

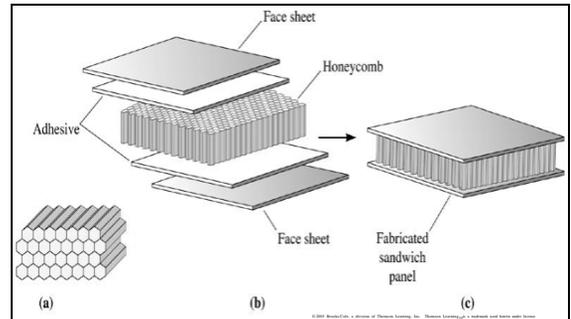
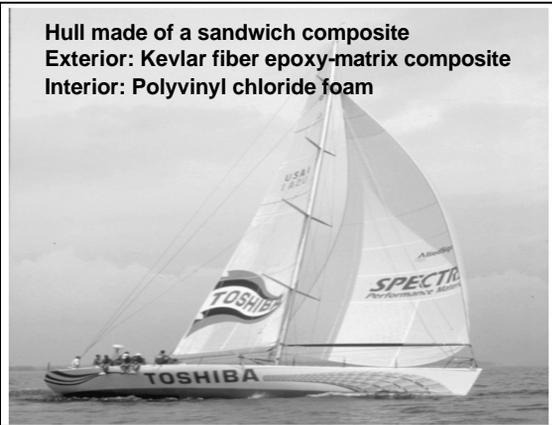
Composites and carbon fibers

Topic 2

Reading assignment

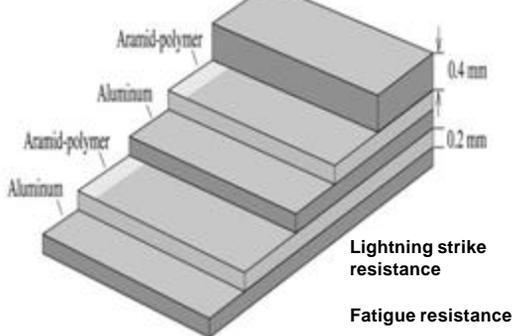
- Askeland and Phule, "The Science and Engineering of Materials", 4th Edition, Ch. 16.
- Shakelford, "Introduction to Materials Science for Engineers", 6th Edition, Ch. 14.
- Chung, "Composite Materials", Ch. 2.
- Chung, "Carbon Fiber Composites", Ch. 1, 2 and 3.

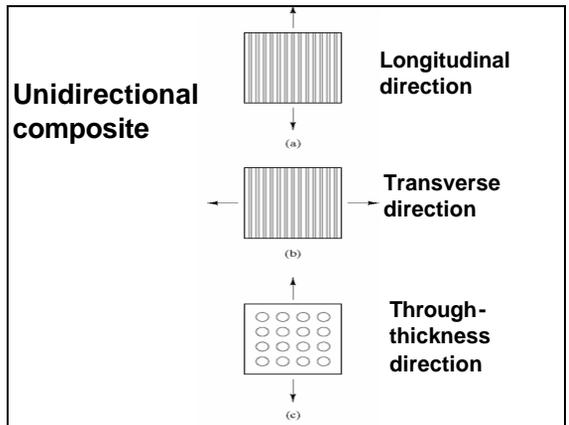
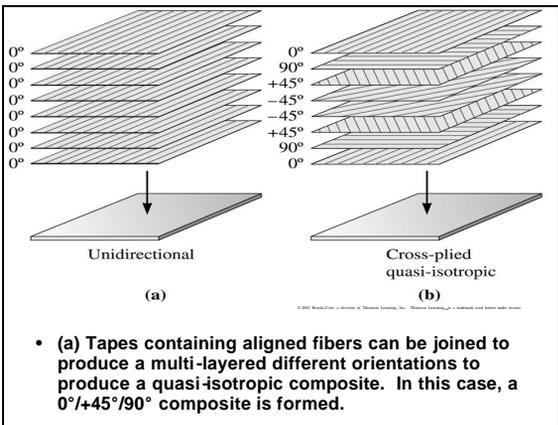
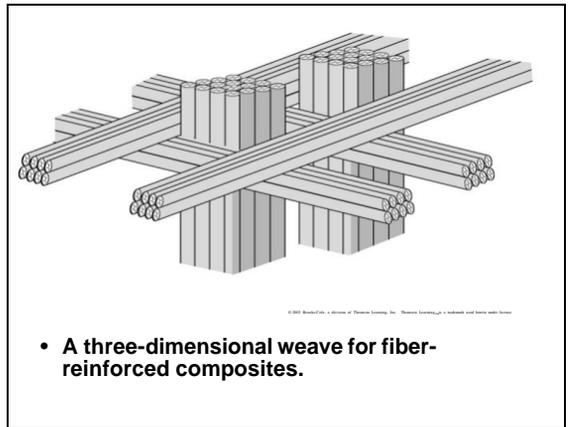
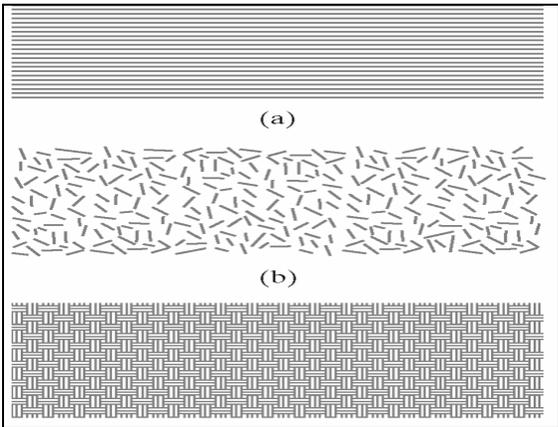
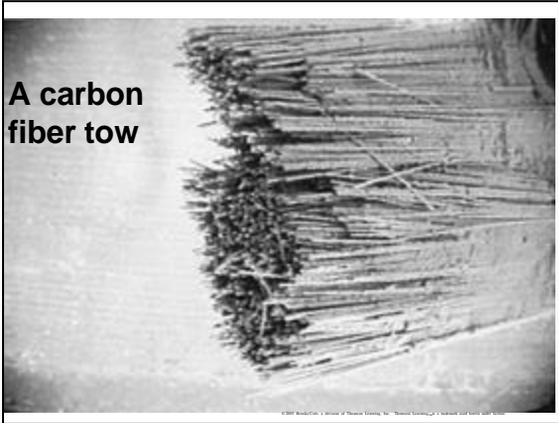
Hull made of a sandwich composite
 Exterior: Kevlar fiber epoxy-matrix composite
 Interior: Polyvinyl chloride foam

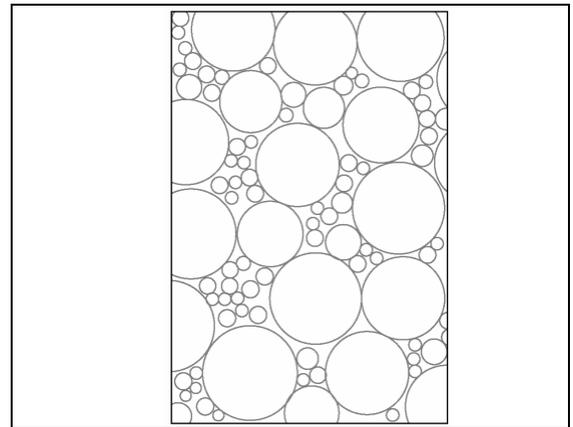
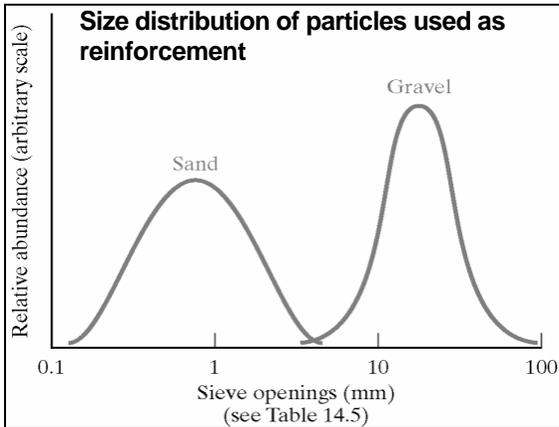
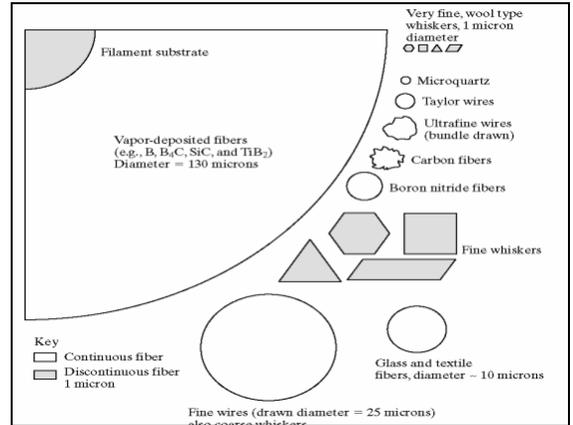
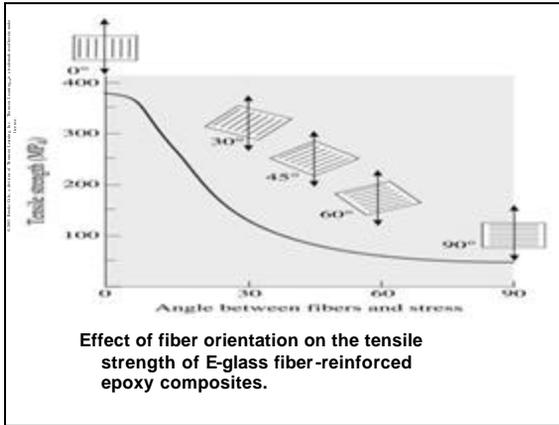


- (a) A hexagonal cell honeycomb core, (b) can be joined to two face sheets by means of adhesive sheets, (c) producing an exceptionally lightweight yet stiff, strong honeycomb sandwich structure.

