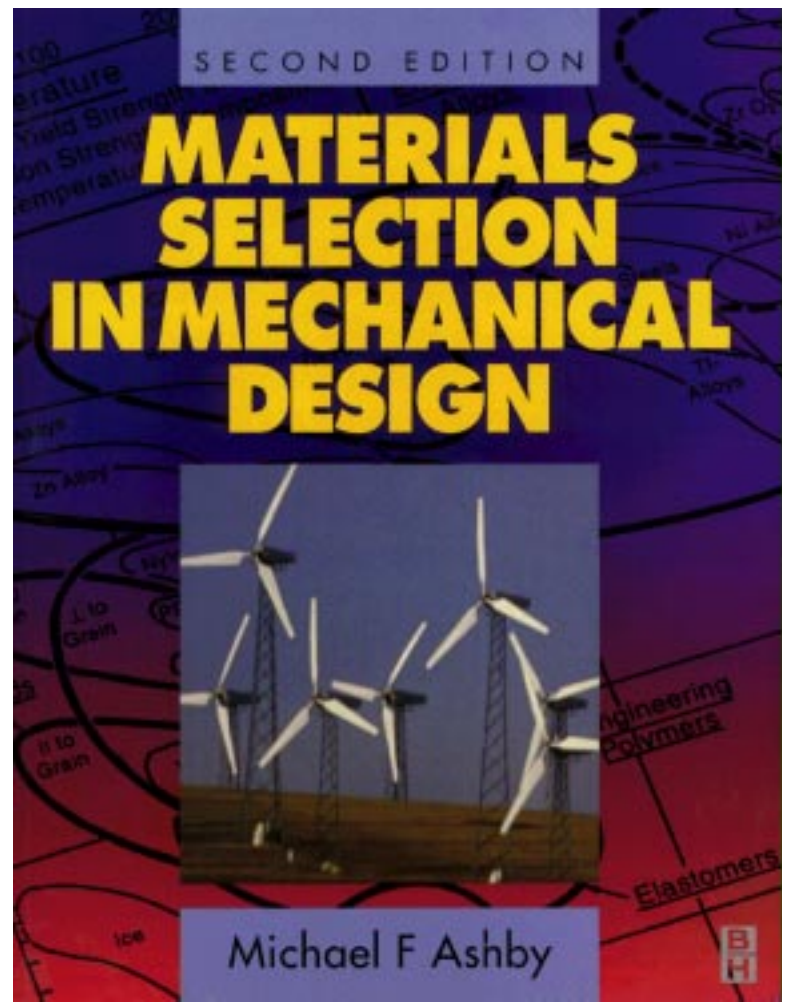
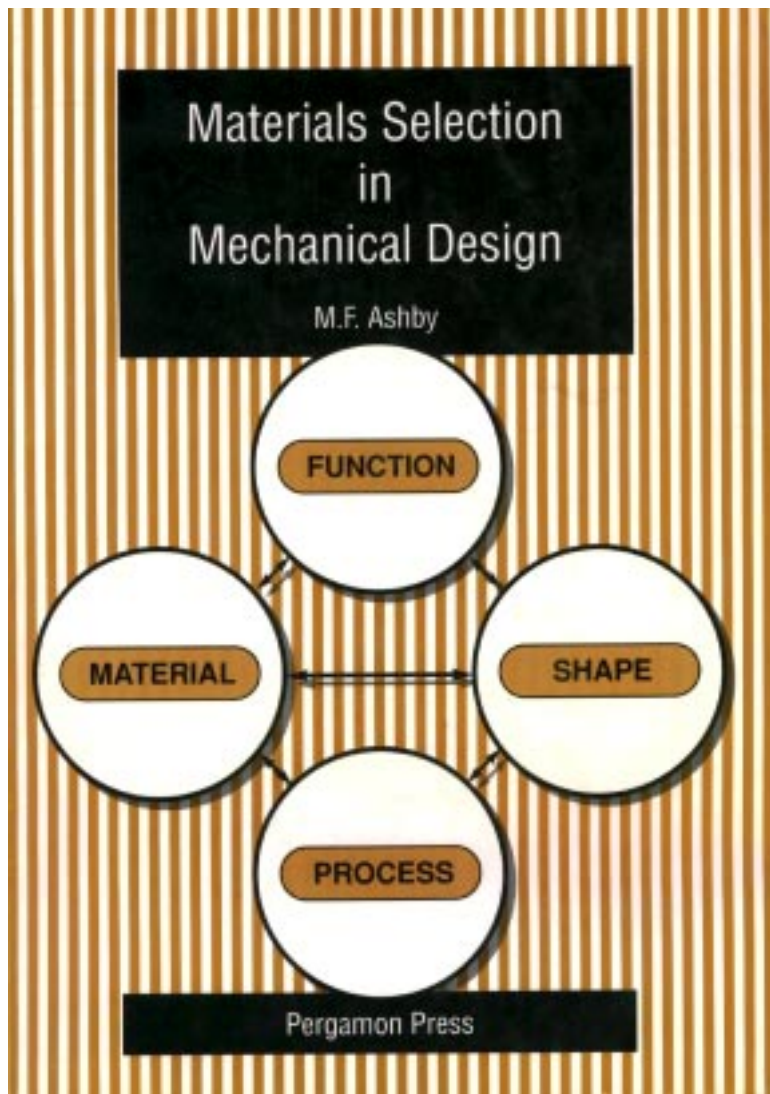


