AML 883 Properties and selection of engineering materials

LECTURE 4. Manipulating density and modulus

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Rule of mixtures

- Most engineering materials are solid solutions: brass (zinc in copper), solder (tin in lead), stainless steel (nickel and chromium in iron)
- Modulus and density do not change much with alloying
- $\rho_{ss} = f\,\rho_A + (1-f)\,\rho_B$
- SS – solid solution; f is the fraction of A atoms;
- Vegard's law

How about modulus?

- Modulus – related to bond stiffness
- A—A, B—B, A—B are the three types of bonds
- However, all three are within the same range in terms of bond stiffness
- Modulus of a mixture – averages out to be the same as that between that of the two pure components

Whither?

Is there a way of manipulating modulus and density at all?

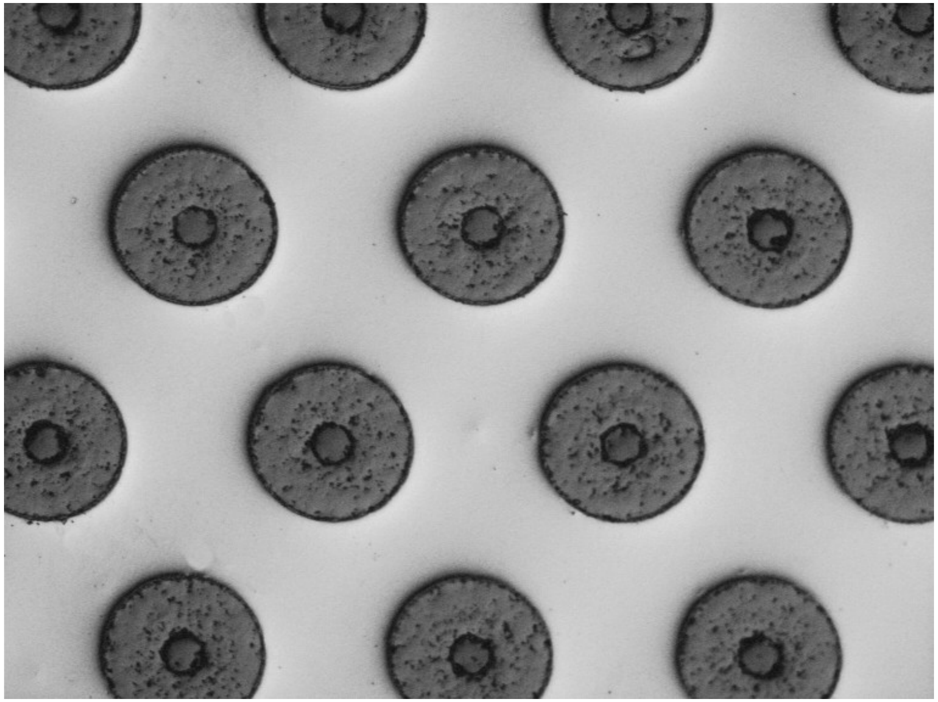
Yes, we can!

Hybrid materials – mixing at a larger length scale.

Composites and foam

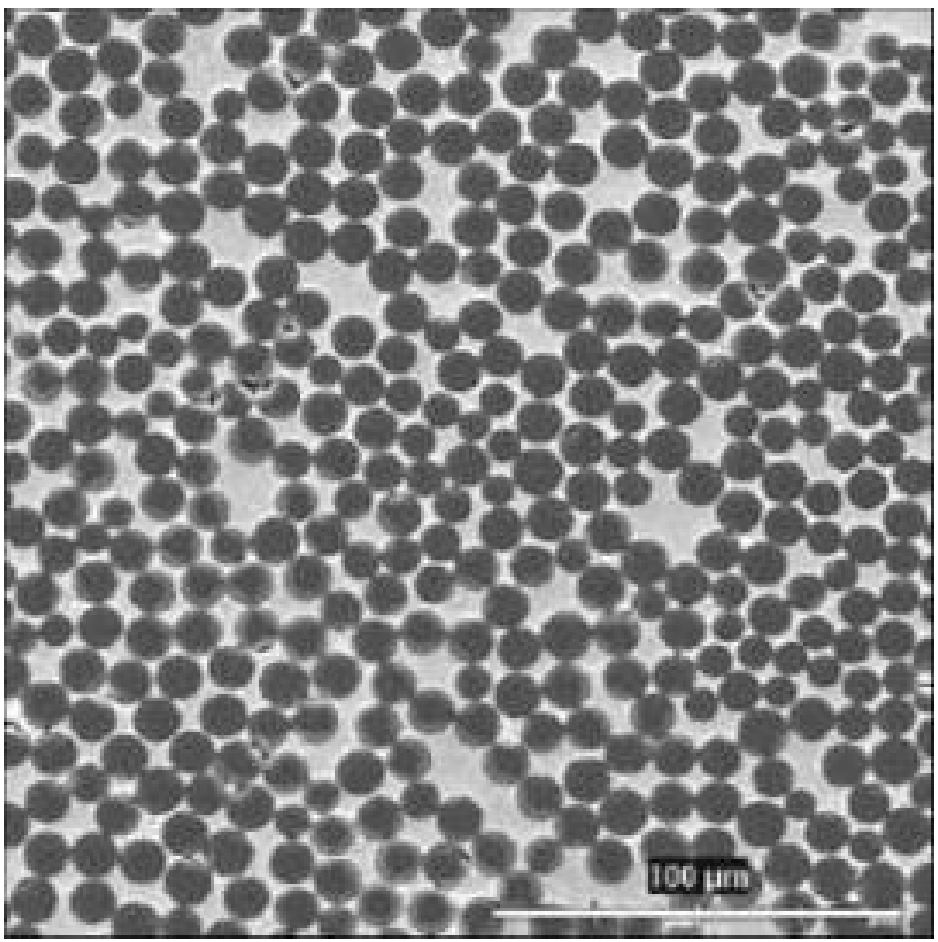
- Composite – mixture of two discrete solids
- Foam – mixing space with materials