Aramid-aluminum laminate
 (layers joined by adhesives)







Single fiber tensile strength

- Carbon fiber 3.5 GPa
- Kevlar fiber 3.6 GPa
- E-glass fiber 3.4 GPa
- Steel 1.3 GPa

Specific strength

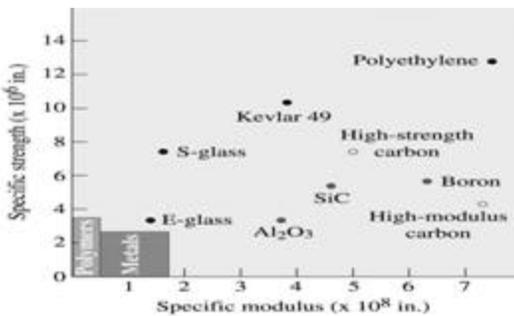
- Carbon fiber 2.00 GPa
- Kevlar fiber 2.50 GPa
- E-glass fiber 1.31 GPa
- Steel 0.17 GPa

Single fiber tensile modulus

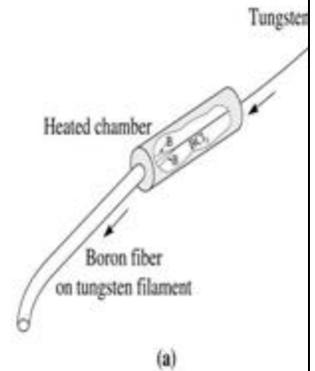
- Carbon fiber 230 GPa
- Kevlar fiber 60 GPa
- E-glass fiber 22 GPa
- Steel 210 GPa

Table 3.2 Mechanical properties of various carbon fibers. From Ref. 3.

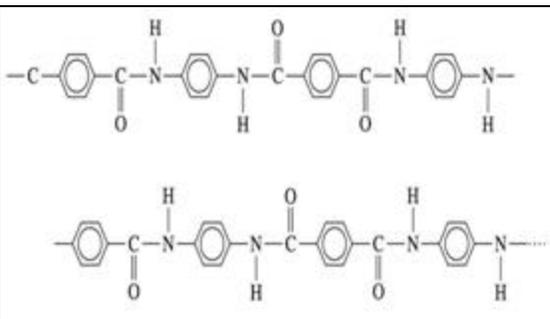
Sample name	Tensile strength (GPa)	Tensile modulus (GPa)	Elongation (%)
Thornel P-100	2.2	690	0.3
P-120	2.4	830	0.3
Carbonic HM50	2.8	490	0.6
HM60	3.0	590	0.5
HM80	3.5	790	0.4
Torayca M46	2.4	450	0.5



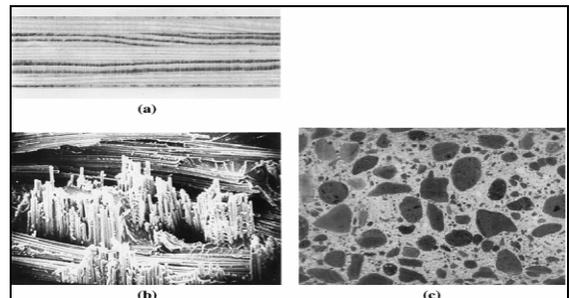
- Comparison of the specific strength and specific modulus of fibers versus metals and polymers.



(a)



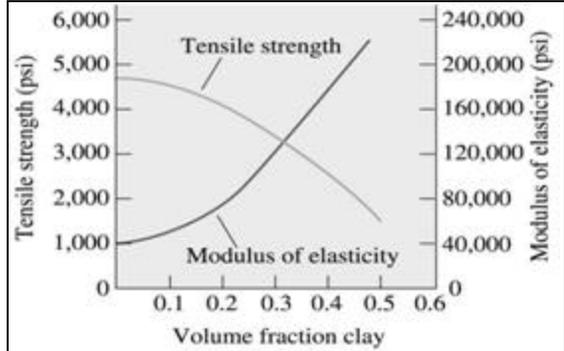
- The structure of Kevlar™. The fibers are joined by secondary bonds between oxygen and hydrogen atoms on adjoining chains.



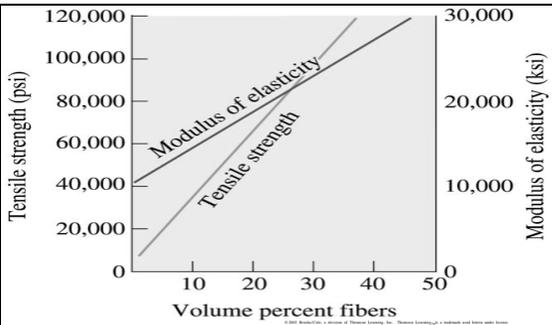
Some examples of composite materials: (a) plywood is a laminar composite of layers of wood veneer, (b) fiberglass is a fiber-reinforced composite containing stiff, strong glass fibers in a softer polymer matrix (≈ 175), and (c) concrete is a particulate composite containing coarse sand or gravel in a cement matrix (reduced 50%).

TABLE 16-3 ■ Examples of fiber-reinforced materials and applications

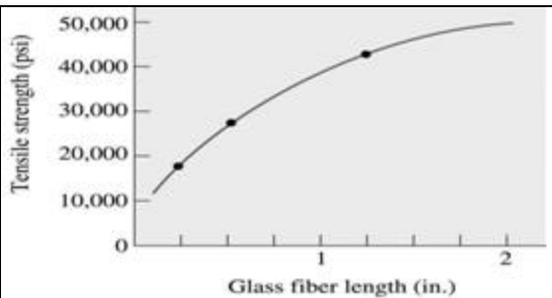
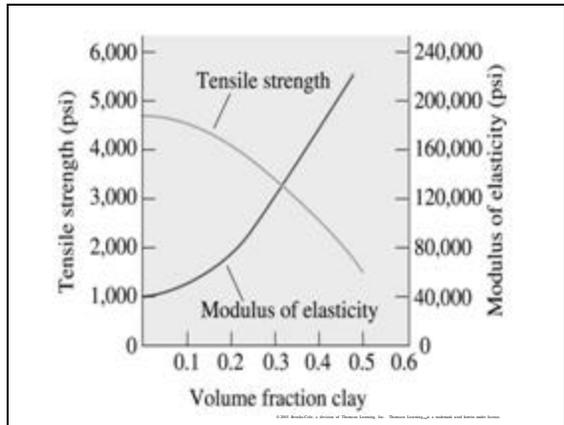
Material	Applications
Boric aluminum	Fan blades in engines, other aircraft and aerospace applications
Kevlar™-epoxy and Kevlar™-polyester	Aircraft, aerospace applications (including space shuttle), boat hulls, sporting goods (including tennis rackets, golf club shafts, fishing rods), falk jackets
Graphite-polymer	Aerospace and automotive applications, sporting goods
Glass-polymer	Lightweight automotive applications, water and marine applications, corrosion-resistant applications, sporting goods equipment, aircraft and aerospace components



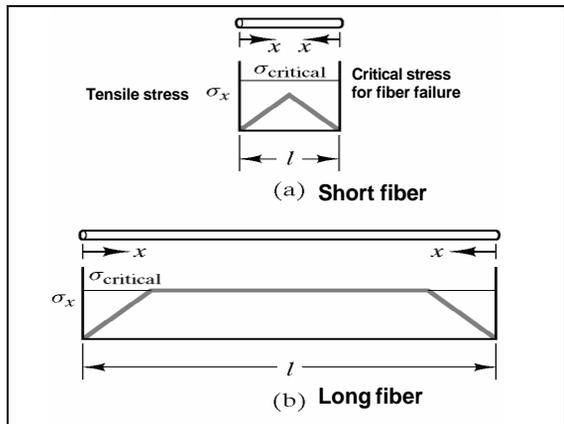
- The effect of clay on the properties of polyethylene.