**SMA ADVANCED MATERIALS PROGRAM  
MATERIALS SELECTION, DESIGN AND ECONOMICS  
SMA 5103 & MIT 3.57  
FALL 1999**

**MATERIALS SELECTION IN MECHANICAL DESIGN**

**PART 1**

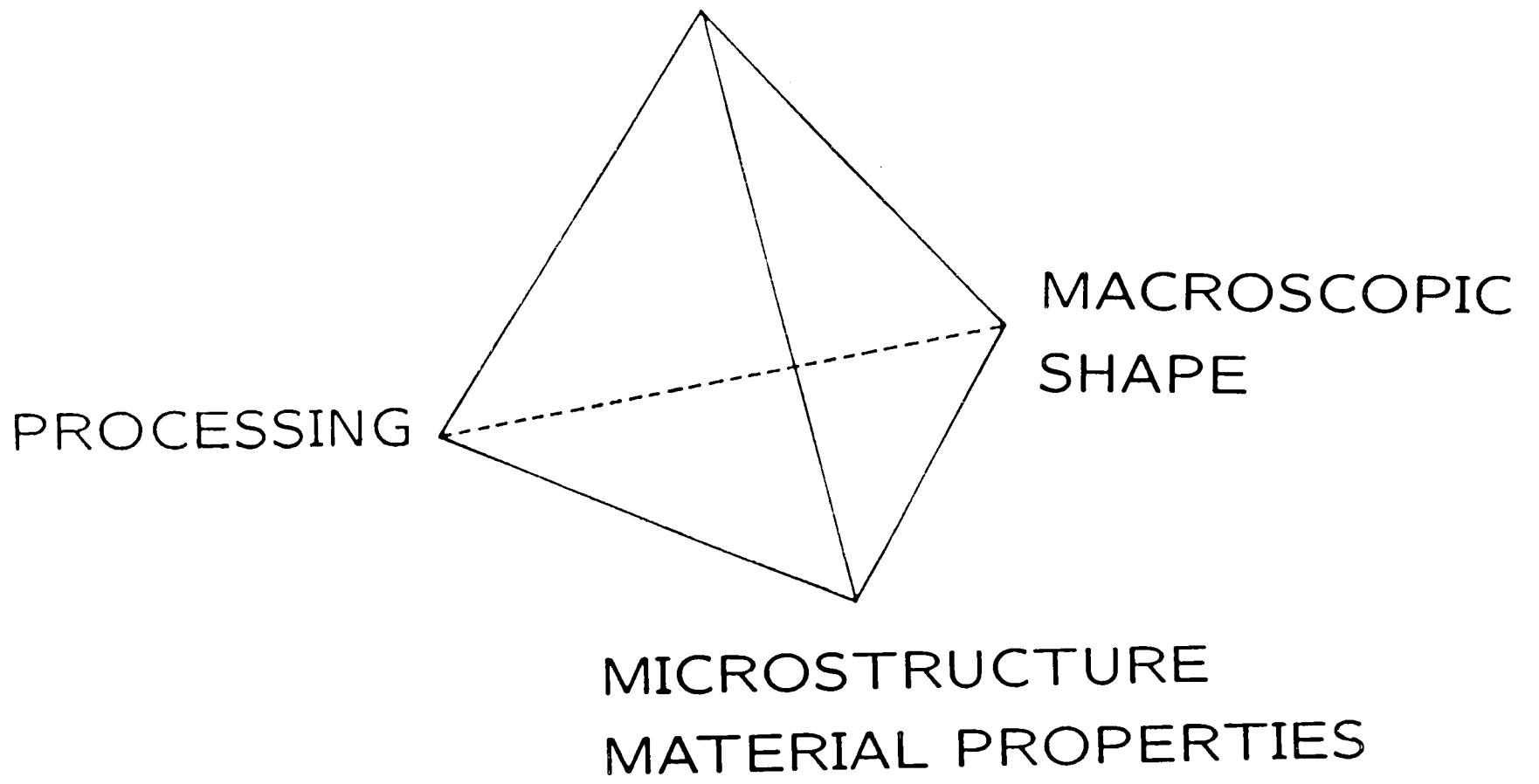
L. Anand



## FOCUS

- Role of materials in mechanical design.
- Mechanical components are designed for certain performance: they carry loads; they conduct heat and electricity.
- They have shape and mass.
- They must be manufactured.
- They must serve their function and not fail due to excessive loading, fatigue, wear and corrosion.

