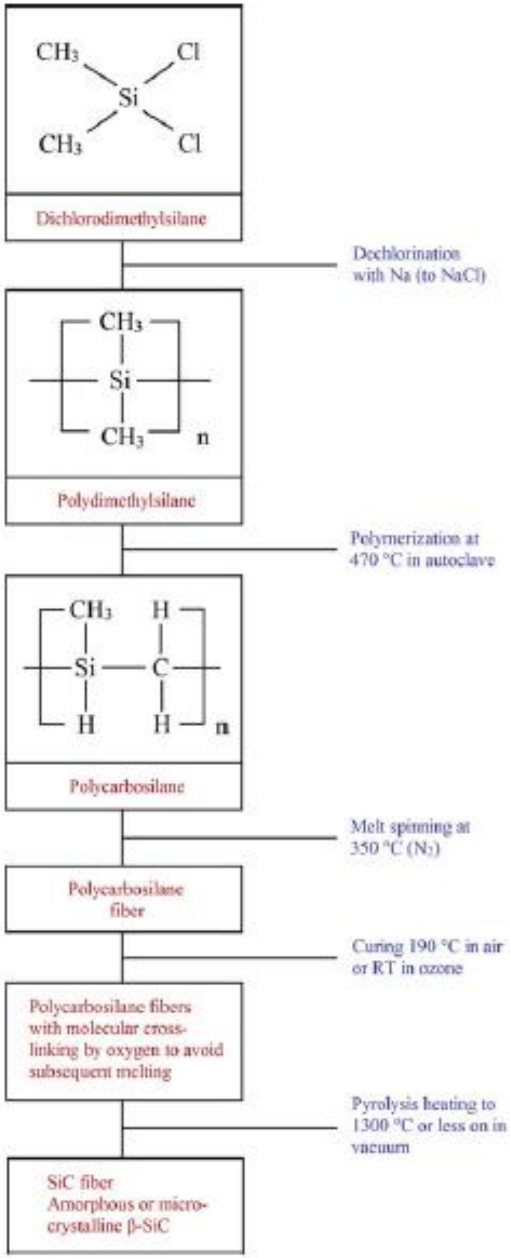


Fig. 2.41 Schematic of ceramic fiber production starting from silicon-based polymers [adapted from Wax (1985), used with permission]

Nonoxide Fibers via Polymers

Fig. 2.42 Schematic of SiC (Nicalon) production [adapted from Andersson and Warren (1984), used with permission]



