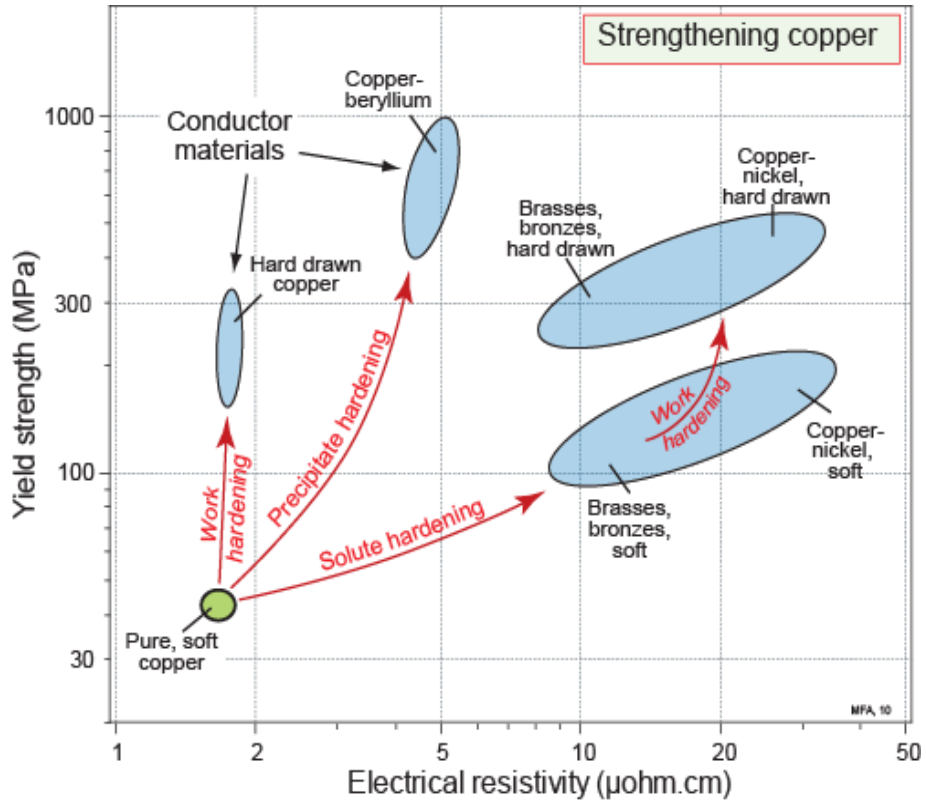
Manipulating properties:

Composition, microstructure, and architecture

Mike Ashby and Hugh Shercliff

Department of Engineering,
University of Cambridge



Learning objectives for this lecture unit

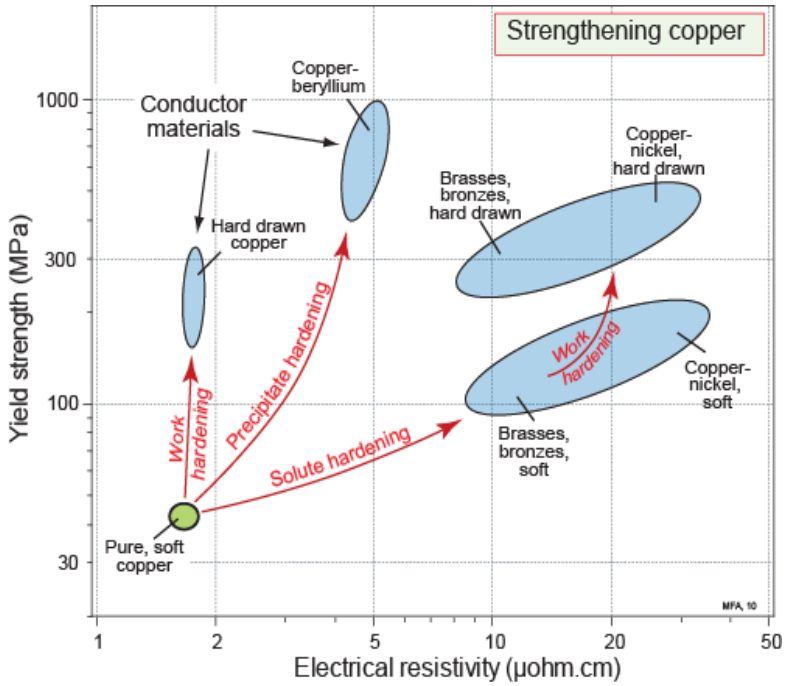
Ansys software mentioned	• Ansys Granta EduPack™, a teaching software for materials education

Intended Learning Outcomes	
Knowledge and Understanding	Understanding the effect of processing on properties
Skills and Abilities	Ability to plot property trajectories as a function of processing
Values and Attitudes	Appreciation of Materials Science linking Physics, Chemistry, and Engineering

Resources

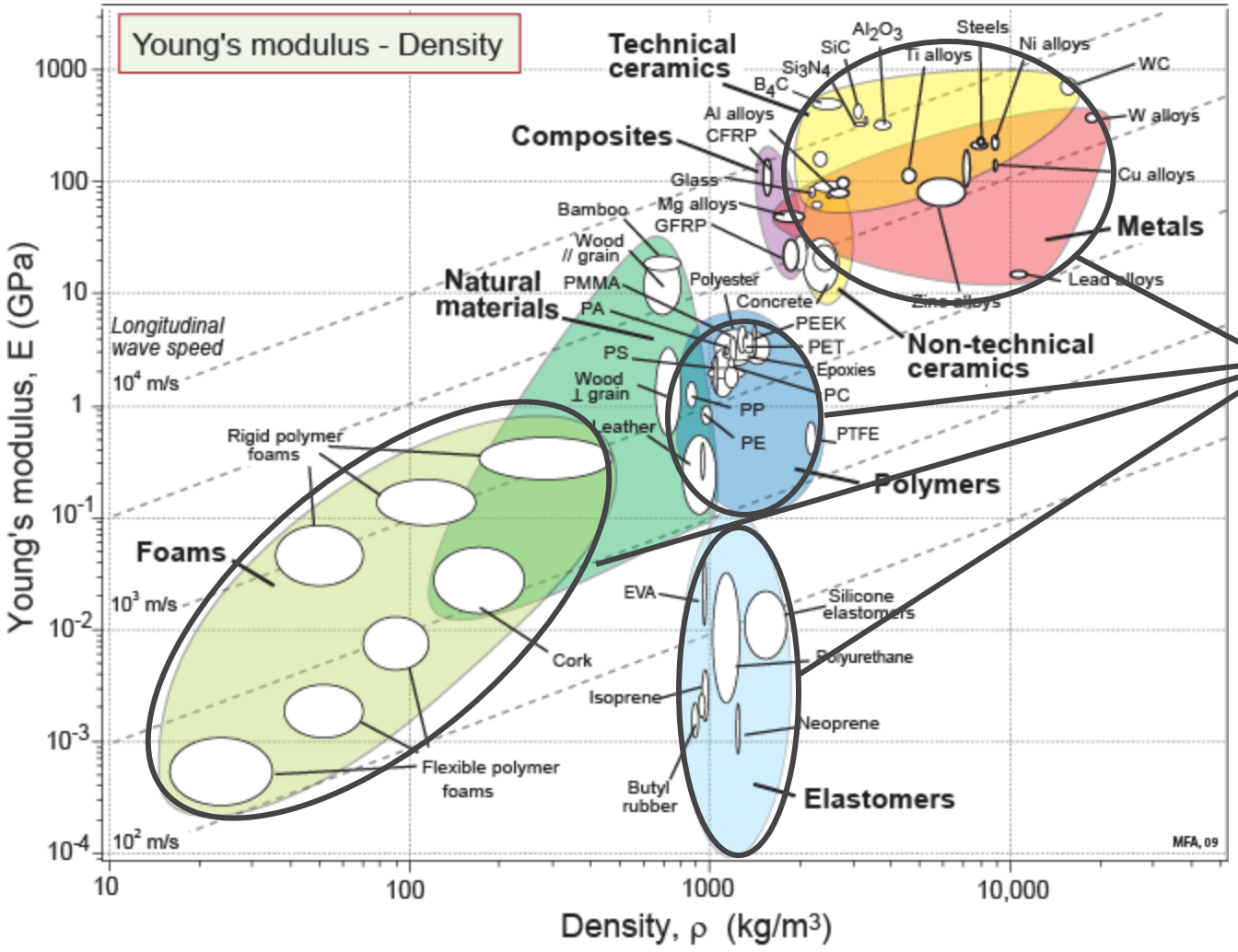
- **Text:** "Materials: engineering, science, processing and design" 4th edition by M.F. Ashby, H.R. Shercliff and D. Cebon, Butterworth Heinemann, Oxford, 2019, Chapters 1-2
- **Texts:** Callister, Budinski, Askeland and others – recommended reading in records
- The Elements Database lecture unit
- Ansys Granta EduPack software

Outline



- *Modulus and density*
- *Strength and toughness*
- *Other property combinations…*
- *Appendix: examples and exercises*

Manipulating properties: Modulus – density



Why the differences?