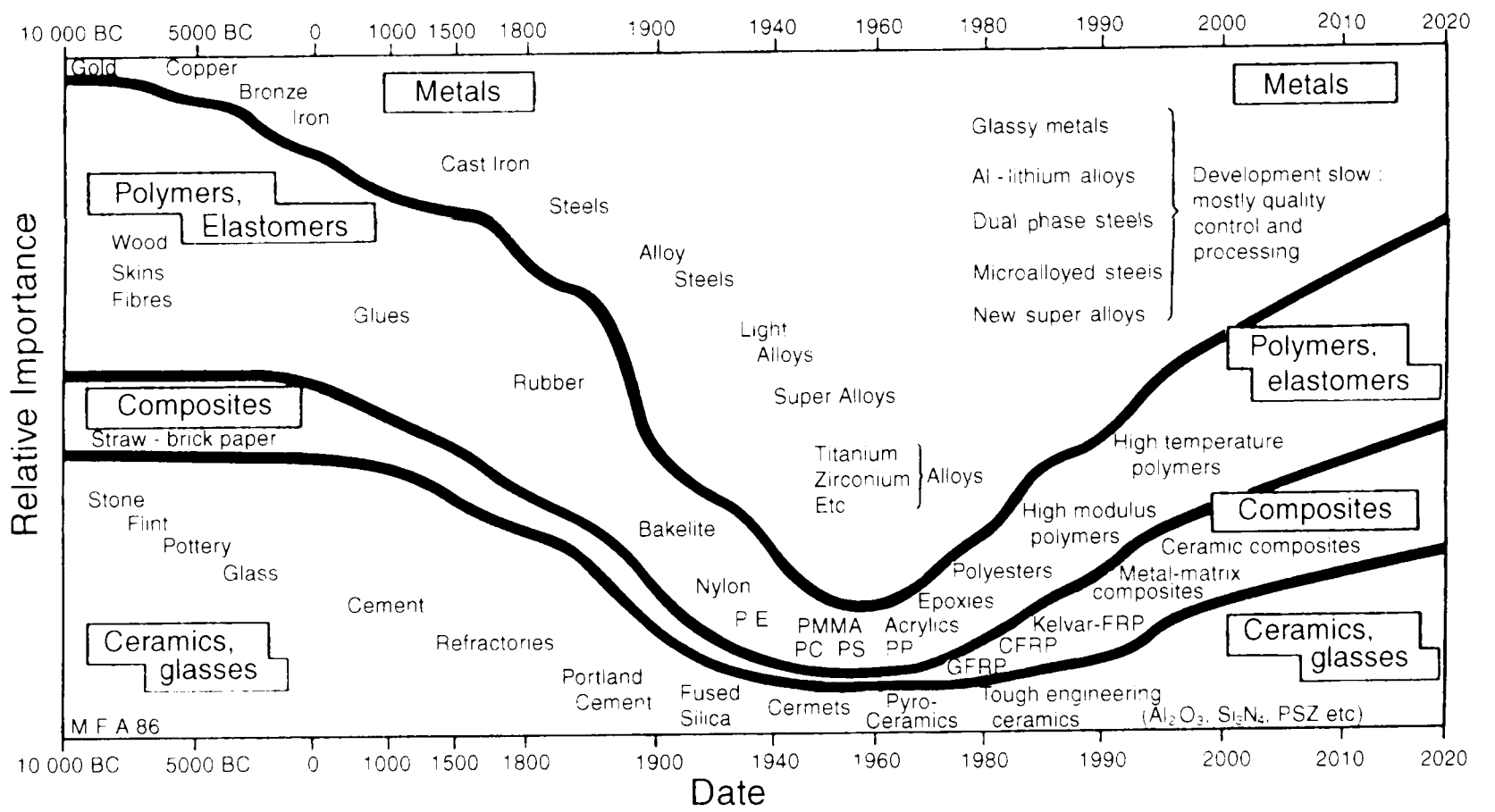
PERFORMANCE  
MECHANICAL or STRUCTURAL



## Evolution Of Engineering Materials

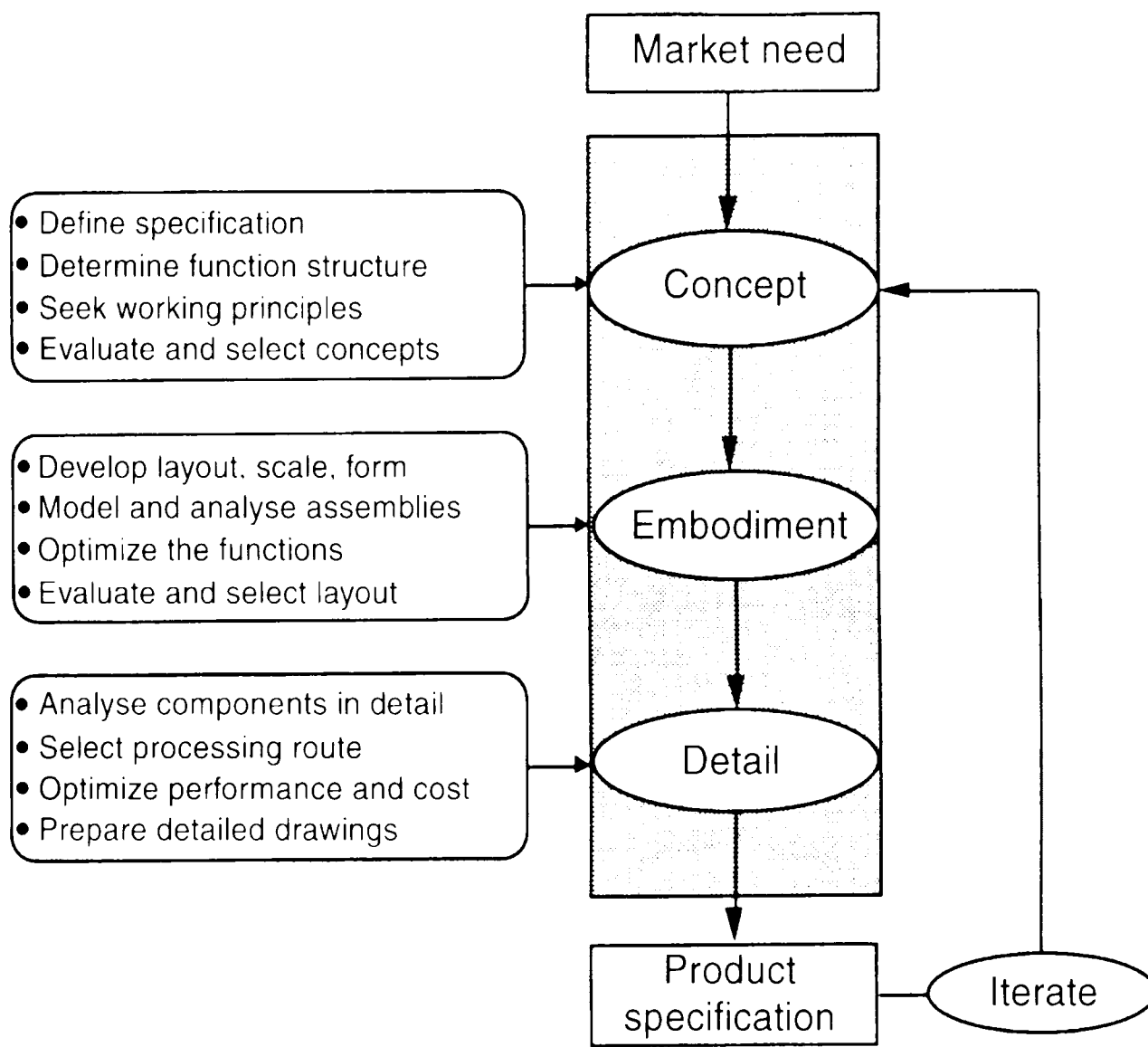
- Stone Age, > 10,000 BC; Bronze Age, 4000 BC – 1000 BC.
- Iron Age, 1000 BC – 1620 AD intro of cast iron technology.
- Evolution of steel 1850s onwards; Aluminum and other light alloys, 1940s onwards.
- By 1960s Engineering Materials  $\equiv$  Metals.
- Since 1960 things have changed dramatically — polymers, composites, ceramics.

However, steel production still accounts for greater than 90% of world metal output!



The evolution of engineering materials with time. 'Relative Importance' in the stone and bronze ages is based on assessments of archaeologists; that in 1960 is based on allocated teaching hours in UK and US universities; that in 2020 on predictions of material usage in automobiles by manufacturers. The time scale is non-linear. The rate of change is far faster today than at any previous time in history.

- The number of engineering materials is large: 40,000 to 80,000!
- From this vast menu an engineer must select a material(s) which is best suited for the task.
- Choosing the familiar traditional material may lead to a very conservative design, and may not provide an opportunity for innovation.
- It is important at the early stages of design to examine the full menu of materials.
- Need for a systematic procedure for materials selection.