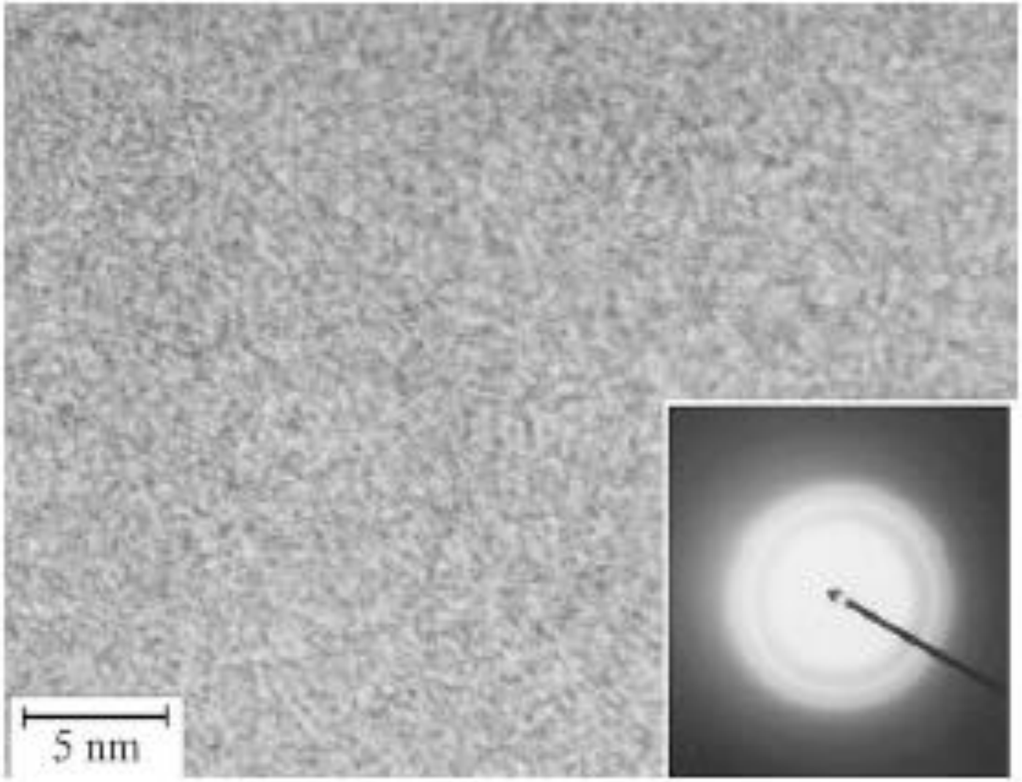


Fig. 2.43 High-resolution transmission electron micrograph of Nicalon fiber showing its amorphous structure [courtesy of K. Okamura]

Structure and Properties

Table 2.10 Properties of some fine-diameter SiC type fibers[a]

Fiber	Tensile strength (GPa)	Young's modulus (GPa)	Coefficient of thermal expansion (10^{-6} K^{-1})
Nicalon 200	2	200	3.2
Hi–Nicalon	2.8	270	3.5
Hi–Nicalon S	2.5	400	–
Sylramic iBN	3.5	400	5.4
Tyranno SA3	2.9	375	–

[a]After A. R. Bunsell and A. Piant (2006)

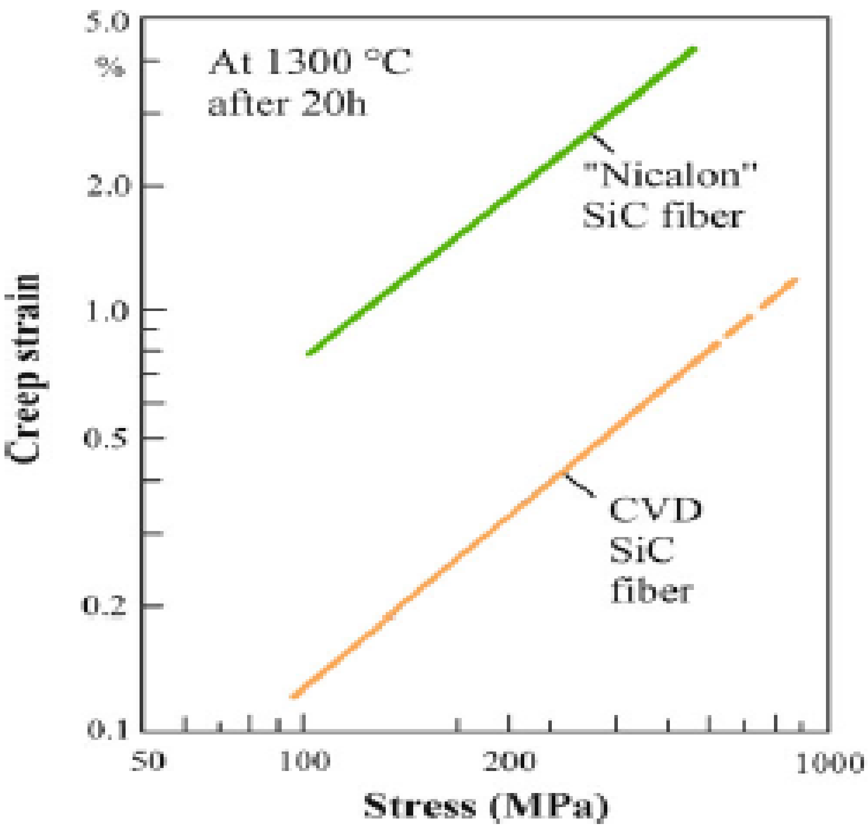


Fig. 2.44 Comparison of creep strain in CVD SiC and Nicalon fibers (reprinted with permission from J Metals 37, No. 6, 1985, a publication of the Metallurgical Society, Warrendale PA)