Composite: microstructures



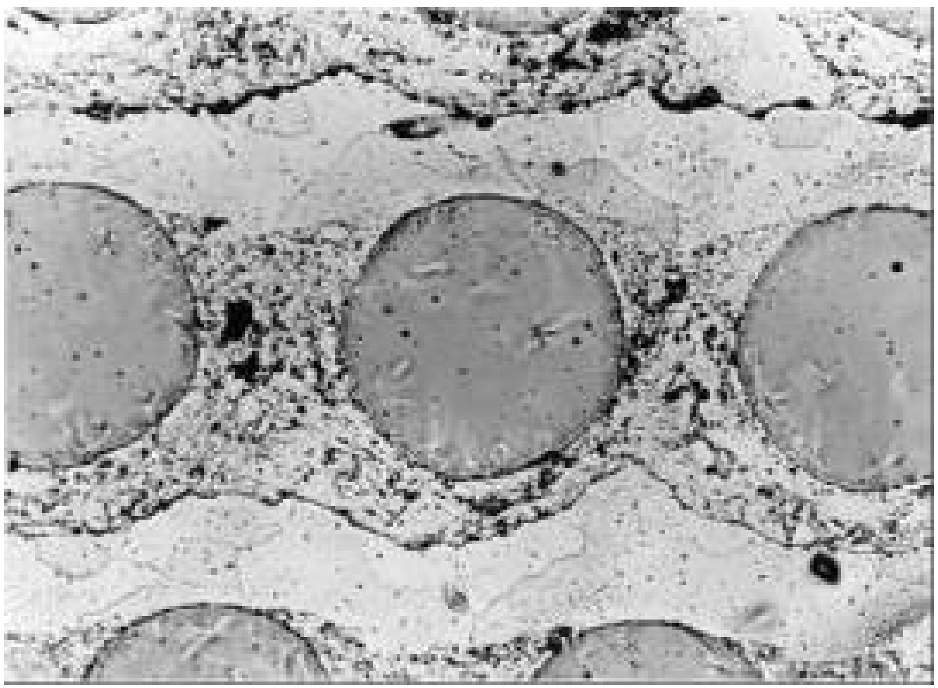
- Ti – SiC
- Image courtesy: Dr. Peng's homepage, University of Bristol (Aerospace department)