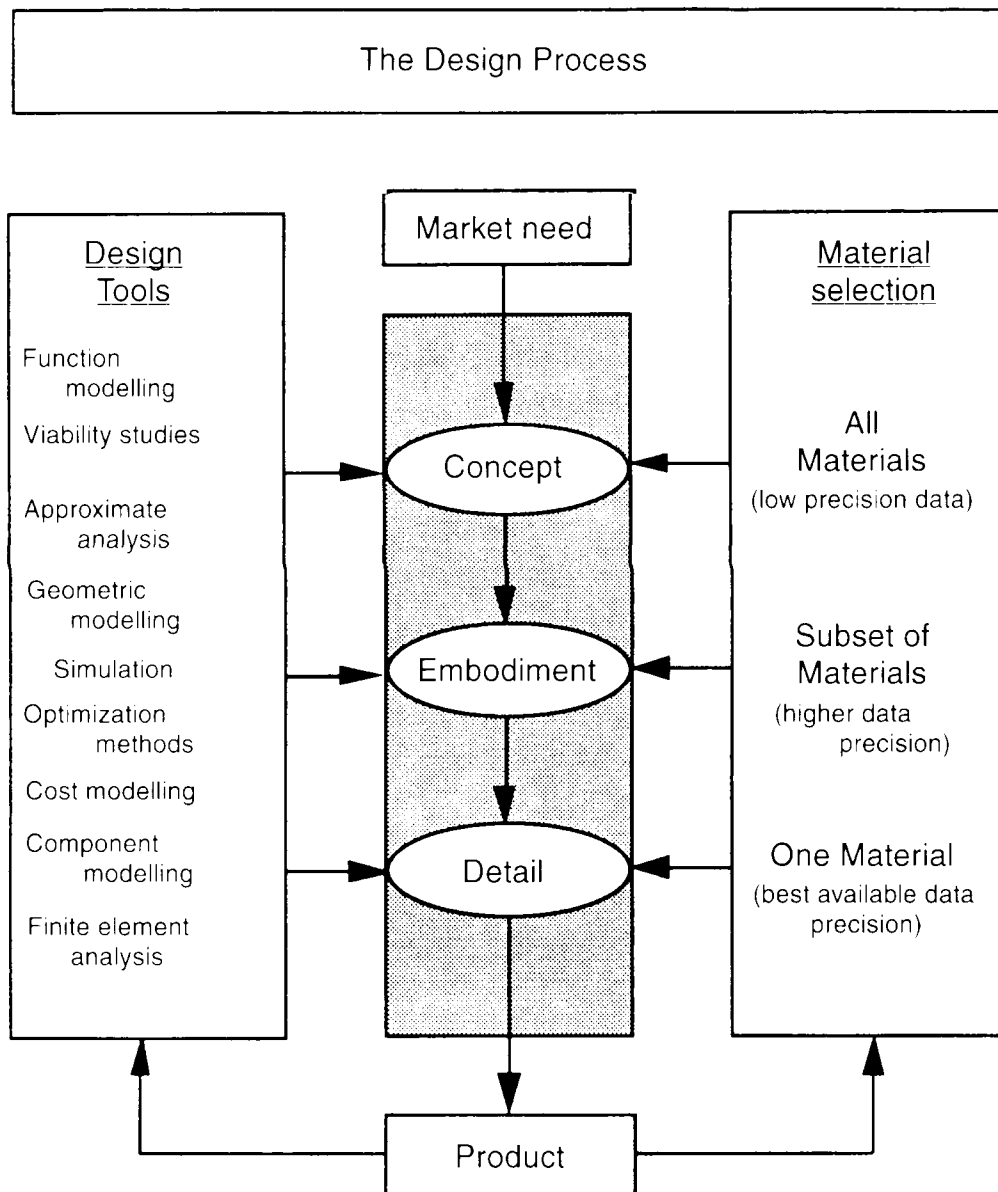
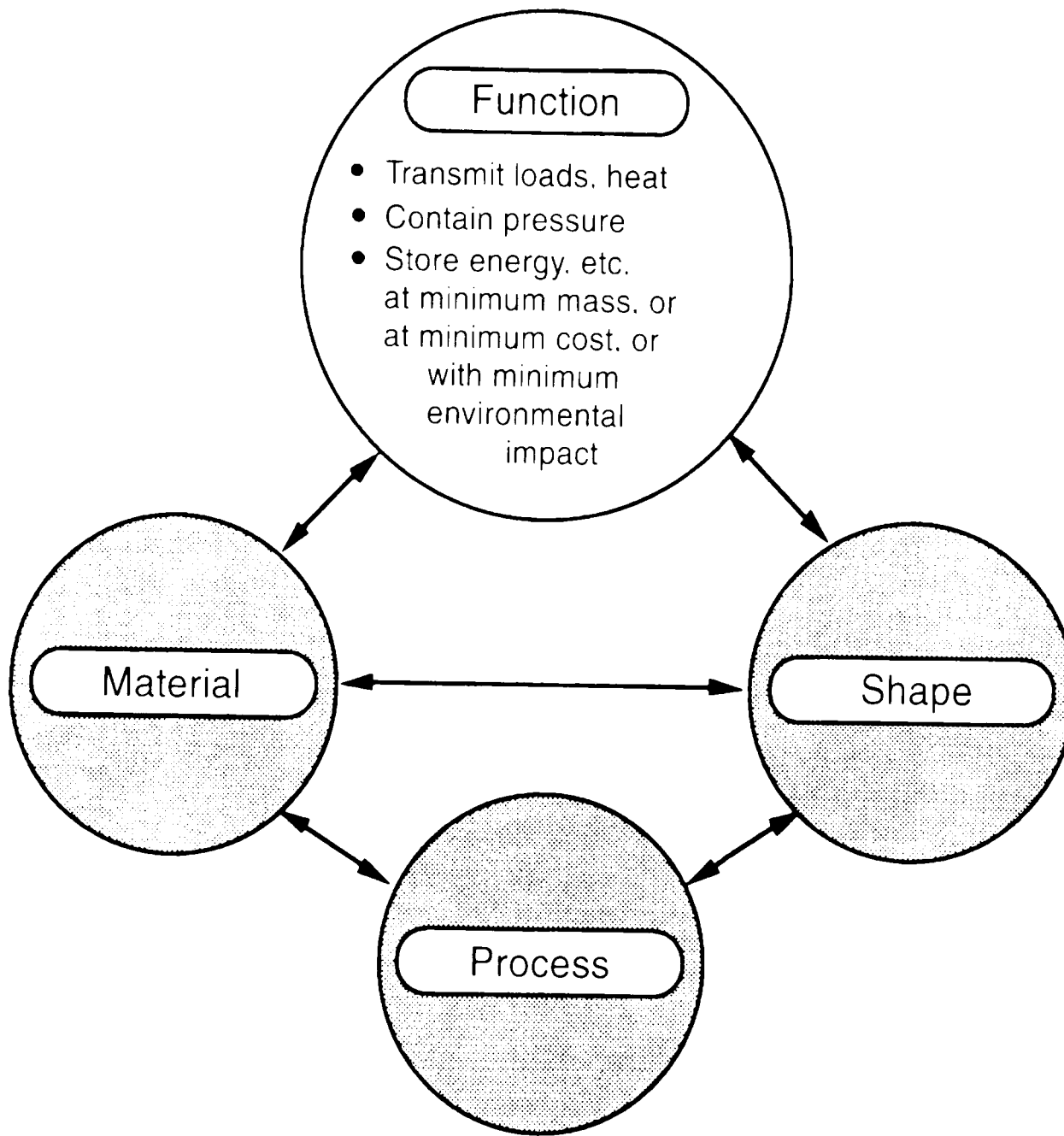
