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POLYMER MATRIX MATERIALS

-Processed easily

-Lightweight

Desirable mechanical properties.

Two main kinds of **polymers** are **thermosets** and **thermoplastics**.

Thermosets:

Once 'set' these plastics cannot be reheated to soften, shape and mould. The molecules of these materials are cross linked in 3D and this is why they cannot be reshaped or recycled. The bond between the molecules is very strong.

1- well-bonded three-dimensional molecular structure after curing.

2- decompose instead of melting on heating.

They can be retained in a partially cured condition too over prolonged periods of time, rendering Thermosets very flexible.

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Thermoplastics

- 1-one- or two-dimensional molecular structure(long chain monomers) The bond between the molecules is weak and become weaker when reheated, allowing reshaping. These types of plastics can be recycled.
- 2- process of softening at elevated temperatures can be reversed to regain its properties during cooling
→facilitating applications of conventional compress techniques to mould the compounds.

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MATRICES

Table 2.5 Selected properties for different types of matrix

Matrix	Density ρ (Mg m ⁻³)	Young's modulus E (GPa)	Poisson's ratio ν	Tensile strength σ_s (GPa)	Failure strain ϵ_s (%)	Thermal expansivity α (10 ⁻⁶ K ⁻¹)	Thermal conductivity K (W m ⁻¹ K ⁻¹)
<i>Thermosets</i>							
epoxy resins	1.1-1.4	3-6	0.38-0.40	0.035-0.1	1-6	60	0.1
polyesters	1.2-1.5	2.0-4.5	0.37-0.39	0.04-0.09	2	100-200	0.2
<i>Thermoplastics</i>							
Nylon 6.6	1.14	1.4-2.8	0.3	0.06-0.07	40-80	90	0.2
polypropylene				0.02-0.04	300	110	0.2
PEEK				0.17	50	47	0.2
<i>Metals</i>							
Al				0.2-0.6	6-20	24	130-230
Mg				0.1-0.3	3-10	27	100
Ti				0.1-1.0	4-12	9	6-22
<i>Ceramics</i>							
borosilicate glass				0.10	0.2	3	12
SiC	3.4	400	0.20	0.4	0.1	4	50
Al ₂ O ₃	3.8	380	0.25	0.5	0.1	8	30

High affinity for Oxygen
Problem in production
Chemical reaction between R and M

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FIBRE ARCHITECTURE

- Composites properties are strongly dependant on the **arrangement** and the **distribution** of fibres:
- Diameter and length(L/D=aspect ratio)
- Volume fraction(%)
- Alignment (orientation)
- Packing arrangement (distribution)

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VOLUME FRACTION AND WEIGHT FRACTION

- Depending on the property we want to discuss, we need to consider either type of description
- **Volume fraction:** used for most properties (strength ...)
- **Weight fraction:** used for properties such as density

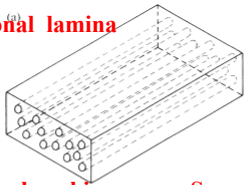
$$v_f = \frac{w_f / \rho_f}{(w_f / \rho_f) + (w_m / \rho_m)}$$

$$w_f = \frac{v_f \rho_f}{(v_f \rho_f) + (v_m \rho_m)}$$

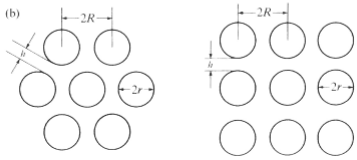
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FIBRE PACKING ARRANGEMENTS

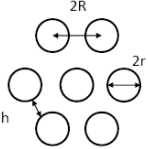
Unidirectional lamina



Hexagonal packing **Square packing**

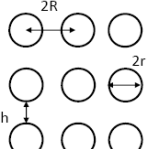


Exercise: calculate the max of V_f in both arrangements



$$V_f = \left(\frac{\pi}{2\sqrt{3}}\right)\left(\frac{r}{R}\right)^2$$

$$h = 2\left[\left(\frac{\pi}{2V_f\sqrt{3}}\right)^{\frac{1}{2}} - 1\right]r$$



$$V_f = \left(\frac{\pi}{4}\right)\left(\frac{r}{R}\right)^2$$

$$h = 2\left[\left(\frac{\pi}{4V_f}\right)^{\frac{1}{2}} - 1\right]r$$

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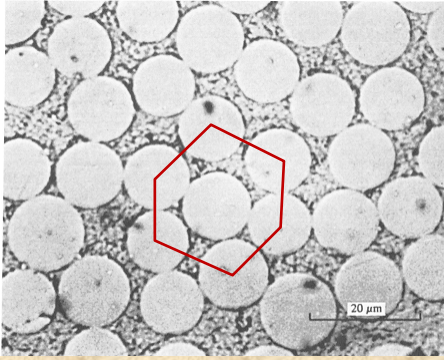
CLUSTERING OF FIBERS

- these ideal arrangement do not occur usually and there is usually clustering of fibers (some localized region).

Hexagonal array in some part

Non regular packing in other regions

In practice Max $V_f=0.7$

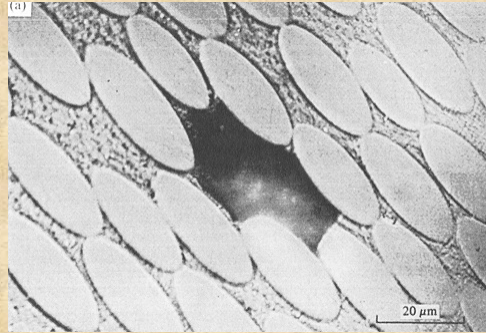


glass fibre/polyester resin.

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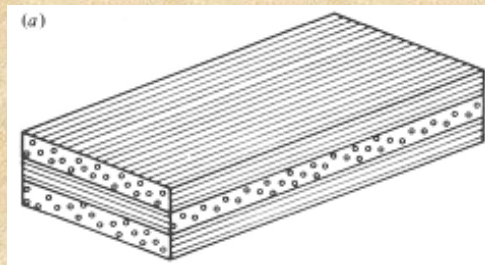
CLUSTERING OF FIBERS

- Properties are then affected because V_f (max of 0.7) is lower
- For a resin to penetrate a dense pack of fibres is difficult which leads to defects (voids) and lower properties



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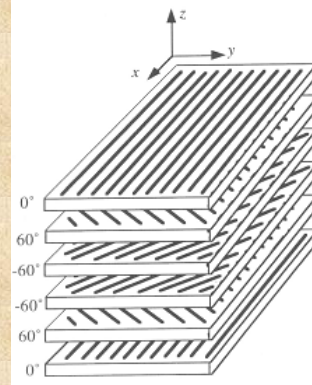
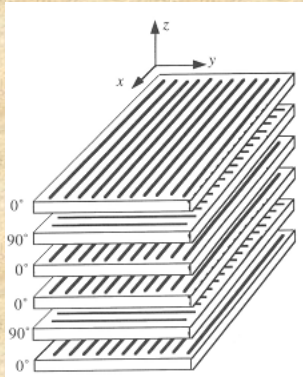
- Set of plies stacked together
- Good properties within the plane of the plies
- Plies can be arranged in a stack to make the properties isotropy.



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LAMINATES

- Laminates are described by their stacking sequence.



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MAXIMUM VOLUME FRACTION

Exercise: calculate the max of V_f in both arrangements

For a hexagonal array, when $r = R$, the $V_{f,max}$ ○
 $=0.907$

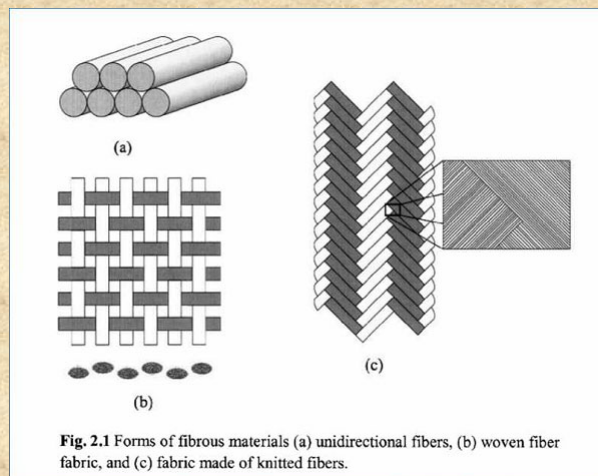
For a square array, when $r = R$, the $V_{f,max}$ ○
 $=0.785$

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CONTINUOUS FIBERS

- Continuous ceramic fibers for reinforcing metallic or ceramic materials
- Combine rather high strength and elastic modulus with high-temperature capability and a general freedom from environmental attack
- Making them attractive as reinforcements in high temperature structural materials.
- Fibers have some unique features which stem mainly from their small cross-section and large aspect ratio.
- These features include:
 - **1-High degree of flexibility.**
 - This flexibility permits a variety of techniques to be employed for making composites with these fibers. Flexibility of a material is a function of its elastic modulus, E , and its diameter. We can write $1/MR = 64/Ed^4$, where M is the bending moment and R is the radius of curvature, and $1/MR$ denotes the degree of flexibility.
 - **2- Higher strength** than bulk material of the same composition

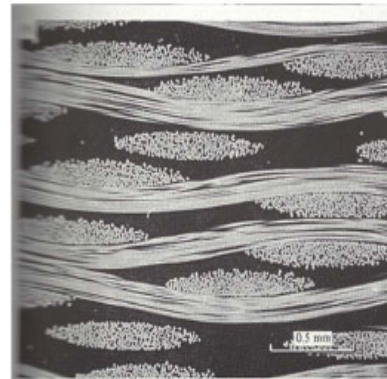
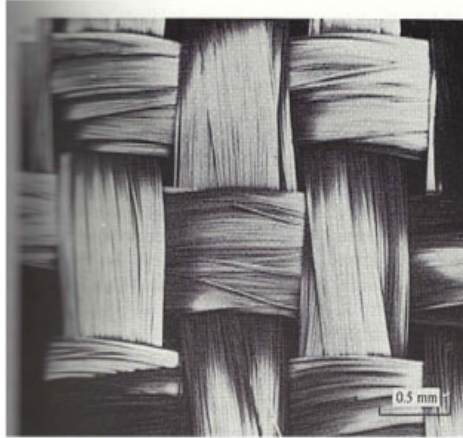
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Continuous Fibers

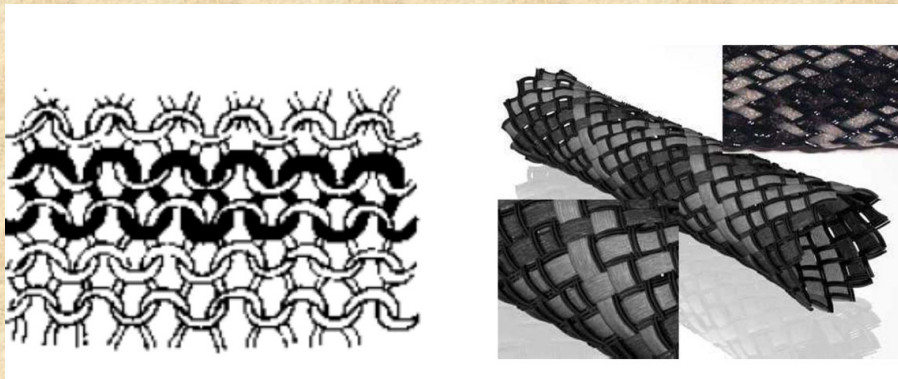
○ Woven arrays of fibres



(a) SEM micrograph of a woven roving before infiltration with resin. (b) SEM micrograph of a polished section through a woven roving laminate parallel to one set of fibres.

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KNITTED ARRAYS OF FIBRES



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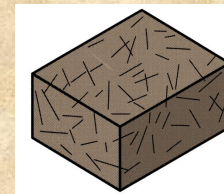
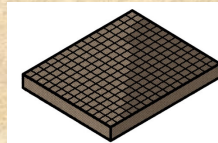
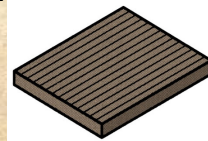
BRAIDED ARRAYS OF FIBRES



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FIBER ORIENTATION – THREE CASES

- **One-dimensional** reinforcement, in which maximum strength and stiffness are obtained in the direction of the fiber
- **Planar reinforcement**, in some cases in the form of a two-dimensional woven fabric
- **Random** or **three-dimensional** in which the composite material tends to possess isotropic properties



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INTERFACE

- The term in composites refers to a bounding surface between the reinforcement and matrix across which there is a **discontinuity in chemical composition, elastic modulus, coefficient of thermal expansion, and or thermodynamic properties such as chemical potential.**

Why interface is important?

1-Because in most composites, the interfacial area per unit volume is very large.

2-a thermodynamic driving force will be present for an interfacial reaction that will reduce the energy of the system.

influence on the properties of the composite

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- interface is a bi-dimensional region across which a discontinuity occurs in one or more material parameters.
- In practice, there is always some volume associated with the interface region, and a gradual transition in material parameters occurs over the thickness of this interfacial zone.

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- ❖ **an interfacial zone with finite thickness, possibly consisting of multiple layers.**
- ❖ The multilayer boundary zone in ***equilibrium*** at the high T but at any other temperature, a complex stress field exists in the boundary zone (mismatch in coefficient of thermal expansion of the layers).
- ❖ These stresses will be proportional to the difference in the ***elastic moduli*** of the components, difference in the ***coefficients of thermal expansion, chemical potential,*** and ***temperature difference*** between the equilibrium (or initial) temperature and final temperature.

