Imperial College London

Materials and Manufacturing

Composites

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Module leader

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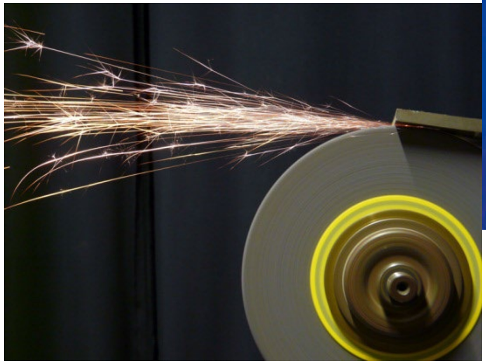
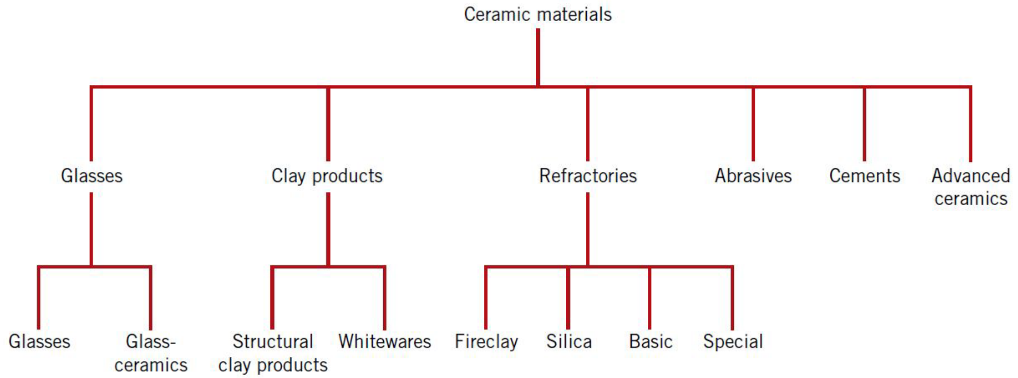
Dyson School of Design Engineering

Last time on M&M…

Ceramics and glasses

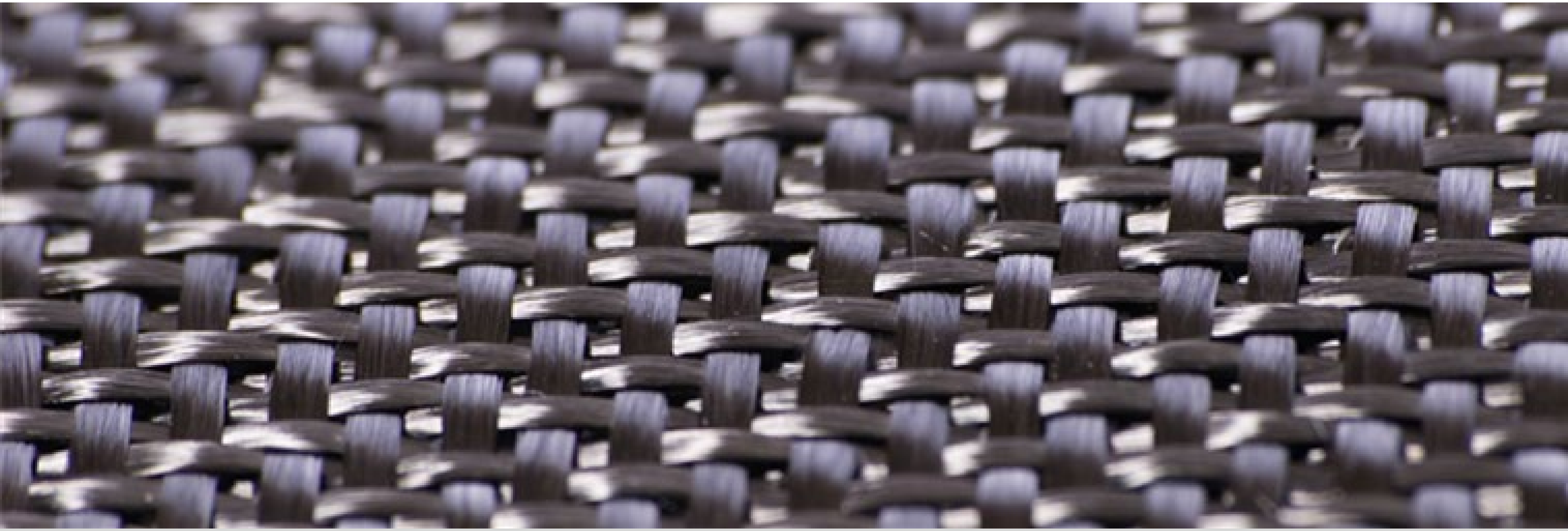
- Mechanical properties – Flexural strength
- Types of ceramics
  - Glasses
  - Clays
  - Refractories
  - Abrasives
  - Cements
  - Advanced ceramics





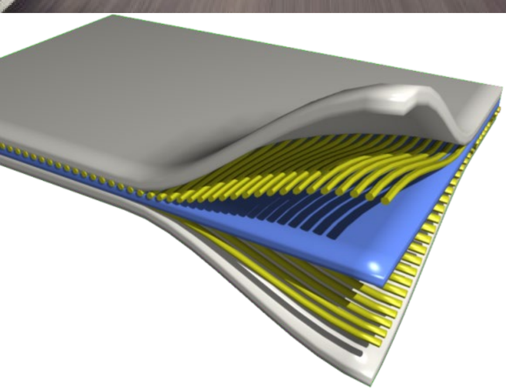
Learning objectives

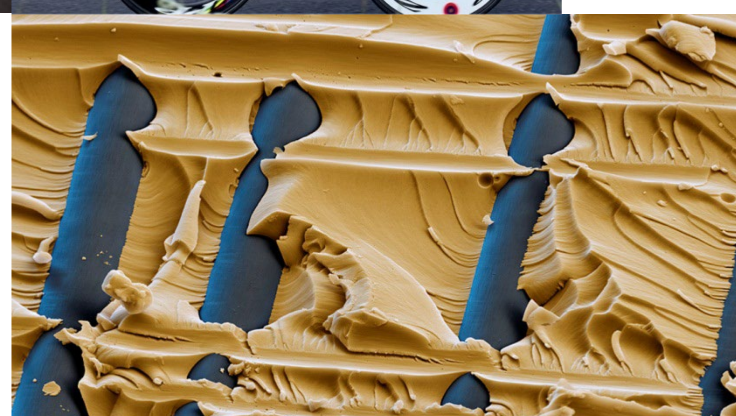
- Describe what composites are and be able to give examples and applications
- Define core concepts around composites including the matric and fibre phases and the interactions
- Explain what is meant by the critical fibre length and be able to determine this value
- Evaluate the mechanical properties of a fibre reinforced composite given properties of its individual phases

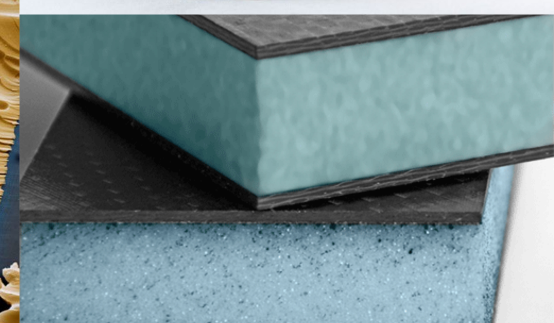


Why is it important?