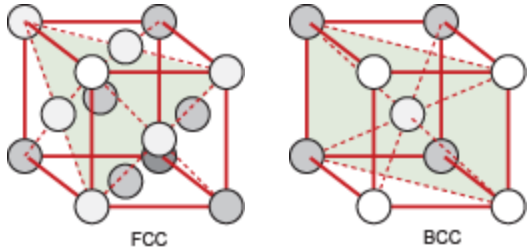
Drilling down: modulus and density

Density: *atomic weight, atom size and packing density*

Modulus: *interatomic bonds and packing density*

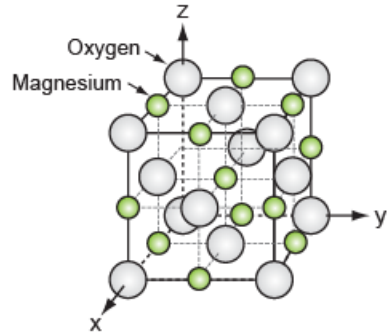
The elements
(most are metals)

Crystalline packing, metallic bonding



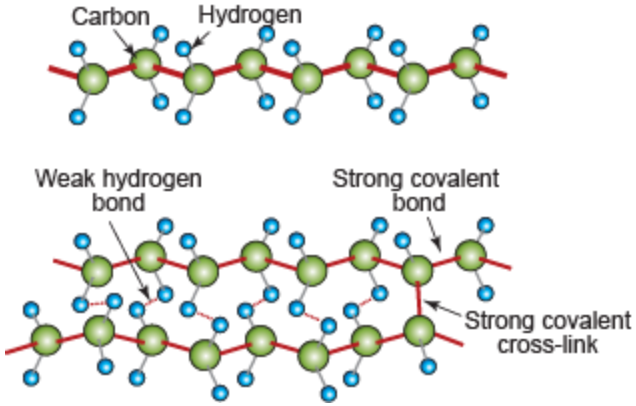
Inorganic compounds

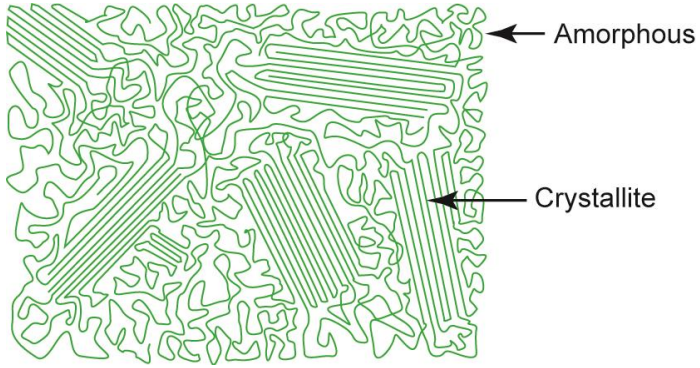
Crystalline oxides, nitrides, carbides, Ionic / Covalent bonding



Organic compounds

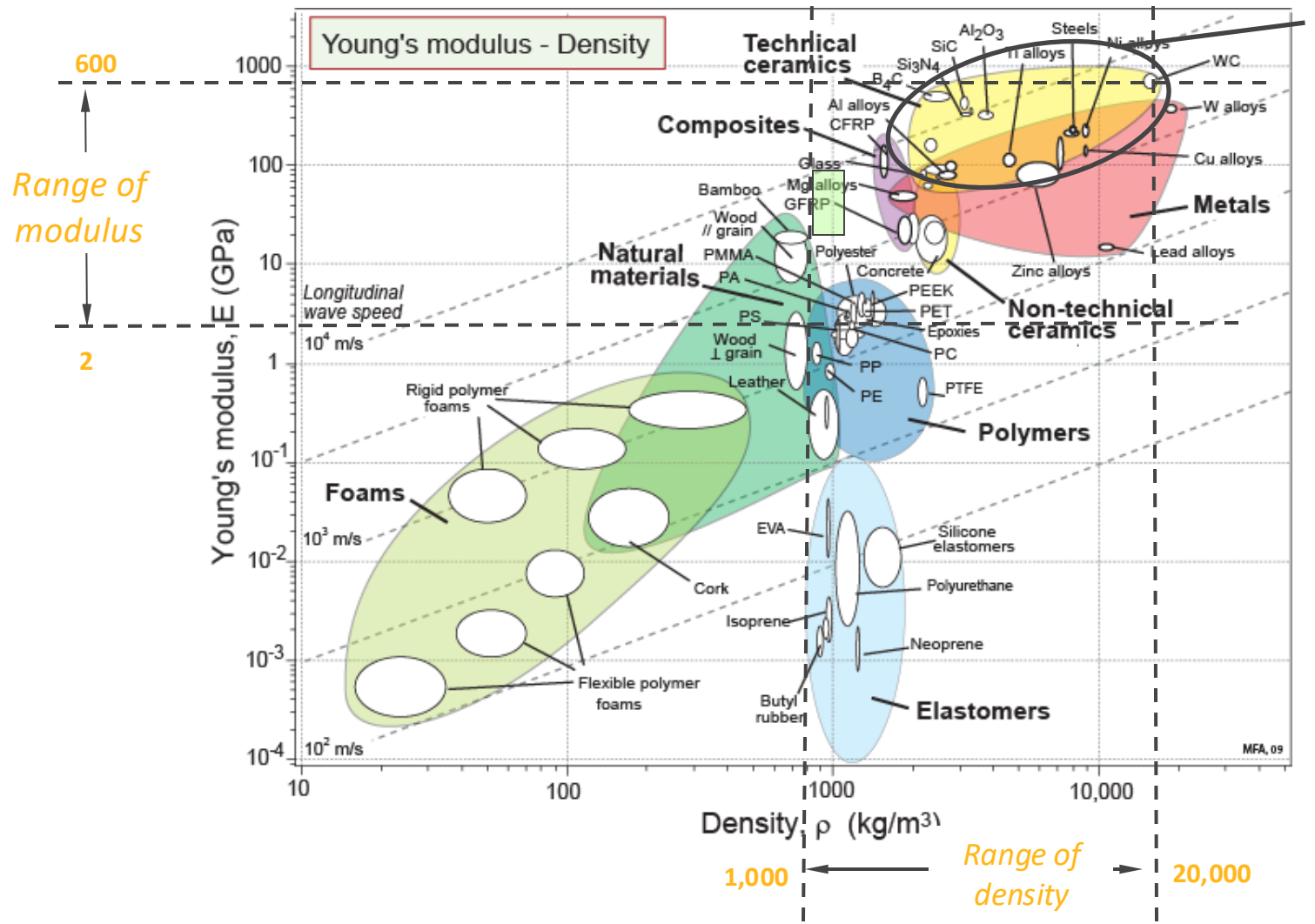
Amorphous thermoplastics, thermosets, elastomers