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- A discontinuity in ***chemical potential*** cause a chemical interaction, leading to an inter-diffusion zone or the formation of a chemical compound at the interface.
- A discontinuity in the ***thermal expansion coefficient*** means that the interface will be in equilibrium only at the temperature where the thermal expansion of the matrix were equal to that of the reinforcement.
- $\sigma = f(E, a, b, r) \Delta\alpha \Delta T$, where σ is the stress field, E is the elastic modulus, a, b, r are geometric parameters, and $\Delta\alpha \Delta T$ is the thermal mismatch between the components of a composite.

At any other temperature, biaxial or triaxial stress fields will be present, because of the thermal mismatch between the components of a composite.

Thermal stresses due to a thermal mismatch will generally have an expression of the form

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- Where $f(E, a, b, r)$ is a function of the elastic constants E and the geometric parameters a , b , and r ; $\Delta\alpha$ is the difference in the expansion coefficients of the components, and ΔT is the change in temperature of the material.
- The term $(\Delta\alpha\Delta T)$ is, the thermal strain. For a given *diameter and volume fraction* of reinforcement, a fibrous composite will have a larger interfacial area than a particulate composite.

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The interfacial area in a composite increases with a decreasing reinforcement diameter. It is easy to visualize the interfacial area becoming very large for reinforcements less than 10--20 μm in diameter.

Since chemical and/or mechanical interactions between the reinforcement and the matrix occur at interfaces, an extremely large area of interface has an enormous importance in determining the final properties and performance of a composite.

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- ***Thermodynamically*** speaking, the phases in the boundary zone will tend to change such that the ***free energy*** of the system is minimized.
- This may involve **generation of dislocations, grain boundary migration, crack nucleation and/or propagation.**
- An ideal interface in a metal matrix composite should promote ***wetting and bond*** the reinforcement and the matrix to a desirable degree.

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Crystallographic Nature of the Fiber–Matrix Interface

- ***Coherent*** : one-to-one correspondence between lattice planes on the two sides of the interface ***like Al-Li system (Al_3Li precipitate is coherent with the aluminum matrix).***
- **lithium and aluminum assuming diamond structures and has a lattice parameter of 6.37 Å.**
- ***Semi-coherent***: eutectic composites and XD-type particulate composites
- **The XD-process (patented by the Martin Marietta Corporation)** Blends of ceramic and metallic powders are heated up to a reaction temperature which is usually above the metal melting point. The components react with each other (preferably exothermically) and form a dispersion of a new ceramic phase in the matrix. Examples are the production of Al composites with a dispersion of borides or nitrides.
- ***Incoherent***: no matching of lattice planes occurs across the boundary

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The Interface

- There is always an *interface* between constituent phases in a composite material
- For the composite to operate effectively, the phases must bond where they join at the interface

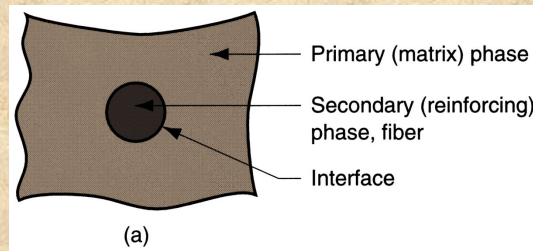


Figure 9.4 - Interfaces between phases in a composite material:
(a) direct bonding between primary and secondary phases

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Interphase

- In some cases, a third ingredient must be added to achieve bonding of primary and secondary phases called an *interphase*, this third ingredient can be thought of as an adhesive

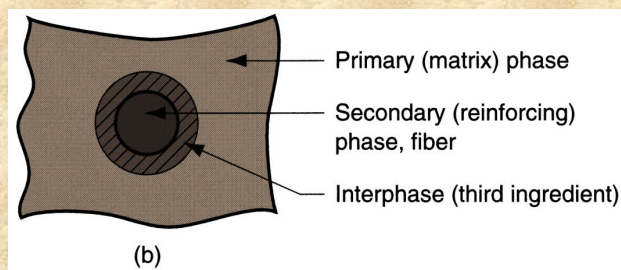
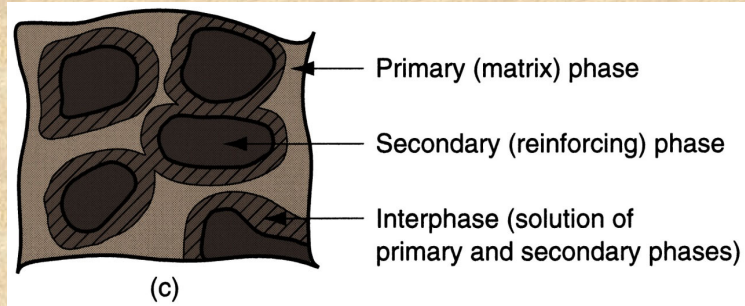


Figure 9.4 - Interfaces between phases: (b) addition of a third ingredient to bond the primary phases and form an interphase

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Another Interphase

Interphase consisting of a solution of primary and secondary phases



Interfaces and interphases between phases in a composite material: (c) formation of an interphase by solution of the primary and secondary phases at their boundary

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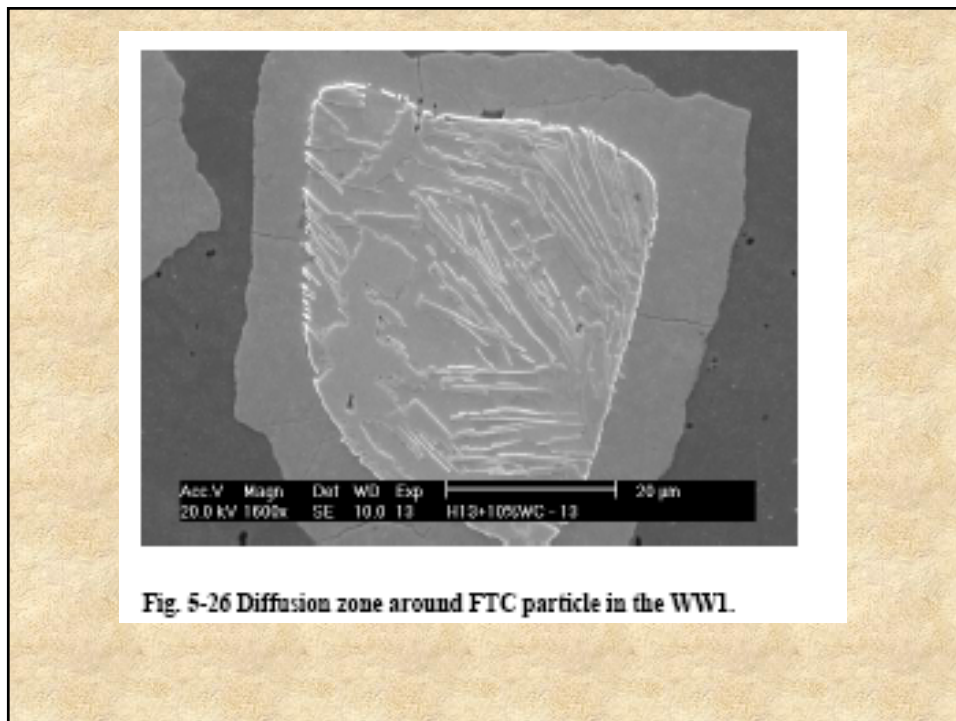


Fig. 5-26 Diffusion zone around FTC particle in the WWI.

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TYPES OF BONDING

Control the degree of bonding between the matrix and the reinforcement is important. ○

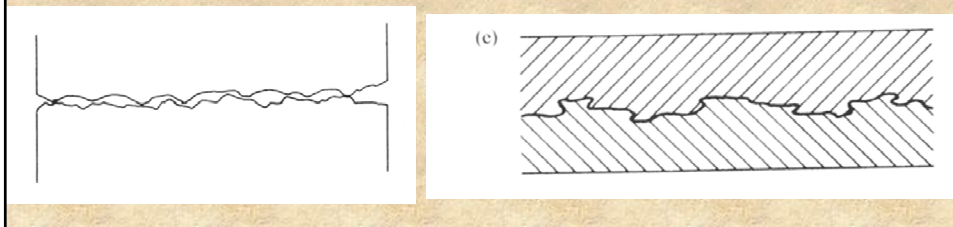
important types of interfacial bonding the reinforcement are: ○

Mechanical Bonding

Physical Bonding

Chemical Bonding (Dissolution -Reaction Bonding) ○

Most fibers have a characteristic surface roughness or texture resulting from the fabrication process ○



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MECHANICAL BONDING

In a mechanical bond, the degree of **interfacial roughness** is a very important parameter, which is controlled by the **fiber surface roughness**.

Surface roughness can contribute to bonding only if the liquid matrix wets the reinforcement surface (otherwise leave interfacial voids on solidification). ○

In PMCs and MMCs, mechanical bonding in addition to chemical bonding is preferred. ○

In CMCs, mechanical bonding rather than chemical bonding. ○

In fiber reinforced composites mechanical bonding will be effective mostly in the longitudinal or fiber direction. Transverse to the fiber, has minor effect. ○

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In a MMC (matrix has a higher coefficient of thermal expansion than ceramics. ceramic fiber and will lead to matrix even in (Al₂O₃ fiber in aluminum) fiber surface, can also lead to mechanical bonding.

more shrinkage on cooling. The matrix pores are filled by liquid flow.

mechanical bonding

Matrix Fiber

Mechanical (or Frictional) Bond

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SOME EXAMPLES OF MECHANICAL BONDING

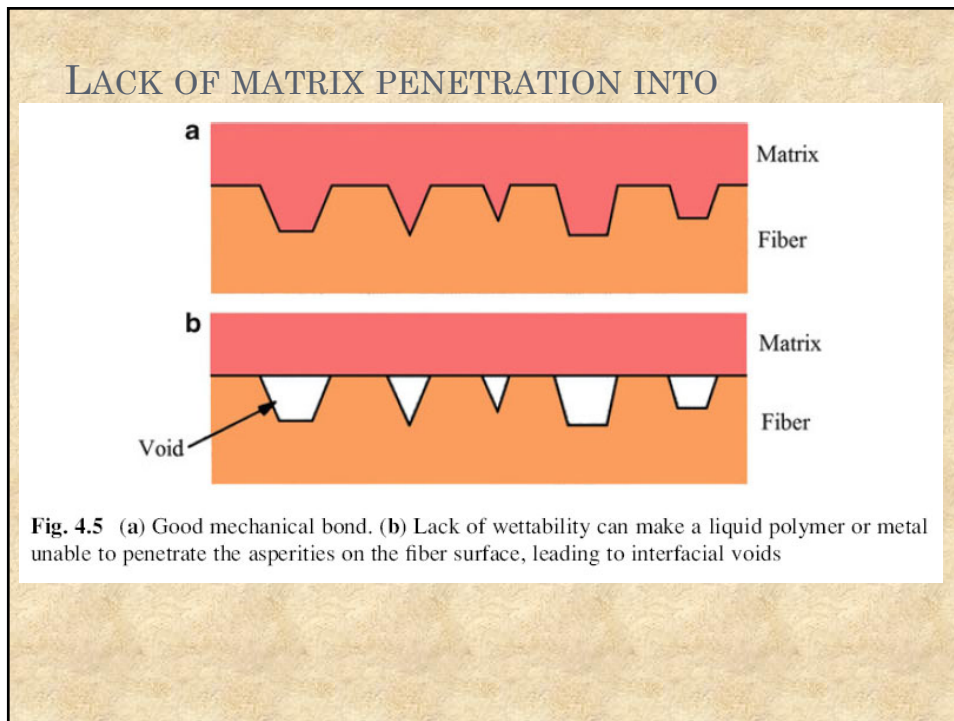
Hill et al. (1969) confirmed the mechanical bonding effects in tungsten filament/aluminum matrix composites.

Chawla and Metzger (1978) (bonding between an aluminum substrate and anodized alumina (Al₂O₃) films) found that with a rough interface a more efficient load transfer from the aluminum matrix to the alumina occurred.

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Pure mechanical bonding alone is not enough in most cases. mechanical bonding is efficient in load transfer when the applied force is parallel to the interface. In the case of mechanical bonding, the matrix must fill the hills and valleys on the surface of the reinforcement. **surface roughness**, can contribute to bond strength only if the liquid matrix can wet the reinforcement surface. A good example of excellent wetting (contact angle, 0) is between WC and Cobalt liquid.

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- PHYSICAL BONDING
- Any bonding involving weak, secondary or van der Waals forces, dipolar interactions, and hydrogen bonding can be classified as physical bonding.
 - The bond energy in such physical bonding is very low, approximately 8–16 kJ/mol.

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CHEMICAL BONDING

Ceramic/Metal interfaces in MMCs are ○

generally formed at high T. Diffusion and chemical reaction kinetics are faster at elevated temperatures.

- Knowledge of thermodynamics and kinetics of reactions (control of processing and obtain optimum properties)
- Chemical bonding in MMCs involves atomic transport by diffusion. Thus, chemical bonding includes solid solution and or chemical compound formation at the interface.
- leads to Formation of an interfacial zone containing a solid solution and or a reinforcement/matrix interfacial reaction zone have a certain thickness.