Composite: microstructures



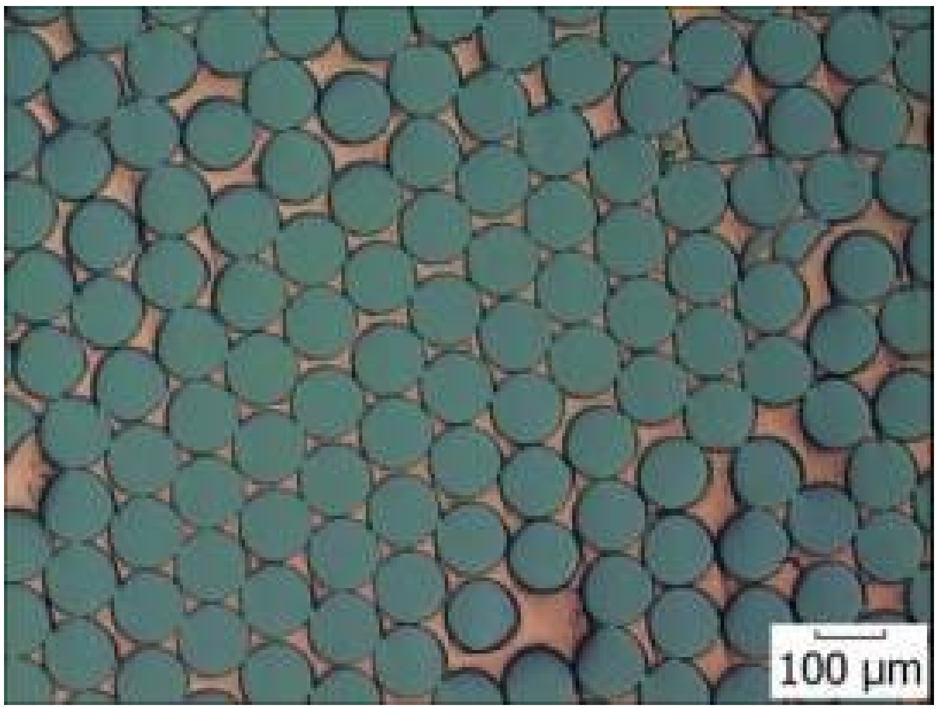
- Cu -- SiC
- Image courtesy: Slovak academy of sciences (Institute of materials and machine mechanics) homepage

Composite: microstructures



- Al -- maraging steel fibres
- Image courtesy: Slovak academy of sciences (Institute of materials and machine mechanics) homepage

Composite: microstructures



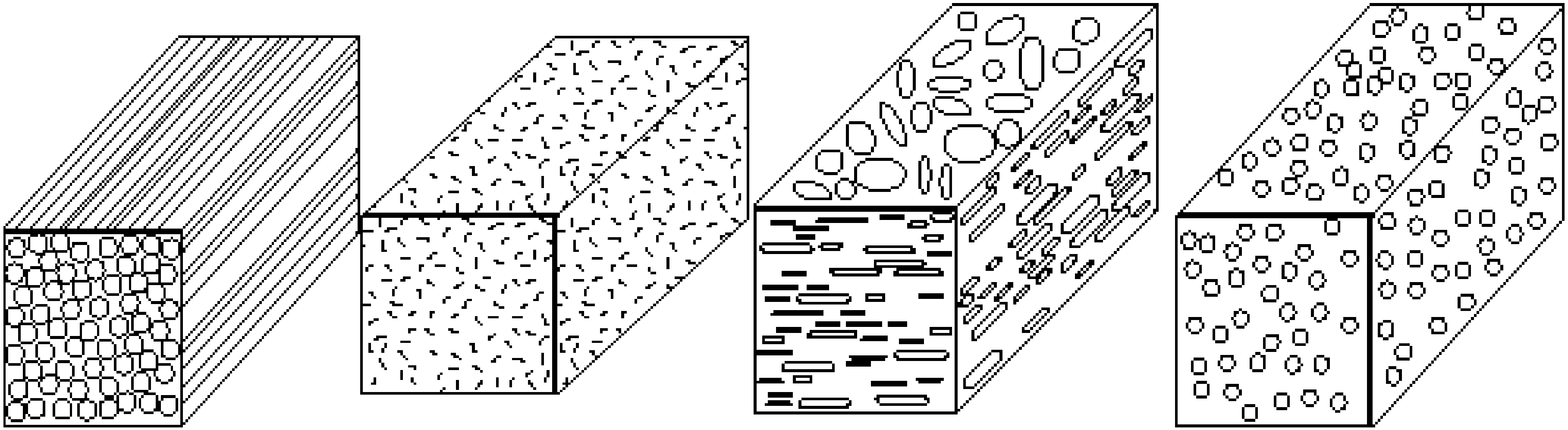
- Cu – W fibres
- Image courtesy: Slovak academy of sciences (Institute of materials and machine mechanics) homepage

Composites

- Matrix (say metallic)
- Reinforcements -- Fibres of another material (metallic, alloy or ceramic)
- Metal-matrix composites (MMC)
- Polymer-matrix composites (PMC)
- Ceramic-matrix composites (CMC)