Drilling down: modulus and density

The elements **Composition**



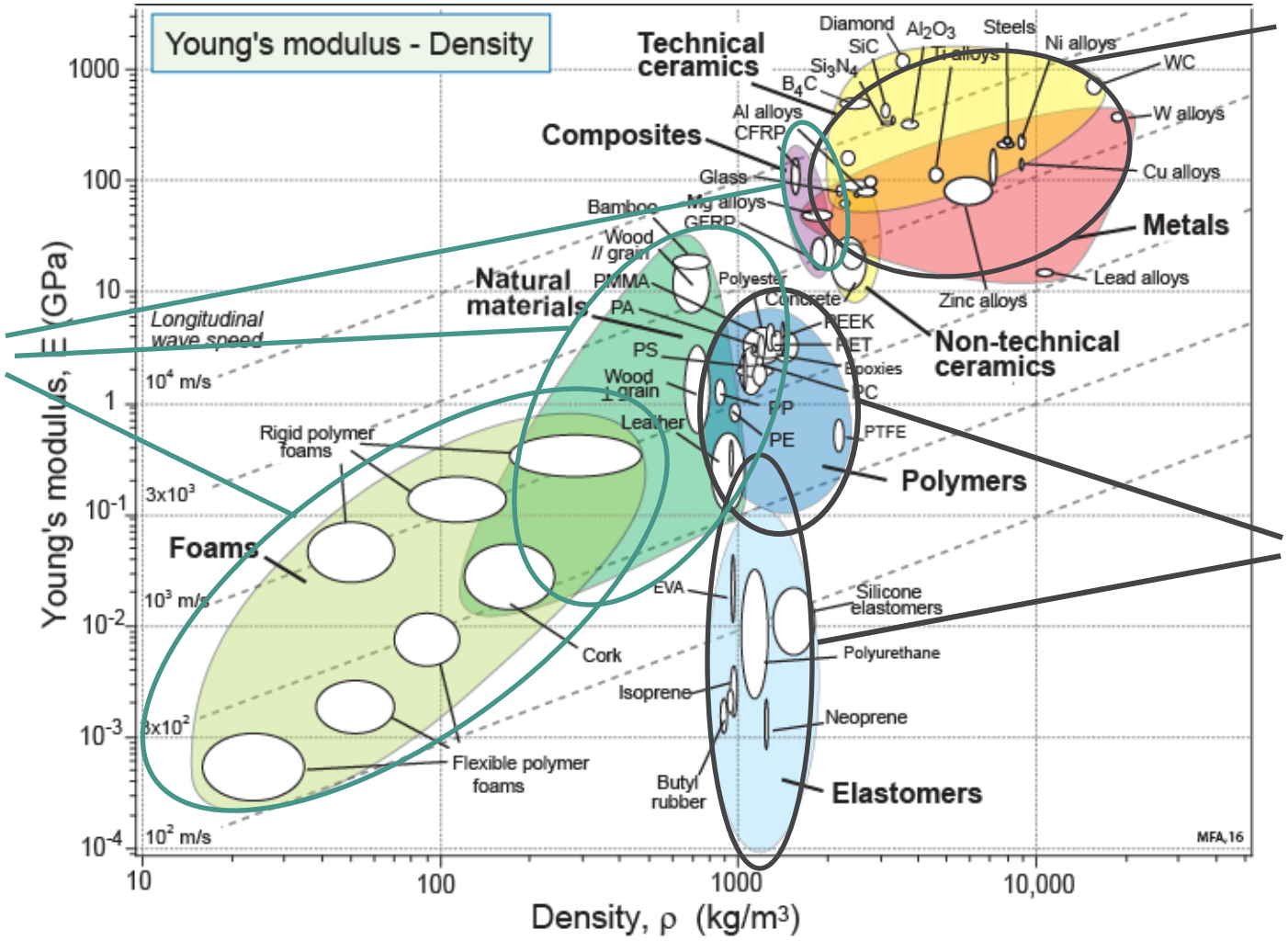
Metals:

Composition – Metallic bond of base element.

Drilling down: modulus and density

Composition (and Microstructure)

But what about these?



Crystalline materials:

Composition – Metallic bond vs. ionic/covalent bonds.

Small "bubbles" – insensitive to *Microstructure*

Polymers & Elastomers:

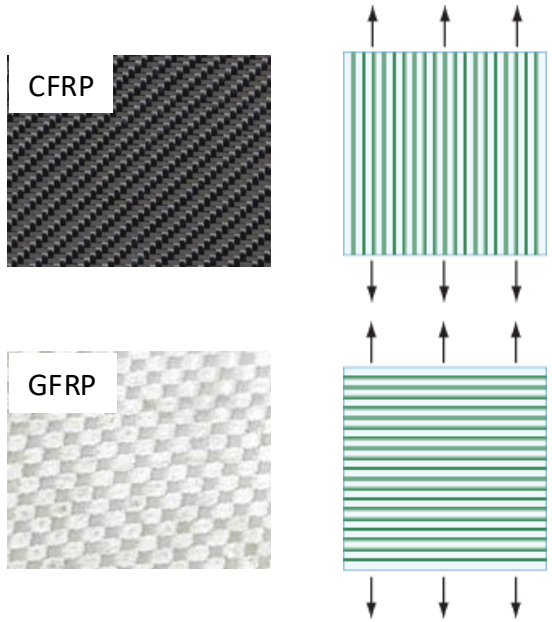
Composition (& Microstructure) – hydrogen-bonded C-chains; cross-linking and crystallinity

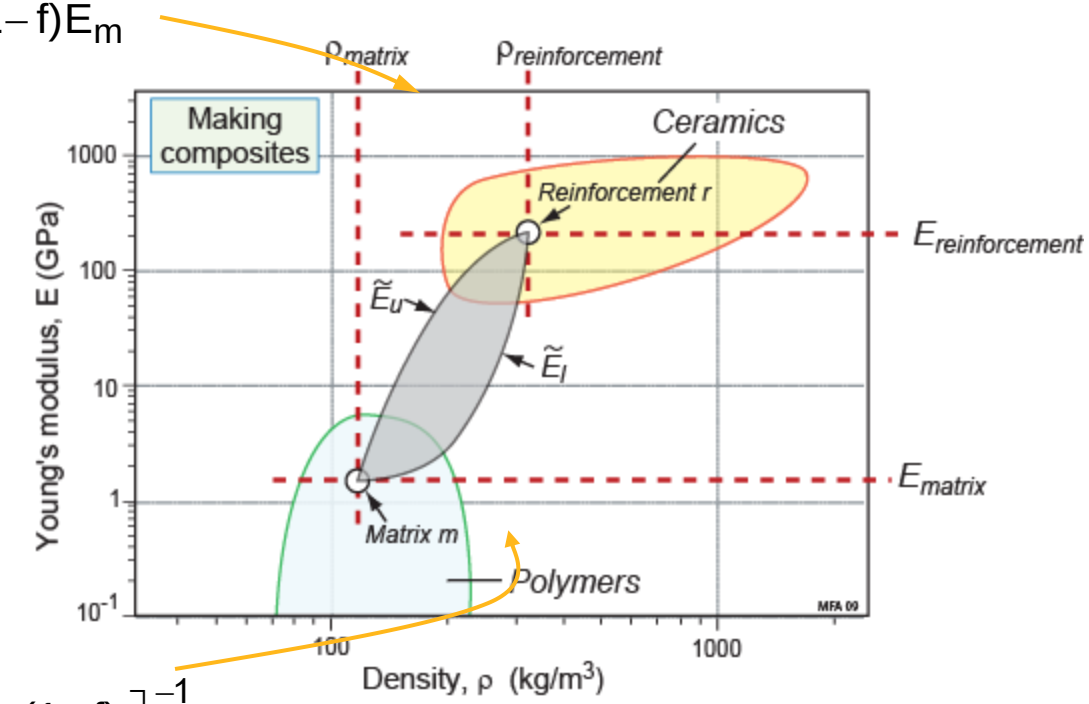
Manipulating modulus & density: architecture

(1) Composites: **"solid – solid hybrids"**

Density: $\rho = f\,\rho_f + (1-f)\,\rho_m$

Modulus: **Upper bound:** $E_u = f E_f + (1-f) E_m$

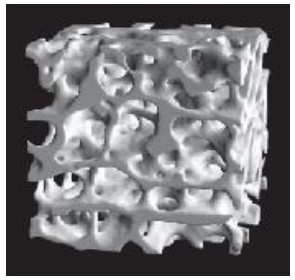




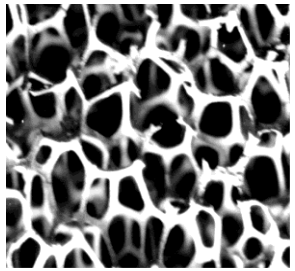
Lower bound: $E_l = \left[\frac{f}{E_f} + \frac{(1-f)}{E_m}\right]^{-1}$