Whiskers

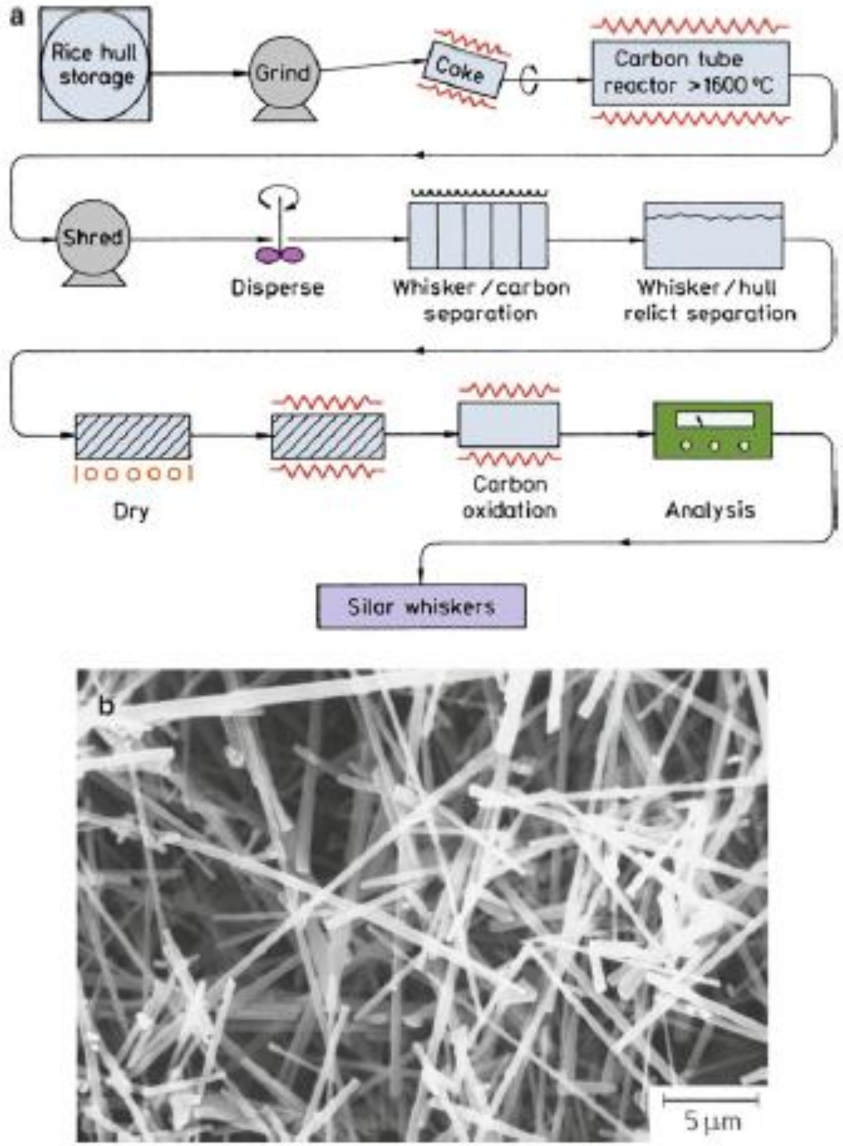


Fig. 2.45 (**a**) Schematic of SiC whisker production process starting from rice hulls. (**b**) Scanning electron micrograph of SiC whiskers obtained from rice hulls [courtesy of Advanced Composite Materials Corporation (formerly Arco)]