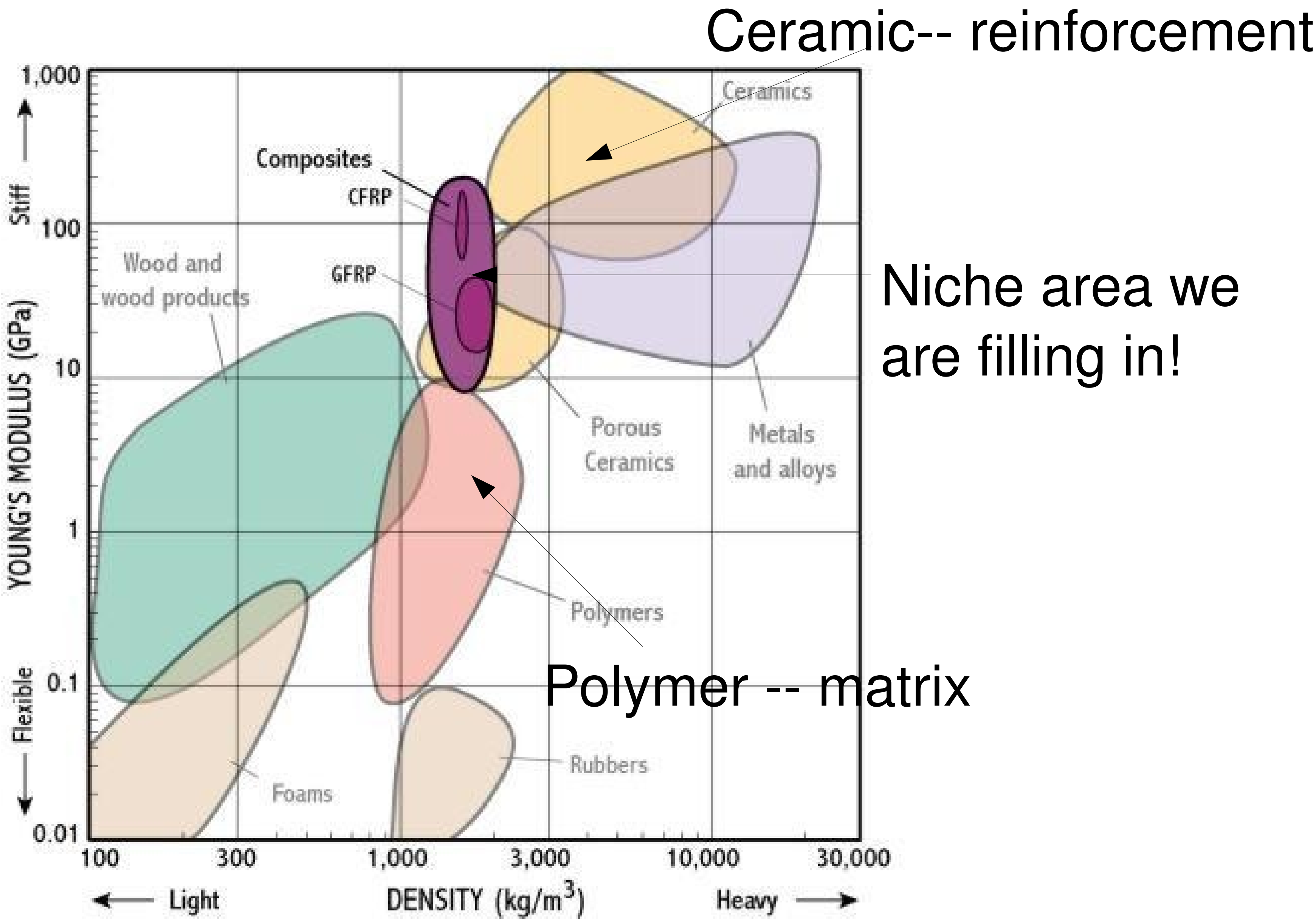
Composites

- Reinforcements – could be fibres (random and continuous), particulates, or flakes!



Images courtesy: Composites page of eFunda

What is the idea?



Composites -- attractions!

- High stiffness per unit weight
- High strength per unit weight
- High temperature performance (MMC and CMC): reason why windtunnel fan blades are planning to be replaced by MMCs

Composites -- Density

- $\rho_c = f\,\rho_r + (1 - f)\,\rho_m$
- “c” – composite; “r” -- reinforcement; “m” -- matrix
- No residual porosity: assumption
- Or, for density, rules of mixtures holds!

Composites -- Modulus

- Modulus of the composite – bracketed by two bounds
- Upper bound (U) and Lower bound (L)
- $E_U = f E_r + (1 - f) E_m$
  $E_L = E_r E_m / [f E_m + (1 - f) E_r]$