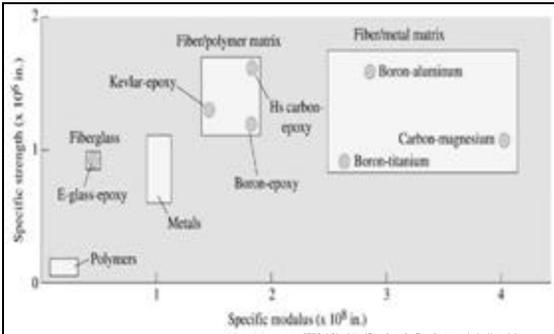


- The influence of volume percent boron-coated SiC (Borsic) fibers on the properties of Borsic-reinforced aluminum parallel to the fibers

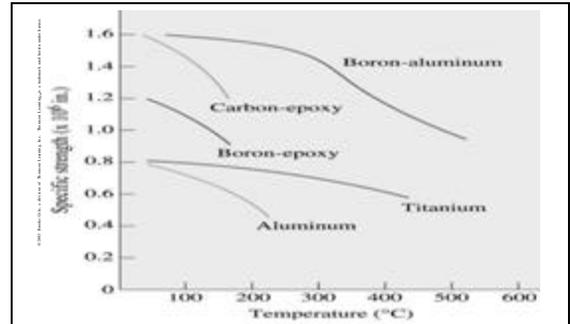


- Increasing the length of chopped E-glass fibers in an epoxy matrix increases the strength of the composite. In this example, the volume fraction of glass fibers is about 0.5.

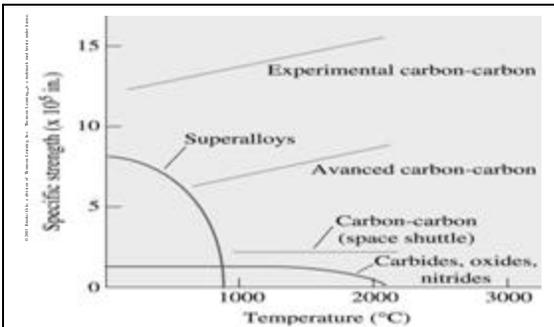




A comparison of the specific modulus and specific strength of several composite materials with those of metals and polymers.

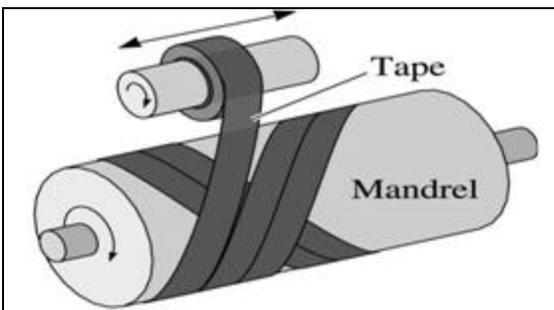


- The specific strength versus temperature for several composites and metals.

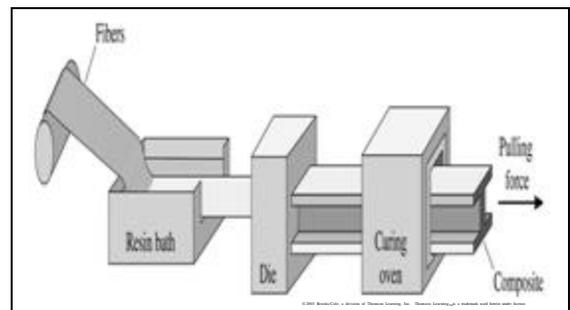


A comparison of the specific strength of various carbon-carbon composites with that of other high-temperature materials relative to temperature.

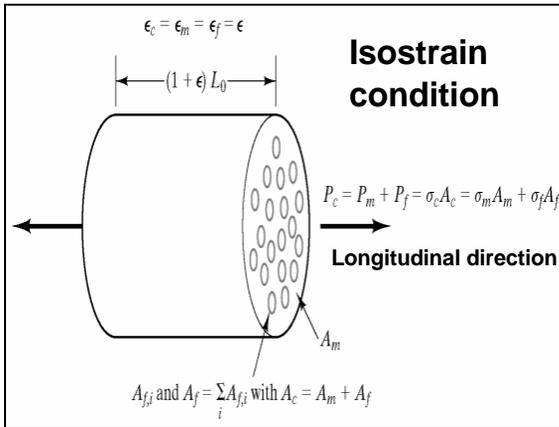
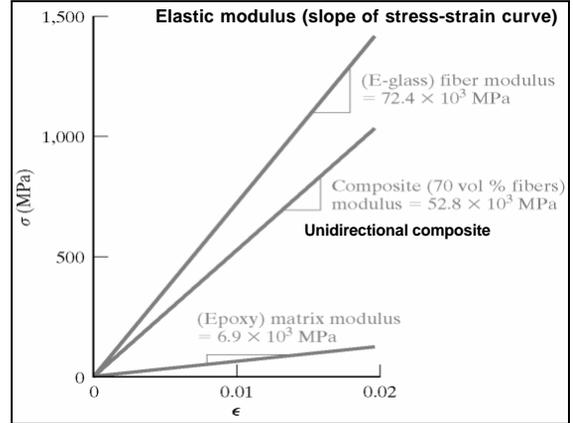
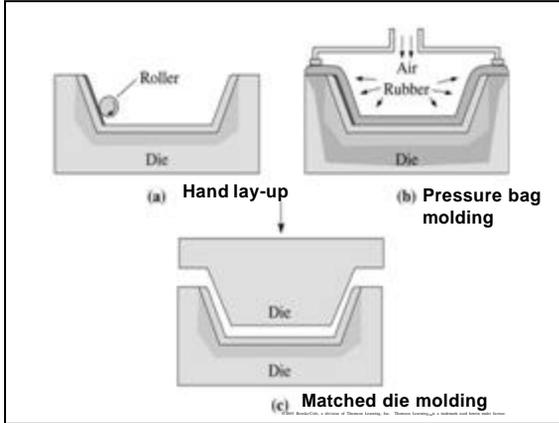
Methods of fabricating polymer-matrix composites



- Producing composite shapes by filament winding.



Producing composite shapes by pultrusion.



$$P_c = P_m + P_f$$

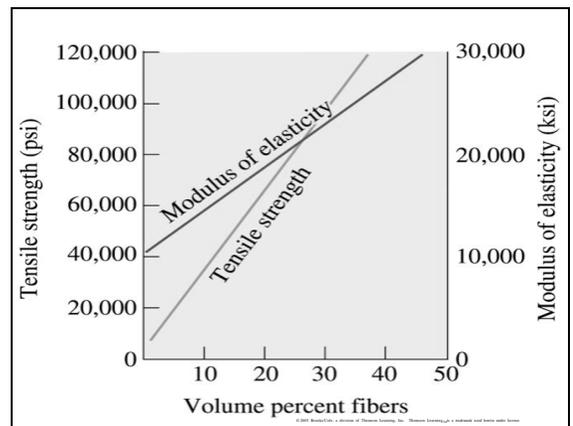
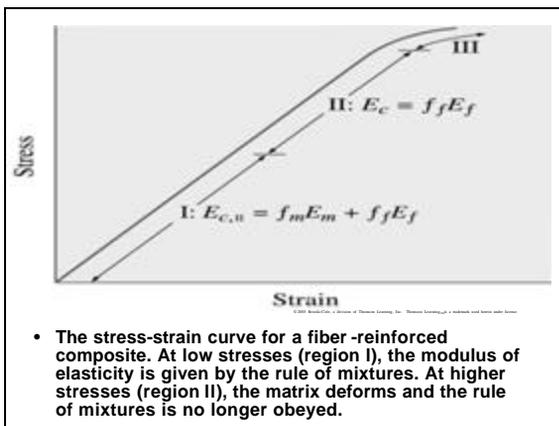
$$\mathbf{s}_c A_c = \mathbf{s}_m A_m + \mathbf{s}_f A_f$$

For isostrain condition ($\mathbf{e}_c = \mathbf{e}_m = \mathbf{e}_f$)

$$E_c \mathbf{e}_c A_c = E_m \mathbf{e}_m A_m + E_f \mathbf{e}_f A_f$$

$$E_c = E_m \frac{A_m}{A_c} + E_f \frac{A_f}{A_c}$$

$$E_c = \mathbf{n}_m E_m + \mathbf{n}_f E_f$$

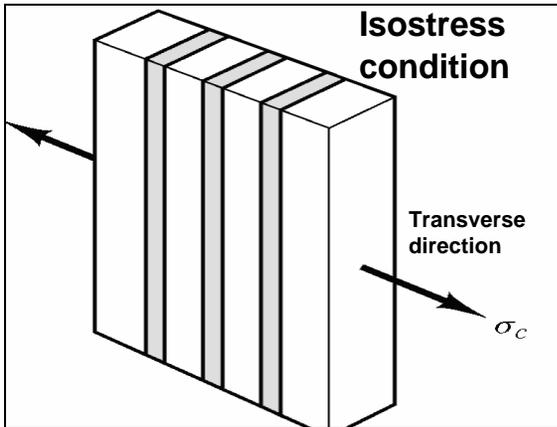


$$X_c = n_m X_m + n_f X_f$$

Rule of Mixtures (ROM)

