Selection of Engineering Materials

IM 515E

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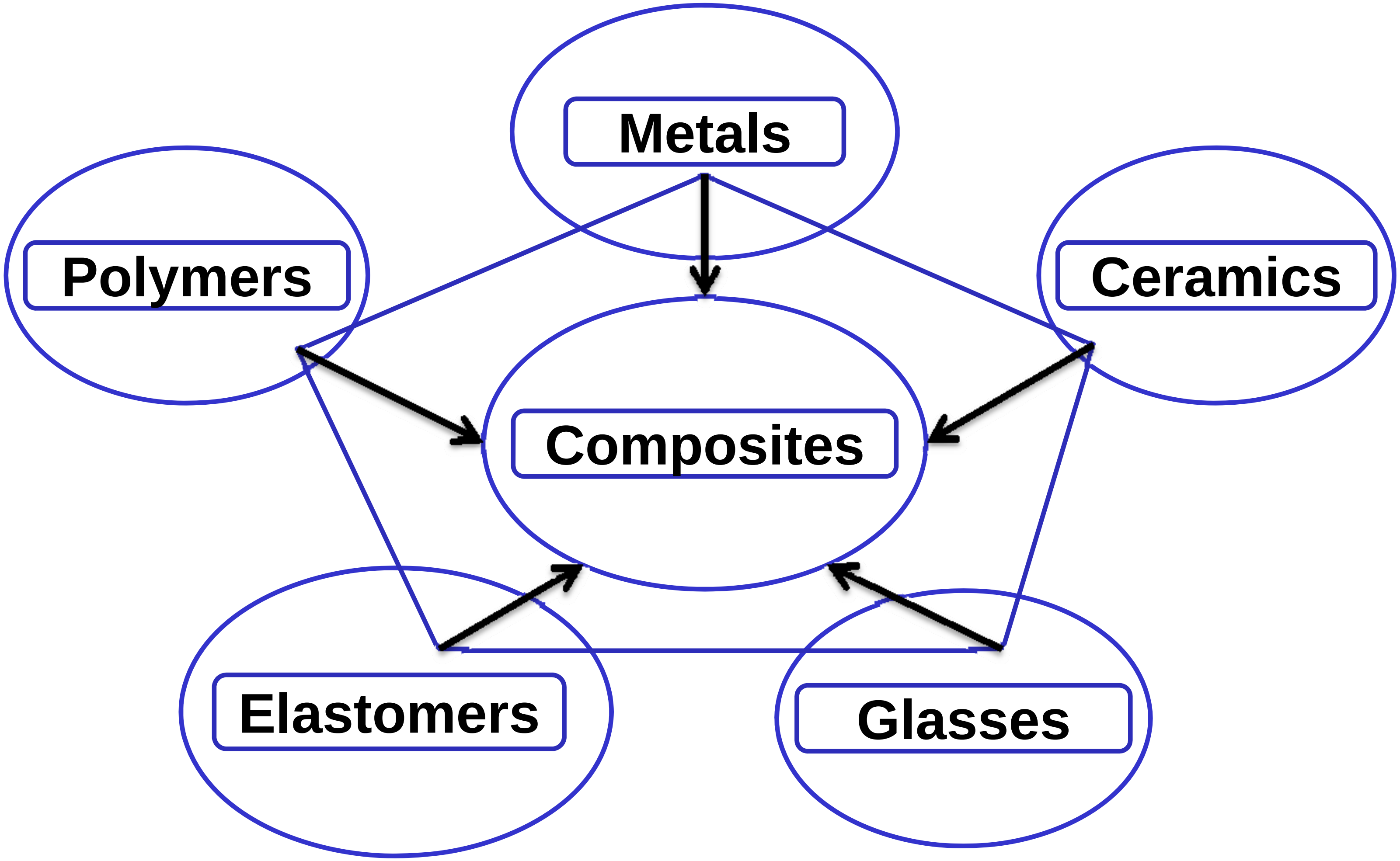
Engineering Materials & Their Properties



Metals

Polymers

Ceramics

Composites

Elastomers

Glasses

The menu of engineering materials.

Engineering Materials & Their Properties

- Engineering Materials fall into **six** broad classes as shown in the figure:
  - Metals
  - Polymers
  - Elastomers
  - Ceramics
  - Glasses
  - Composites which are combinations of two or more of the above
- Members of each class have similar properties, similar processing routes and often they can be be used for similar applications.