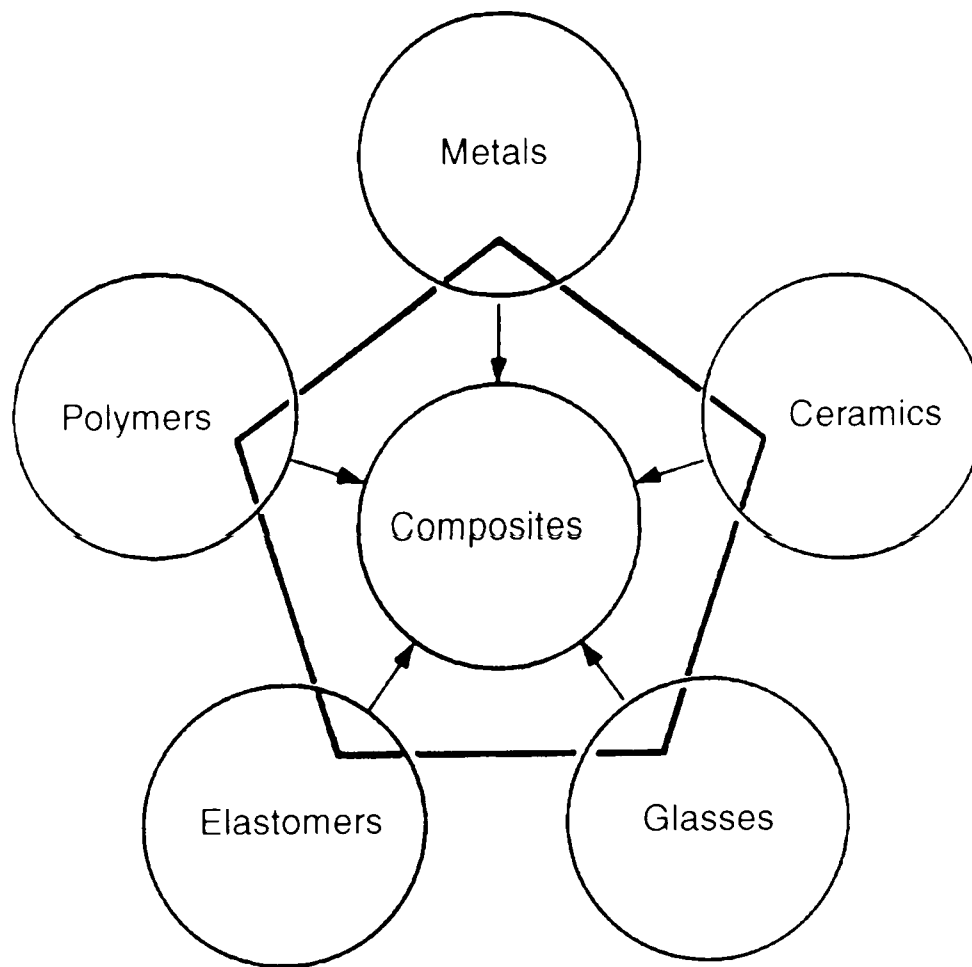