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CHEMICAL BONDING

This encompasses all types of covalent, ionic, and metallic bonding. ○

Chemical bonding involves primary forces and the bond energy is in the range of approximately 40–400 kJ/mol. ○

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CHEMICAL BONDING

Dissolution bonding: ○

interaction between components occurs at an electronic scale. ○

interactions are of rather short range and need that components come into intimate contact on an atomic scale. ○

Surfaces should be appropriately treated to remove any impurities. ○

Any contamination of fiber surfaces, or entrapped air or gas bubbles at the interface, will hinder the required intimate contact between the components. ○

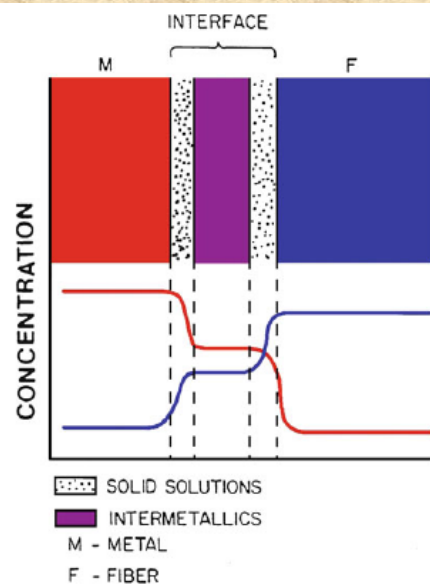
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Reaction bonding: ○
 transport of molecules, atoms, or ions occurs from one or both ○
 of the components to the reaction site, that is, the interface. ○
 This atomic transport is controlled by diffusional processes. ○
 Such a bonding can exist at a variety of interfaces, e.g., ○
 glass/polymer, metal/metal, metal/ceramic, or ○
 ceramic/ceramic. ○

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In metallic systems, solid solution and intermetallic ○
 compound formation can occur at the interface.

Fig. 4.6 Interface zone in a metal matrix composite showing solid solution and intermetallic compound formation



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Most MMC systems are Non-equilibrium systems in the thermodynamic sense; **ie**, there exists a chemical potential gradient across the fiber/matrix interface. ○

At given favorable kinetic conditions (high enough temperature or long enough time) diffusion and/or chemical reactions occur between the components. ○

Prolonged contact between liquid metal and reinforcement can lead to a significant chemical reaction, which may adversely affect the behavior of the composite. ○

$x^2 \approx Dt$ X: thickness of the reaction zone

$D = A \exp(-\Delta Q/kT)$ D : diffusivity

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OPTIMUM INTERFACIAL BOND STRENGTH

obtaining an optimum interfacial bond involve **treatments of fiber or reinforcement surface** or **modification of matrix composition.** ○

maximizing the bond strength is not always the goal. ○

In brittle matrix composites, too strong a bond would cause embrittlement ○

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VERY WEAK INTERFACE OR FIBER BUNDLE (NO MATRIX)

- This extreme situation will prevail when we have no matrix and the composite consists of only a fiber bundle.
- The bond strength in such a composite will only be due to interfiber friction.
- A statistical treatment of fiber bundle strength shows that the fiber bundle strength is about 70–80 % of average single fiber strength.

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VERY STRONG INTERFACE

- when the interface is as strong or stronger than the higher-strength component of the composite, generally the reinforcement.
- In this case, of the three components—reinforcement, matrix, and interface—the interface will have the lowest strain-to-failure.
- The composite will fail when any cracking occurs at a weak spot along the brittle interface.
- Typically, in such a case, a catastrophic failure will occur, and we will have a composite with very low toughness.

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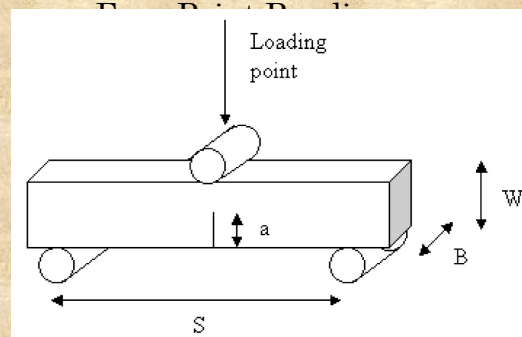
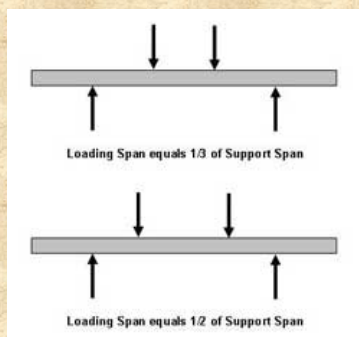
- OPTIMUM INTERFACIAL BOND STRENGTH
- An interface with an optimum interfacial bond strength will result in a composite with an enhanced toughness, but without a severe penalty on the strength parameters.
 - Such a composite will have multiple failure sites, most likely spread over the interfacial area, which will result in a diffused or global spread of damage, rather than a very local damage.

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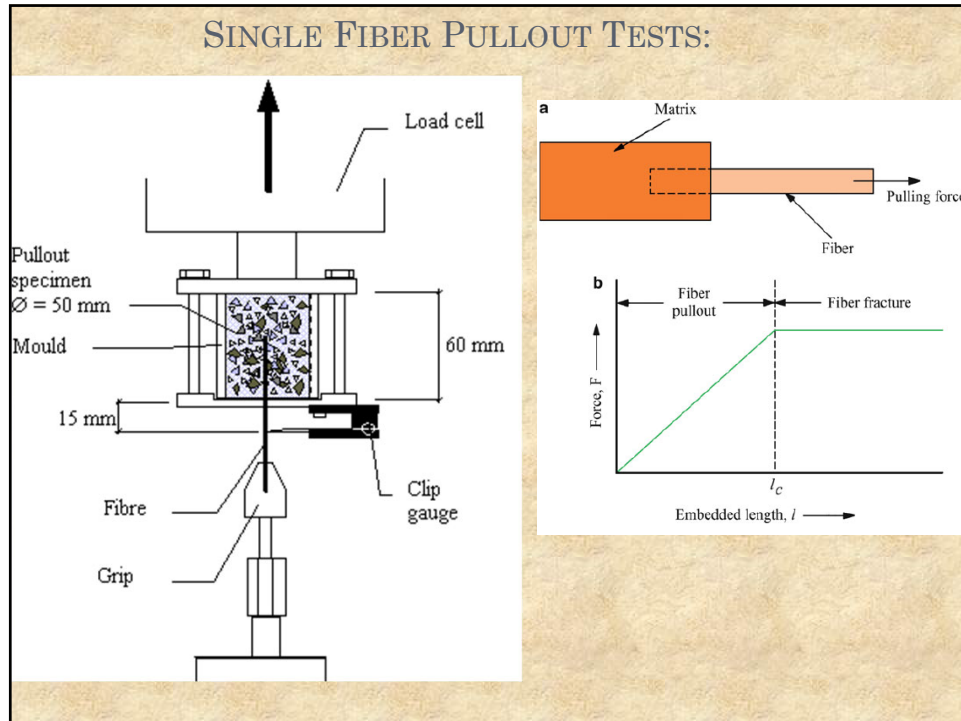
TESTS FOR MEASURING INTERFACIAL STRENGTH

Flexural or bend tests: ○

Three-Point Bending ○



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METAL MATRIX COMPOSITES

MMCs consist of a metal or an alloy as the continuous matrix and a reinforcement that can be particle, short fiber or whisker, or continuous fiber.

There are three kinds of MMCs:

- Particle reinforced MMCs
- Short fiber or whisker reinforced MMCs
- Continuous fiber or sheet reinforced MMCs

Table 6.1 Typical reinforcements used in metal matrix composites

Type	Aspect ratio	Diameter (μm)	Examples
Particle	~1-4	1-25	SiC, Al ₂ O ₃ , WC, TiC, BN, B ₄ C
Short fiber or whisker	~10-1,000	0.1-25	SiC, Al ₂ O ₃ , Al ₂ O ₃ + SiO ₂ , C
Continuous fiber	>1,000	3-150	SiC, Al ₂ O ₃ , Al ₂ O ₃ + SiO ₂ , C, B, W, NbTi, Nb ₃ Sn

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IMPORTANT METALLIC MATRICES

Aluminum Alloys: low density (2.7 g/cm^3) and excellent strength, toughness, and resistance to corrosion

Young's modulus 70 GPa

applications in the aerospace field.

Al-Cu-Mg , Al-Zn-Mg-Cu, Al-Li alloys (Lithium increases the E and decreasing the density of the alloy)

precipitation-hardenable alloys

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Titanium Alloys: Titanium is one of the important aerospace materials. It has a density of 4.5 g/cm^3

Young's modulus of 115 GPa.

High strength/weight and modulus/weight ratios are important.

High melting point (1672 C) and retains strength to high temperatures with good oxidation and corrosion resistance.

Aerospace applications , jet engines (turbine and compressor blades), fuselage parts.

Expensive material

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Magnesium Alloys:

- very light. Density of 1.74 and Young's modulus of 45 GPa
- In castings , are used in aircraft gearbox housings, chain saw housings, electronic equipment.
- Magnesium, being a hexagonal close-packed metal, is difficult to cold work.

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COPPER

Density of 8.96 g/cm^3 and Young's modulus of 110-128 GPa .
 FCC structure.
 Application in electrical conductor
 Good thermal conductivity
 Used as either in as cast or wrought condition.

One of the major applications of copper in a composite as a matrix material is in niobium-based superconductors.

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Intermetallic Compounds: ○

ordered (Ni_3Al) or disordered (molybdenum disilicide (MoSi_2)). ○

long-range ordering in crystal structure (different atoms occupy specific positions in the lattice) . ○

Motion of dislocations in intermetallics is much more restricted than others. And results in retention (in some cases, even an increase) of strength at elevated temperatures and high creep resistance. ○

E.g. nickel aluminide shows a marked increase in strength up to 800C. ○

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INTERMETALLIC COMPOUNDS

Extremely low ductility. ○

Ductility could improve by Rapid solidification or addition of boron to Ni_3Al . ○

With extremely small amounts of boron (0.06 wt.%), the ductility increases from about 2% to about 50%. ○

Enhancing toughness by making composites with intermetallic matrix materials is a potential possibility. ○

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PROCESSING

Liquid-State ○

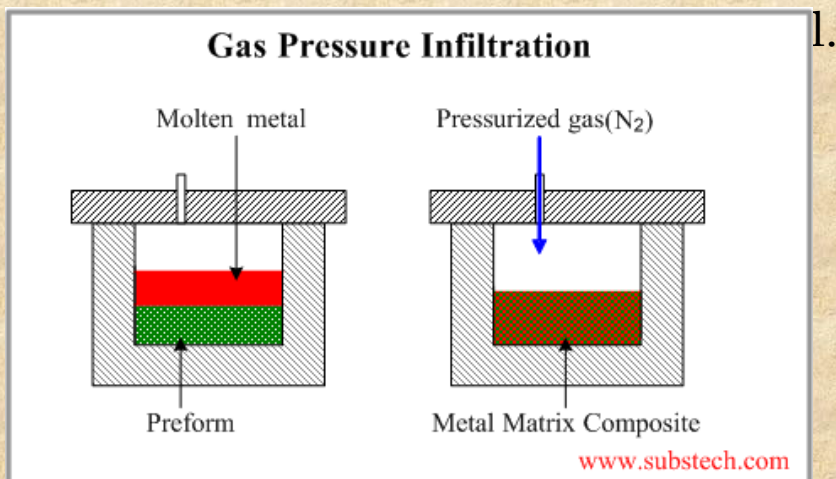
Solid State ○

In Situ ○

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LIQUID-STATE PROCESSES

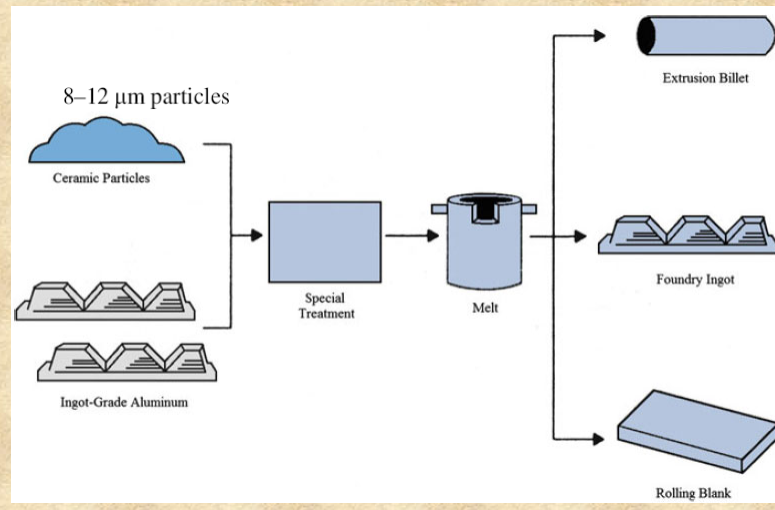
Casting, or liquid infiltration: involves ○
infiltration(**spontaneous or forced**
)infiltration of a fiber bundle by liquid



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LIQUID-STATE PROCESSES

Duralcan process :One commercially liquid infiltration process involving particulate reinforcement. ○



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Some tips

Reactions between the fiber and the molten metal degrade fiber properties. ○

Fiber coatings applied prior to infiltration, which improve wetting and control reactions. ○

Fiber coatings must not be exposed to air prior to infiltration because surface oxidation will alter the positive effects of ○

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SOME TIPS

Too small particles, 2–3 μm , will result in a very large interface region and thus a very viscous melt.