Engineering Materials & Their Properties

- **Metals**
  - have relatively high moduli
  - their good ductility allows them to be formed by deformation processes, e.g. rolling, forging and extrusion.
  - even high strength metals show some ductility (e.g. spring steel ~ 2%) and they generally fracture in a ductile manner.
  - they are prone to fatigue.
  - of all classes of materials, they are the least resistant to corrosion

Engineering Materials & Their Properties

- **Ceramics and glasses**
  - have high moduli i.e. stiffness.
  - they are brittle.
  - they are hard and abrasion resistant (hence they are used in bearings and cutting tools).
  - they retain their strength at high temperature.
  - they are corrosion resistant.
  - because they have no ductility, they have a low tolerance for stress concentration (such as holes or cracks) and for high contact stresses (e.g. at clamping points).

Engineering Materials & Their Properties

– Plastic deformation can occur in more ductile materials allowing accommodation of the stress concentration by redistributing loads more evenly.

– ceramics, like other brittle materials, display a wide scatter in strength and, as a consequence, design with ceramics is quite difficult.

Engineering Materials & Their Properties

- **Polymers and Elastomers**
  - they have low moduli (50 times less than metals).
  - they are strong.
  - elastic deflections can be large.
  - they creep even at room temperature (a polymer under load can, in time, develop a permanent set).
  - their properties show a large temperature dependence e.g.
    - At 20°C tough and flexible
    - At 4 °C brittle
    - At 100°C can creep rapidly
  - their strength is inadequate above 200°C.

Engineering Materials & Their Properties

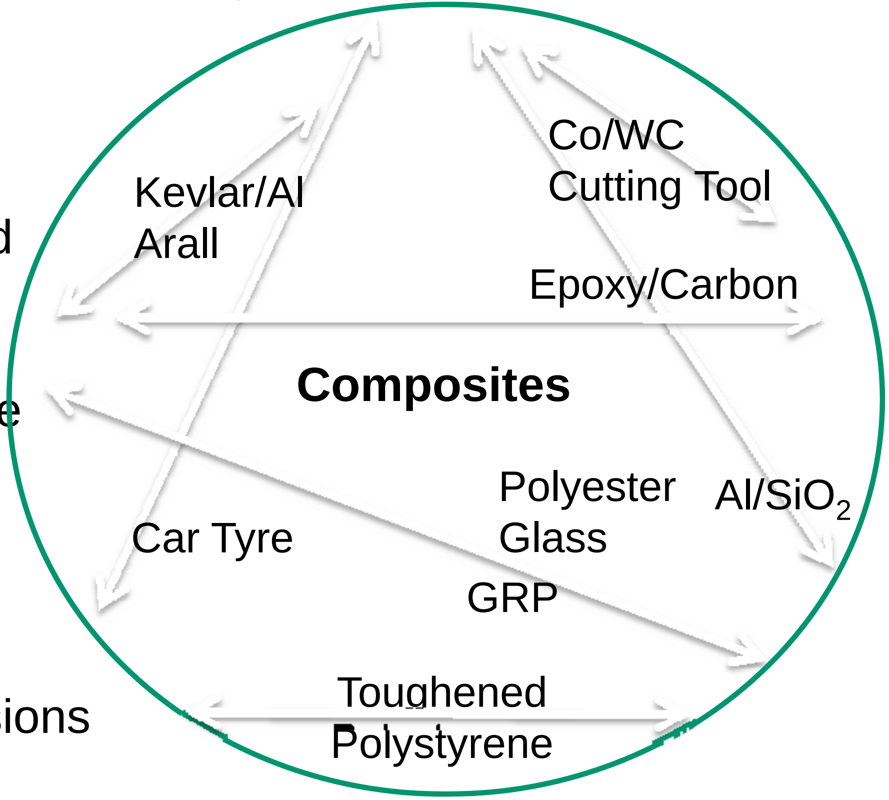
Their advantages

- Combinations of their properties can be good e.g. strength per unit weight
- they are easy to shape
- complicated parts performing several functions can be moulded from a polymer in a single operation
- their large elastic deflections allow the design of polymer components which snap together, making assembly fast and cheap
- by accurately sizing the mould, no finishing is required
- polymers are corrosion resistant
- they have low friction coefficient
- they are being increasingly exploited

Engineering Materials & Their Properties

- **Composites**
  - combine the attractive properties of the other classes of materials while avoiding their drawbacks.
  - widely used types include polymer matrix composites, e.g. epoxy or polyester reinforced with fibres of glass, carbon or Kevlar.
  - at room temperature, their performance can be outstanding.
  - for polymer matrix composites, they cannot be used above 250°C because the polymer matrix softens.
  - components made from composites are expensive and they are difficult to form and join.
  - the engineer will use composites when the **increased performance** justifies **the higher cost**.