Fraction of load carried by fibers

$$\frac{P_f}{P_c} = \frac{s_f A_f}{s_c A_c} = \frac{E_f e_f A_f}{E_c e_c A_c} = \frac{E_f}{E_c} n_f$$



Isostress condition

$$s_c = s_m = s_f$$

$$\Delta L_c = \Delta L_m + \Delta L_f$$

$$\frac{\Delta L_c}{L_c} = \frac{\Delta L_m}{L_c} + \frac{\Delta L_f}{L_c}$$

$$L_m = A_m L_c$$

$$L_f = A_f L_c$$

$$\frac{\Delta L_c}{L_c} = \frac{A_m \Delta L_m}{L_m} + \frac{A_f \Delta L_f}{L_f}$$

$$e_c = n_m e_m + n_f e_f$$

For isostress condition ($s = E_c e_c = E_m e_m = E_f e_f$),

$$\frac{s}{E_c} = n_m \frac{s}{E_m} + n_f \frac{s}{E_f}$$

$$\frac{1}{E_c} = \frac{n_m}{E_m} + \frac{n_f}{E_f}$$

$$E_c = \frac{E_m E_f}{n_m E_f + n_f E_m}$$

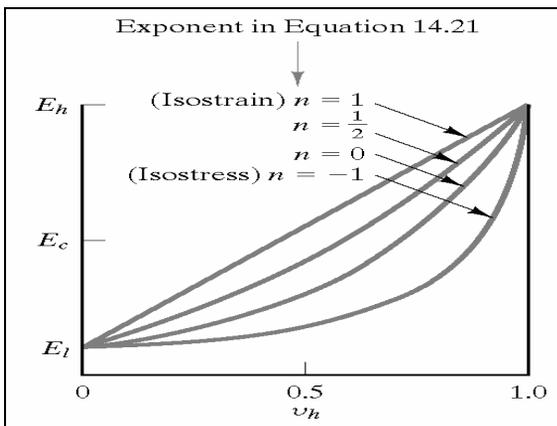
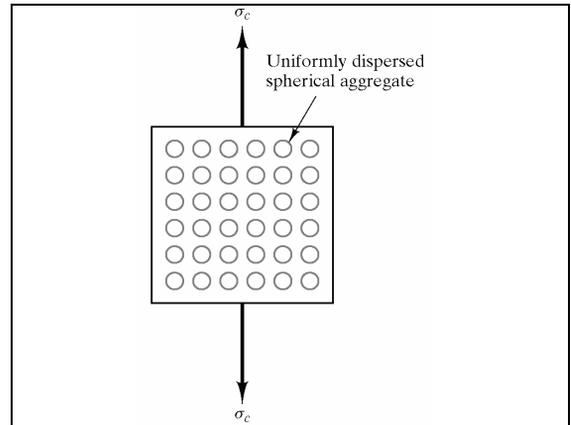
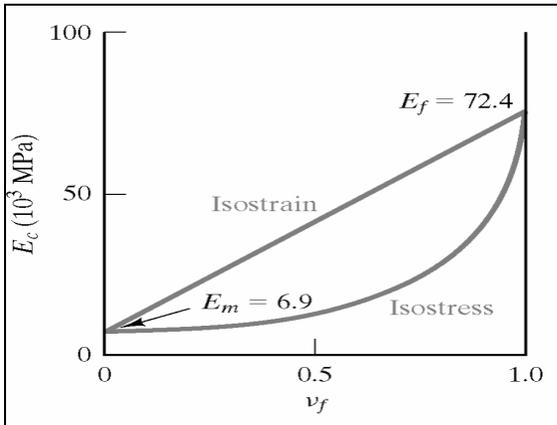
$$X_c = \frac{X_m X_f}{n_m X_f + n_f X_m}$$

$$E_c^n = n_t E_l^n + n_h E_h^n$$

$n = 1$ Isostrain

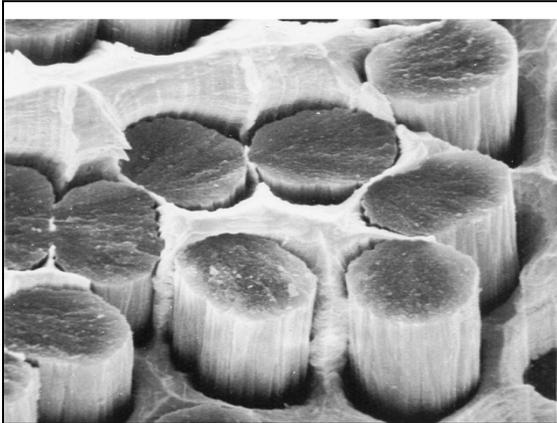
$n = -1$ Isostress

Rule of Mixtures (ROM)



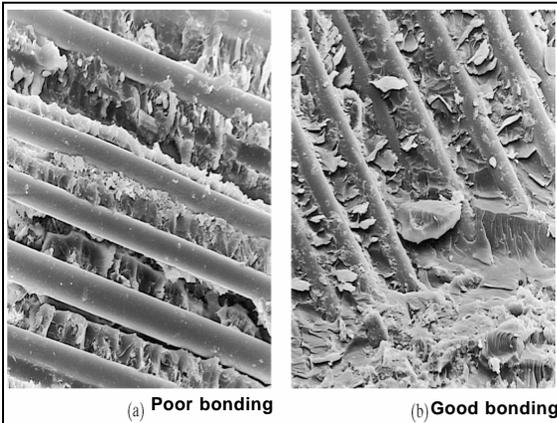
Fiber-matrix debonding

- Silver-copper alloy matrix
- Carbon fiber reinforcement
- Fracture surface observation (fractography)



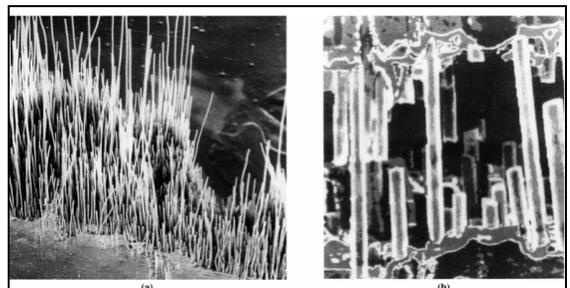
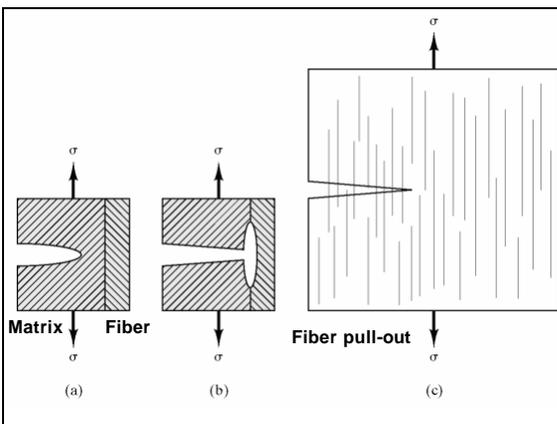
Fiber-matrix debonding

- Polymer matrix
- Glass fiber reinforcement

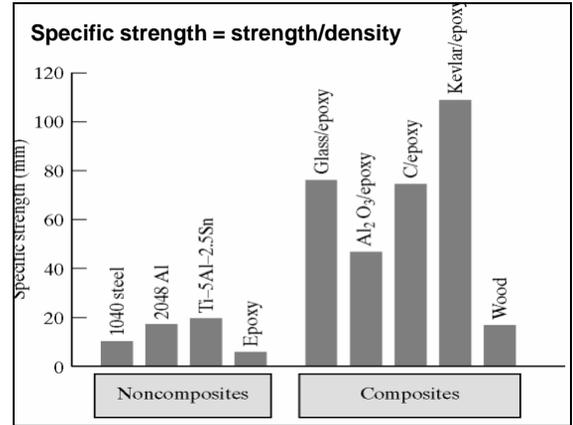
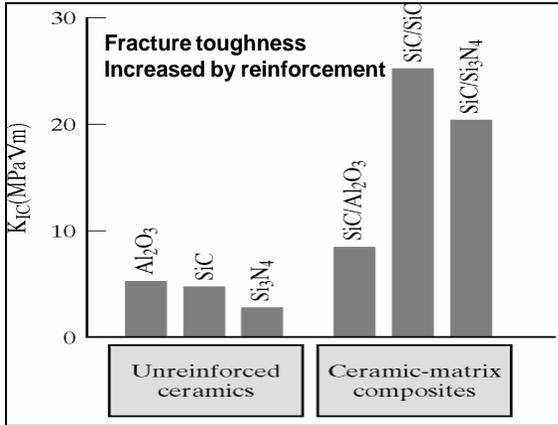


Failure mechanisms

- Failure in fibers (ductile-matrix composites, e.g., polymer-matrix and metal-matrix composites), so a high interfacial strength is desired.
- Failure in matrix (brittle-matrix composites, e.g., ceramic-matrix and carbon-matrix composites), so a low interfacial strength is desired (to allow cracks to deflect along fiber-matrix interface, thereby allowing fibers to pull out for the purpose of increasing the toughness)



- Two failure modes in ceramic-ceramic composites: (a) Extensive pull-out of SiC fibers in a glass matrix provides good composite toughness (x20). (b) Bridging of some fibers across a crack enhances the toughness of a ceramic-matrix composite (unknown magnification).