Control of modulus by architecture

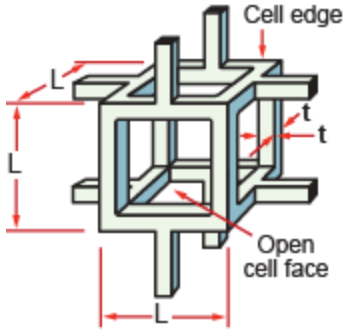
(2) Foams: **"solid – air hybrids"**

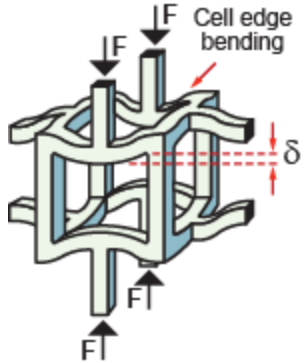


Ceramic foam

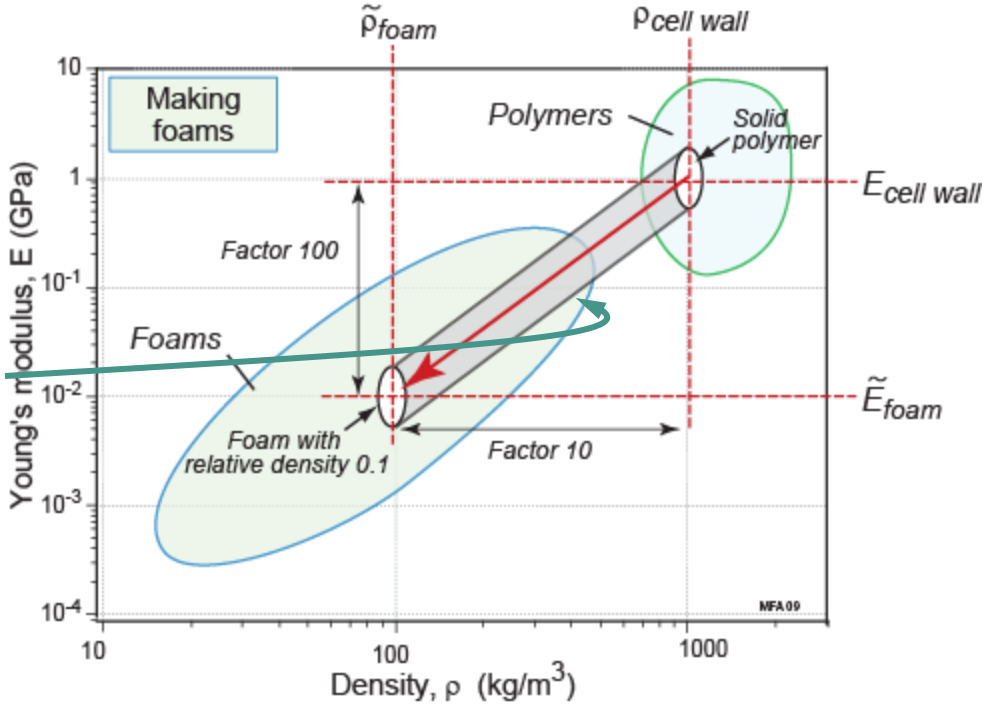


Metal foam





Density: $\tilde{\rho}_{foam}$



Modulus: $$\tilde{E}_{foam} = \left(\frac{\tilde{\rho}_{foam}}{\rho_{solid}}\right)^2 E_{solid}$$

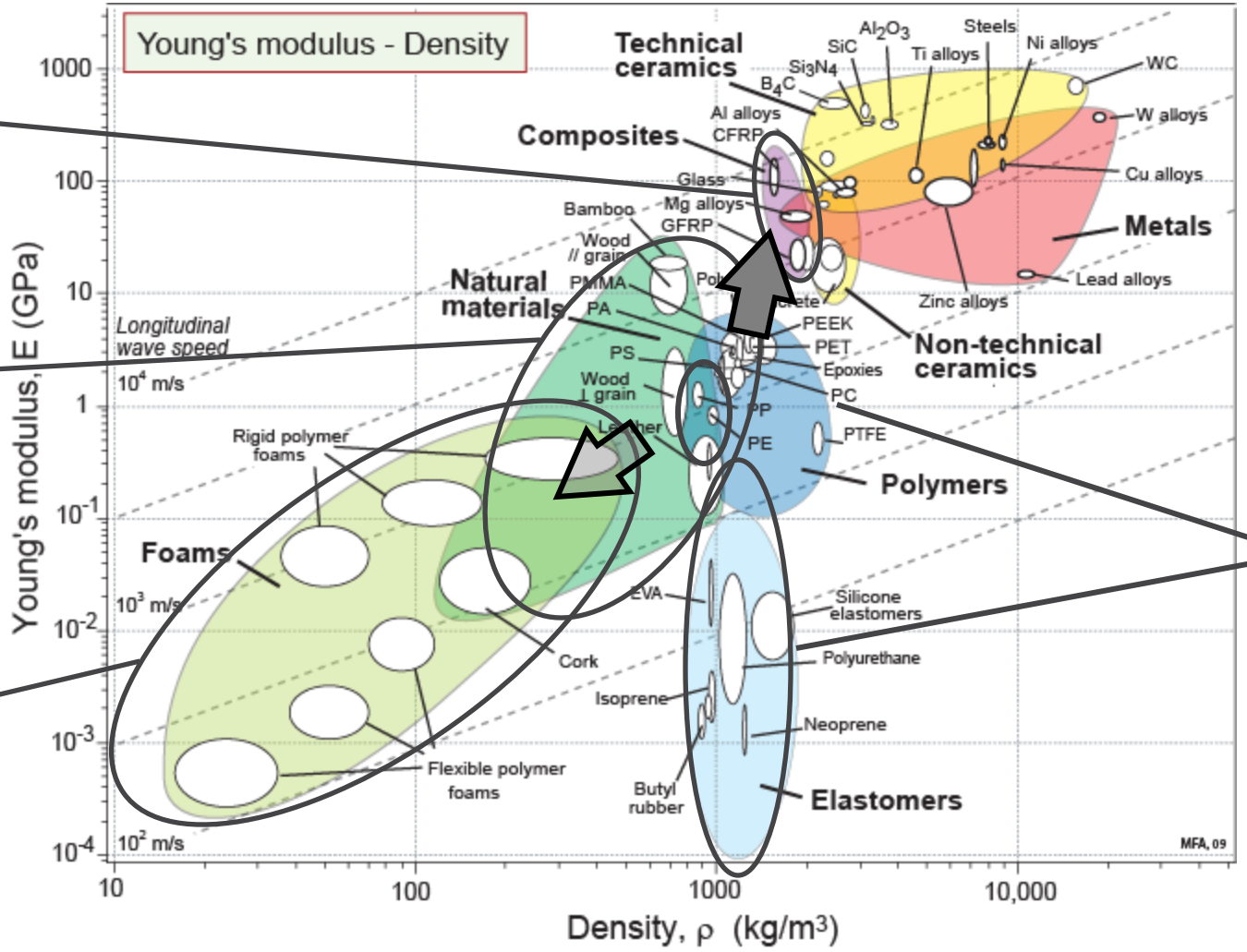
Manipulating properties: modulus – density