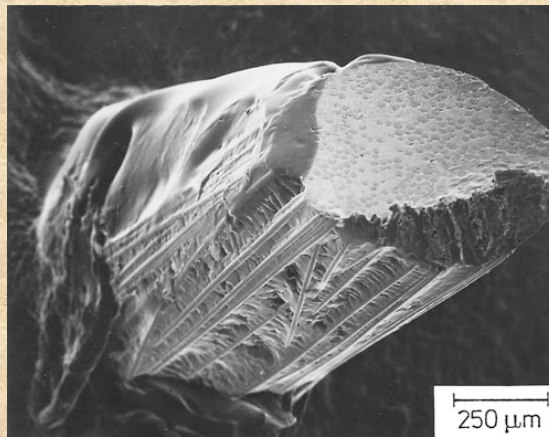
In foundry-grade MMCs, high Si aluminum alloys (e.g., A356) are used, while in wrought MMC, Al–Mg type alloys (e.g., 6061) are used.

Alumina particles are typically used in foundry alloys, while silicon carbide particles are used in the wrought aluminum alloys.

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For making continuous fiber reinforced MMCs, tows of fibers are passed through a liquid metal bath, where the individual fibers are wet by the molten metal, excess metal is wiped off, and a composite wire is produced.

A silicon carbide fiber/aluminum wire preform. SiC fibers can be seen in the transverse section as well as along the length the wire preform.



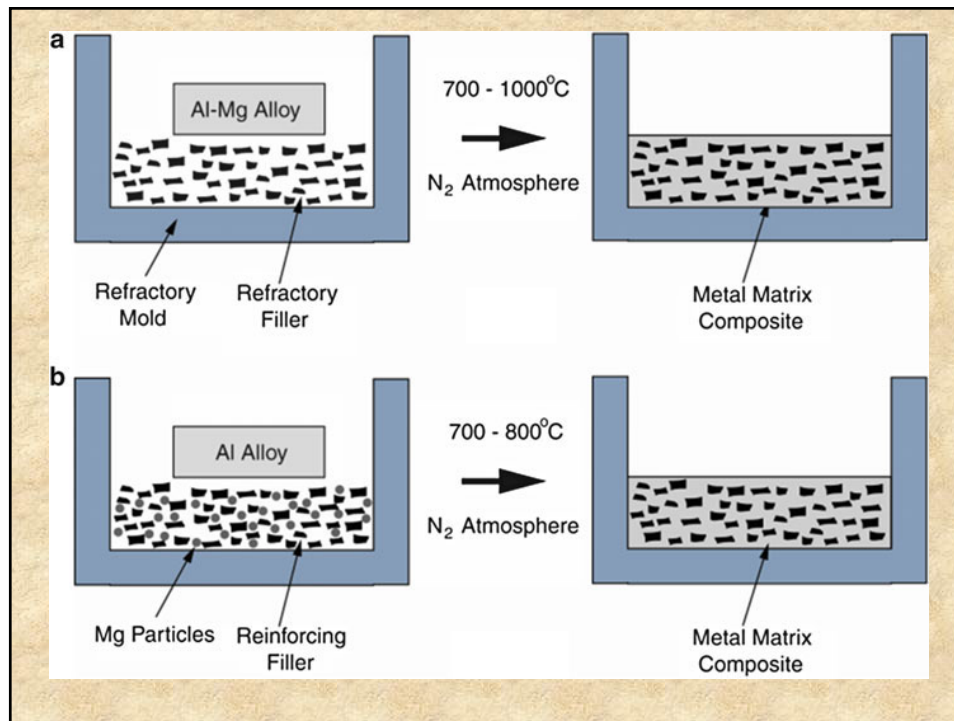
120

Another pressureless liquid metal infiltration process of making MMCs is **Lanxide's Primex™** process, which can be used with certain reactive metal alloys such Al–Mg to infiltrate ceramic preforms.

For an Al–Mg alloy, the process takes place between 750 and 1000 C in a nitrogen-rich atmosphere.

Typical infiltration rates are less than 25 cm/h.

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TUNGSTEN-COPPER COMPOSITES

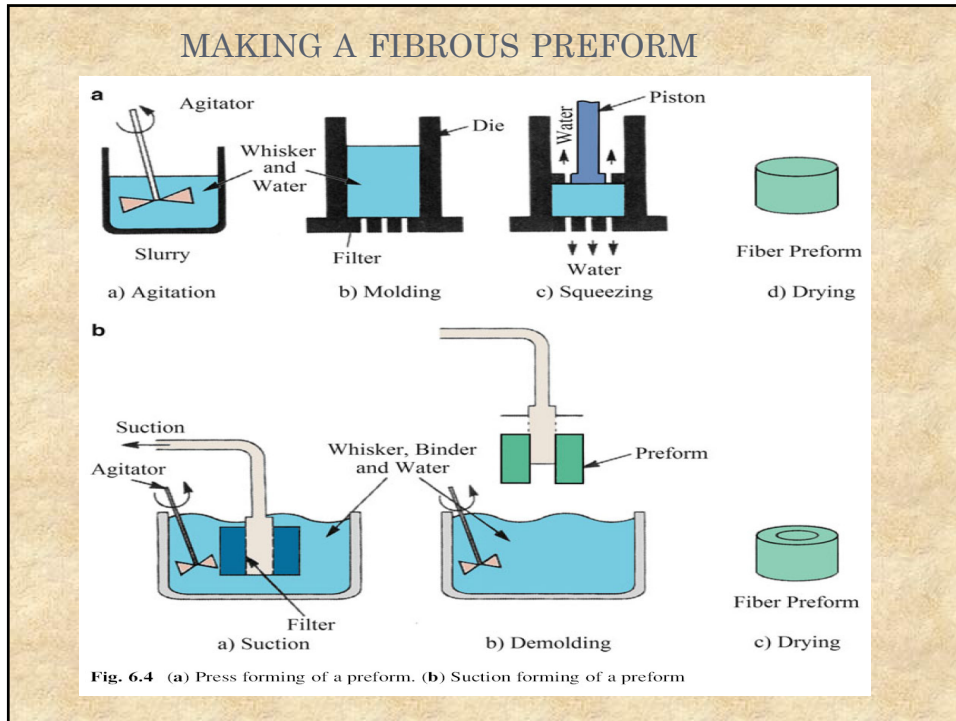
- Coating the Tungsten Powder (average particle size of $\sim 1-5 \mu\text{m}$) with nickel. ○
- Mixing the tungsten powder with a polymer binder and Compacting the powder (Metal injection molding, die pressing, isostatic pressing). ○
- Solvent debinding. ○
- Sintering the green compact at 1204-1315C in H_2 atmosphere for 2 hrs. ○
- Placing the sintered part on a copper plate (powder) in the infiltration/sintering furnace. ○
- Infiltration of the sintered tungsten skeleton porous structure with copper at 1110-1260C in either H_2 atmosphere or vacuum for 1 hour. ○

123

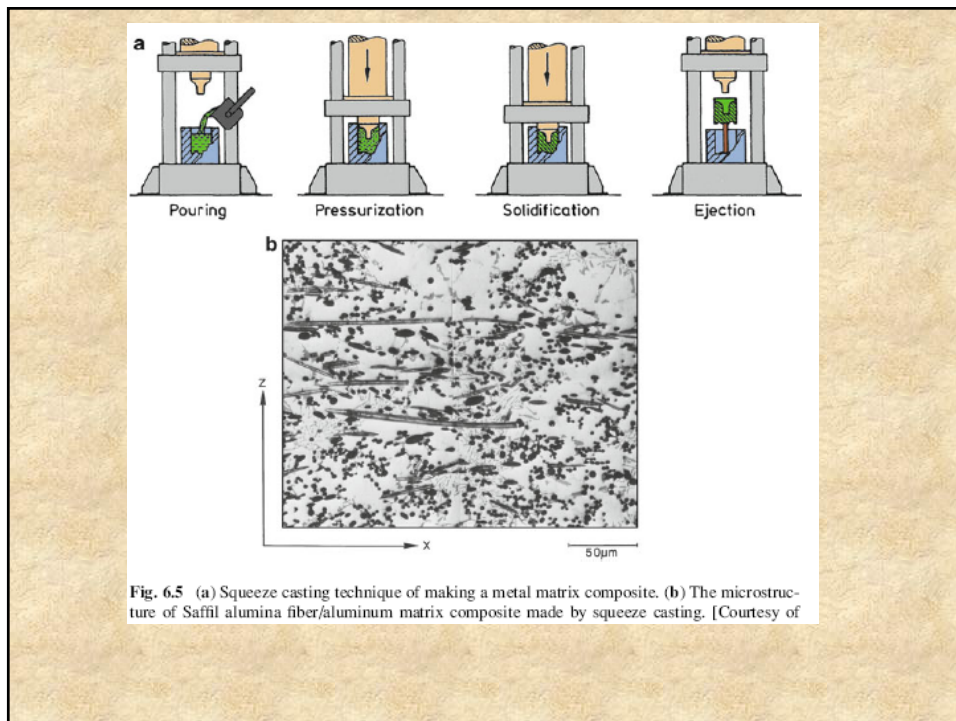
SQUEEZE CASTING, OR PRESSURE INFILTRATION

- forcing the liquid metal (Pressure) into a fibrous preform. ○
- By forcing the molten metal through small pores of fibrous preform, this method obviates the requirement of good wettability of the fibers by the molten metal. ○
- Minimal reaction between the fibers and molten metal due to short dwell time at high temperature ○
- free from common casting defects such as porosity and shrinkage cavities. ○

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aluminum MMCs are made by pressure casting , alumina fiber reinforced intermetallic matrix composites (e.g., TiAl, Ni₃Al, and Fe₃Al matrix materials).

Melting of matrix alloy in a crucible in vacuum, while the fibrous preform is heated separately. The molten matrix material (at about 100C above the T_m) is poured onto the fibers, and argon gas is introduced simultaneously. Argon gas pressure forces the melt to infiltrate the preform.

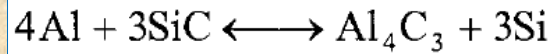
The melt generally contains additives to aid in wetting the fibers.

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Liquid phase processing of MMCs, more specifically, casting of aluminum matrix containing ceramic particles, one of the popular systems, requires some modifications to conventional aluminum casting processes, which are summarized as follows:

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1- molten Al can react with SiC to form Al_4C_3 and Si: ○



When it goes rightward, it injects Si in the molten Al, which can have important consequences. Change of matrix alloy composition is one.

Addition of Si in Al also results in lowering of the melting point of the alloy; in fact it will

Solution: using high levels of Si in the matrix (10% Si) . It is the reason that only high silicon Al alloys are suitable for SiC particles for making composites by casting route.

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2-Covering the melt with an inert ○
gas atmosphere will reduce
oxidation of the melt.

3-Increasing viscosity of the melt by ○
addition of reinforcement particles,
thus, the temperature of the
composite melt should be above a
certain limit ($\sim 745\text{C}$ for Al–Si/SiC)
to keep the melt from becoming
highly viscous.

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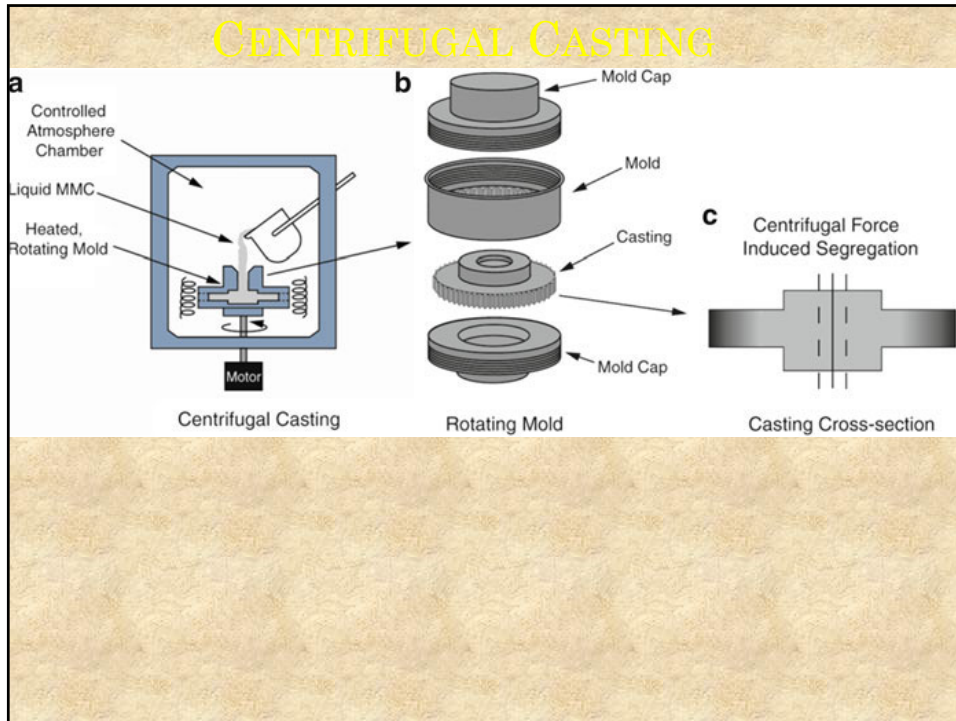
4-Stirring of the composite melt ○
 because of difference between
 density of SiC (3.2 g/cm^3) and Al (2.5 g/cm^3), that causes sinking of
 particles. Alternating currents in a
 magnetic field and mechanical
 vibration improve wetting and
 permeability of the reinforcement in
 the liquid matrix.