Reasons for fiber-matrix interface engineering

- To control fiber-matrix bond strength (shear bond strength)
- To improve wetting of matrix precursor on fiber
- To improve fiber dispersion

Methods for fiber-matrix interface engineering

- Fiber surface treatment
- Dispersant as an additive to the matrix

Methods of fiber surface treatment

- Chemical treatment fiber
- Coating of fiber

Table 2.2 Effects of various surface treatments on properties of high-modulus carbon fibers and their epoxy-matrix composites. All liquid treatments at reflux temperature.

Fiber treatment	Fiber properties		Composite properties	
	Wt. loss (%)	Tensile strength loss (%)	Flexural strength loss (%)	ILSS gain (%)
400°C in air (30 min)	0	0	0	18
500°C in air (30 min)	0.4	6	12	50
600°C in air (30 min)	4.5	50	Too weak to test	-
60% HNO ₃ (15 min)	0.2	0	8	11
5.25% NaOCl (30 min)	0.4	1.5	5	30
10-15% NaOCl (15 min)	0.2	0	8	6
15% HClO ₄ (15 min)	0.2	0	12	0
5% KMnO ₄ /10% NaOH (15 min)	0.4	0	15	19
5% KMnO ₄ /10% H ₂ SO ₄ (15 min)	6.0(+)	17	13	95
10% H ₂ O ₂ /20% H ₂ SO ₄ (15 min)	0.1	5	14	0
42% HNO ₃ /30% H ₂ SO ₄ (15 min)	0.1	0	4(+)	0
10% NaClO ₂ /15% NaOH (15 min)	0.2	0	12	12
10% NaClO ₂ /25% H ₂ SO ₄ (15 min)	0.2	2	5(+)	91
15% NaClO ₂ /40% H ₂ SO ₄ (15 min)	0.7	4	15	108
10% Na ₂ Cr ₂ O ₇ /25% H ₂ SO ₄ (15 min)	0.3	8	15(+)	18
15% Na ₂ Cr ₂ O ₇ /40% H ₂ SO ₄ (15 min)	1.7	27	31	18

Types of polymer-matrix composites

- **Thermoplastic-matrix composites**
- **Thermoset-matrix composites**

Lower manufacturing cost of thermoplastic-matrix composites

- no cure
- unlimited shelf-life
- reprocessing possible (for repair and recycling)
- less health risks due to chemicals during processing
- low moisture content
- thermal shaping possible
- weldability (fusion bonding possible)

Better performance of thermoplastic-matrix composites

- high toughness (damage tolerance)
- good hot/wet properties
- high environmental tolerance

Disadvantages of thermoplastic-matrix composites

- limitations in processing methods
- high processing temperatures
- high viscosities
- prepreg (collection of continuous fibers aligned to form a sheet which has been impregnated with the polymer or polymer precursor) being stiff and dry when solvent is not used (i.e., not drapeable or tacky)
- fiber surface treatments less developed

Attractive properties of carbon fiber polymer-matrix composites

- **low density (40% lower than aluminum)**
- **high strength (as strong as high-strength steels)**
- **high stiffness (stiffer than titanium, yet much lower in density)**
- **good fatigue resistance (a virtually unlimited life under fatigue loading)**
- **good creep resistance**

Attractive properties of carbon fiber polymer-matrix composites

- **low friction coefficient and good wear resistance (a 40 wt.% short carbon fiber nylon-matrix composite has a friction coefficient nearly as low as Teflon and unlubricated wear properties approaching those of lubricated steel)**
- **toughness and damage tolerance (can be designed by using laminate orientation to be tougher and much more damage tolerant than metals)**
- **chemical resistance (chemical resistance controlled by the polymer matrix)**
- **corrosion resistance (impervious to corrosion)**

Attractive properties of carbon fiber polymer-matrix composites

- **dimensional stability** (can be designed for zero coefficient of thermal expansion)
- **vibration damping ability** (excellent structural damping when compared with metals)
- **low electrical resistivity**
- **high electromagnetic interference (EMI) shielding effectiveness**
- **high thermal conductivity**

Limitation of polymer-matrix composites

Inability to resist high temperatures

Carbon-matrix composites

Ability to resist high temperatures

Carbon-carbon (C/C) composites

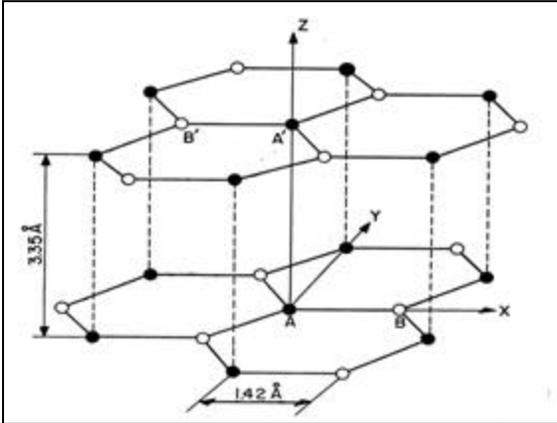
- **Carbon fiber**
- **Carbon matrix**
- **Carbon matrix made from pitch or polymer**

Carbon matrix precursors

- **Pitch**
- **Resins**
- **Carbonaceous gases**

Conversion of carbon matrix precursor to carbon

- **Pyrolysis (also called carbonization)**
- **Heating at around 1000°C in the absence of oxygen to cause decomposition, like charring**

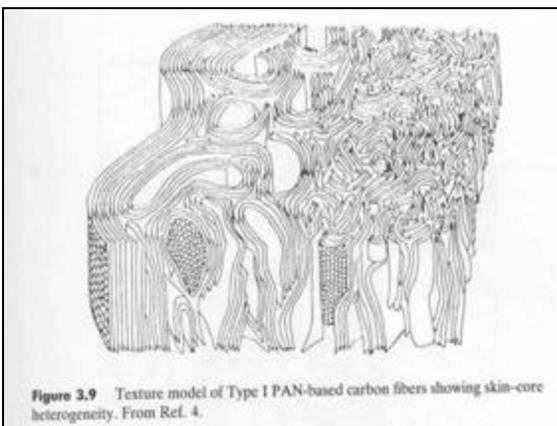
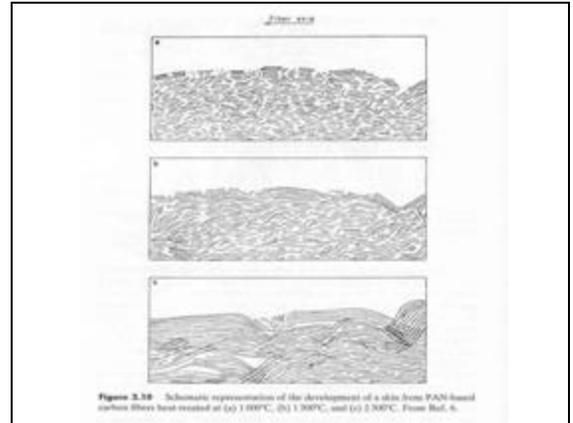


Bonding in graphite

- ♦ In-plane:
covalent and metallic bonding
- ♦ Out-of-plane:
van der Waals bonding

Properties of graphite

- ♦ Anisotropic
- ♦ Easy shear between carbon layers limiting the strength
- ♦ High electrical and thermal conductivity and high modulus in the plane of the carbon layers



Fiber microstructure

Fiber texture, i.e., preferred crystallographic orientation with the carbon layers along the fiber axis.

Carbon

- ◆ Non-crystalline, turbostratic
- ◆ Metastable form
 - graphitizes upon heating above 2000°C.