Upper bound

- Assume that on loading, the two components strain by the same amount – like springs in parallel
- The stress is the average of the stresses in the matrix and the stiffer reinforcement
- Continuous fibres – modulus lies closer to this bound

$$E_U = f\,E_r + (1-f)\,E_m$$

Lower bound

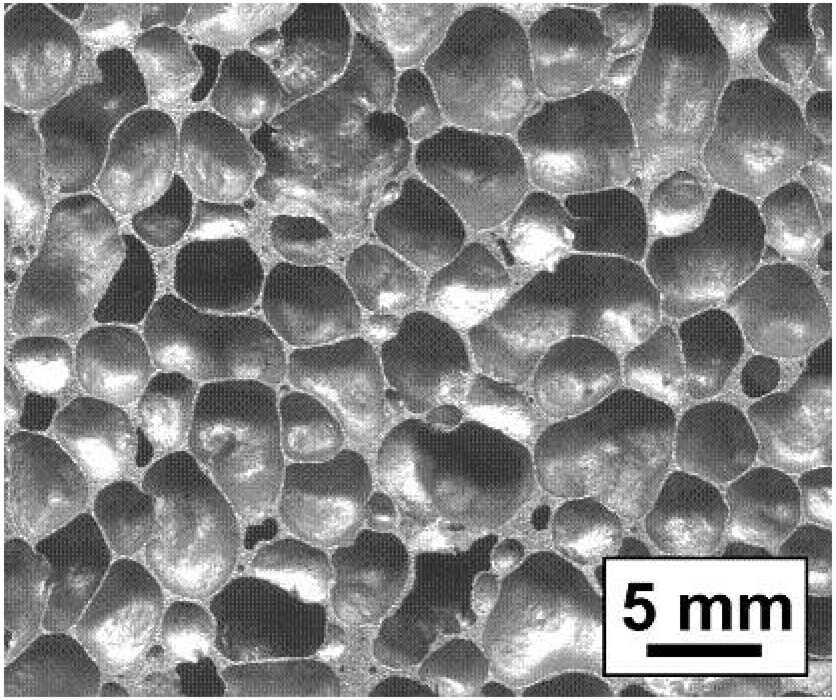
- Assume that on loading, the two components carry the same stress – like springs in series
- The strain is the average of the strains in the matrix and the stiffer reinforcement
- Particles – modulus lies closer to this bound

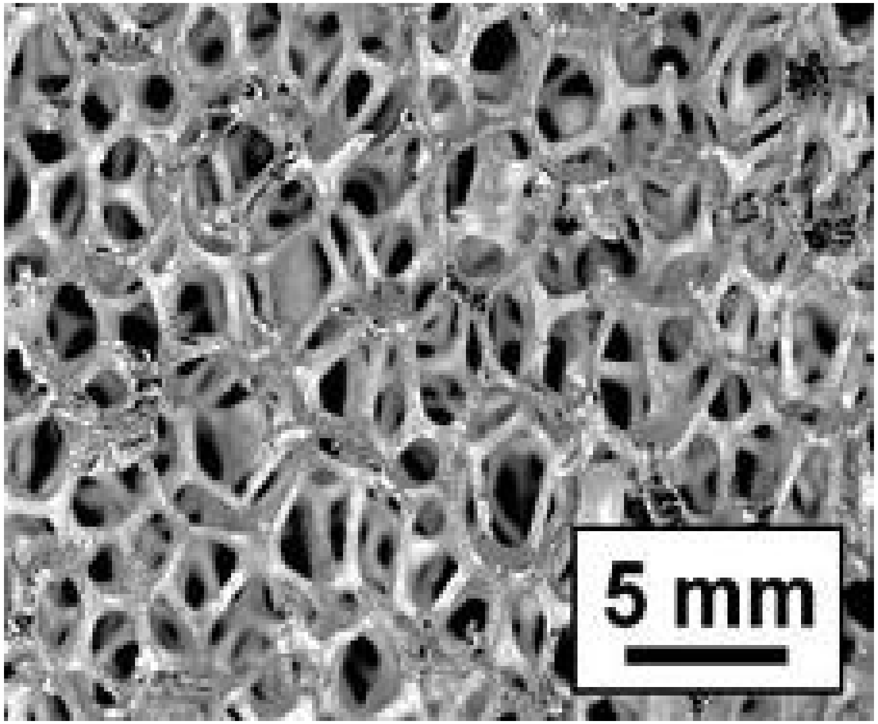
$$E_L = E_r E_m / [fE_m + (1-f)E_r]$$

Foams

- Aluminium foam
- Mixture of aluminium and free space
- Metallic foam
- Image courtesy: wiki