FIGURE 1.1 The design flow chart, showing how design tools and materials selection enter the procedure. Information about materials is needed at each stage, but at very different levels of breadth and precision.



# Classes Of Engineering Materials



## 1. METALS

- They have relatively high elastic moduli.
- They can be made strong by alloying, mechanical working, and heat treatment.
- They show good ductility. This allows them to be formed by deformation processes.
- They typically yield before fracturing.
- They are prone to fatigue failure.
- Relative to other material classes, they are not very resistant to corrosion.

## 2. Ceramics and Glasses

- They too have high elastic moduli, but unlike metals they are brittle.
- Their strength in compression is about 15 times larger than the strength in tension. Brittle materials always show a wide scatter in strength.
- Because ceramics have no ductility, they have a low tolerance for stress concentrations or for high contact stresses.
- They are stiff, hard, and abrasion resistant, hence their use in bearings and cutting tools.
- They retain their strength to high temperatures.
- They are resistant to corrosion.

### 3. Polymers and Elastomers

- They have low elastic moduli, about 50 times less than those of metals. However, some polymers can be very strong – nearly as strong as metals. As a consequence, the elastic deflections can be large.
- Polymers creep even at room temperature. Very few polymers have useful strength above 250° C.
- When specific properties, e.g. strength-per-unit-mass, are important, then some polymers are as good as metals.
- They are easy to shape.
- Polymers are corrosion resistant.
- They have low coefficients of friction.