Composition, microstructure and architecture

Composites:
Architecture –
Components, lay-up

Natural materials:
Composition, microstructure, architecture

Foams:
Architecture –
cell structure

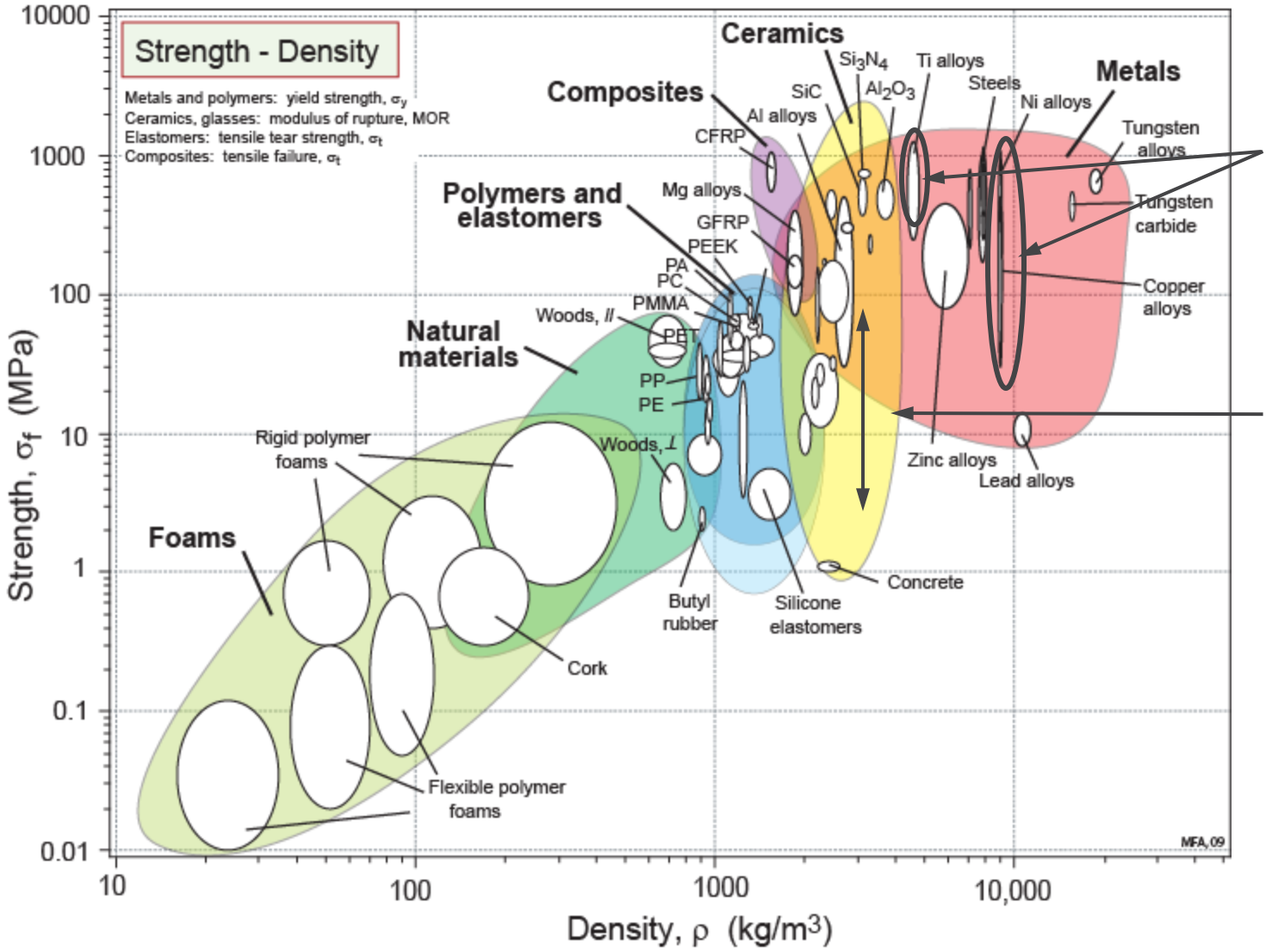


Crystalline materials:
Composition –
metallic bond vs. ionic/covalent bonds.

Polymers & Elastomers:
Composition & Microstructure –
hydrogen-bonded C-chains; cross-linking and crystallinity.

Manipulating properties: strength

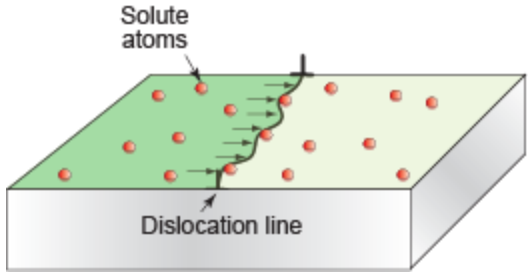
Composition, microstructure and architecture



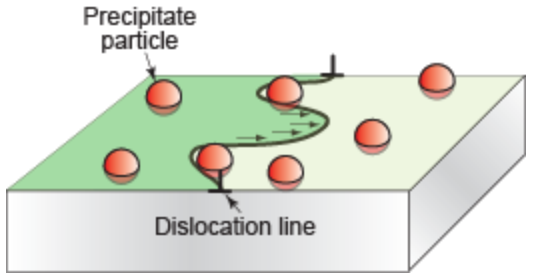
Greatly elongated bubbles

Polymer strengths overlap with metals.

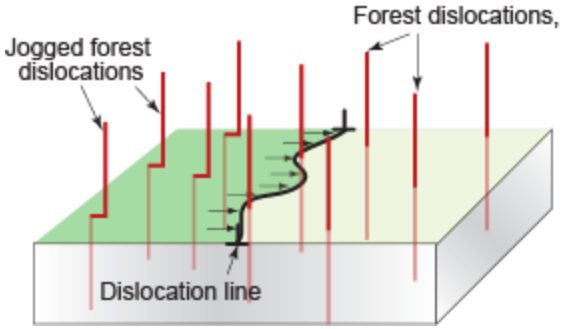
Drilling down: control of microstructure



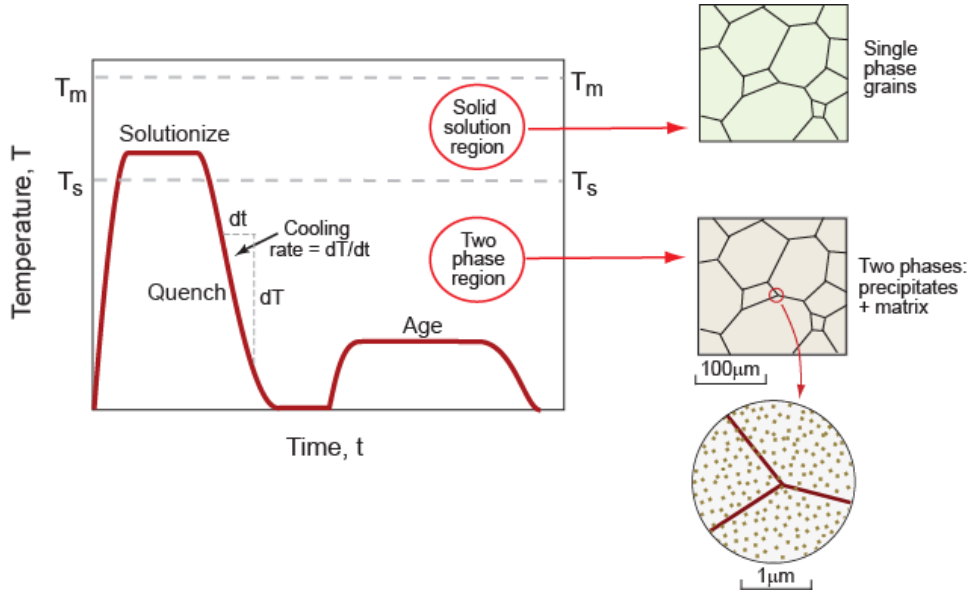
Solid solution hardening
(Composition)



Precipitation hardening
(Composition and microstructure)



Work hardening
(Microstructure)