Conversion of carbon to graphite

- Graphitization (i.e., crystallization)
- Heating at 2000°C or above in the absence of oxygen to cause the turbostratic carbon to be converted to graphite (crystalline)

Carbon/graphite fabrication

- ◆ Stabilization (oxidation)
- ◆ Carbonization (pyrolysis)
- ◆ Graphitization

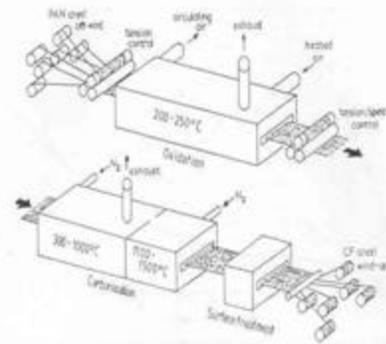
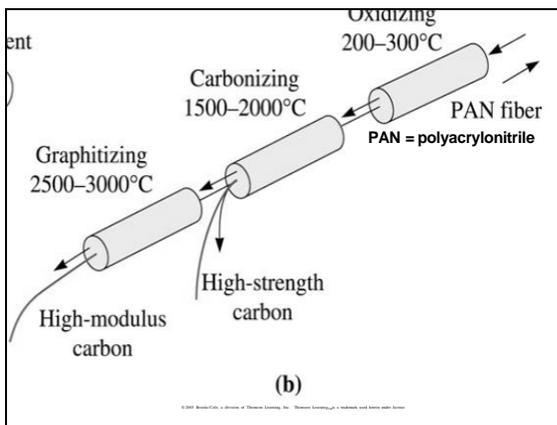
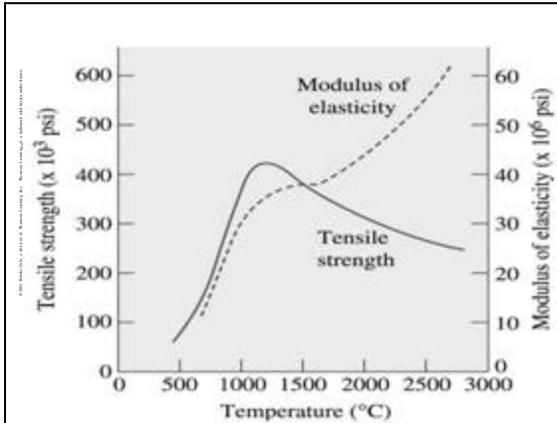


Figure 2.14 Apparatus for the fabrication of carbon fibers from PAN. From Ref. 29. (Reprinted by courtesy of Elsevier Science Publishers B.V.)



Grades of carbon fiber

- High-strength carbon fiber (without graphitization)
- High-modulus carbon fiber (with graphitization)



Properties of carbon compared to graphite

- ♦ Less conductive
- ♦ Lower in modulus
- ♦ Higher in strength
- ♦ Lower in oxidation resistance
- ♦ Cannot be intercalated

Fiber vs. nanofiber

- ♦ Fiber (diameter 1 micron or above, typically around 10 microns)
- ♦ Nanofiber (also called filament, diameter below 1 micron, typically 0.1 micron or less)

Types of carbon nanofiber

- ♦ Nanofiber with fish-bone morphology
- ♦ Multi-walled nanotube (concentric cylinders in shell)
- ♦ Single-walled nanotube (chirality)

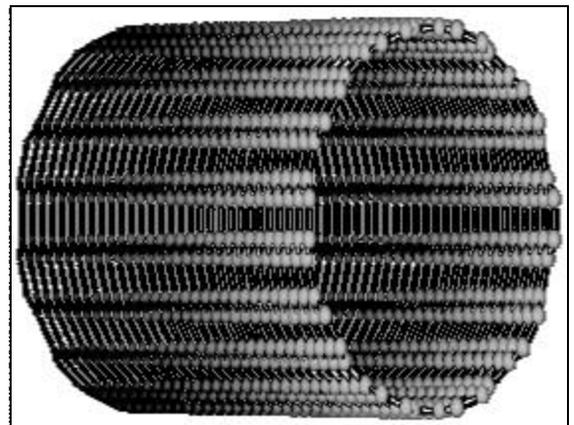
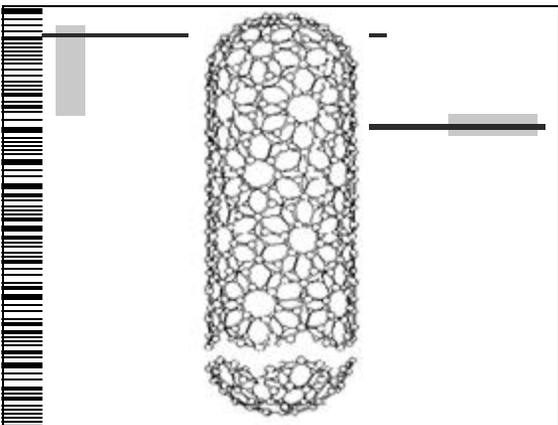
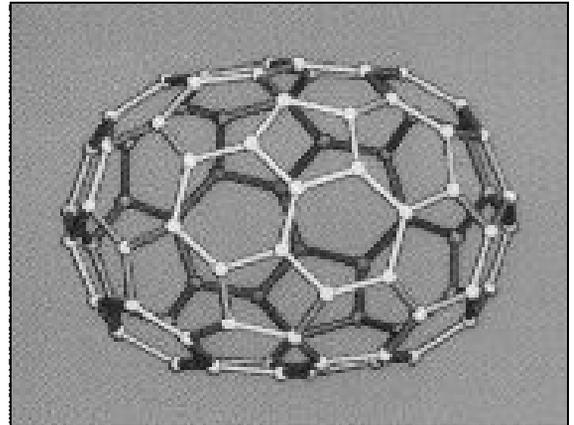
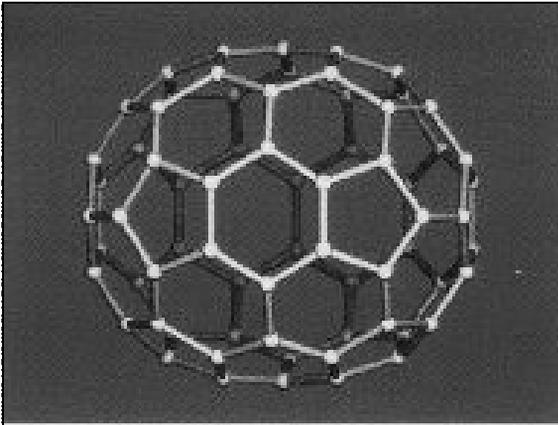
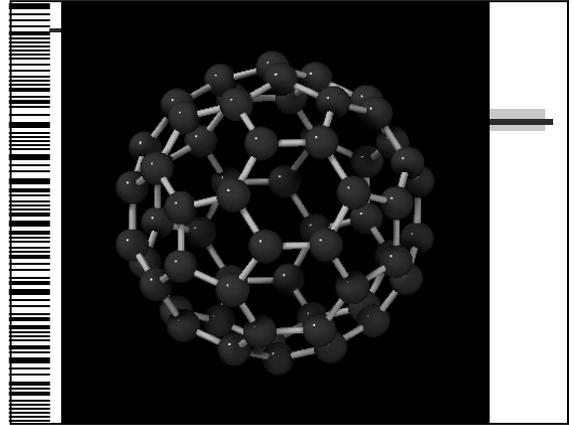


Carbon nanotube

Hybrid of graphite and fullerene

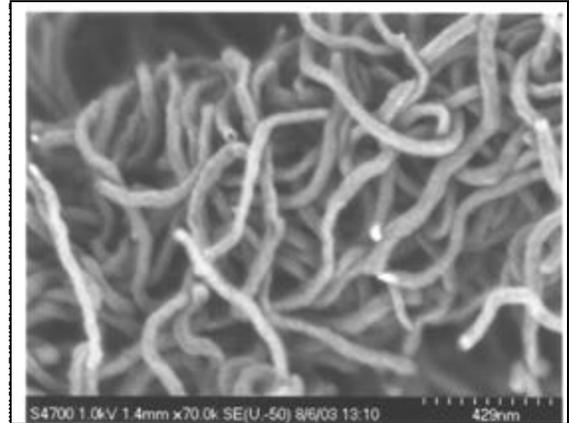
Crystal forms of carbon

- ◆ Graphite
- ◆ Diamond
- ◆ Fullerene



Nanofiber group morphology

- ◆ Intertwined
- ◆ Parallel



Fabrication of carbon nanofibers

- ◆ Catalytic growth from carbonaceous gas
- ◆ Arc discharge
- ◆ Laser evaporation

Catalytic method

- ◆ Carbonaceous gases: acetylene, ethylene, methane, natural gas, benzene, etc.
- ◆ Catalyst: iron, nickel, etc. (particles typically 10 nm, from salts or organometallics)
- ◆ Reducing gases: CO, hydrogen

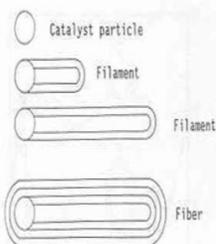


Figure 2.27 Diagram showing how a carbon filament is formed from a catalytic particle and how a carbon fiber is formed from a carbon filament. From Ref. 39. (Reprinted with permission from Pergamon Press plc.)