With a knowledge of the various types of composites, as well as an understanding of the dependence of their behaviors on the characteristics, relative amounts, geometry/distribution, and properties of the constituent phases, it is possible to design materials with property combinations that are **better** than those found in the metal alloys, ceramics, and polymeric materials







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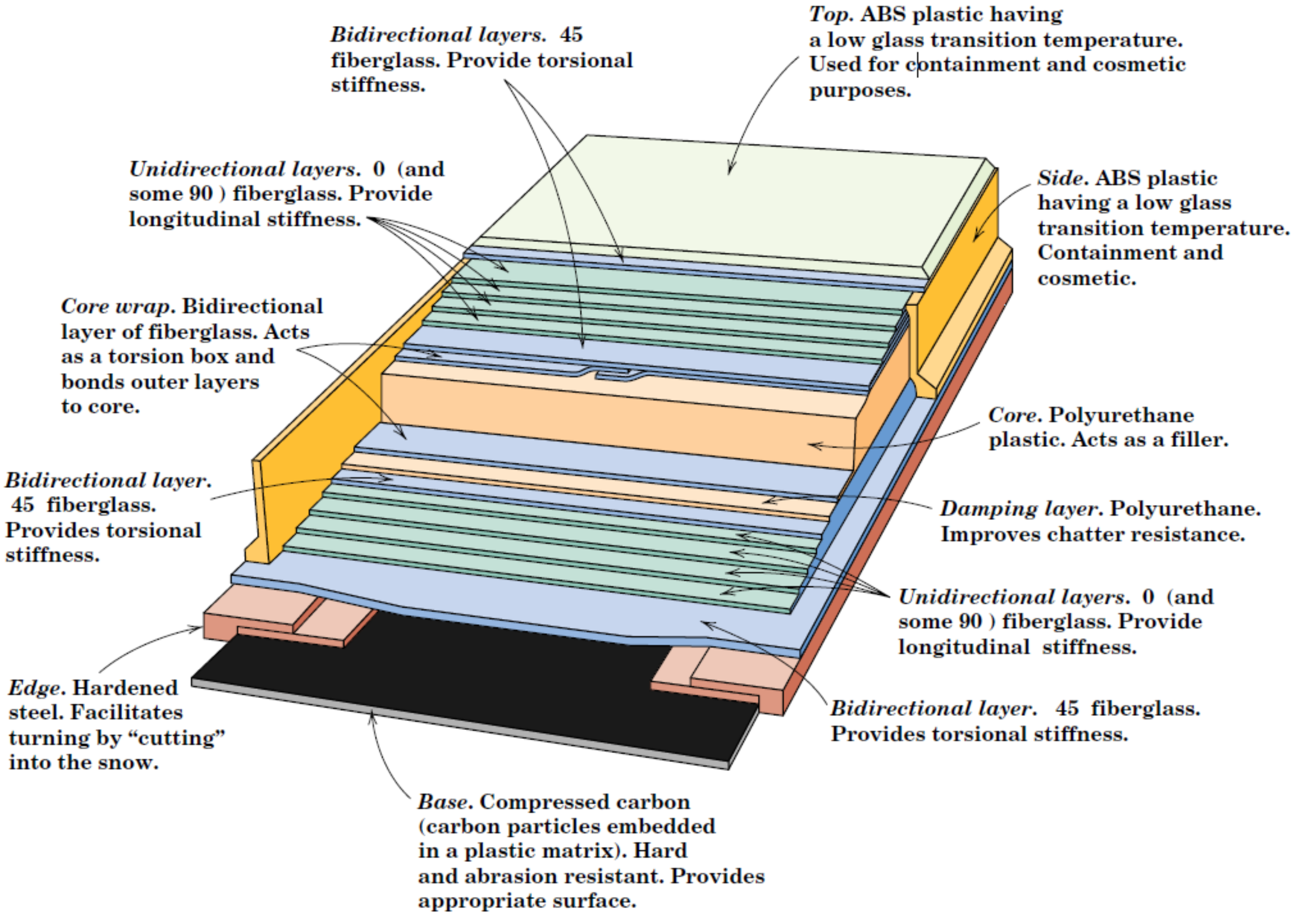
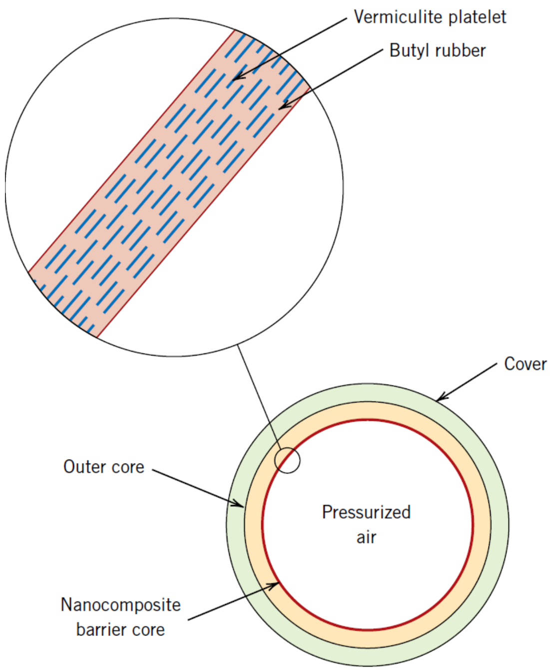
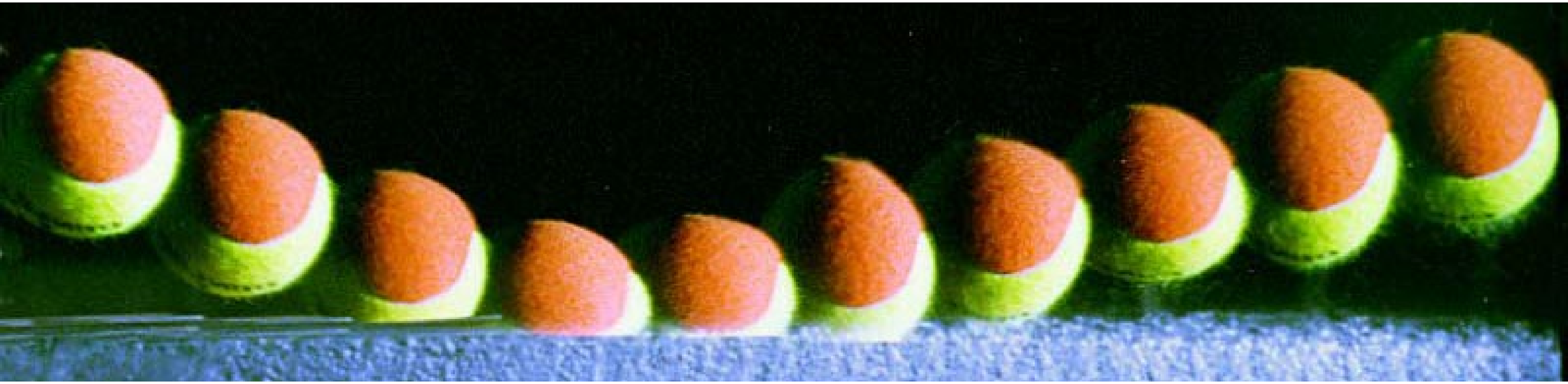