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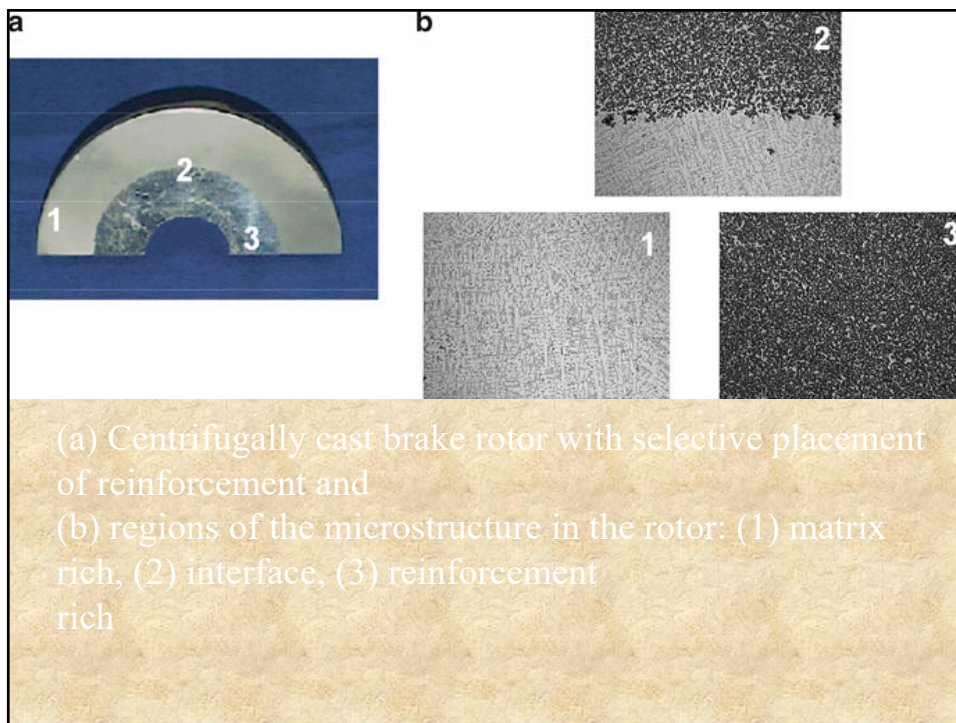
MMCs with ceramic reinforcement are ○
 typically more difficult to machine than
 the unreinforced alloy.

In centrifugal casting, optimal ○
 placement of the reinforcement can be
 achieved by inducing a centrifugal force
 immediately during casting which allows
 a gradient in reinforcement volume
 fraction

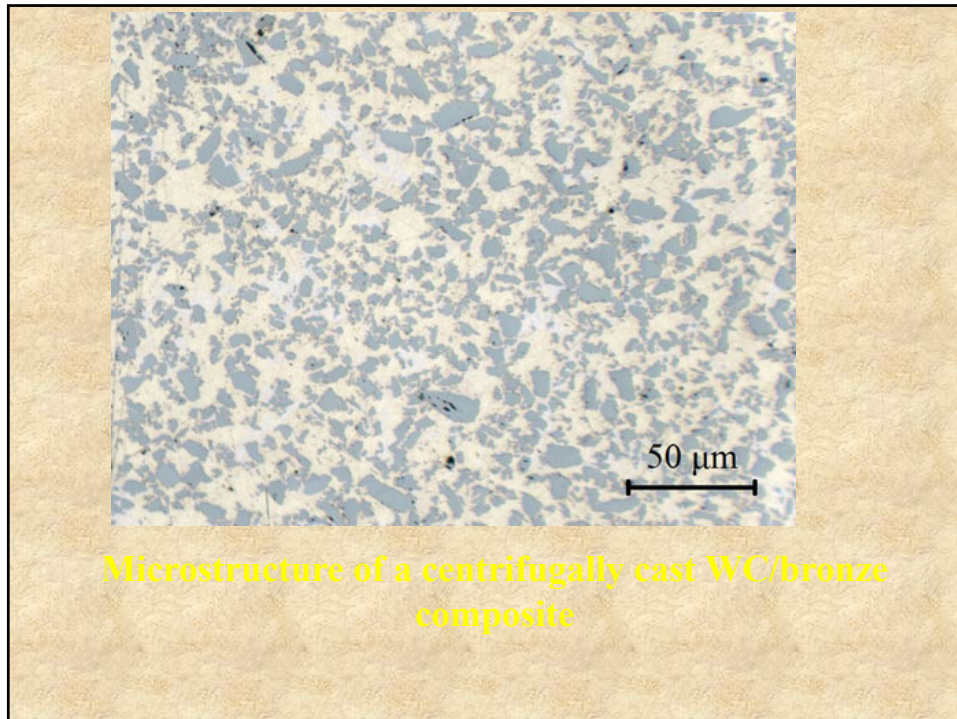
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PROCESSING OF WC/Co COMPOSITES

WC/ (Co) composites, cemented carbides, ○
are produced by powder processing.

Liquid phase state: Even though ○
powders are the starting materials in
this process, because of pressureless
liquid phase sintering .

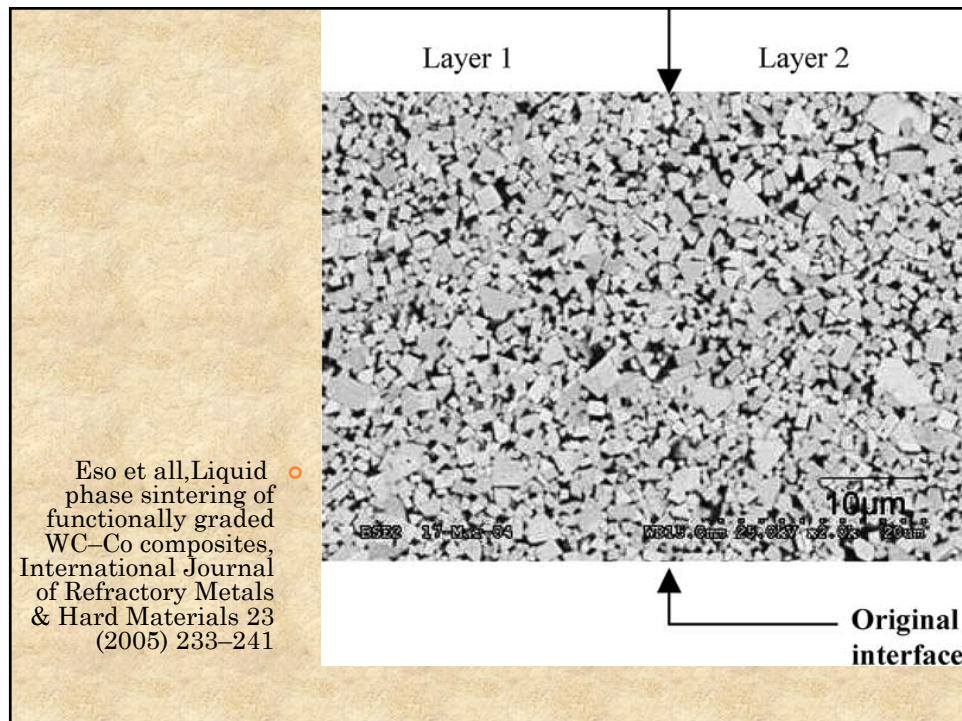
liquid cobalt wets WC particles very ○
easily; it has a contact angle of zero
degree with WC.

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PROCESSING OF WC/Co COMPOSITES

- 1- Blending **WC particles + Co powders + an organic liquid** (minimize heating and prevent oxidation) by milling.
 - 2- removing the liquid by a spray-drying process, resulting in free-flowing, spherical granules of WC/Co.
 - 3- Compacting the granules under pressure(50–150 Mpa) , green compacts 65% of the theoretical density.
 - 4- Pressureless, liquid phase sintering. Good infiltration of WC particles by liquid cobalt occurs because of capillary action and enhanced interfacial diffusion.
- A high density composite, accompanied by large amount shrinkage, is obtained. The capillary action results in some rearrangement of particles, leading to a closer packing of WC particles in Co matrix.

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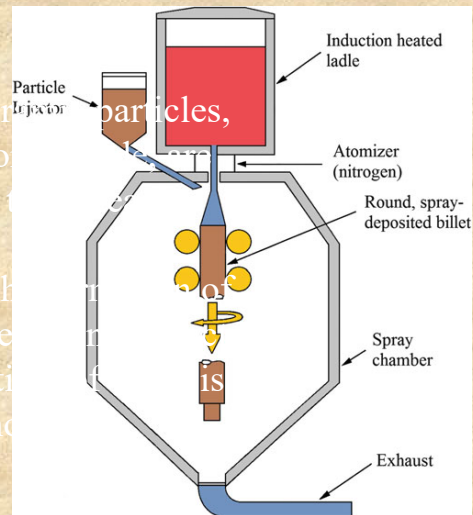
138

SPRAY FORMING

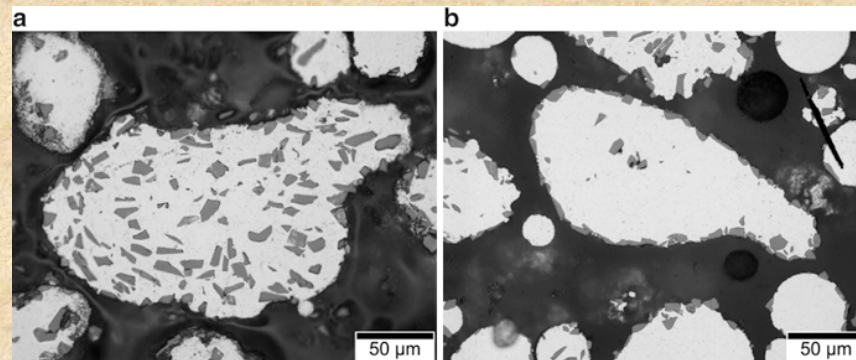
A spray gun is used to atomize a molten aluminum alloy matrix.

Preheated ceramic particles, such as silicon, are injected into the spray chamber.

One avoids the deleterious reaction because the time is extremely short.



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spray co-deposition:

- (a) Homogeneous particle distribution for particle injection, while matrix is in liquid state and
- (b) particles at periphery of matrix droplet, due to particle injection of liquid in semisolid state

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IN SITU PROCESSES

reactive and nonreactive processes ○

In the reactive processes two ○
components are allowed to react
exothermically to form the
reinforcement phase.

E.g. XD process (Martin Marietta ○
1987).

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THE XD™ PROCESS

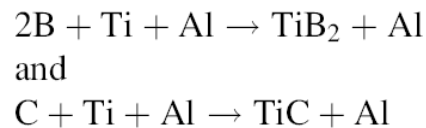
An exothermic reaction between two components produces a ○
third component.

self-propagating high-temperature synthesis (SHS) process ○

Generally, a master alloy containing rather high volume ○
fraction of reinforcement is produced by the reaction
synthesis.

Mixing and remelting of master alloy with base alloy to ○
produce a desirable amount of particle reinforcement.

Typical examples : TiB₂ , SiC and TiC reinforcements ○
particles in an aluminum, nickel, or intermetallic matrix .

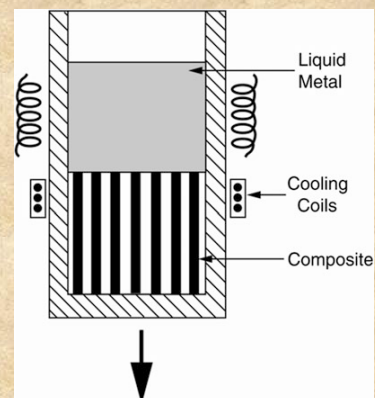


142

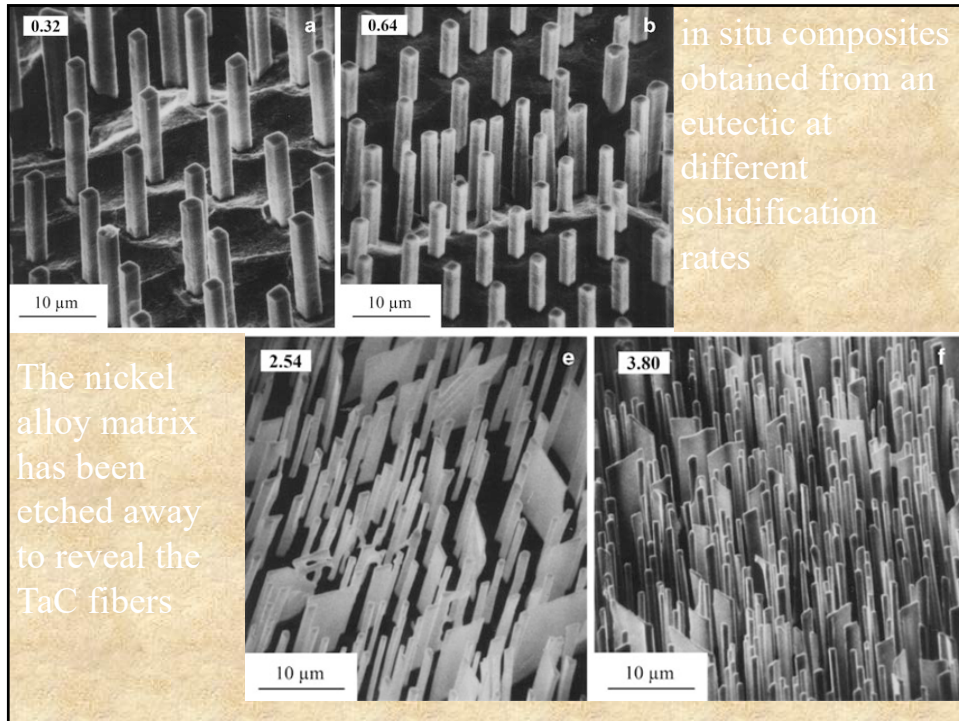
- Processing variables such as reaction temperature can be used to tailor the desired reinforcement particle size, which is usually in the 0.25–1.5 μm range.
- Alternative process that combines spray co-deposition and reaction is to atomize an Al–Ti alloy (at sufficiently high temperature) with a C-containing gas to form TiC particles (Chawla 2012).