## 4. Composites

- They combine attractive properties of other classes of materials while avoiding some of their drawbacks.
- They are light, stiff and strong, and they can also be tough.
- Most currently available composites have polymer matrices – epoxy or polyester, usually enforced by fibers of glass, graphite, or kevlar. They cannot be used above 250° C because of the polymer matrices.
- Composite components are expensive, and manufacturing processes are not well-developed.
- They are also difficult to join.

## Importance of Material Properties versus Material Classes

- Each material has some **attributes**, its **properties**, e.g. density, modulus, strength, toughness, thermal conductivity, etc.
- A designer does not seek a particular material, per se, but a specific combination of these attributes: a **property-profile**.
- The material name is merely the identifier for a particular property-profile.



# Design-Limiting Properties Of Engineering Materials

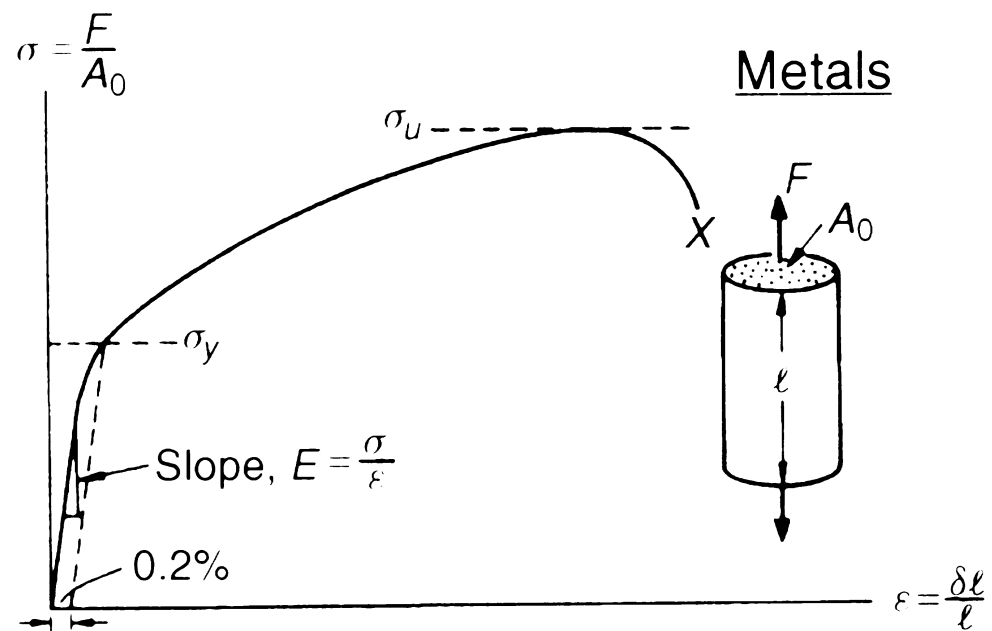
Table 1.1 Design-limiting material properties and their usual SI units\*

<i>Class</i>	<i>Property</i>	<i>Symbol and units</i>	
General	Cost	$C_m$	(\$/kg)
	Density	$\rho$	(kg/m <sup>3</sup> )
Mechanical	Elastic moduli (Young's, shear, bulk)	$E, G, K$	(GPa)
	Strength (yield, ultimate, fracture)	$\sigma_f$	(MPa)
	Toughness	$G_c$	(kJ/m <sup>2</sup> )
	Fracture toughness	$K_{Ic}$	(MPa m <sup>1/2</sup> )
	Damping capacity	$\eta$	(—)
	Fatigue endurance limit	$\sigma_e$	(MPa)
	Thermal	Thermal conductivity	$\lambda$
Thermal diffusivity		$a$	(m <sup>2</sup> /s)
Specific heat		$C_p$	(J/kg K)
Melting point		$T_m$	(K)
Glass temperature		$T_g$	(K)
Thermal expansion coefficient		$\alpha$	(°K <sup>-1</sup> )
Thermal shock resistance		$\Delta T$	(°K)
Creep resistance		-	(—)
Wear	Archard wear constant	$k_A$	(MPa <sup>-1</sup> )
Corrosion/	Corrosion rate	$K$	(mm/year)
Oxidation	Parabolic rate constant	$k_p$	(m <sup>2</sup> /s)

\*Conversion factors to imperial and cgs units appear inside the back and front covers of this book.