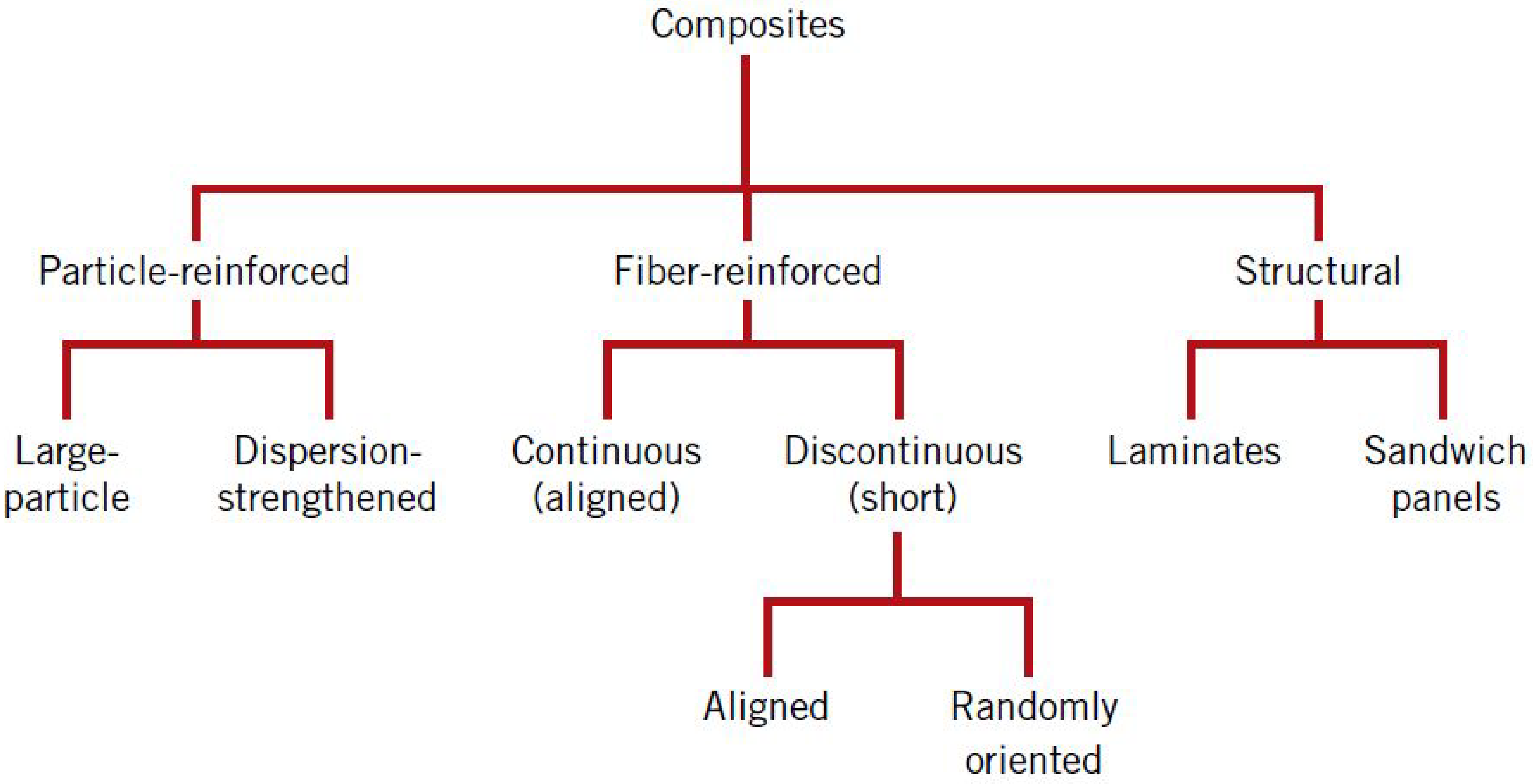
Tennis balls

- Nanocomposites use nanosized particles in a matrix
- Air permeation through the walls of the ball is inhibited by a factor of two due to the presence of a flexible and very thin (10 to 50 μm) nanocomposite barrier coating that covers the inner core
- Vermiculite platelets (natural clay material) act as barriers for gas diffusion and butyl rubber retains elasticity
- Helps to keep the bounce in tennis balls



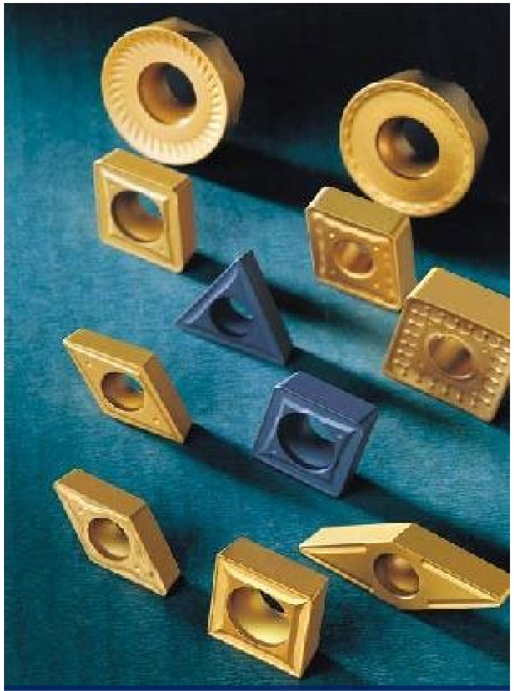


Types of composites?