Closed and open cells



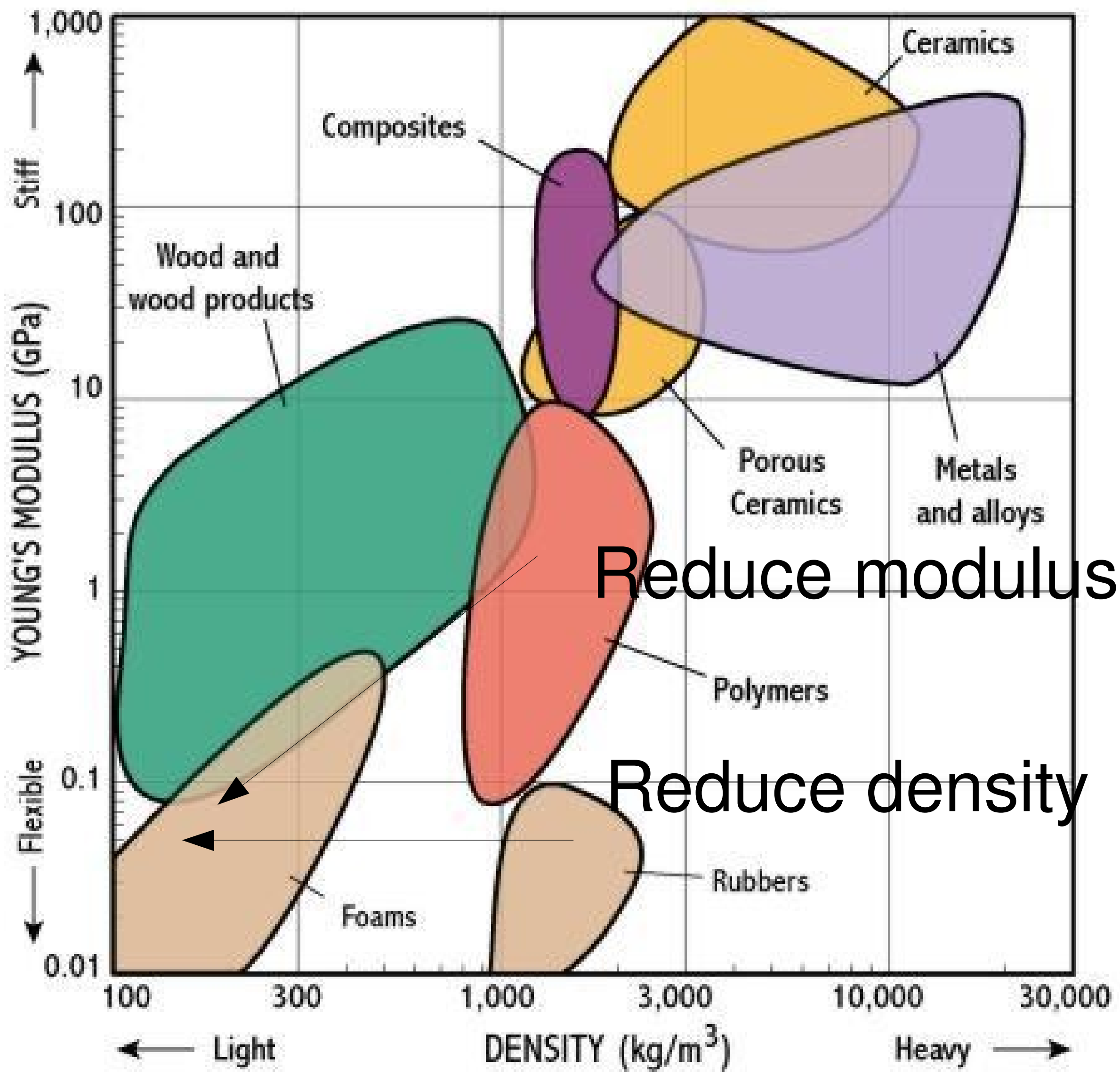


Aluminium foams; image courtesy: Wiki

Foams for engineering applications

- Metallic (Aluminium)
- Polymer (styrofoam – extruded polystyrene foam)
- Ceramics (alumina)
- Glass (recycling)

What is the idea?



Why foaming?

- Insulation
- Floatation
- Filler in cushions and packaging
- Protective shielding
- ...