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- advantage of two-phase systems, such as eutectic or monotectic alloys, to form the fiber and matrix in situ.
- Controlled directional solidification is conducted to separate the two phases.



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Table 6.2 Some important in situ composite systems

System	Carbide (vol. %)	T_E^a (°C)
Co-NbC	12	1,365
Co-TiC	16	1,360
Co-TaC	10	1,402
Ni-HfC	15–28	1,260
Ni-NbC	11	1,330
Ni-TiC	7.5	1,307

^a T_E is the eutectic temperature

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SOLID-STATE PROCESSING

- The main drawback in liquid phase techniques is the difficulty in controlling reinforcement distribution and obtaining a uniform matrix microstructure.
- adverse interfacial reactions between the matrix and the reinforcement at high T.
- The most common solid-phase processes are based on powder metallurgy techniques.

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POWDER METALLURGY PROCESSING

- Powder processing involves cold pressing and sintering or hot pressing to fabricate primarily particle- or whisker-reinforced MMCs.

blending to produce a homogeneous distribution cold pressing to produce a green body

Particle reinforced metal matrix composite Extrusion Hot pressing Graphite die

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DIFFUSION BONDING

A common solid-state processing technique for joining similar or dissimilar metals.

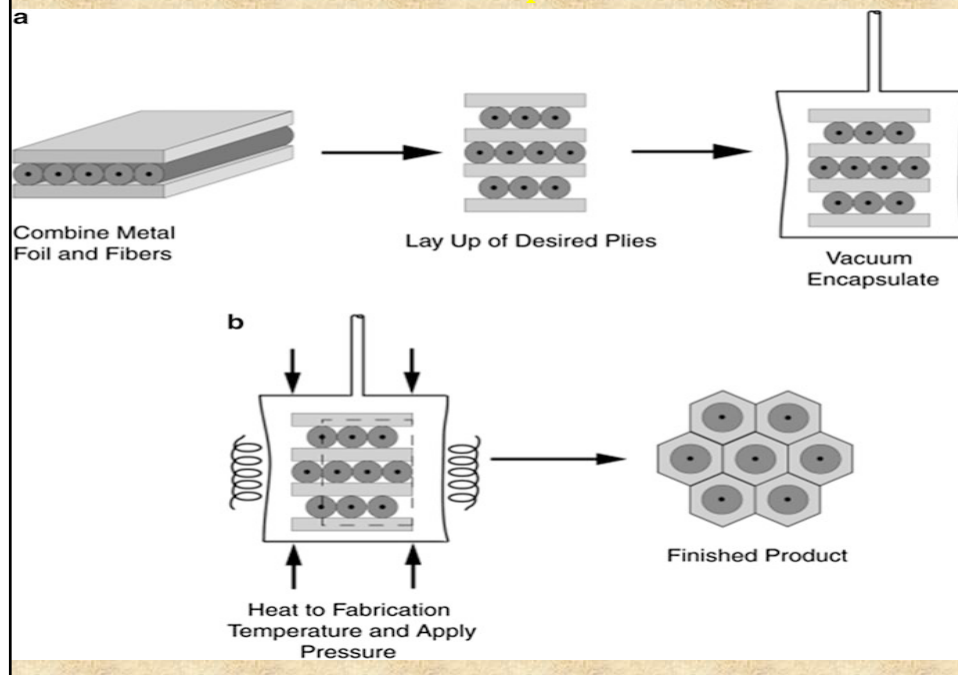
Interdiffusion of atoms, at an elevated temperature, from clean metal surfaces in contact with each other, leads to bonding.

Advantages: ability to process a wide variety of matrix metals, control of fiber orientation and volume fraction.

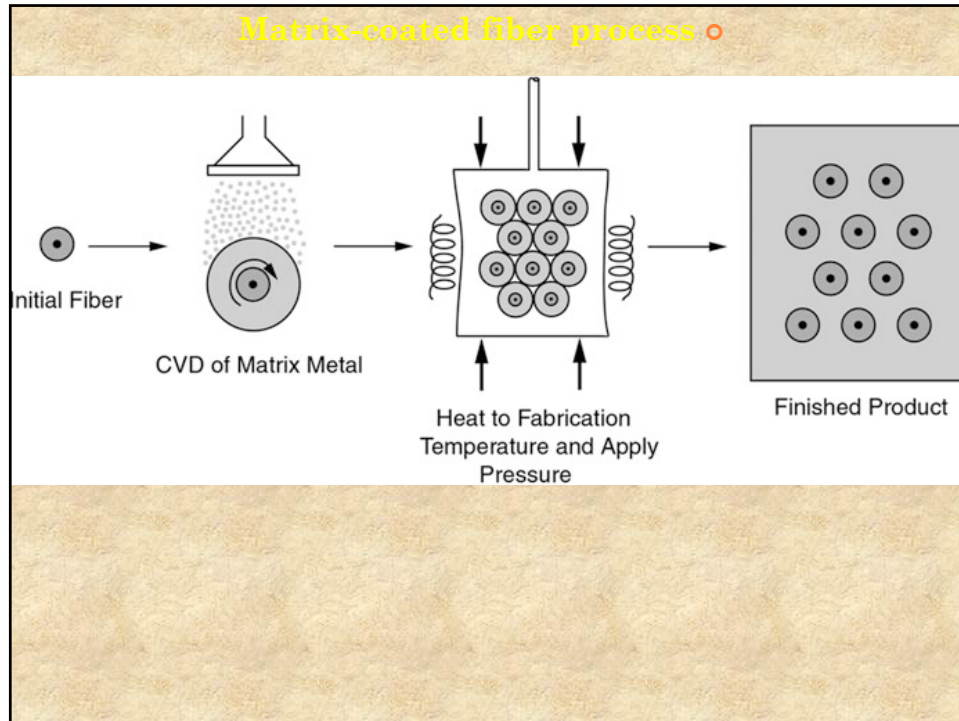
Disadvantages: long processing times, high processing temperatures and pressures (cost), limitation on complexity of shapes that can be produced

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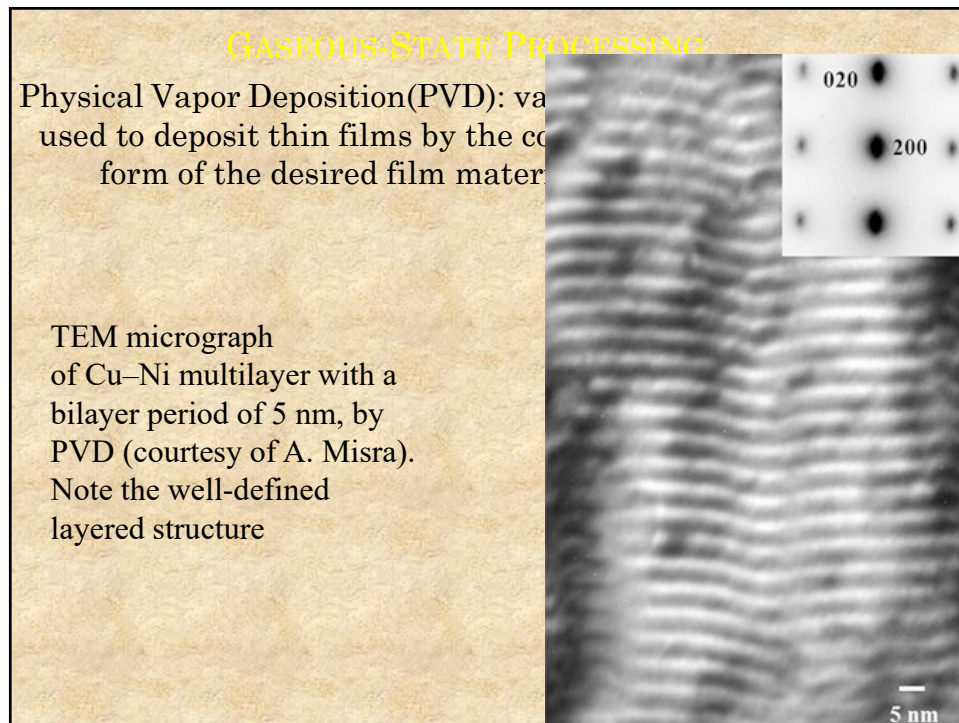
Foil-fiber-foil process



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ELASTIC DEFORMATION OF LONG-FIBRE COMPOSITES

Task Prediction of the behavior (**mechanical properties**) of the resulting composites

Simplest way: elastic behavior of a composite with continuous fibers, all aligned in the same direction

Assume: perfect bonding between fiber and matrix across the interface.

- Axial stiffness
- Transverse stiffness
- Shear stiffness
- Poisson contraction effect

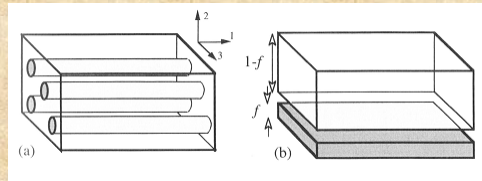
154

COMPOSITES

❖ Long fibres are usually aligned and used to improve strength or stiffness in the axial direction.

Basic slab model:

- The composite can be treated as if composed of parallel slabs of the two constituents
- Relative thicknesses proportional to the volume fraction of matrix and fibers.



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Axial stiffness

(c)

A STRESS IS APPLIED IN THE AXIAL DIRECTION. ❖

❖ Both constituents are constrained to have the same length thus they exhibit the same strain in the axial direction (Voigt model or iso-strain)

❖ Equal strain condition is valid for loading along the fiber axis, provided that there is no **interfacial sliding.**

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$$V_f + V_m = 1 \circ$$

The load on the composite, P_c , is \circ
shared between the two phases, so
that

$$P_c = P_f + P_m \circ$$

$$\varepsilon_c = \varepsilon_f = \varepsilon_m \text{ (iso-strain)}. \circ$$

Since stress = P/A , we can write: \circ

$$\sigma_c A_c = \sigma_f A_f + \sigma_m A_m$$

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AXIAL STIFFNESS

In composites in which fibers are much stronger than the matrix ($E_f \gg E_m$) the reinforcement is subject to much higher stresses ($\sigma_f \gg \sigma_m$)

for a given length of a composite, $A_f/A_c = V_f$ and $A_m/A_c = V_m$.

and from the iso-strain condition, dividing through by the relevant strains, we have:

$$\frac{\sigma_c A_c}{\varepsilon_c} = \frac{\sigma_f A_f}{\varepsilon_f} + \frac{\sigma_m A_m}{\varepsilon_m}$$

$$\text{or } E_c = E_f V_f + E_m (1 - V_f) \dots\dots\dots$$

Voigt

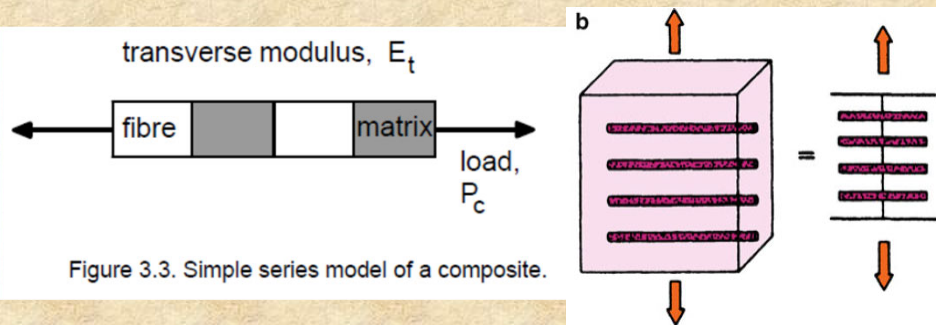
**Rule of
Mixture (ROM)**

158

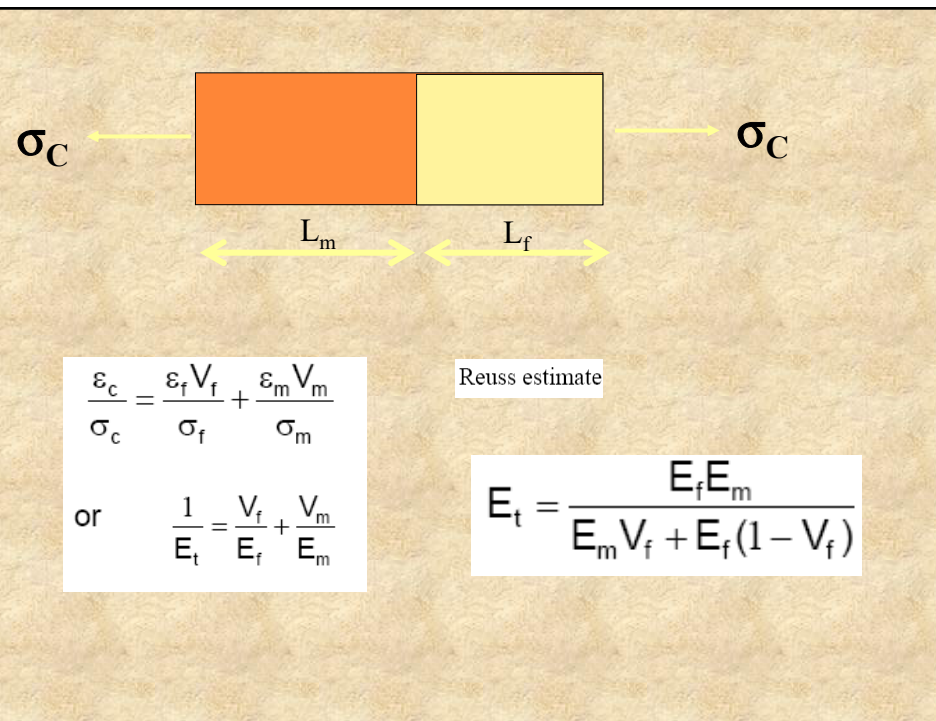
INVERSE RULE OF MIXTURE(ISO STRESS)