Particle reinforced composites

- Divided into **large particle** and **dispersion-strengthened composites**
- Classification is based on the strengthening mechanism
- **Large particle**
  - The term large is used to indicate that particle-matrix interactions cannot be treated on the atomic level but rather using continuum mechanics
  - Most of the time the particulate phase is harder and stiffer than the matrix phase
  - Particles retrain movement of matrix
  - Matrix transfers some of the load to the particle
- **Dispersion-strengthened**
  - Particles are much smaller (~10-100 nm)
  - Particle-matrix interactions that lead to strengthening occur at the atomic or molecular level
  - Similar to precipitation hardening
  - Matrix takes the majority of the load and the dispersion hinders dislocation movement



Cemented carbide – Tungsten carbide in a matrix of cobalt

Large-particle composites

- For effective reinforcement, the particles should be small and evenly distributed throughout the matrix
- Mechanical properties are enhanced with increasing particulate content
- The **rule of mixtures** predicts the upper and lower bounds of the Young's modulus

$$E_c(u) = E_m V_m + E_p V_p$$

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

E = Young's modulus

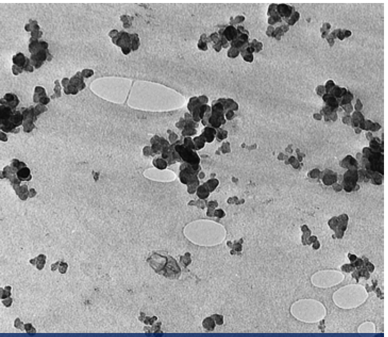
V = Volume fraction

Subscript

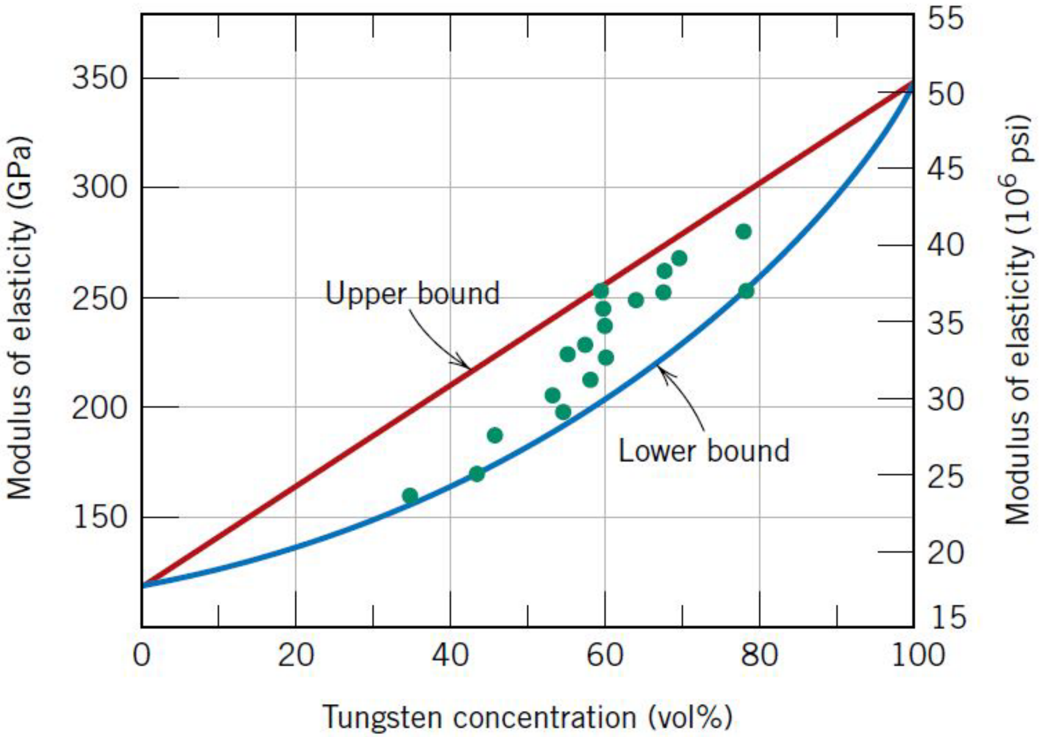
m = Matrix phase

p = Particulate phase

c = Composite phase

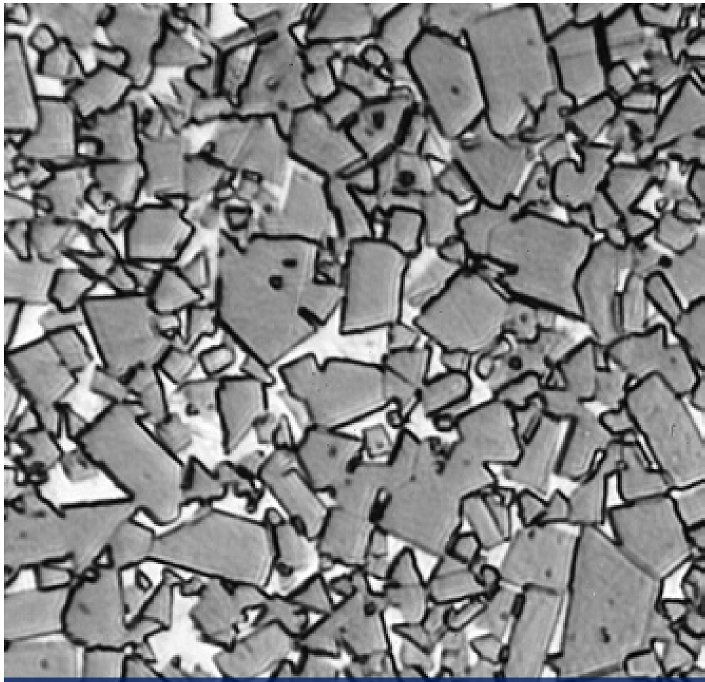


Carbon black is added in rubber to provide reinforcement



Cermets

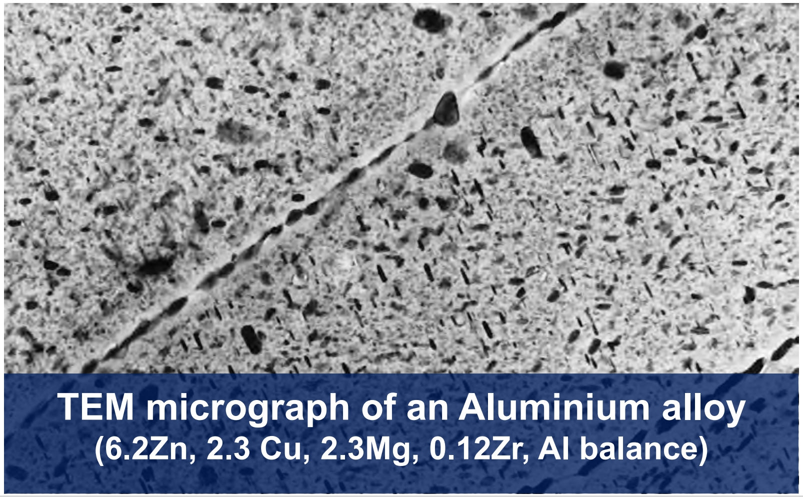
- **Cermets** (ceramic-metal composites) is an example of a large-particle composite
- The most common cermet is **cemented carbide**
- Composed of extremely hard particles of refractory carbides
  - Tungsten carbide or titanium carbide
- These are embedded into a metal matrix
  - Typically cobalt or nickel
- Used extensively for cutting tools
- Hard carbides provide the current surface but are too brittle
- Toughness is enhanced by their inclusion into a more ductile metal matrix
  - Matrix isolates the carbide particles to prevent particle-to-particle crack propagation