Engineering Materials & Their Properties



Metals
Fe, Al, Ni, Cu, Ti, Pb, etc
Strong, Stiff, Dense, Tough,
High Energy to Produce

Polymers
PE, PAN, PP, etc
Easily Formed, Soft
But Fibres are Stiff and Strong
Low Density
Low Energy to Produce

Ceramics
C, Al_2O_3, SiC, B4C
Hard, High Melting
Stiff
Intermediate Density
Can be Low Energy to Produce

Kevlar/Al
Arall

Co/WC
Cutting Tool

Epoxy/Carbon

Composites

Car Tyre

Polyester
Glass

Al/SiO_2

GRP

Toughened
Polystyrene

Glass
Inorganic
Polymeric
Metallic

Rubber
Elastomers
High Extensions

The five generic classes of engineering materials and their combinations in composite materials

Definitions of Materials Properties

- **Density** (usual units Mg/m^3) is the weight per unit volume. We measure density by weighing in air and in a fluid of known density.
- **Elastic Modulus** (units GPa or GN/m^2) is given by the elastic part of the stress-strain curve.
  - Young's modulus, E, describes tension or compression
  - Shear modulus, G, describes shear loading
  - Bulk modulus, K, describes the effect of hydrostatic pressure
  - Poisson's ratio, ν, is dimensionless and is the negative of the ratio of the lateral strain to the axial strain $\varepsilon_2 / \varepsilon_1$ in axial loading.
  - The slopes of stress-strain curves give the moduli but more accurate values are measured dynamically.

Definitions of Materials Properties

- Commonly

$$\nu = \frac{1}{3} \qquad \boldsymbol{G} \approx \frac{3}{8}\boldsymbol{E} \qquad \boldsymbol{K} \approx \boldsymbol{E}$$

$$\boldsymbol{E} = \frac{3\boldsymbol{G}}{1 + \boldsymbol{G}/3\boldsymbol{K}} \qquad \boldsymbol{G} = \frac{\boldsymbol{E}}{2\left(1+\nu\right)} \qquad \boldsymbol{K} = \frac{\boldsymbol{E}}{3\left(1-2\nu\right)}$$

Definitions of Materials Properties

- **Strength**, σ_f (units MPa or MN/m^2)

For metals, σ_f is taken as the 0.2% offset yield strength σ_y .

For polymers, σ_f is defined as the stress σ_y at which the stress-strain curve becomes markedly non linear (typically at 1% strain). Polymers are slightly stronger (by ~20%) in compression than tension.

For ceramics and glasses, strength strongly depends upon the **mode of loading**. In tension, strength is the fracture strength $\sigma_{\mathbf{f}}^{\mathbf{t}}$ whereas in compression, it means the crushing strength $\sigma_{\mathbf{f}}^{\mathbf{c}}$ which is much larger, such that

$$\sigma_{\mathbf{f}}^{\mathbf{c}} \approx 15\sigma_{\mathbf{f}}^{\mathbf{t}}$$

Definitions of Materials Properties

For composites, the strength is often taken as the **0.5%** offset linear elastic behaviour. Composites containing fibres are weaker by up to **30%** in compression than in tension because the fibres buckle. Here, the strength of composites is taken as the tensile strength.

Definitions of Materials Properties

Design Limiting Material Properties

Class	**Property**	**Symbol and Units**	
General	Relative Cost	C_R	(--)
	Density	ρ	(Mg/m^3)
Mechanical	Elastic moduli	E, G, K	(GPa)
	Strength (yield, ultimate, fracture)	σ	(MPa)
	Toughness	G_c	(kJ/m^2)
	Fracture toughness	K_c	(MPam$^{1/2}$)
	Damping capacity	η	(--)
	Fatigue ratio	f	(--)
Thermal	Thermal conductivity	λ	(W/m K)
	Thermal diffusivity	a	(m^2/s)
	Specific heat	C_p	(J/kg K)
	Melting point	T_m	(K)

Definitions of Materials Properties

	Glass temperature	T_g	(K)
	Thermal expansion coefficient	α	(K^{-1})
	Thermal shock resistance	ΔT	(K)
	Creep resistance	---	(--)
Wear	Archard wear constant	K_A	(MPa^{-1})
Corrosion/ Oxidation	Corrosion rate (parabolic rate constant)	-- K_p	(--) (m^2/s)

Definitions of Materials Properties

For multiaxial loading:

- **Metals** – Von Mises yield function works well

$$\left(\sigma_1-\sigma_2\right)^2+\left(\sigma_2-\sigma_3\right)^2+\left(\sigma_3-\sigma_1\right)^2=2\sigma_f^2$$