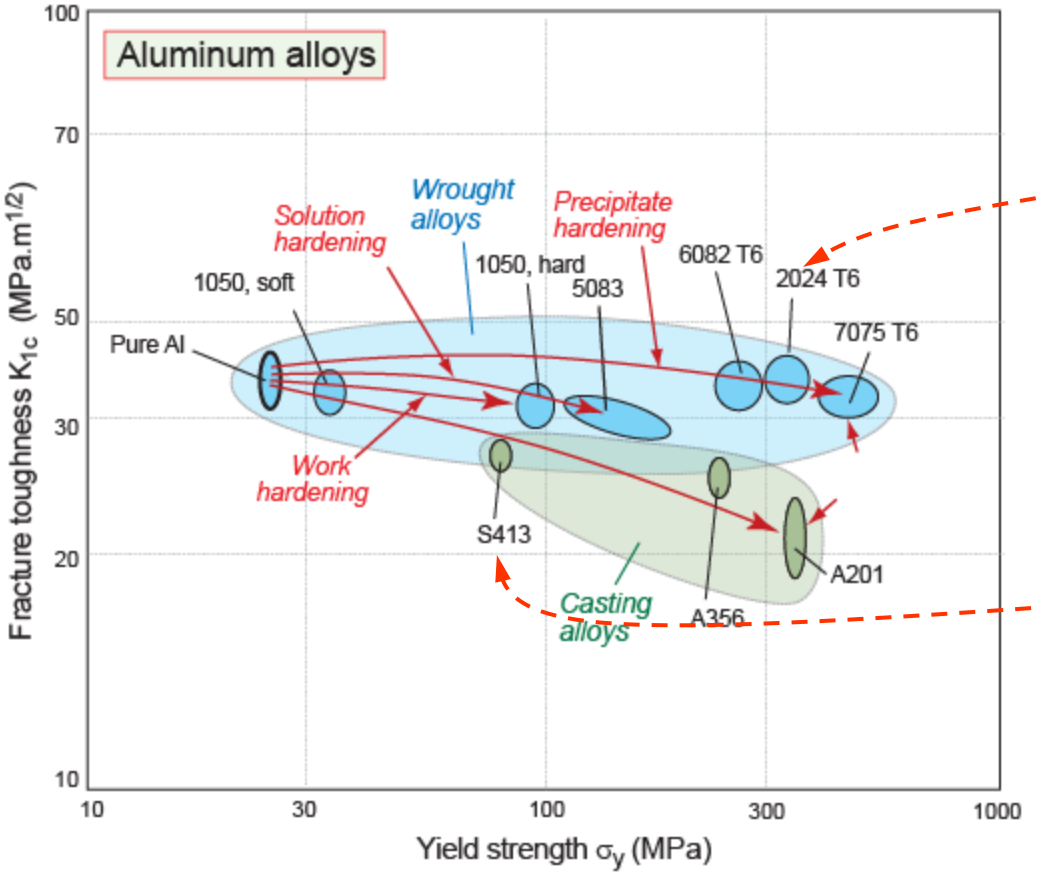
Examples:

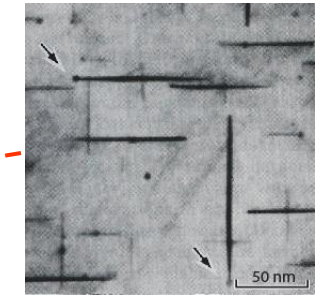
Heat-treatable Al alloys
(age hardening)

Carbon & alloy steels
(quench and temper)

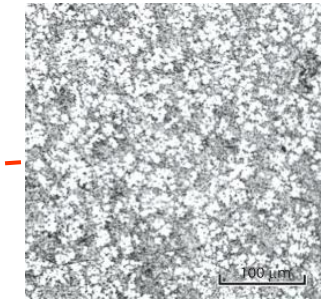
Property control: composition and microstructure