- No single material could possibly provide the combination of properties possessed by a cermet



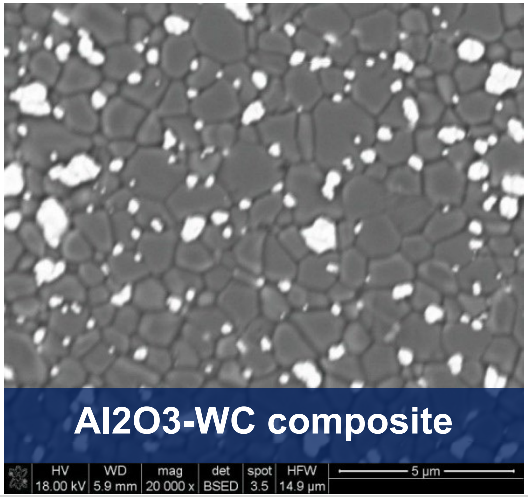
Micrograph of tungsten carbide particles in a cobalt matrix

Dispersion-strengthened composites

- Metals and metal alloys may be strengthened and hardened by the uniform dispersion of several volume percent of fine particles of a very hard and inert material
- The dispersed phase may be metallic or nonmetallic; oxide materials are often used
- Strengthening mechanism involves reducing mobility of slip planes
- Dispersion strengthening effect is not as pronounced as with precipitation hardening
- Strengthening is retained at elevated temperatures and for extended time periods because the dispersed particles are chosen to be unreactive with the matrix phase
- Precipitation-hardened alloys, the increase in strength may disappear upon heat treatment as a consequence of precipitate growth or dissolution of the precipitate phase



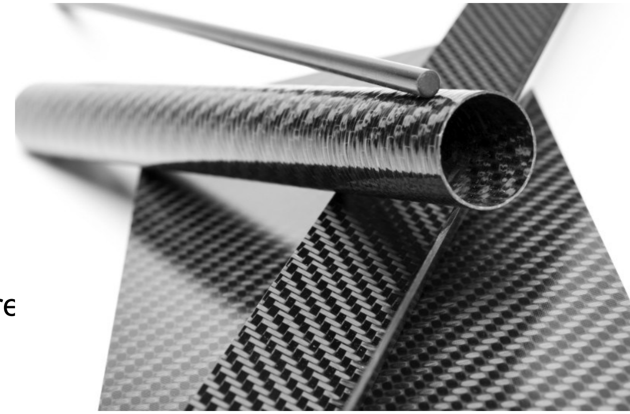
TEM micrograph of an Aluminium alloy
(6.2Zn, 2.3 Cu, 2.3Mg, 0.12Zr, Al balance)



Al2O3-WC composite

Polymer-matrix composites

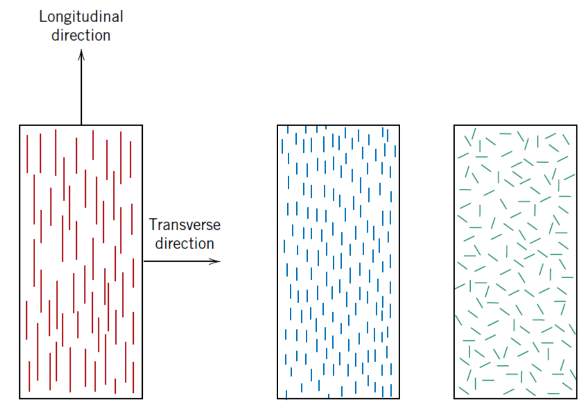
- **Polymer-matrix composites** (PMCs) consist of a polymer resin as the matrix, with fibers as the reinforcement medium
- Most popular of the composites
  - Easy to make, relatively low cost and room temperature properties

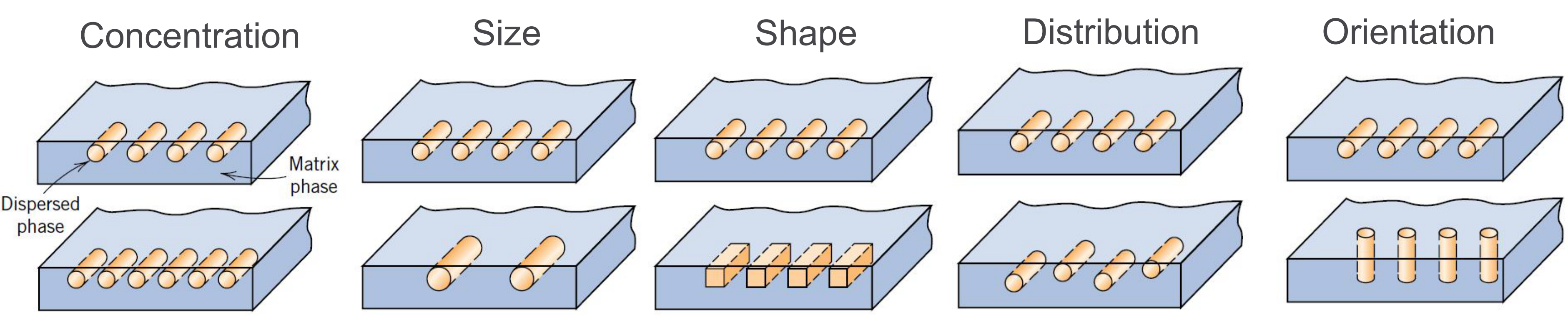


- **Glass fiber-reinforced polymer (GFRP) composites**
  - Very high specific strength, easy to make and chemically inert
  - Not as stiff as some materials
  - Limited to less than 200°C – Polymer starts to flor at higher temperature
  - Used in: boats, pipes, storage containers etc
- **Carbon fiber-reinforced polymer (CFRP) composites**
  - Carbon fibers have the highest specific modulus and specific strength of all reinforcing fiber materials
  - Retain strength at high temperatures
  - Used in fishing rods, golf cubs, pressure vessels, aircraft structures, helicopters etc
- **Aramid fiber-reinforced polymer composites**
- Most of the time polyesters and vinyl esters are used as the matrix due to low cost
- Epoxies and polyimide resins are better but more expensive