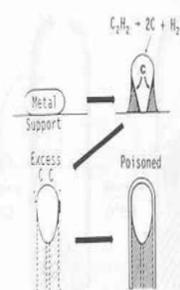
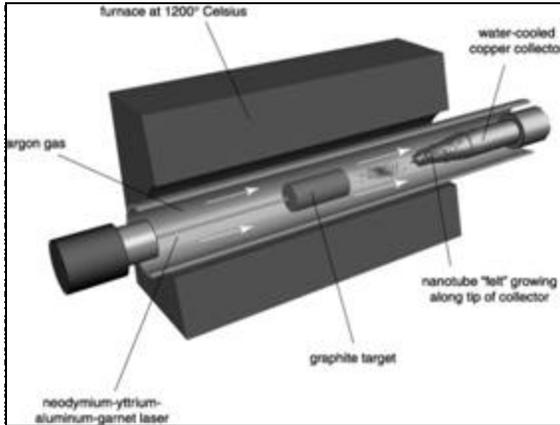


Figure 2.30 The most common mechanism of carbon filament formation. From Ref. 46. (Reprinted by permission of Kluwer Academic Publishers.)



Methods of making carbon-carbon composites

- Carbonization, followed by impregnation of pitch or resin, and repeating the carbonization-impregnation process again and again until sufficient density has been attained.
- Chemical vapor infiltration (CVI) using a carbonaceous gas, i.e., CVD under a temperature/pressure gradient so as to prevent crust formation, thereby allowing complete infiltration; CVI can be an extra step that follows carbonization-impregnation for the purpose of filling the pores.

Table 2.3 Pitch properties.

Pitch	Molecular weight	Carbon yield (%)	
		0.1 MPa	10 MPa
A	726	45.2	85.9
B	782	54.4	86.4
C	931	84.5	89.8

Grades of pitch

- Isotropic pitch
- Mesophase pitch (liquid crystal form called the mesophase)

Main problem with carbon-carbon composites

Oxidation at high temperatures in the presence of oxygen

Methods for oxidation protection of carbon-carbon composites up to 1700° C

1. SiC conversion coating
2. Oxidation inhibitors
3. Glassy sealant
4. Dense SiC or Si₃N₄ overlayer on glassy sealant or SiC conversion coating

SiC conversion coating method

SiC coating (known as SiC conversion coating, due to graded composition from pure SiC at the surface to pure carbon inside)

Methods of applying SiC conversion coating

- Pack cementation,
- Reaction sintering,
- Silicone resin impregnation/pyrolysis, or
- Chemical vapor deposition (CVD) to the outer surface of the composite.

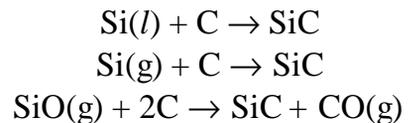
Pack cementation

Packing the composite in a mixture of SiC and Si powders and heat up to 1600°C

Chemical conversion of the outermost surface of the composite to SiC

SiC coating thickness typically 0.3-0.7 mm.

Pack cementation



Problem with entrapped silicon vaporising.

Reaction sintering

Dipping C/C composite into a suspension of Si powder (10 μm) in an alcohol solution and then sintering at 1600°C for 4 hours in argon.

Silicone resin impregnation/pyrolysis

Vacuum impregnation and cold isostatic pressing (30,000 psi or 200 MPa) a silicone resin into the matrix of a C/C composite and subsequent pyrolysis at 1600°C for 2 hours in argon.

Note: Silicone is a polymer with silicon atoms as a part of the backbone.

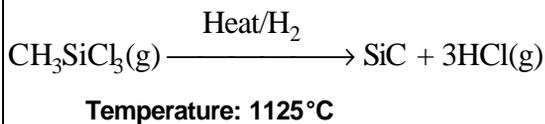
Prior deposition of carbon film (10 μm) by CVD

- Prior to pack cementation, reaction sintering or resin impregnation
- To improve homogeneity of C/C surface
- To ease the reaction with Si

Dense SiC or Si₃N₄ overlayers

- SiC overlayer is more dense than the SiC conversion coating.
- As oxygen barrier
- To control venting of reaction products to the outside
- Made by chemical vapor deposition (CVD)

Chemical vapor deposition (CVD) by thermal decomposition of a volatile silicon compound



SiSiC overlayer

- CVD overlayer contains a small percentage of unreacted silicon dispersed in the SiC,
- The excess Si upon oxidation becomes SiO₂, which has a very low oxygen diffusion coefficient.

Advantages of SiC or Si₃N₄

- Thermal expansion compatibility with C/C
- Low oxidation rate
- Thin amorphous SiO₂ scale that grows has low oxygen diffusion coefficient.

SiC or ineffective above 1800°C

- Reactions at the interface between SiO₂ and SiC or Si₃N₄
- Reduction of SiO₂ by carbon to form CO gas.

Oxygen inhibitors

- Oxygen getters
- Glass formers

To provide additional oxidation protection from within by migrating to the outer surface and sealing cracks and voids during oxidation.

Examples of inhibitors

- Elemental Si, Ti and B
- SiC, Ti_5Si_3 and TiB_2
- Alloys such as Si_2TiB_{14}
- Organoborosilazane polymer solution

Oxidation of the elemental Si, Ti or B within the carbon matrix forms a viscous glass, which serves as a sealant that flows into the microcracks of the SiC coating.

Boron as an oxidation inhibitor

- Boron is oxidized to form B_2O_3 .
- B_2O_3 blocks active sites, such as the edge carbon atoms.
- B_2O_3 forms a mobile diffusion barrier for oxygen.

Oxidation rate

Rate of weight loss

Inhibition factor

Ratio of oxidation rate of untreated carbon to that of the treated carbon

Method of introducing oxidation inhibitors to the carbon matrix

Incorporating particulate fillers in the resin or pitch

- (i) prior to prepregging, during lay-up and
- (ii) during densification cycles.

Glassy sealants

- Glazes comprising mainly silicates (SiO_2) and borates (B_2O_3).
- Glaze can be filled with SiC particles
- Particularly important if the SiC conversion coating is porous
- Glaze fills microcracks in the dense overlayer

Application of a glassy sealant on top of the SiC conversion coating mainly by slurry brush-on, so that the sealants melt, fill voids and stop oxygen diffusion, and, in some cases, act as oxygen getters.

Effectiveness of borate sealants

- Borates wet C and SiC quite well
- Borates cannot be used above 1200°C due to volatilization
- Borates have poor moisture resistance due to hydrolysis, which results in swelling and crumbling
- Borate has a tendency to galvanically corrode SiC coatings at high temperatures

Modified borate sealants

- The problems of borate can be alleviated by using multicomponent systems such as $10\text{TiO}_2 \cdot 20\text{SiO}_2 \cdot 70\text{B}_2\text{O}_3$.
- TiO_2 has a high solubility in B_2O_3 and is used to prevent the volatilization of B_2O_3 and increase the viscosity.
- SiO_2 acts to increase the moisture resistance, reduce B_2O_3 volatility, increase viscosity and prevent corrosion of SiC by B_2O_3 .

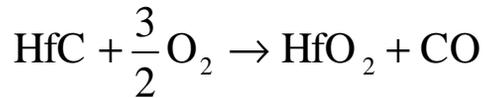
Dense SiC or Si_3N_4 overlayer

- Applied by CVD.
- On top of glassy sealant or on top of SiC conversion coating
- To control and inhibit transfer of oxygen to the substrate
- To control the venting of reaction products to the outside

Method of oxidation protection of C/C above 1700°C

Four-layer coating scheme:

- (1) **Refractory oxide** (e.g., ZrO_2 , HfO_2 , Y_2O_3 , ThO_2) as the outer layer for erosion protection.
- (2) **SiO_2 glass inner layer** as an oxygen barrier and sealant.
- (3) **Another refractory oxide layer** for isolation of the SiO_2 from the carbide layer underneath.
- (4) **Refractory carbide layer** (e.g., TaC, TiC, HfC, ZrC) to interface with the C/C substrate and to provide a carbon diffusion barrier



Fundamental approaches for oxidation protection of carbons

- Prevention of catalysis
- Retardation of gas access to the carbon
- Inhibition of carbon-gas reactions
- Improvement in the carbon crystalline structure

Carbon matrix precursors

- **Pitch** (preferred for oxidation protection)
- **Chemical vapor infiltration (CVI) carbon** (preferred for oxidation protection)
- **Resins** (not preferred for oxidation protection)

Effects of carbon fiber on oxidation protection

- Alignment of the matrix molecules near the fibers
- Microstructure of fiber affecting that of matrix
- Microstructure of matrix affecting amount of accessible porosity in the matrix

Disadvantage of coatings on C/C

Degrade room temperature mechanical properties of C/C

Metal-matrix composites

- **Better temperature resistance than polymer-matrix composites**
- **Lower temperature resistance than ceramic-matrix composites**
- **High fabrication cost compared to polymer-matrix composites**
- **Low fabrication cost compared to ceramic-matrix composites**

TABLE 16-1 ■ Examples and applications of selected dispersion-strengthened composites