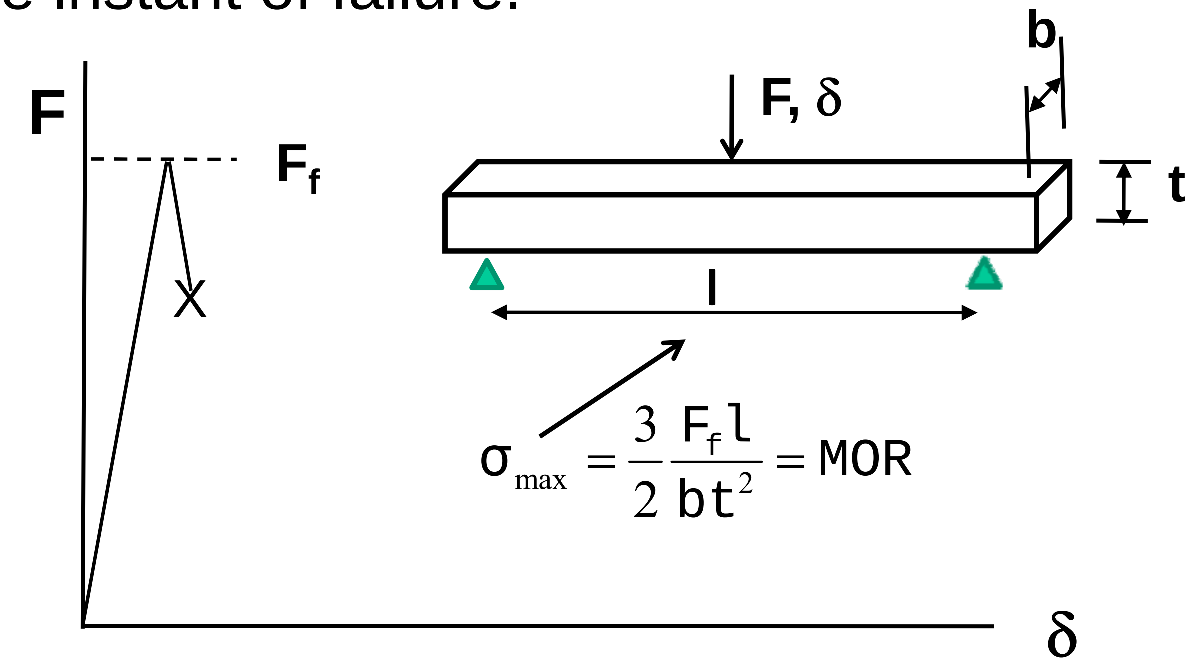
- **Polymers** – the yield function includes the effect of pressure P

$$\left(\sigma_1-\sigma_2\right)^2+\left(\sigma_2-\sigma_3\right)^2+\left(\sigma_3-\sigma_1\right)^2=2\sigma_f^2\left(1-\frac{\beta\cdot P}{\sigma_f}\right)^2$$

where β is a numerical coefficient which characterises the pressure dependence of flow strength, and $P=-\frac{1}{3}\left(\sigma_1+\sigma_2+\sigma_3\right)$ where σ_1, σ_2, σ_3, are the principal stresses, positive when tensile.

Definitions of Materials Properties

- When a material is difficult to grip (e.g. ceramics), then the strength is often measured in bending.
- The **modulus of rupture** (MOR), (units MPa or MN/m^2) is the maximum surface stress in a bent beam at the instant of failure.



$$\sigma_{max} = \frac{3}{2}\frac{F_f l}{bt^2} = MOR$$

Definitions of Materials Properties

Ultimate tensile strength σ_u (units MPa)

- For brittle solids e.g. ceramics, glasses σ_u is equal to the tensile failure stress.
- For metals, ductile polymers and composites σ_u is larger than strength σ_f by a factor of 1.1 → 3 due to work hardening (or in composites) load transfer to the reinforcement.

Hardness H in MPa is measured by pressing a pointed diamond or hardened steel ball into the surface of a material. Hardness is defined as the indenter force divided by the projected area of the indent – and it is related to strength by $H \sim 3\,\sigma_f$.

Definitions of Materials Properties

- **Toughness** G_c (in kJ/m^2) and Fracture Toughness K (in MPam$^{1/2}$ or MN/m$^{3/2}$) measure the resistance of the material to the propagation of a crack.
- The fracture toughness is measured by loading a specimen containing a crack of length 2c. The tensile stress σ_c is measured at which the crack propagates and K_c is then calculated from:

$$K_c = Y\sigma_c\sqrt{\pi c}$$

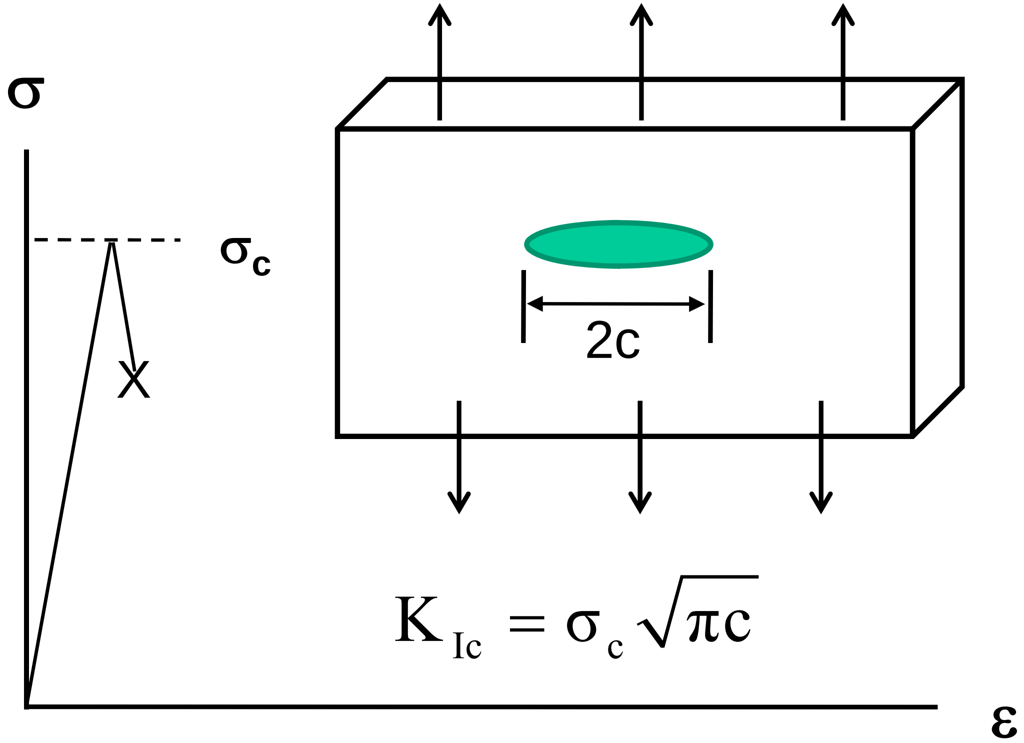
and the toughness:

$$G_c = \frac{K_c^2}{E(1+\nu)}$$

where Y is the compliance which depends on specimen and crack geometries, E is Young's modulus and ν is Poisson's ratio

Definitions of Materials Properties

- Although K and G are adequate for brittle solids, excessive plasticity can occur at the crack tip in more ductile materials, requiring more sophisticated analysis (based on J or COD)



$$K_{Ic} = \sigma_c \sqrt{\pi c}$$

Definitions of Materials Properties

- The **loss coefficient** η (dimensionless) measures the degree to which a material dissipates vibrational energy. When a material is loaded elastically to a stress σ, it stores elastic energy per unit volume:

$$U = \int_0^{\sigma_{max}} \sigma \cdot d\varepsilon = \frac{1}{2} \cdot \frac{\sigma^2}{E}$$

- If it is loaded and then unloaded, it dissipates energy:

$$\Delta U = \oint \sigma \cdot d\varepsilon$$

- The loss coefficient is:

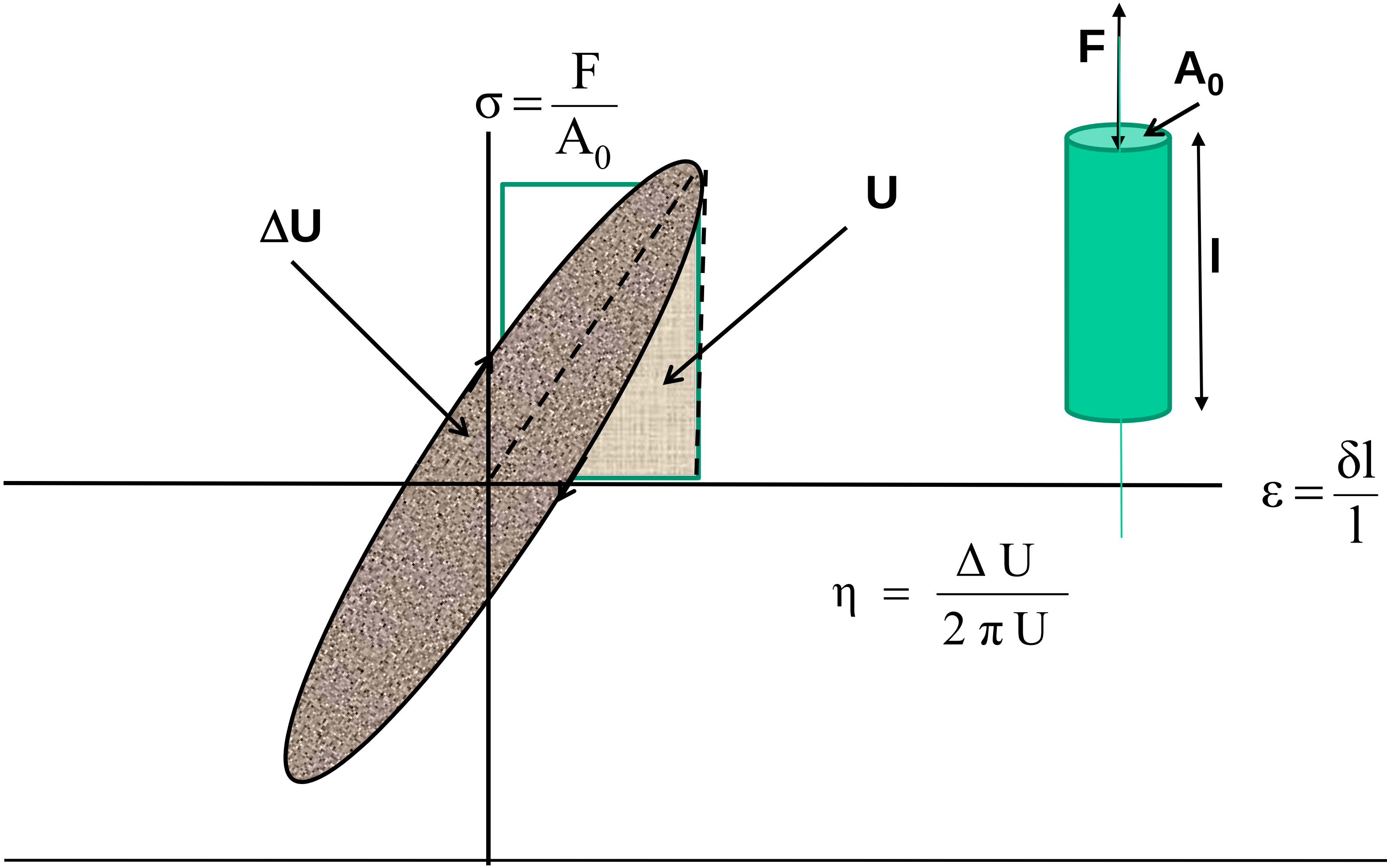
$$\eta = \frac{\Delta U}{2 \cdot \pi \cdot U}$$