Fiber-reinforced composites

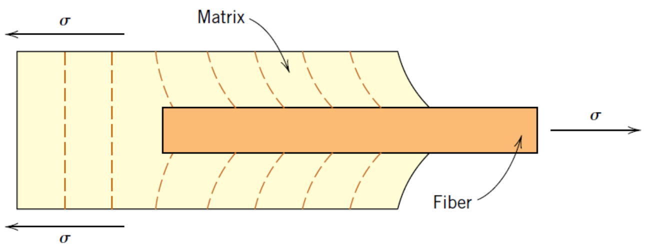
- Technologically, the most important composites are those in which the dispersed phase is in the form of a fiber
- Design goals of fiber-reinforced composites often include **high strength** and/or **stiffness** on a weight basis
- Can be affected by a range of factors
  - Concentration, size, shape, distribution and orientation of fibers
  - Direction that the load is applied





Critical fiber length

- The mechanical characteristics of a fiber-reinforced composite depend not only on the properties of the fiber, but also on the degree to which an applied load is transmitted to the fibers by the matrix phase
- Under an applied stress, this fiber-matrix bond ceases at the fiber ends
  - There is no load transmittance from the matrix at each fiber extremity

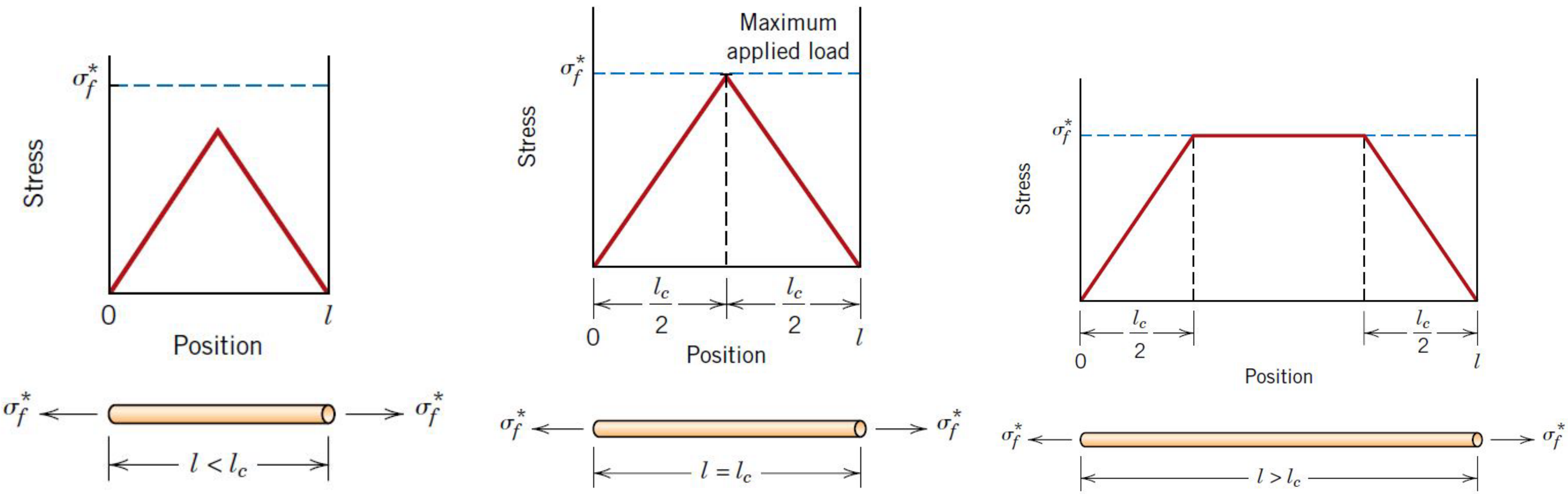


$$l_c = \frac{\sigma_f^* d}{2\tau_c}$$

l_c = Critical fiber length

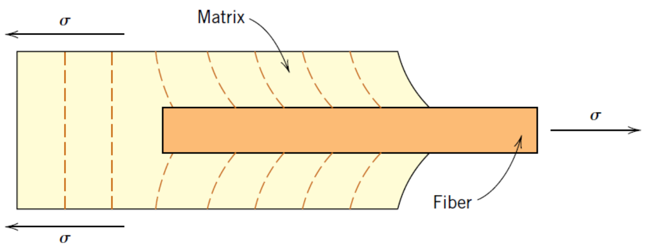
σ_f^* = Tensile strength of fiber

τ_c = Fiber-matrix bond strength



Critical fiber length

- Fibers for which $l \gg l_c$ (normally $l > 15 l_c$) are called **continuous**
- **Discontinuous** or **short fibres** are shorter than this
- Force transmittance is low and very little strengthening
- The fibres are effectively just particulates