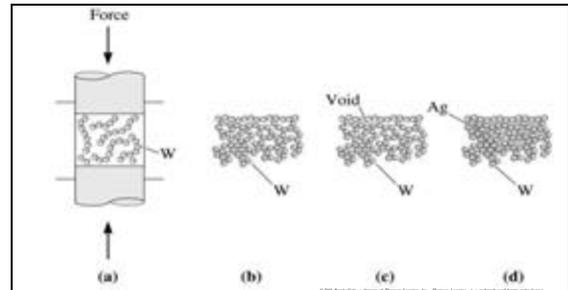
System	Applications
Ag-CdO	Electrical contact materials
Al-Al ₂ O ₃	Possible use in nuclear reactors
Be-BeO	Aerospace and nuclear reactors
Co-ThO ₂ , Y ₂ O ₃	Possible creep-resistant magnetic materials
Ni-20% Cr-ThO ₂	Turbine engine components
Pb-PbO	Battery grids
Pt-ThO ₂	Filaments, electrical components
W-ThO ₂ , ZrO ₂	Filaments, heaters

Methods of fabricating metal-matrix composites

- Liquid metal infiltration
- Hot pressing above the solidus of the matrix metal
- Powder metallurgy (diffusion bonding)
- Plasma spraying
- Slurry casting

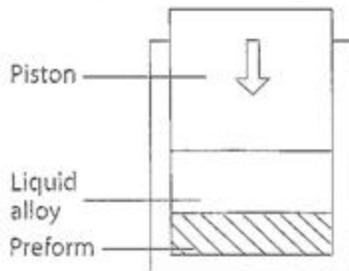
Advantages of liquid metal infiltration

- Near-net shape
- Fast



- The steps in producing a silver-tungsten electrical composite: (a) Tungsten powders are pressed, (b) a low-density compact is produced, (c) sintering joins the tungsten powders, and (d) liquid silver is infiltrated into the pores between the particles.

Liquid metal infiltration (squeeze casting)



Difficulty in liquid metal infiltration

Liquid metal does not wet ceramic or carbon particles/fibers well.

Reaction between metal and reinforcement

- Helps wetting
- Degrades reinforcement
- Reaction product (e.g., a carbide) lining the metal-reinforcement interface may be brittle

Methods of wetting enhancement

- Coat reinforcement with a metal (e.g., Ni, Cu, Ag) by plating
- Coat reinforcement with a ceramic (e.g., TiC, SiC, B₄C, TiB₂, TiN, K₂ZrF₆, ZrO₂) by CVD, solution coating, etc.

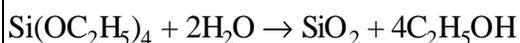
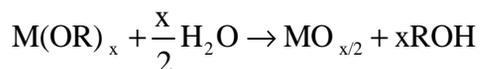
Coating of TiB₂ on carbon fiber by CVD

- TiCl₄ and BCl₃ gases, which are reduced by zinc vapor
- Coating particularly good for liquid aluminum

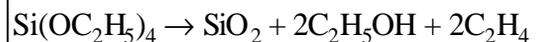
Solution coating method

- Dip in organometallic solution (e.g., alkoxides, which are M(OR)_x, where M is the metal, and R is a hydrocarbon group, such as methyl, ethyl, etc.)
- Hydrolysis or pyrolysis to organometallic compounds

Hydrolysis of organometallic compound



Pyrolysis of organometallic compound

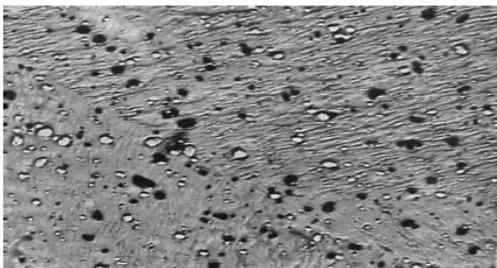
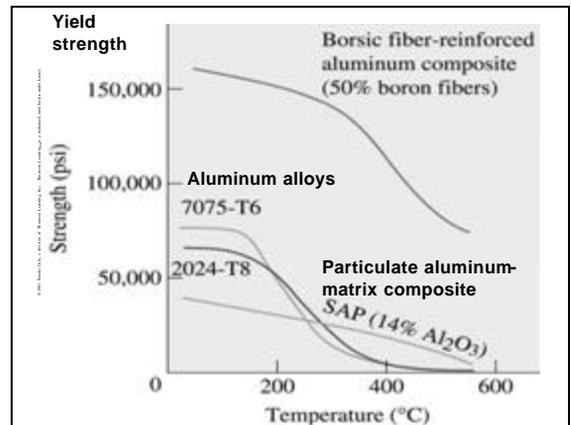
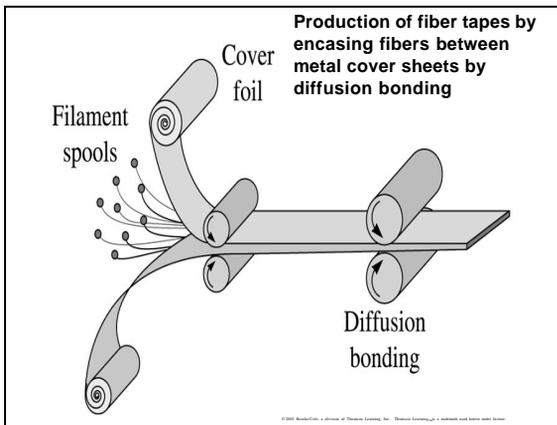


Powder metallurgy

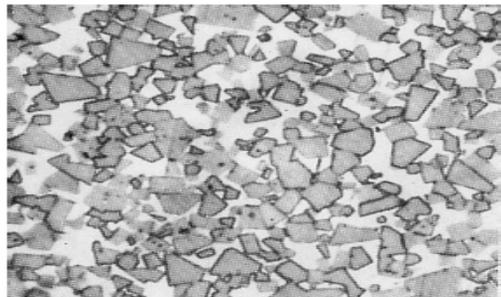
- Near-net shape
- Size limited by the pressure requirement

Two methods of powder metallurgy

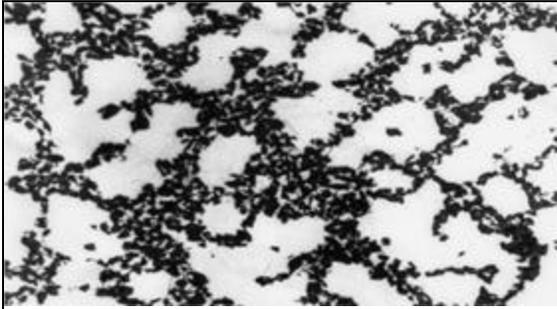
- Mixture of matrix powder and reinforcement particles/fibers
- Matrix coated reinforcement particles/fibers



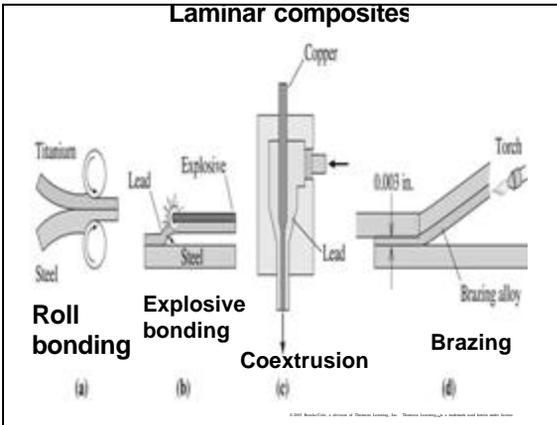
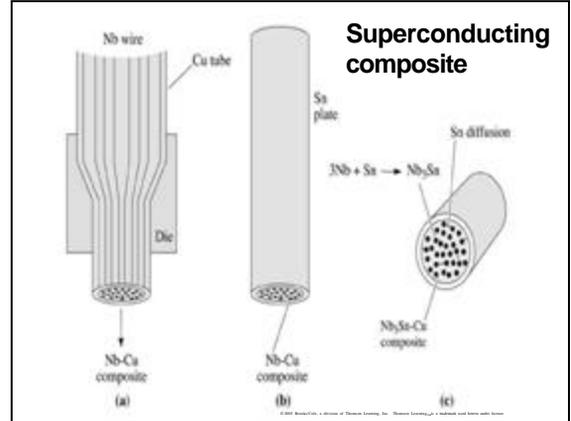
Electron micrograph of TD-nickel. The dispersed ThO₂ particles have a diameter of 300 nm or less ($\times 2000$). (From Oxide Dispersion Strengthening, p. 714, Gordon and Breach, 1968. © AIME.)



Microstructure of tungsten carbide—20% cobalt-cemented carbide (1300). (From Metals Handbook, Vol. 7, 8th Ed., American Society for Metals, 1972.)



- Microstructure of an aluminum casting alloy reinforced with silicon carbide particles. In this case, the reinforcing particles have segregated to interdendritic regions of the casting (125).



- Ceramic-matrix composites**
- Ceramic-ceramic composites (ceramic-fiber ceramic-matrix composites)
 - Better oxidation resistance than carbon-carbon composites
 - Technology less matured than carbon-carbon composite technology

- Examples of ceramic matrices**
- Silicon carbide
 - Silicon nitride
 - Alumina (aluminum oxide Al_2O_3)
 - Mullite ($\text{Al}_2\text{O}_3\text{-SiO}_2$)
 - Glasses