Aluminum alloys: precipitation, solution and work hardening





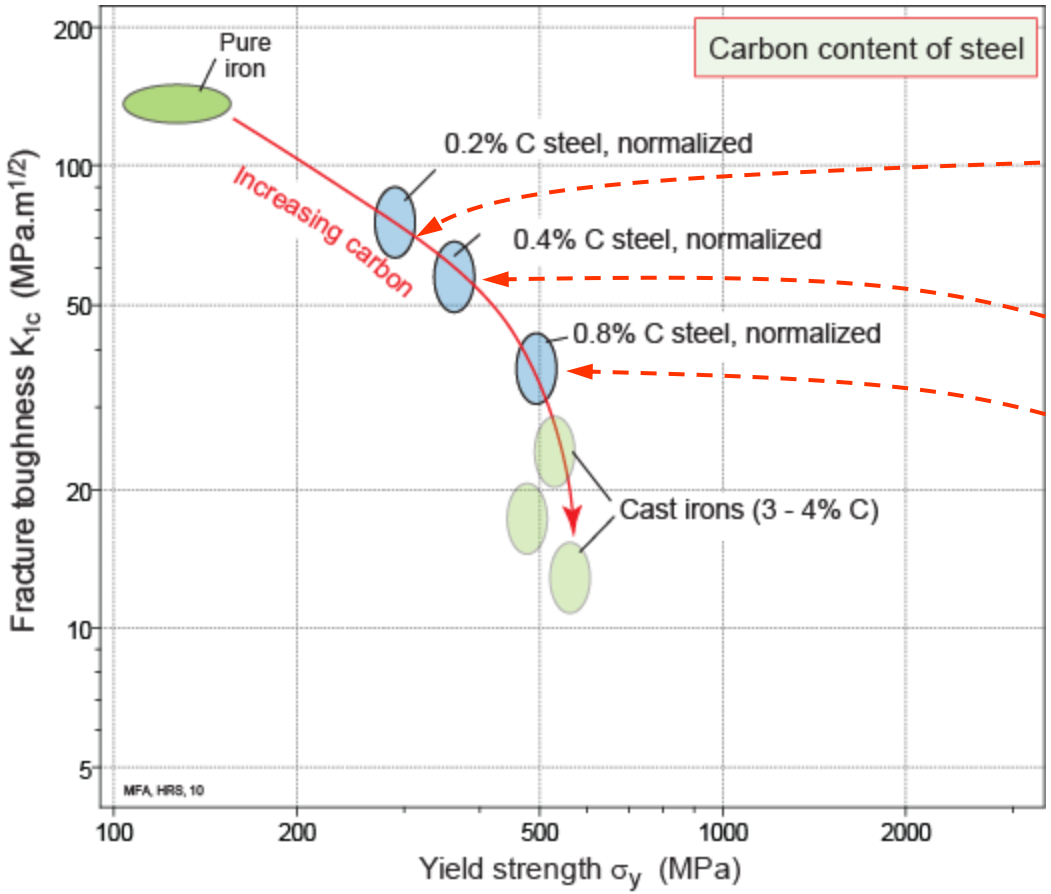
Al -Cu 2024



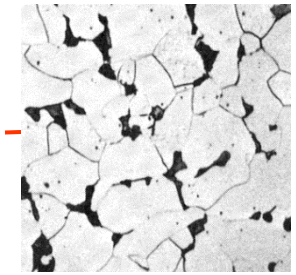
Al -Si S413

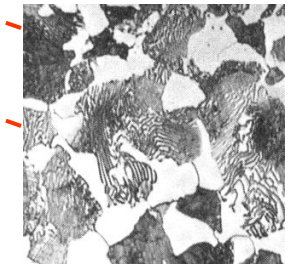
Control by composition: steels

Steels: strength, toughness and carbon content



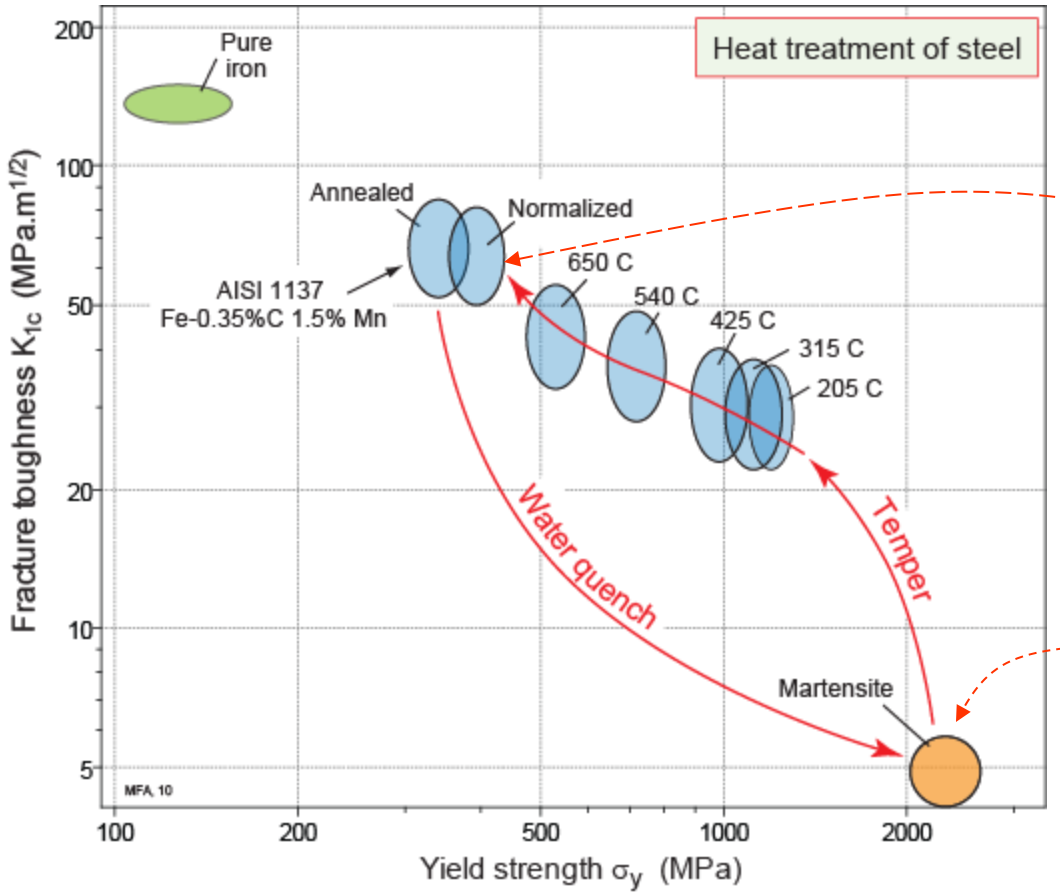
Ferrite + pearlite

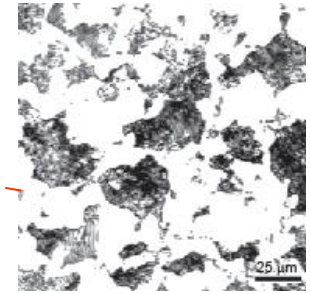




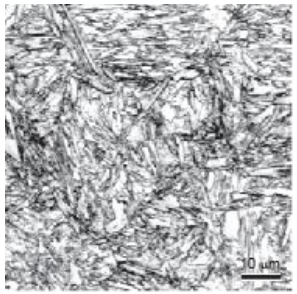
Control by microstructure: steels

Steels: Change of microstructure at constant composition





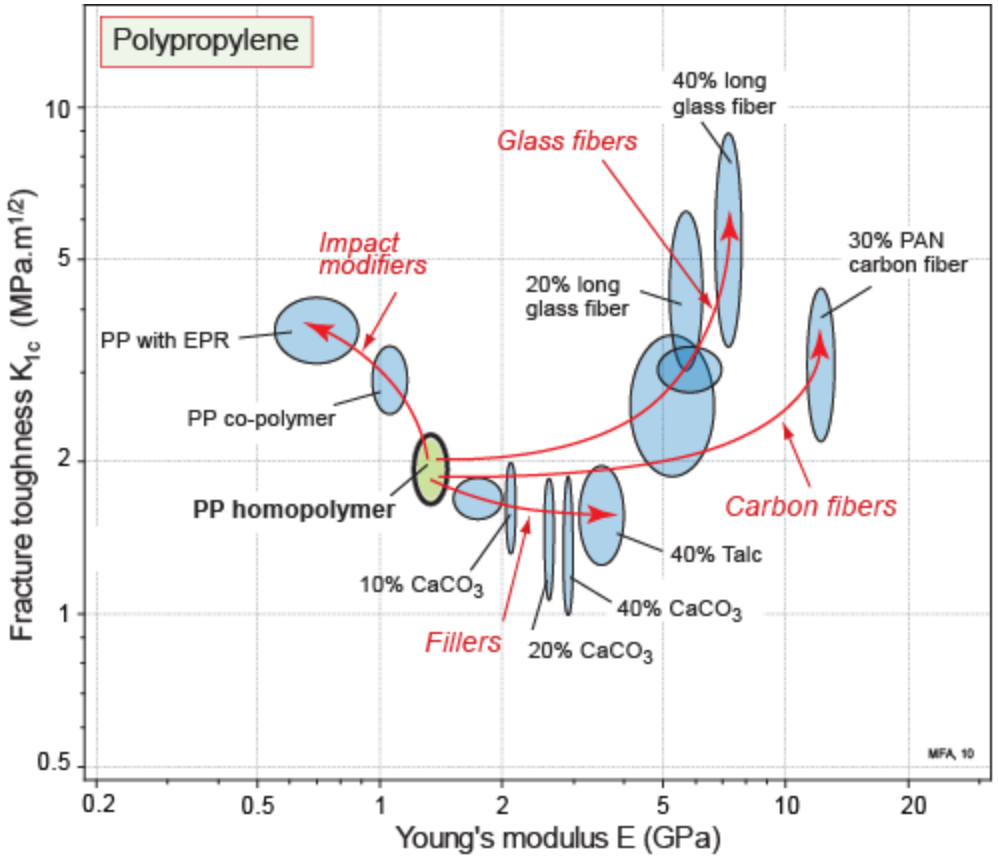
Normalised
(ferrite + pearlite)



As-quenched
(martensite)

Composition and architecture: polymers

***Polymers (PP)*:** fracture toughness-modulus trajectories



Summary

***Design-led teaching of Materials*:**

- design context → properties → property charts: route to material selection
- context provides motivation for exploring microstructural origins of properties

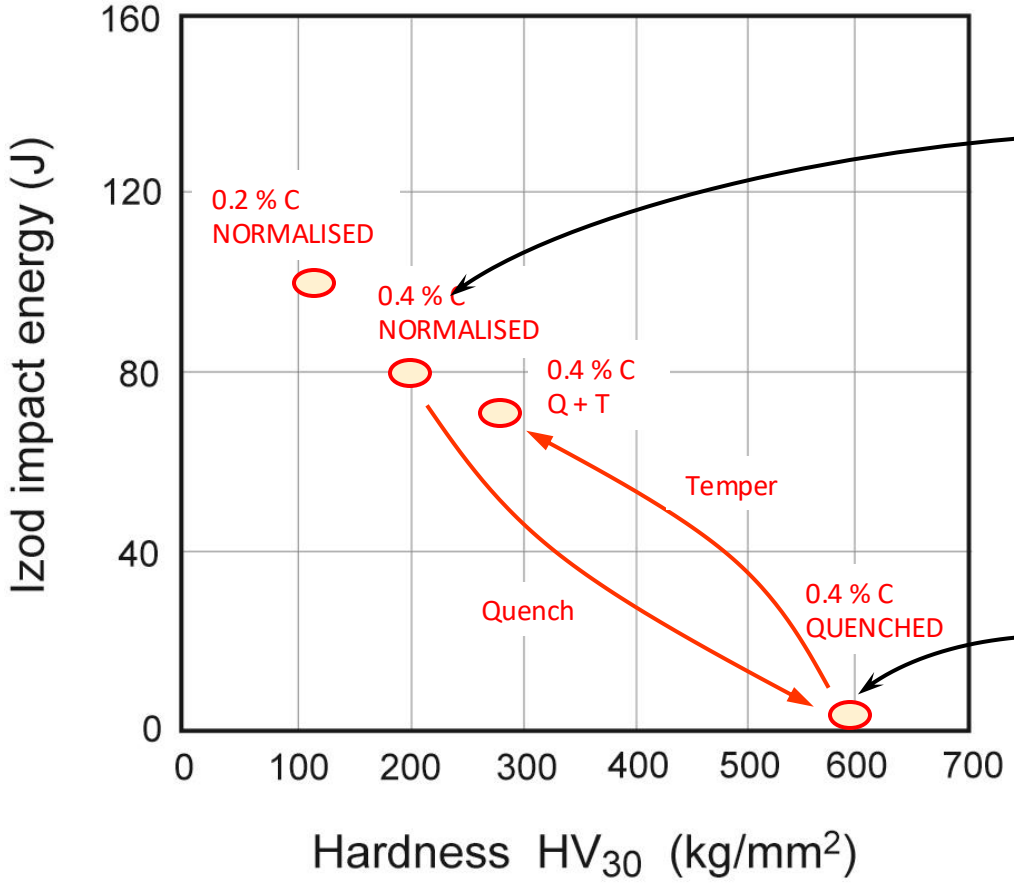
***Processing for Properties*:**

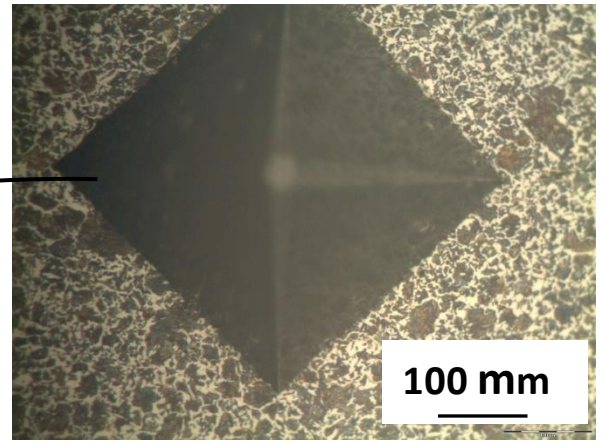
- emphasis on those properties that can be manipulated
- core concept: "Composition + Processing → Microstructure + Properties"