Other Nonoxide Reinforcements

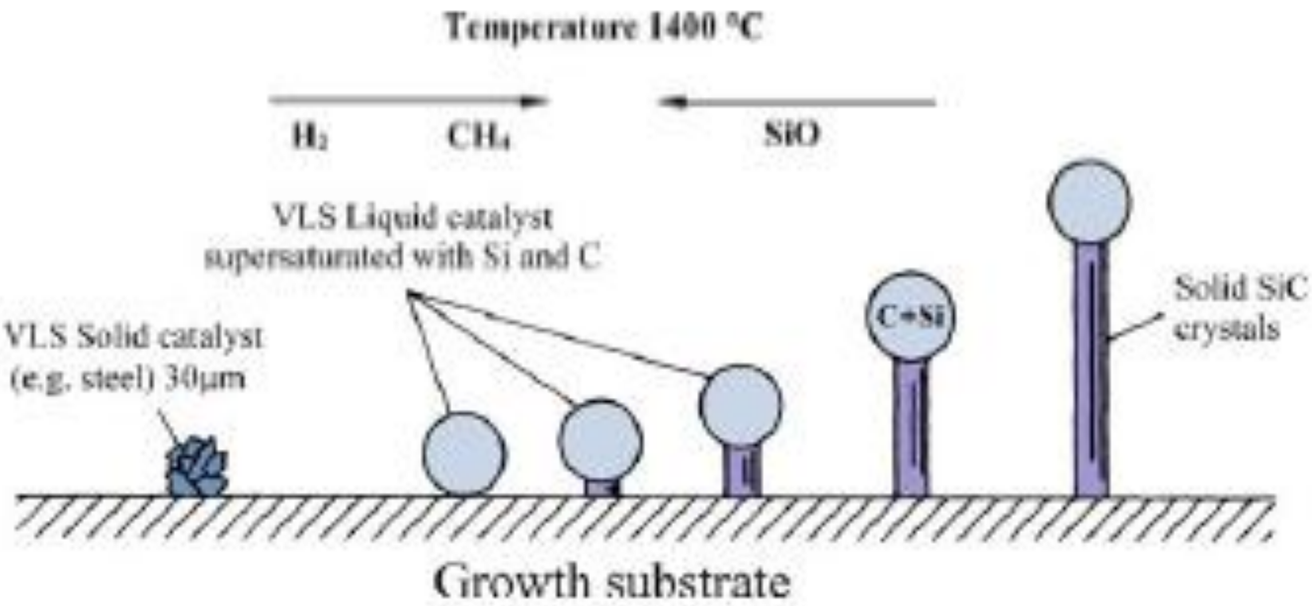


Fig. 2.46 The VLS process for SiC whisker growth [after Milewski et al. (1985), used with permission]