Foam -- density

- Relative density
- Fraction of foam occupied by the solid

Foam -- modulus

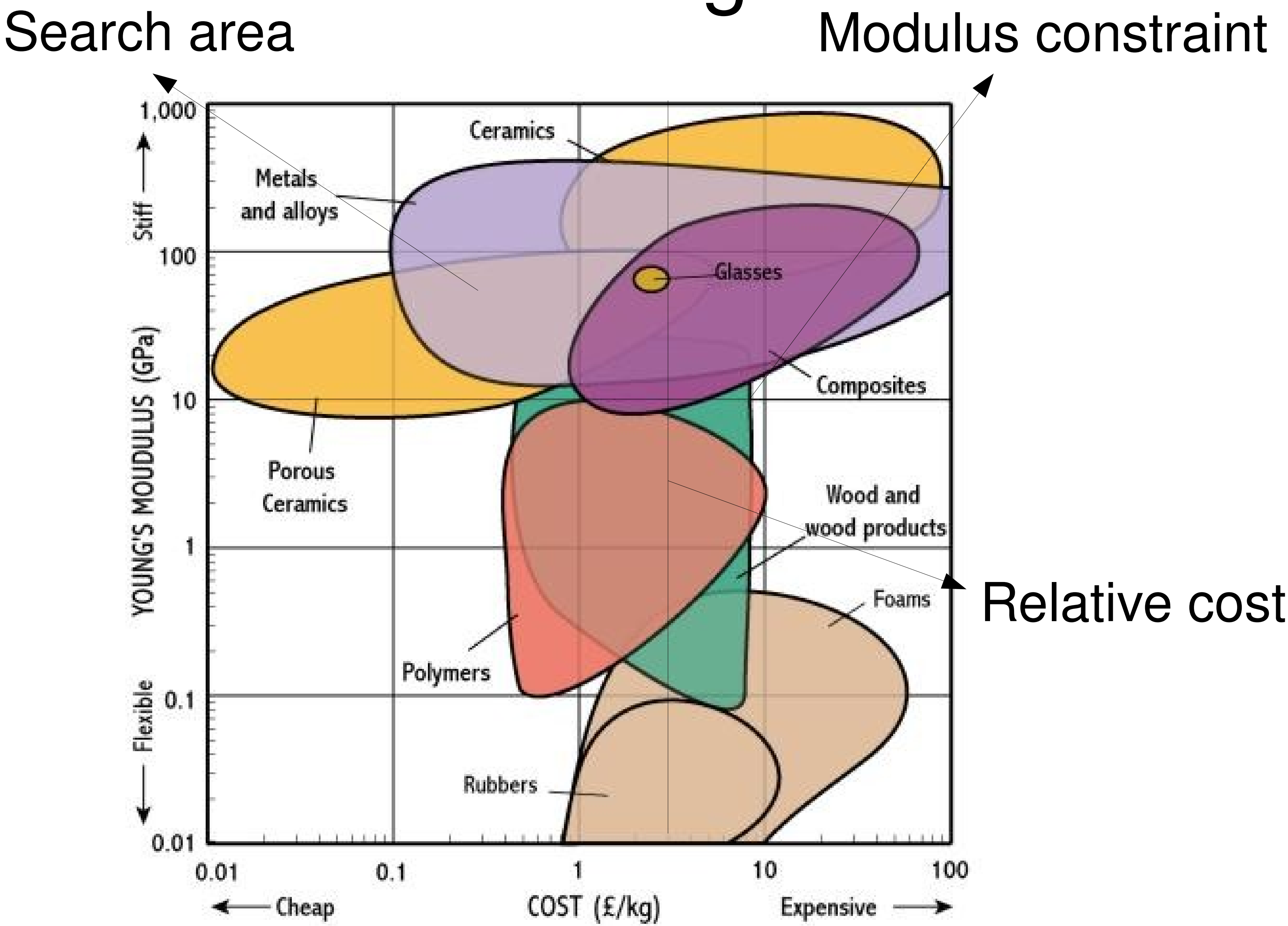
- In general, $E_{foam}/E_{solid} = C(\rho_{foam}/\rho_{solid})^m$
- C, m -- constants

Property charts and graphical selection

Screening

- Suppose you are given that you want to use materials with $E > 10$ GPa but the relative cost should be less than 3 (units)

Screening



Search area
Modulus constraint
Relative cost
Ceramics
Metals
and alloys
Glasses
Composites
Porous
Ceramics
Wood and
wood products
Foams
Polymers
Rubbers
1,000
100
10
1
0.1
0.01
Stiff
Flexible
YOUNG'S MOUDULUS (GPa)
0.01
0.1
1
10
100
Cheap
COST (£/kg)
Expensive