- A measure of damping is given by the specific damping capacity

$$D = \frac{\Delta U}{U}$$

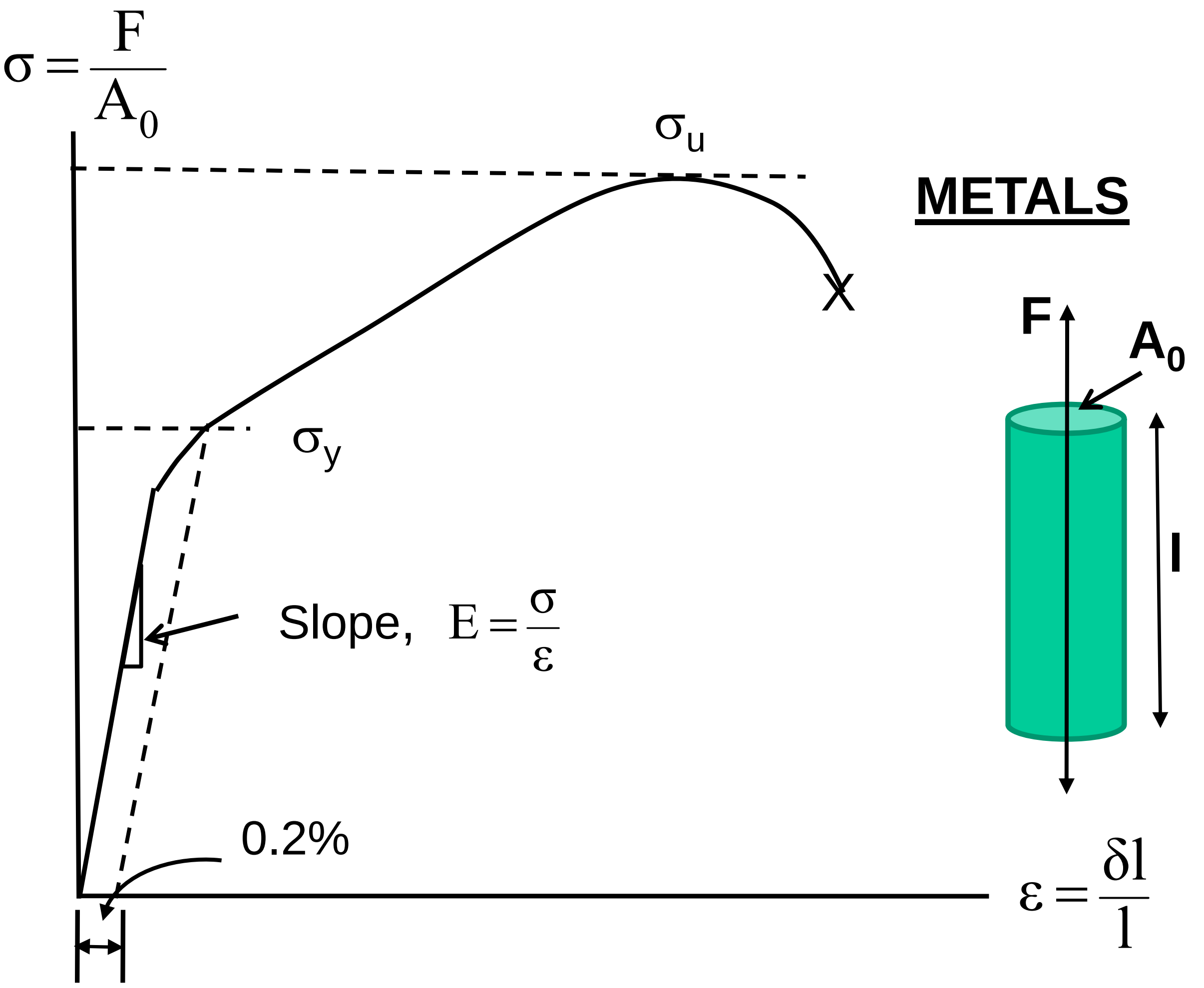
Definitions of Materials Properties

- The loss coefficient η measures the fractional energy dissipated in a stress-strain cycle.