***Property Charts*:**

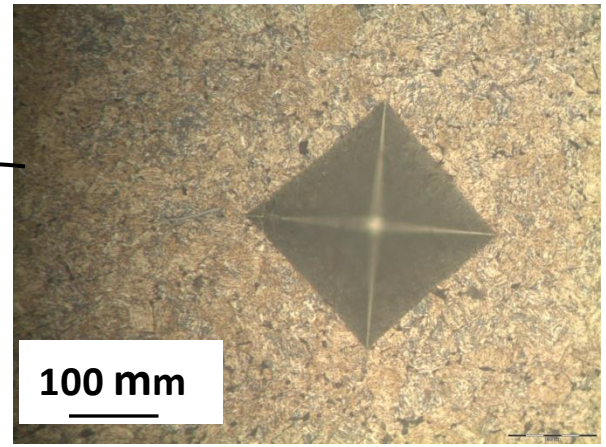
- visual approach: graphical illustration of "composition & process trajectories"
- widely applicable concept: metals, polymers, ceramics, foams, composites...

Appendix: Application in laboratory (steels)





Normalised
(ferrite + pearlite)

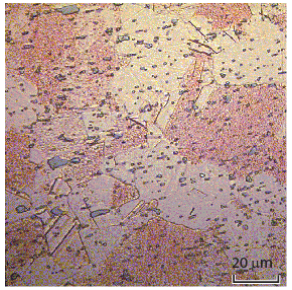


As-quenched
(martensite)

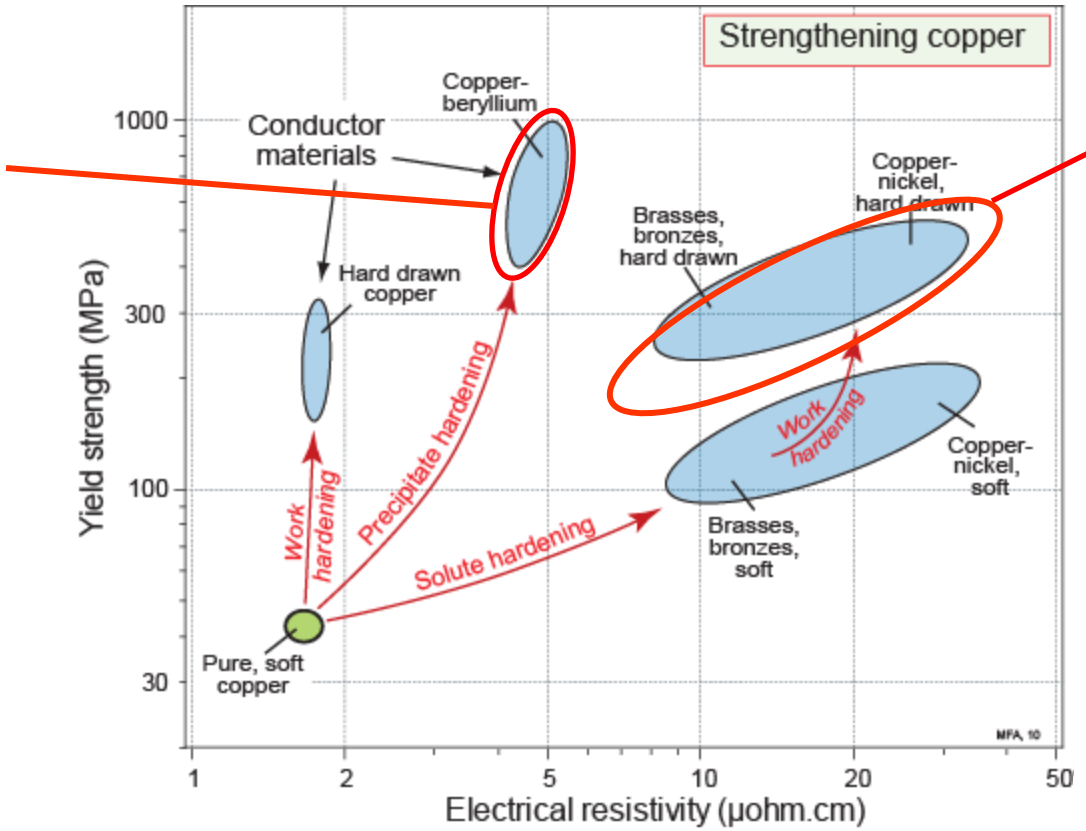
Appendix: electrical properties

Copper alloys: composition and process “trajectories”

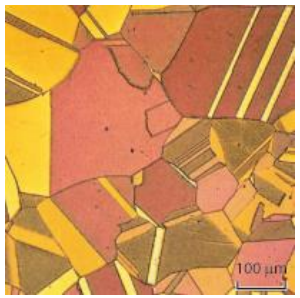
Precipitation hardening:
greatest strength



Copper - beryllium



Solid solution:
strongest effect on resistivity



70-30 Brass

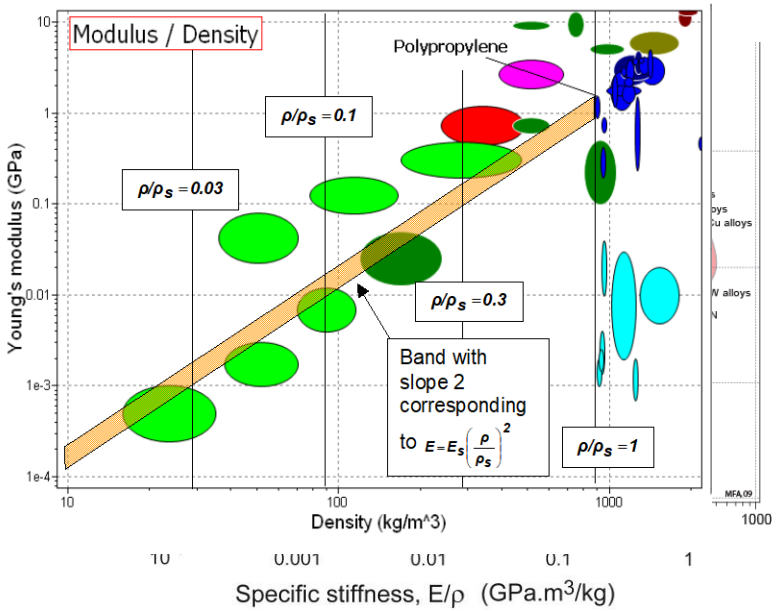
Appendix: Suggested exercises with Ansys Granta EduPack software

Polymers: modulus – strength of PP: effect of fillers

Polymers: fibres vs. bulk: modulus – strength

Ceramics: modulus – strength of alumina vs. porosity

Thermal properties: expansion vs. conductivity



Cu-Ni alloys: modulus, strength, toughness, resistivity ... vs. composition

Alloy comparisons: cast vs. wrought Mg alloys? resistivity – strength, Al alloys?

Foams: predict effect of architecture – modulus and density of PP foams

Ansys Education Resources Feedback Survey

Here at Ansys, we rely on your feedback to ensure the educational content we create is up-to-date and fits your teaching needs.

Please click the link below to fill out a short survey (~7 minutes) to help us continue to support academics around the world utilizing Ansys tools in the classroom.

Feedback Survey Link

Use and Reproduction

The content used in this resource may only be used or reproduced for teaching purposes; and any commercial use is strictly prohibited.

Document Information

This lecture unit is part of a set of teaching resources to help introduce students to materials, processes and rational selections.

Ansys Education Resources

To access more undergraduate education resources, including lecture presentations with notes, exercises with worked solutions, microprojects, real life examples and more, visit www.ansys.com/education-resources.