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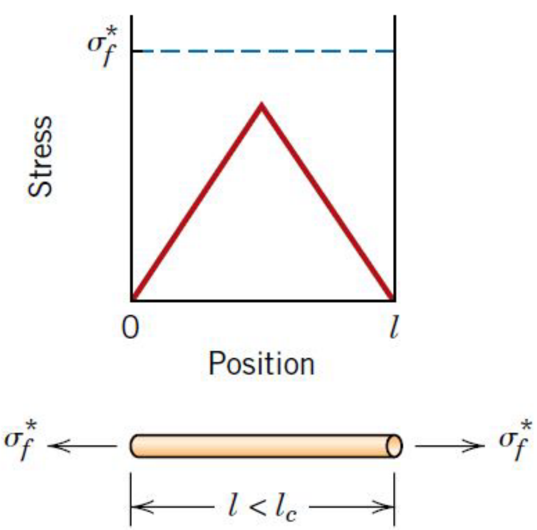
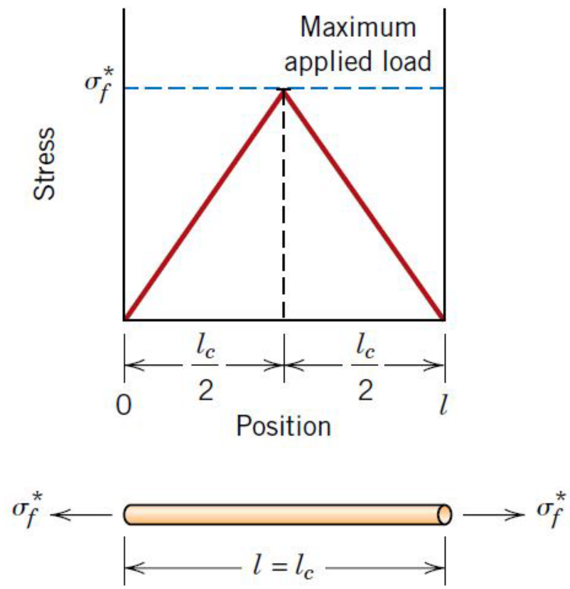
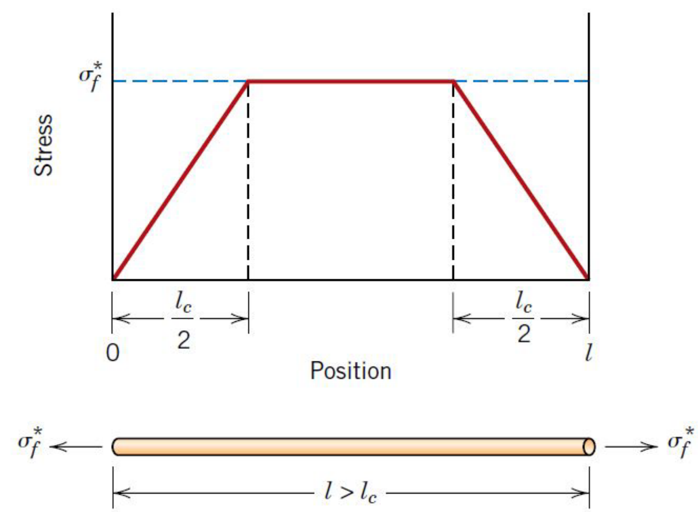




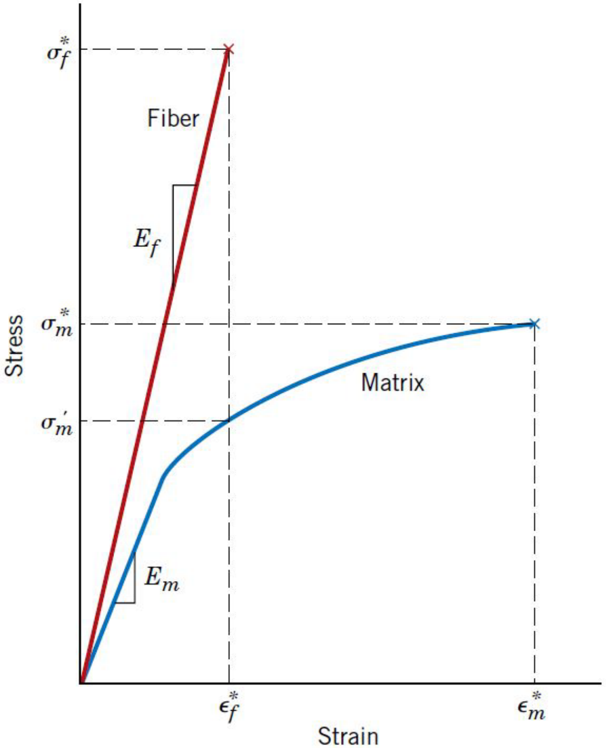


Continuous and aligned fibres

- The properties of a composite having its fibers aligned are highly **anisotropic**
- Consider the stress-strain behaviour where stress and fiber alignment is **longitudinal**
- Normally fiber is stiff and brittle
- Matrix is ductile

σ_f^*, ϵ_f^* = fracture stress and strain of fibre

σ_m^*, ϵ_m^* = fracture stress and strain of matrix

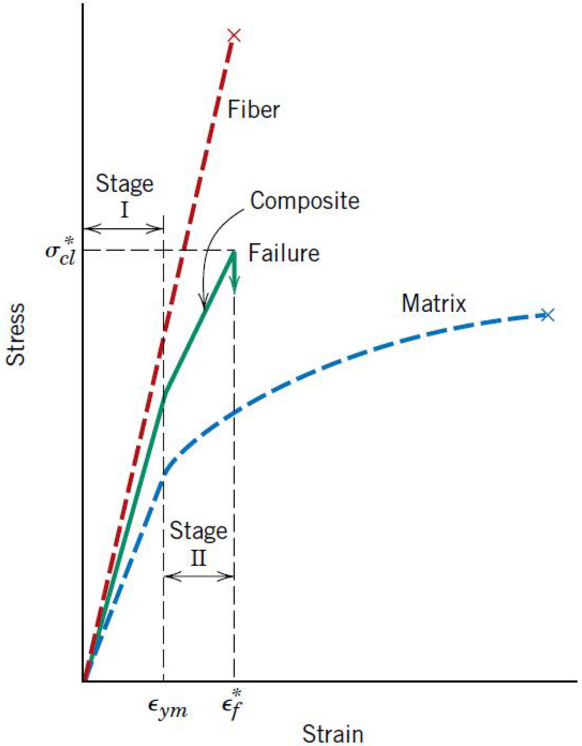


Normally

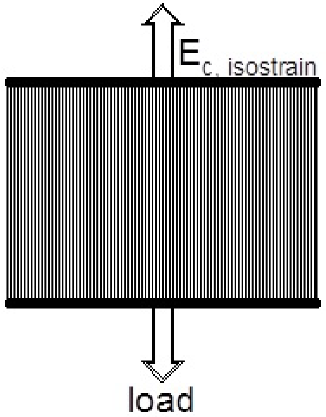
$\sigma_f^* > \sigma_m^*$

$\epsilon_f^* < \epsilon_m^*$

- **Stage I** = Elastic deformation (linear)
- **Stage II** = Matrix yields plastically, fibers yield elastically (linear)
  - Fibers take much more of the load
  - Composite failures at fiber failure strain
  - Matrix still exists after fiber failure



Elastic behaviour-Longitudinal loading



- Assume continuous and oriented fibers with longitudinal loading
- Assume fiber-matrix bond is very good (same deformation **isostrain**)

Load is equally split

$F_c = F_m + F_f$ $\qquad F = \sigma A$

$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f$ $\qquad$ Divide by A_c

$\sigma_c = \sigma_m \dfrac{A_m}{A_c} + \sigma_f \dfrac{A_f}{A_c}$ $\qquad \dfrac{A_m}{A_c}$ = Area fraction of matrix $\qquad \dfrac{A_f}{A_c}$ = Area fraction of fiber