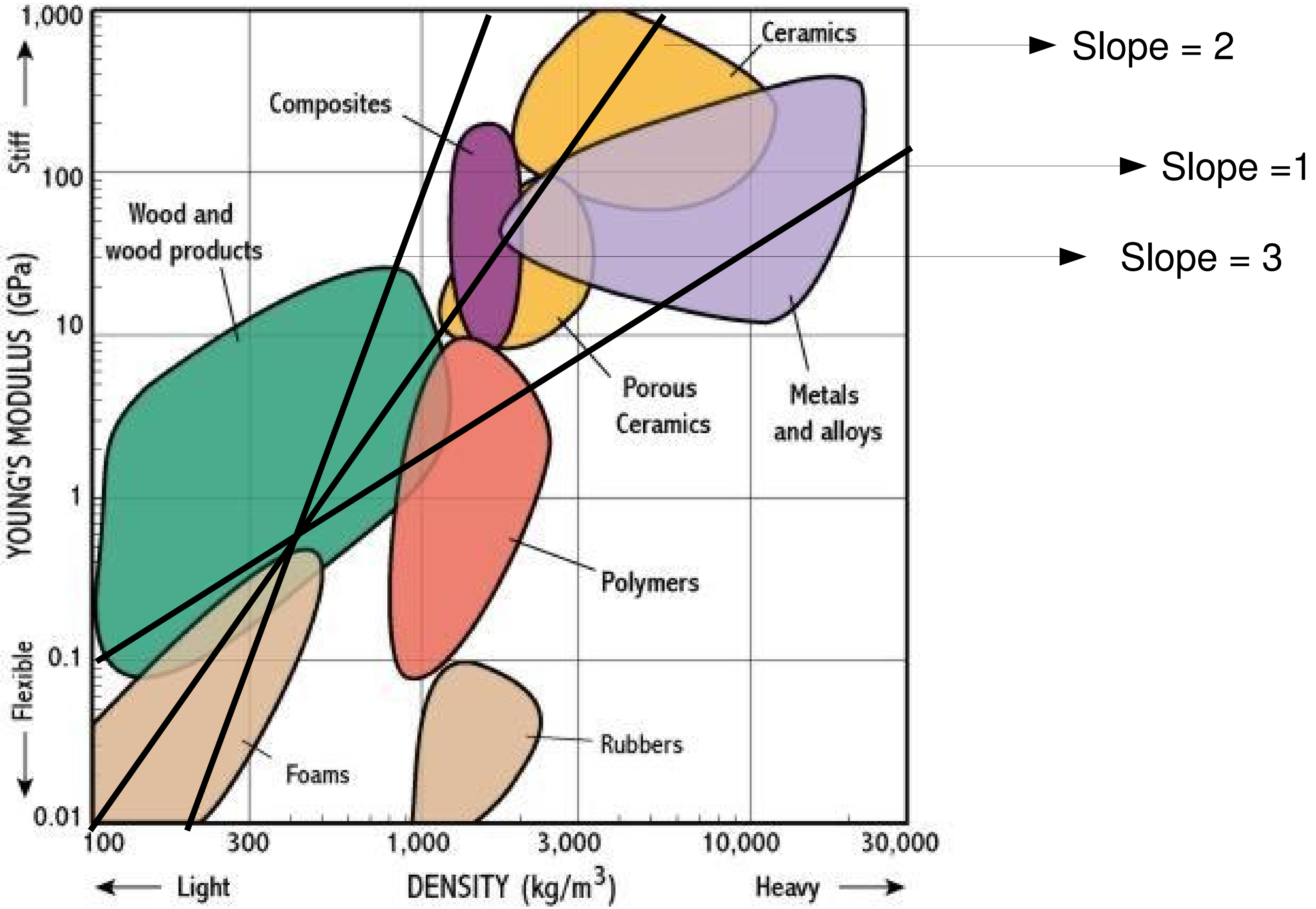
Screening

- Suppose you want to know which materials are good as stiff rods, panels and beams
- The material indices are, respectively,

$$E/\rho \, , E^{1/3}/\rho \, , E^{1/2}/\rho$$

- How to choose it using materials property charts?
- Material index = constant
- Take log on either side
- Straight lines with different slopes!

Screening -- schematic



Reading off!

- All materials for a given line perform equally well; those below less and above better
- Different lines parallel to the given line show materials of a given material index
- This process can be automated, of course!

Summary!

- Stiffness at reasonable densities is one of the important design considerations (and, probably, the first)
- While choosing materials with adequate stiffness, the stiffness criterion is usually the constraint
- The objective (the quantity we want to extremise) is either cost or light weight

Summary!

- In stiffness limited design, the material index of interest is usually a combination of density and modulus
- There are five steps in identifying the material index – objective function, the free parameter in the objective function, the constraint equation, free parameter in the objective function vice versa that in the constraint equation, material index
- Property charts can be used for efficient selection of materials!

Summary!

- Density – related to atomic identities (mostly) and to packing and size
- Crystalline/non-crystalline/semi-crystalline
- FCC/HCP/BCC
- Modulus – related to bonding
- Young's modulus, shear modulus, bulk modulus and Poisson's ratio
- Anisotropy – composites; all the other – effectively isotropic

Summary!

- Elastomers are different; this is due to the cross-linking and its effect on properties
- Alloying – one way of modifying density and modulus – not very effective
- Composites – to increase modulus while keeping the densities low
- Foam – to decrease both the modulus and densities

What next?

Strengh-limited design and the origins and manipulation of strength