The total extension is $\delta_C = \delta_f + \delta_m$

- $\sigma_c = \sigma_f = \sigma_m$
- $\epsilon_c L_c = \epsilon_f L_f + \epsilon_m L_m$
- so that $\epsilon_c = \epsilon_f (L_f / L_c) + \epsilon_m (L_m / L_c)$
- But $L_f / L_c = V_f$ and $L_m / L_c = V_m = 1 - V_f$

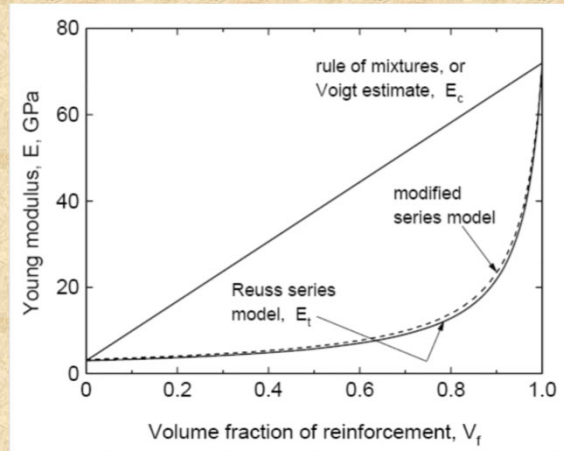


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هیچ کامپوزیتی وجود ندارد که مدول آن از Reuss پایین تر و از Voigt بالاتر باشد.



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EXAMPLE 1- CALCULATE E

Boron fibers (40 v%) are used to reinforce aluminum for an engineering application. Use the table provided below to calculate the density, **modulus of elasticity**, and tensile strength along the fiber orientation. Also estimate the **modulus of elasticity** if the load is to be

Material	Density (g/cc)	Modulus (ksi)	UTS (ksi)
Fibers	2.36	55,000	400
Aluminum	2.70	10,000	5

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FROM THE RULE OF MIXTURE

For density: $\rho_c = V_m \rho_m + V_f \rho_f$
 $\rho_c = (0.6)(2.7) + (0.4)(2.36) = 2.56 \text{ g/cc}$

For modulus:

$$E_c = V_m E_m + V_f E_f$$

$$E_c = (0.6)(10 \times 10^6) + (0.4)(55 \times 10^6) = 28 \times 10^6 \text{ psi}$$

For tensile strength:

$$\text{UTS} = (0.6)(5,000) + (0.4)(400,000) = 163,000 \text{ psi}$$

Loading perpendicular to fibers:

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_f}{E_f} = \frac{0.6}{10 \times 10^6} + \frac{0.4}{55 \times 10^6} = 0.06727 \times 10^{-6}$$

$$\frac{1}{E_c} = 14.9 \times 10^6 \text{ psi}$$

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EXAMPLE 2 – CALCULATE V_f

E-glass fibers are used to reinforce nylon in an industrial application. If the nylon contains 30 vol% glass fibers, what fraction of the applied force is carried by the glass fibers? (E of elasticity for E-glass fibers and nylon are 10.5×10^6 psi and 0.4×10^6 psi, respectively)

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ASSUME EQUAL STRAIN (ISO-STRAIN) CONDITION

Why? If the bonding is good, the composite should
 $\epsilon_c =$ yield only one strain value.

$$\epsilon_m = \frac{\sigma_m}{E_m} = \epsilon_f = \frac{\sigma_f}{E_f}$$

$$\frac{\sigma_m}{E_m} = \frac{\sigma_f}{E_f} \Rightarrow \frac{\sigma_f}{\sigma_m} = \frac{E_m}{E_f} = \frac{10.5 \times 10^6 \text{ psi}}{0.4 \times 10^6 \text{ psi}} = 26.25$$

$$\text{Force fraction} = \frac{F_f}{F_f + F_m} = \frac{\sigma_f A_f}{\sigma_f A_f + \sigma_m A_m} = \frac{\sigma_f (0.3)}{\sigma_f (0.3) + \sigma_m (0.7)}$$

The fraction is then divided by σ_f

$$= \frac{0.3}{(0.3) + (\sigma_m / \sigma_f)(0.7)} = \frac{0.3}{(0.3) + (1/26.25)0.7} = 0.918 = 92\%$$

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HOW ABOUT PARTICLE REINFORCEMENT?

The formula can be modified as: ○

$$E_c = V_m E_m + K_c V_p E_p$$

K_c is an empirical constant. If its value is smaller ○
 than one, then the equal (iso) strain condition can't
 be applied.

K_s and K_c are different constants, both are ○
 determined in the lab (TS = Tensile strength)

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DEFORMATION MECHANISMS IN COMPOSITES

Parallel to fiber orientation:

Stage I: Strain is small, fibers and matrix both elongate (or deform) elastically

Fibers carry the load, $E_c \cong V_f E_f$

Stage II: Incompatibility of the lateral matrix and fiber deformation strains

Matrix deforms plastically; Fibers elastically deform

Stage III: Fiber deformed plastically before fracture (found in metallic fibers)

Both matrix and fibers deform plastically

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PARTICLES AND FLAKES

- A second common shape of imbedded phase is *particulate*, ranging in size from microscopic to macroscopic
- *Flakes* are basically two-dimensional particles - small flat platelets
- The distribution of particles in the composite matrix is random, and therefore strength and other properties of the composite material are usually isotropic
- Strengthening mechanism depends on particle size

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PROPERTIES OF COMPOSITE MATERIALS

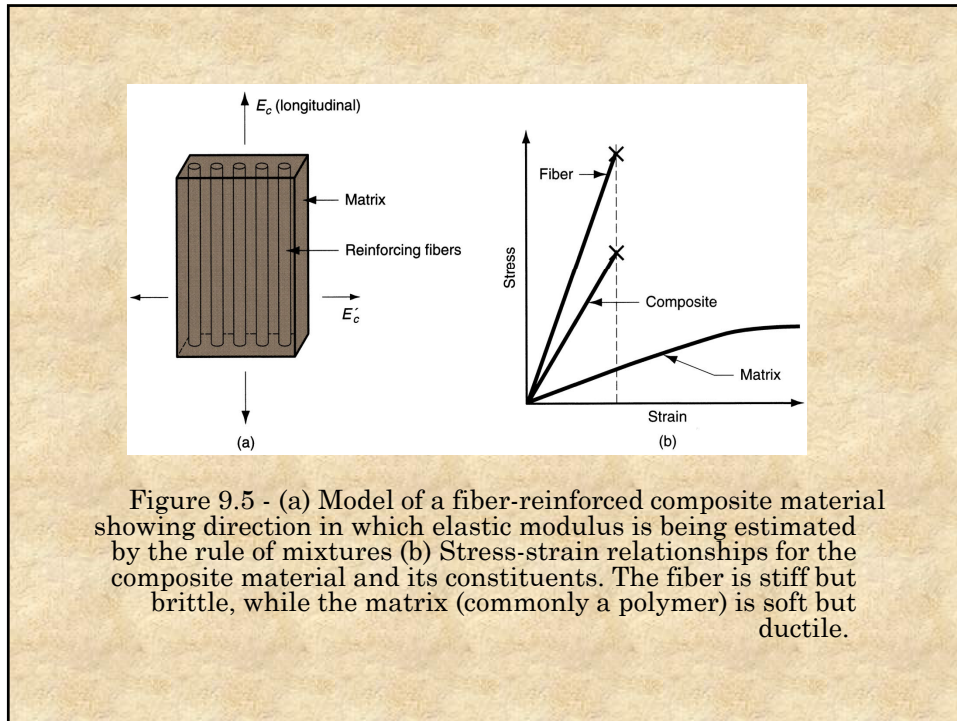
- In selecting a composite material, an optimum combination of properties is usually sought, rather than one particular property
 - Example: fuselage and wings of an aircraft must be lightweight and be strong, stiff, and tough
 - Several fiber-reinforced polymers possess this combination of properties
 - Example: natural rubber alone is relatively weak
 - Adding significant amounts of carbon black to NR increases its strength dramatically

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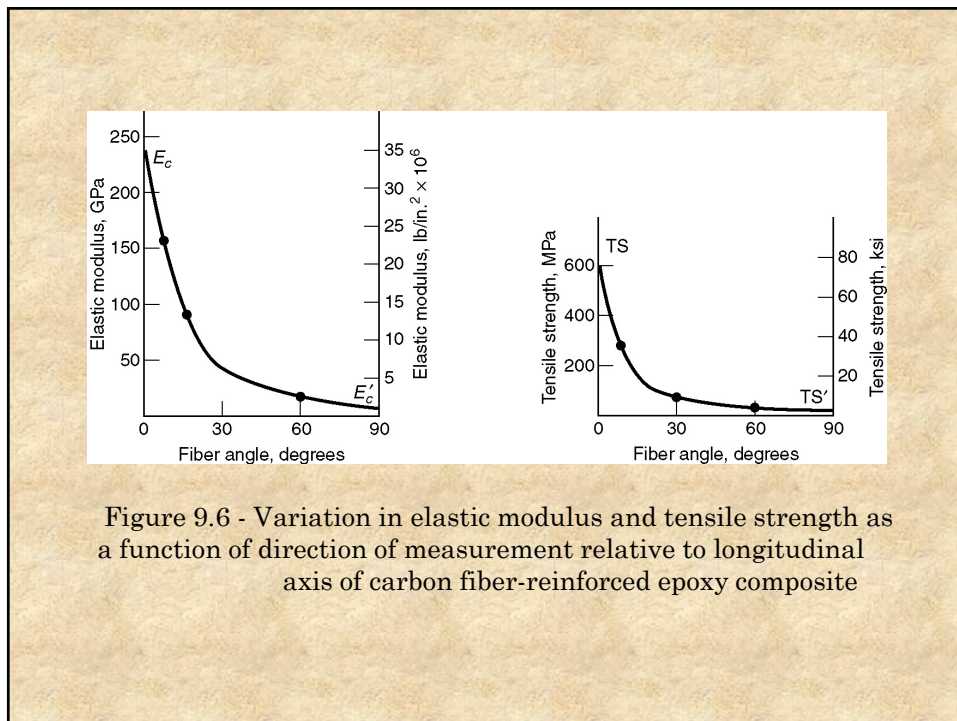
PROPERTIES ARE DETERMINED BY THREE FACTORS:

1. The materials used as component phases in the composite
2. The geometric shapes of the constituents and resulting structure of the composite system
3. The manner in which the phases interact with one another

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FIBERS ILLUSTRATE IMPORTANCE OF GEOMETRIC SHAPE

- Most materials have tensile strengths several times greater as fibers than in bulk
- By imbedding the fibers in a polymer matrix, a composite material is obtained that avoids the problems of fibers but utilizes their strengths
- The matrix provides the bulk shape to protect the fiber surfaces and resist buckling
- When a load is applied, the low-strength matrix deforms and distributes the stress to the high-strength fibers

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OTHER COMPOSITE STRUCTURES

- Laminar composite structure – conventional
- Sandwich structure
- Honeycomb sandwich structure

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Laminar Composite Structure

Two or more layers bonded together in an integral piece

- Example: *plywood* in which layers are the same wood, but grains are oriented differently to increase overall strength of the laminated piece

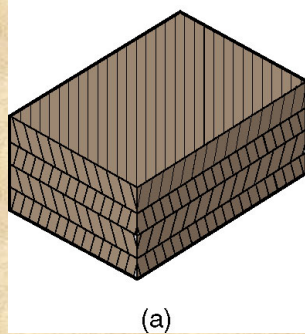


Figure 9.7 - Laminar composite structures: (a) conventional laminar structure

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Sandwich Structure – Foam Core

Consists of a relatively thick core of low density foam bonded on both faces to thin sheets of a different material

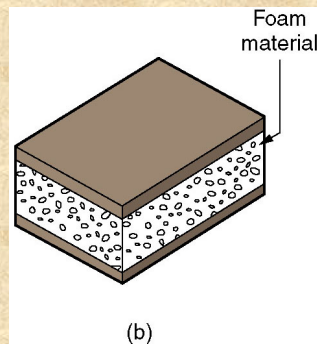


Figure 9.7 - Laminar composite structures: (b) sandwich structure using foam core

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Sandwich Structure – Honeycomb Core

- An alternative to foam core
- Either foam or honeycomb achieves high strength-to-weight and stiffness-to-weight ratios