Assume composite, matrix and fiber phases are equal $\frac{A_m}{A_c} = V_m$ and $\frac{A_f}{A_c} = V_c$

$\sigma_c = \sigma_m V_m + \sigma_f V_f$ $\qquad \epsilon_c = \epsilon_m = \epsilon_f$

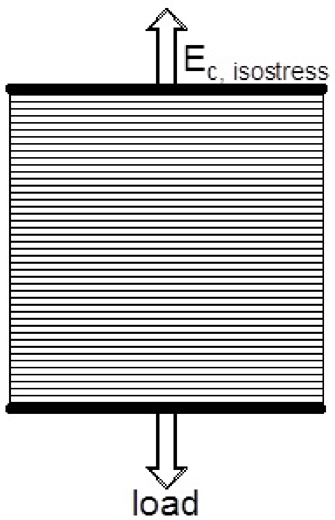
$$\frac{\sigma_c}{\epsilon_c} = \frac{\sigma_m}{\epsilon_m} V_m + \frac{\sigma_f}{\epsilon_f} V_f$$

$E_{cl} = E_m V_m + E_f V_f$ $\qquad E_{cl} = E_m(1 - V_f) + E_f V_f$

- Thus, E_{cl} is equal to the volume-fraction weighted average of the moduli of elasticity of the fiber and matrix phases.
- Other properties, including density, also have this dependence on volume fractions

Elastic behaviour-Transverse loading

- Assume continuous and oriented fibers with transverse loading
- This time assume the stresses are the same (**isostress**)



$$\sigma_c = \sigma_m = \sigma_f = \sigma$$

$$\epsilon_c = \epsilon_m V_m + \epsilon_f V_f \qquad \epsilon = \sigma / E$$

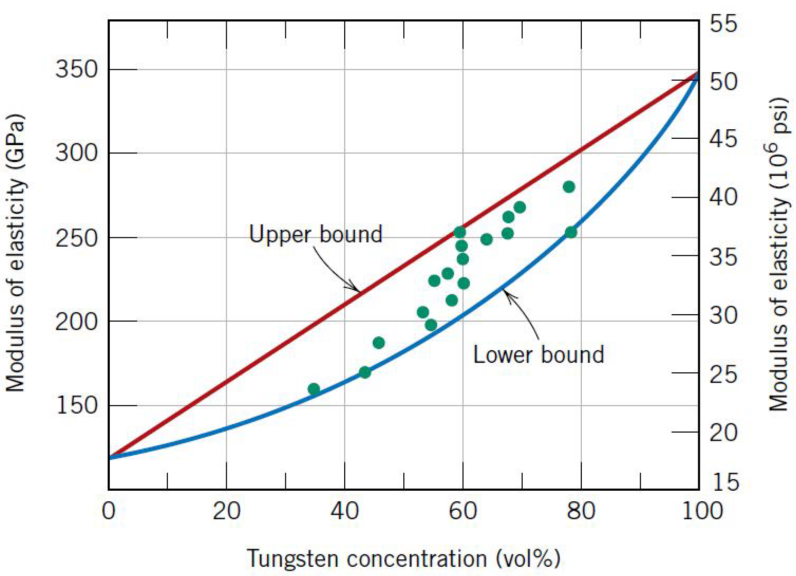
$$\frac{\sigma}{E_{ct}} = \frac{\sigma}{E_m} V_m + \frac{\sigma}{E_f} V_f$$

Divide by σ

$$\frac{1}{E_{ct}} = \frac{1}{E_m} V_m + \frac{1}{E_f} V_f$$

$$E_{ct} = \frac{E_m E_f}{V_m E_f + V_f\, E_m} = \frac{E_m E_f}{(1 - V_f) E_f + V_f E_m}$$

- Equivalent to lower bound of Young's modulus
- Previous expression equivalent to upper bound



Summary

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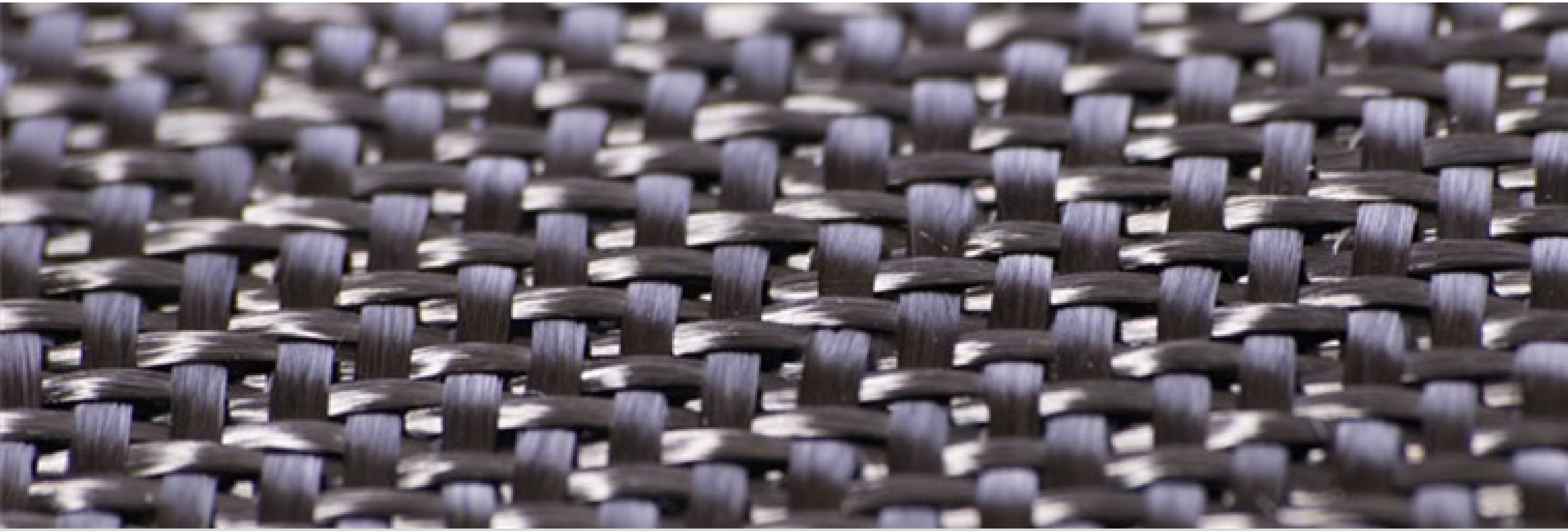

Next time on M&M…

Recycling, selection and design