Comparison of Fibers

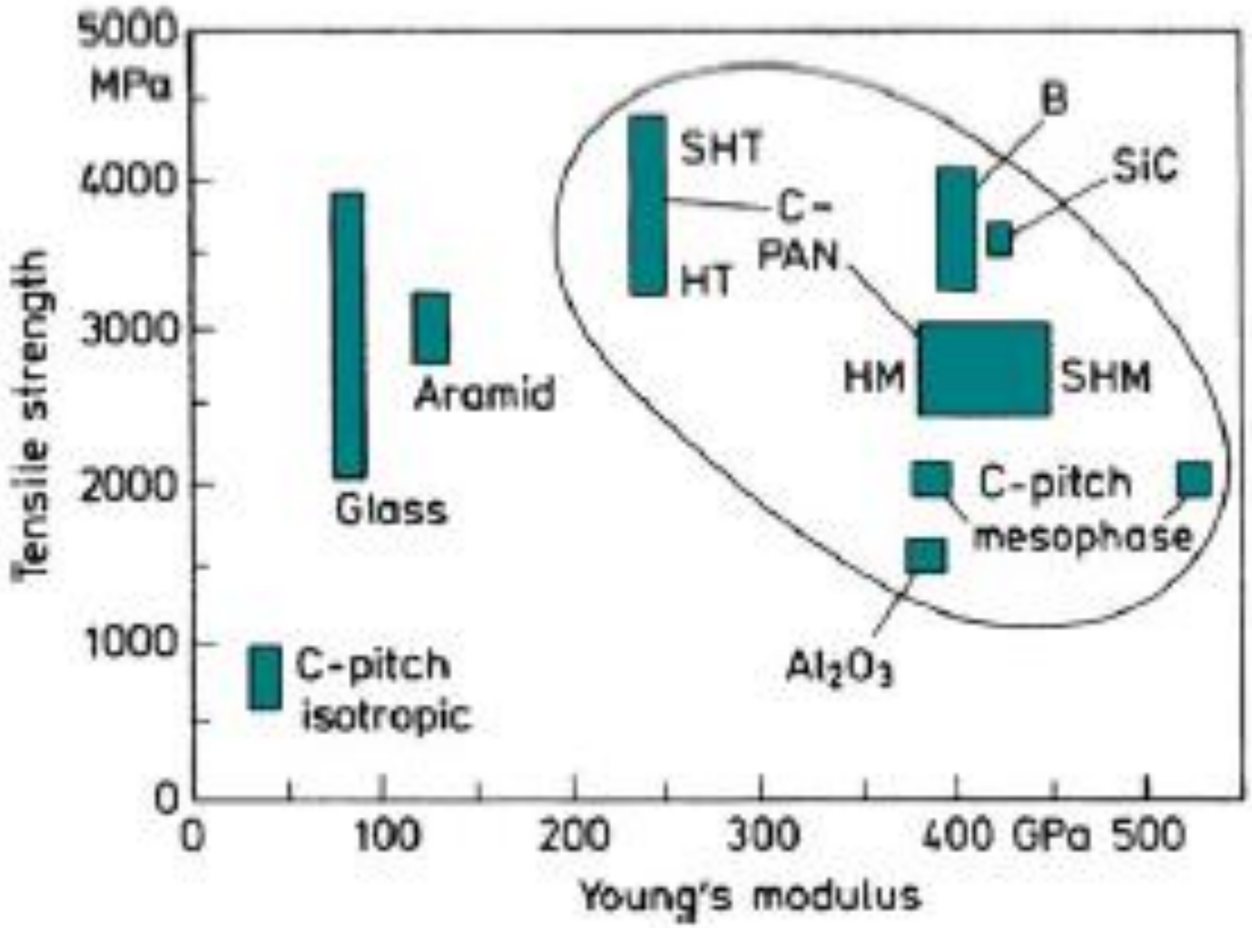


Fig. 2.47 Comparison of different fibers

Table 2.11 Properties of reinforcement fibers

Characteristic	PAN-based carbon HM	PAN-based carbon HS	Kevlar 49	E glass	SiC CVD	SiC Nicalon	Al_2O_3	Boron (W)
Diameter (μm)	7–10	7.6–8.6	12	8–14	100–200	10–20	20	100–200
Density (g/cm^3)	1.95	1.75	1.45	2.55	3.3	2.6	3.95	2.6
Young's modulus (GPa)								
Parallel to fiber axis	390	250	125	70	430	180	379	385
Perpendicular to fiber axis	12	20	–	70	–	–	–	–
Tensile strength (GPa)	2.2	2.7	2.8–3.5	1.5–2.5	3.5	2	1.4	3.8
Strain to fracture (%)	0.5	1.0	2.2–2.8	1.8–3.2	–	–	–	–
Coefficient of thermal expansion ($10^{-6}\ K^{-1}$)								
Parallel to fiber axis	−0.5–0.1	0.1–0.5	−2–5	4.7	5.7	–	7.5	8.3
Perpendicular to fiber axis	7–12	7–12	59	4.7	–	–	–	–