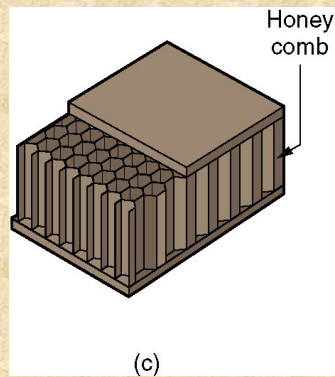


Figure 9.7 - Laminar composite structures: (c) sandwich structure using honeycomb core

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OTHER LAMINAR COMPOSITE STRUCTURES

- *Automotive tires* - consists of multiple layers bonded together
- *FRPs* - multi-layered fiber-reinforced plastic panels for aircraft, automobile body panels, boat hulls
- *Printed circuit boards* - layers of reinforced plastic and copper for electrical conductivity and insulation
- *Snow skis* - composite structures consisting of layers of metals, particle board, and phenolic plastic
- *Windshield glass* - two layers of glass on either side of a sheet of tough plastic

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METAL MATRIX COMPOSITES (MMCs)

A *metal* matrix reinforced by a second phase

Reinforcing phases: ○

Particles of ceramic (these MMCs are commonly called *cermets*) .1

Fibers of various materials: other metals, ceramics, carbon, and boron .2

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CERMETS

MMC with *ceramic* contained in a *metallic matrix*

- The ceramic often dominates the mixture, sometimes up to 96% by volume
- Bonding can be enhanced by slight solubility between phases at elevated temperatures used in processing
- Cermets can be subdivided into
 1. Cemented carbides – most common
 2. Oxide-based cermets – less common

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CEMENTED CARBIDES

One or more *carbide* compounds bonded in a *metallic matrix*

- The term *cermet* is not used for all of these materials, even though it is technically correct
- Common cemented carbides are based on tungsten carbide (WC), titanium carbide (TiC), and chromium carbide (Cr_3C_2)
- Tantalum carbide (TaC) and others are less common
- Metallic binders: usually cobalt (Co) or nickel (Ni)

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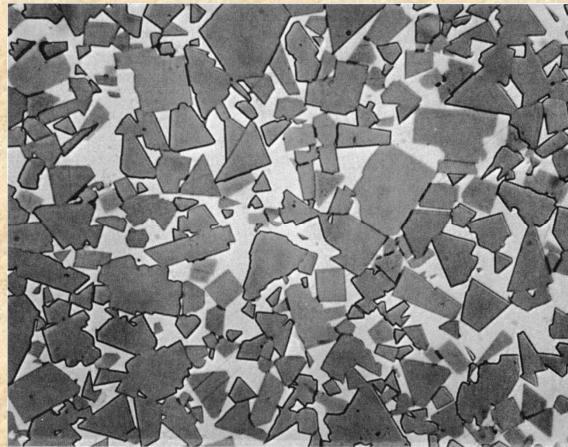


Figure 9.8 - Photomicrograph (about 1500X) of cemented carbide with 85% WC and 15% Co (photo courtesy of Kennametal Inc.)

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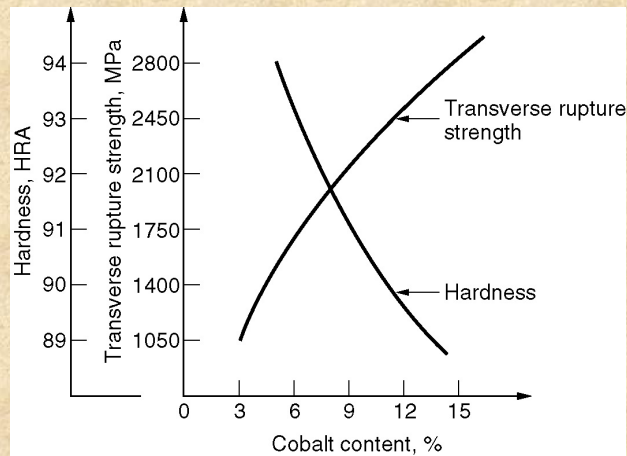


Figure 9.9 - Typical plot of hardness and transverse rupture strength as a function of cobalt content

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APPLICATIONS OF CEMENTED CARBIDES

- *Tungsten carbide* cermets (Co binder) - cutting tools are most common; other: wire drawing dies, rock drilling bits and other mining tools, dies for powder metallurgy, indenters for hardness testers
- *Titanium carbide* cermets (Ni binder) - high temperature applications such as gas-turbine nozzle vanes, valve seats, thermocouple protection tubes, torch tips, cutting tools for steels
- *Chromium carbides* cermets (Ni binder) - gage blocks, valve liners, spray nozzles, bearing seal rings

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CERAMIC MATRIX COMPOSITES (CMCs)

A *ceramic* primary phase imbedded with a secondary phase, which usually consists of fibers

- Attractive properties of ceramics: high stiffness, hardness, hot hardness, and compressive strength; and relatively low density
- Weaknesses of ceramics: low toughness and bulk tensile strength, susceptibility to thermal cracking
- CMCs represent an attempt to retain the desirable properties of ceramics while compensating for their weaknesses

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POLYMER MATRIX COMPOSITES (PMCs)

A *polymer* primary phase in which a secondary phase is imbedded as fibers, particles, or flakes

Commercially, PMCs are more important than ○
MMCs or CMCs

Examples: most plastic molding compounds, rubber ○
reinforced with carbon black, and fiber-reinforced
polymers (FRPs)

FRPs are most closely identified with the term ○
composite

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FIBER-REINFORCED POLYMERS (FRPs)

A PMC consisting of a *polymer matrix* imbedded with high-strength *fibers*

- Polymer matrix materials:
 - Usually a *thermosetting* (TS) plastic such as unsaturated polyester or epoxy
 - Can also be *thermoplastic* (TP), such as nylons (polyamides), polycarbonate, polystyrene, and polyvinylchloride
 - Fiber reinforcement is widely used in *rubber* products such as tires and conveyor belts

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FIBERS IN PMCS

- Various forms: discontinuous (chopped), continuous, or woven as a fabric
- Principal fiber materials in FRPs are glass, carbon, and Kevlar 49
- Less common fibers include boron, SiC, and Al_2O_3 , and steel
- Glass (in particular E-glass) is the most common fiber material in today's FRPs; its use to reinforce plastics dates from around 1920

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COMMON FRP STRUCTURE

- Most widely used form of FRP is a *laminar structure*, made by stacking and bonding thin layers of fiber and polymer until desired thickness is obtained
- By varying fiber orientation among layers, a specified level of anisotropy in properties can be achieved in the laminate
- Applications: parts of thin cross-section, such as aircraft wing and fuselage sections, automobile and truck body panels, and boat hulls

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FRP PROPERTIES

- High strength-to-weight and modulus-to-weight ratios
- Low specific gravity - a typical FRP weighs only about 1/5 as much as steel; yet, strength and modulus are comparable in fiber direction
- Good fatigue strength
- Good corrosion resistance, although polymers are soluble in various chemicals
- Low thermal expansion - for many FRPs, leading to good dimensional stability
- Significant anisotropy in properties

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FRP APPLICATIONS

- *Aerospace* – much of the structural weight of today's airplanes and helicopters consist of advanced FRPs
- *Automotive* – some body panels for cars and truck cabs
 - Continued use of low-carbon sheet steel in cars is evidence of its low cost and ease of processing
- *Sports and recreation*
 - Fiberglass reinforced plastic has been used for boat hulls since the 1940s
 - Fishing rods, tennis rackets, golf club shafts, helmets, skis, bows and arrows.

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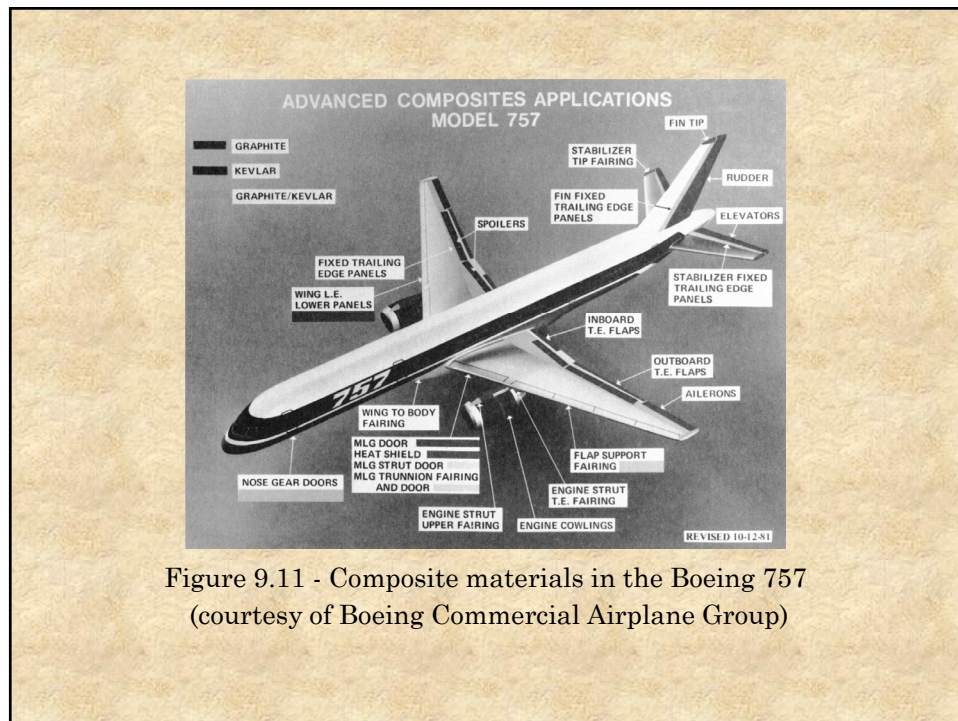


Figure 9.11 - Composite materials in the Boeing 757
(courtesy of Boeing Commercial Airplane Group)

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OTHER POLYMER MATRIX COMPOSITES

In addition to FRPs, other PMCs contain particles, flakes, and short fibers as the secondary phase

Called *fillers* when used in molding compounds

Two categories:

Reinforcing fillers – used to strengthen or otherwise improve mechanical properties .1

Examples: wood flour in phenolic and amino resins; and carbon black in rubber

Extenders – used to increase bulk and reduce cost per unit weight, but little or no effect on mechanical properties .2

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GUIDE TO PROCESSING COMPOSITE MATERIALS

The two phases are typically produced separately before being combined into the composite part

Processing techniques to fabricate MMC and CMC components are similar to those used for powdered metals and ceramics

Molding processes are commonly used for PMCs with particles and chopped fibers

Specialized processes have been developed for FRPs

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Table 1. Metal matrix composites investigated

MMC type	Designation: matrix/reinforcement/vol% letter of type	Processing [1]
Particle	AlMg1SiCu/Al ₂ O ₃ /22p	Stir cast, extruded
Reinforced	AlSi10Mg/SiC/10-20p	Stir cast, gravity cast
PRM	AlSi7Mg/SiC/55-70p	Gas pressure
	AlSi7Mg/R-SiC/85	infiltrated
	Al99.5/SiC/70p	preforms
Short	AlSi1.1/Al ₂ O ₃ /20s	Saffil™ fiber
Fiber	AlSi7/Al ₂ O ₃ /20s	preforms
Reinforced	AlSi12/Al ₂ O ₃ /20s	Infiltrated
SFRM	AlSi18/Al ₂ O ₃ /20s	by squeeze casting
Continuous	Al99.8/C-M40/70f-UD	Gas pressure
Fiber	AlMg1/Al ₂ O ₃ -N610/65f-UD	infiltrated
Reinforced	Mg99.8/C-HTA5331/60f-UD	wound
CFRM	MgAl _{0.6} /C-M40/70f-UD	preforms,
	MgAl _{0.2} /C-T300/50f-0/90°woven 50:50	Stapled fiber weaves

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MMC designation: a method of indicating the composition (and in some cases the processing) of the MMC. Designations vary by company, although there exists a proposal for designation of aluminium composites by the Aluminum Association. We follow in the database the designation used by the companies, and in our own writings, we designate the composite as follows: accepted designation of the matrix / abbreviation of the reinforcement's designation / arrangement and volume fraction in % with symbol of type (shape) of reinforcement (e.g., AA6061 / Al203 / 22 p).

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MMC designation: method of indicating the composition and at times also the processing of the MMC. As proposed by the American Aluminum Association for the designation of aluminium composites, MMC should be designated as follows by their constituents: accepted designation of the matrix / abbreviation of the reinforcement's designation / arrangement and volume fraction in % with symbol of type (shape) of reinforcement, such as "p" for particle, "s" for short fibres, "w" for whiskers, "f" for continuous fibres or "m" for monofilaments (The "f" or "m" is assumed to describe unidirectional reinforcement unless otherwise specified). Some examples are: matrix of a magnesium alloy AM10 reinforced by continuous carbon fibres of type T300, perpendicular oriented, amounting to a

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”; or matrix of the aluminium alloy AA6061 reinforced by particulates of alumina of 22 % by volume is designated as: "AA6061/Al₂O₃/22 p". Additional information is supplied as needed for more specific reference to properties with following basic form: ... / form / heat treatment Form is simply an indicator of final forming step as "extruded" or "pmc" for permanent mold casting, while the heat treatment is specified as its standard for the matrix alloy such as "t6" or "O". Thus a more complete designation of the second example above is: "AA6061/Al₂O₃/22 p / extruded / T6 ". MMC product names used by companies vary, hence their use indicates the processing route employed by implicit reference to the producer

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