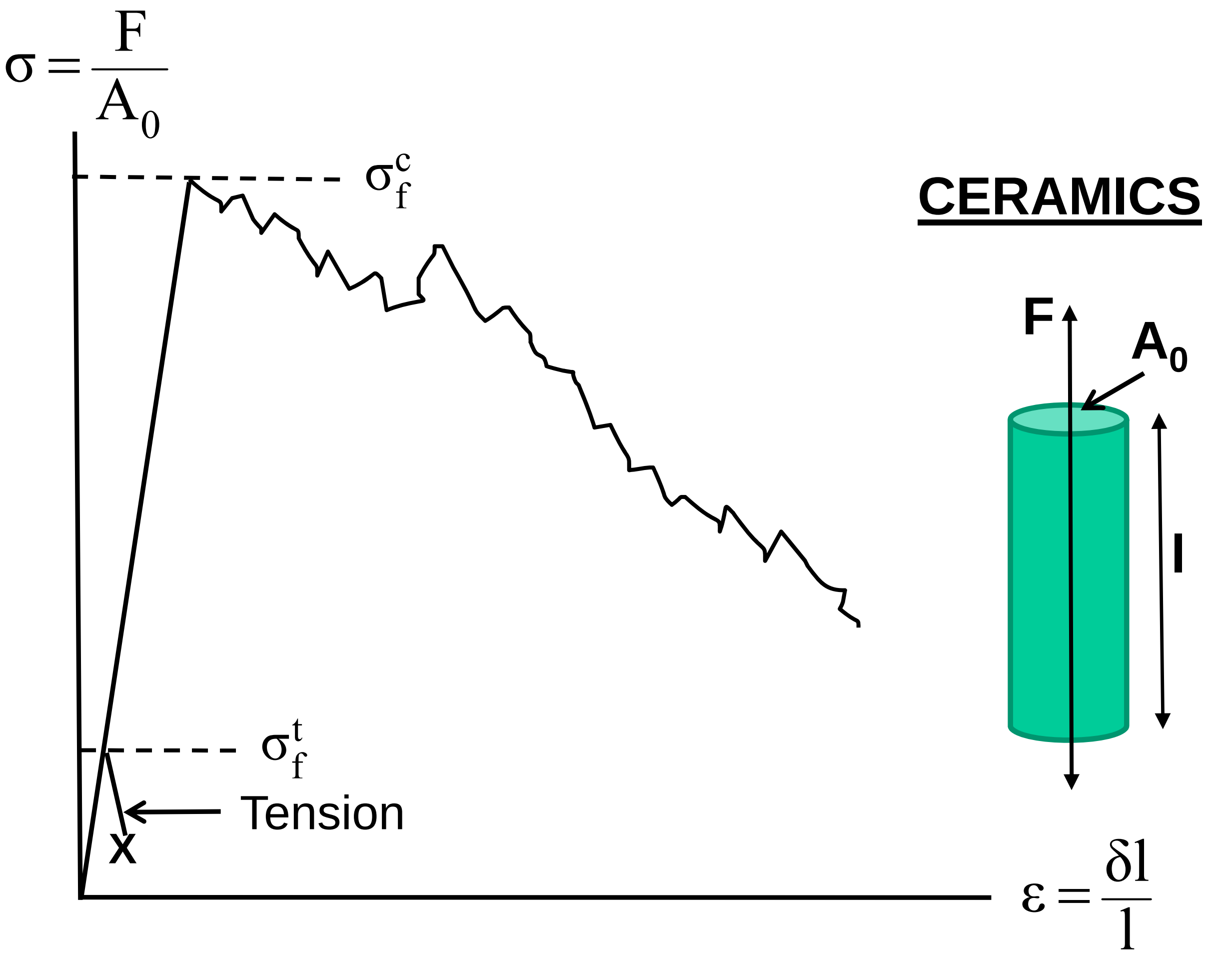


$$\eta = \frac{\Delta U}{2 \pi U}$$

Definitions of Materials Properties

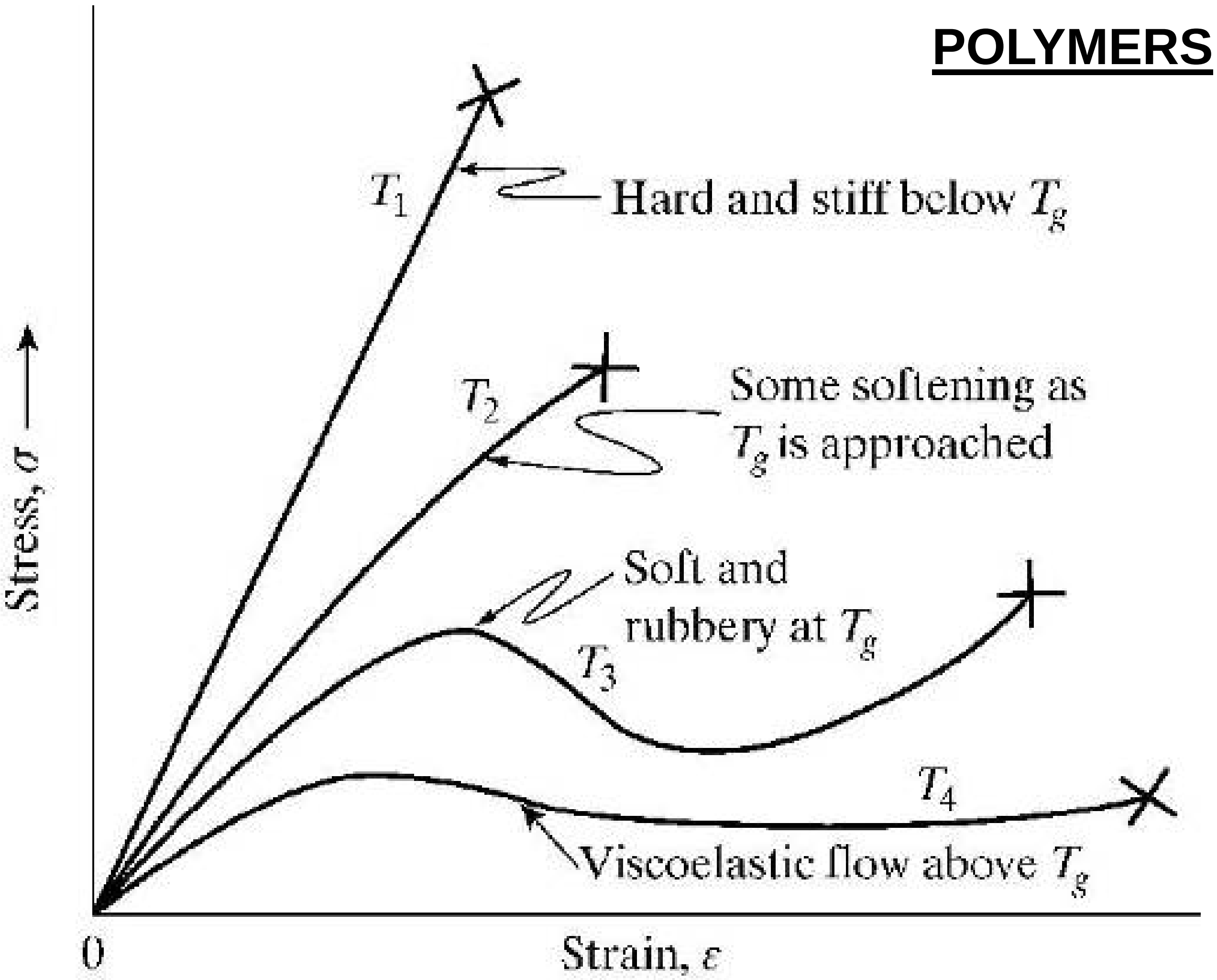


Definitions of Materials Properties



Definitions of Materials Properties

POLYMERS



Definitions of Materials Properties

- **Fatigue** – cyclic loading not only dissipated energy but it also causes crack initiation and growth and eventually fatigue failure. Some materials e.g. mild steel, have a fatigue limit, a stress amplitude below which fatigue failure does not occur. Here, we use the fatigue ratio, f (dimensionless) which is the ratio of the fatigue limit to the yield strength σ_y.