1. **DENSITY**,  $\rho$  — mass per unit volume, Mg/m<sup>3</sup>

2. **STIFFNESS — ELASTIC MODULUS**,  $E$  — Slope of the linear elastic part of the stress-strain curve, GN/m<sup>2</sup> = GPa



For isotropic elastic materials:

$E$  – Young's modulus

$\nu$  – Poisson's ratio

$G = \frac{E}{2(1 + \nu)}$  – Shear modulus

$K = \frac{E}{3(1 - 2\nu)}$  – Bulk modulus

Typically

$$\nu = \frac{1}{3} \Rightarrow G \approx \frac{3}{8}E, \quad K \approx E.$$

Elastomers are exceptional. For these

$$\nu = \frac{1}{2} \Rightarrow G \approx \frac{1}{3}E, \quad K \gg E.$$

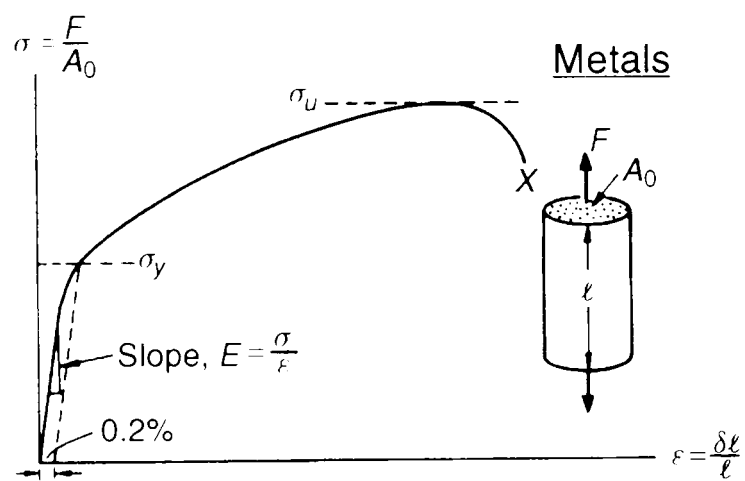
3. **STRENGTH**,  $\sigma_f$ ,  $\text{MN/m}^2 = \text{MPa}$ .

This requires careful definition, and is usually defined differently for different materials and mode of loading.

## METALS

$\sigma_f$  is identified with the 0.2% offset yield strength  $\sigma_y$ .

It is the stress level the application of which has caused dislocations to have moved large distances through the crystals of the metal, so that upon unloading from this stress level there is a measurable permanent "plastic" strain of 0.2%.



$\sigma_y$  in compression is approx. the same as that in tension.

Equivalent tensile stress:

$$\bar{\sigma} \equiv \sqrt{\frac{1}{2} \{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\}}.$$

Mises yield condition:

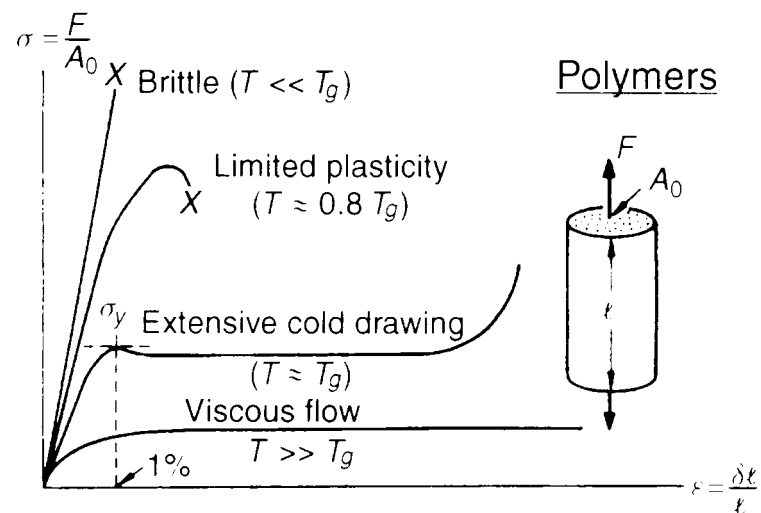
$$\bar{\sigma} \leq \sigma_y$$

$$\bar{\sigma} < \sigma_y \text{ — No yielding}$$

$$\bar{\sigma} = \sigma_y \text{ — Yielding!}$$

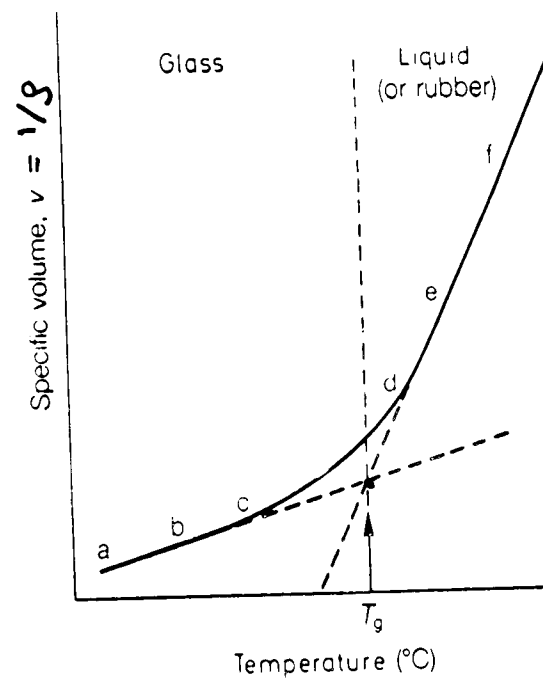
## POLYMERS

$\sigma_f$  is identified as the stress  $\sigma_y$  at which the stress strain curve has become markedly non-linear — typically a strain of 1%. Yield mechanisms: shear yielding, crazing.



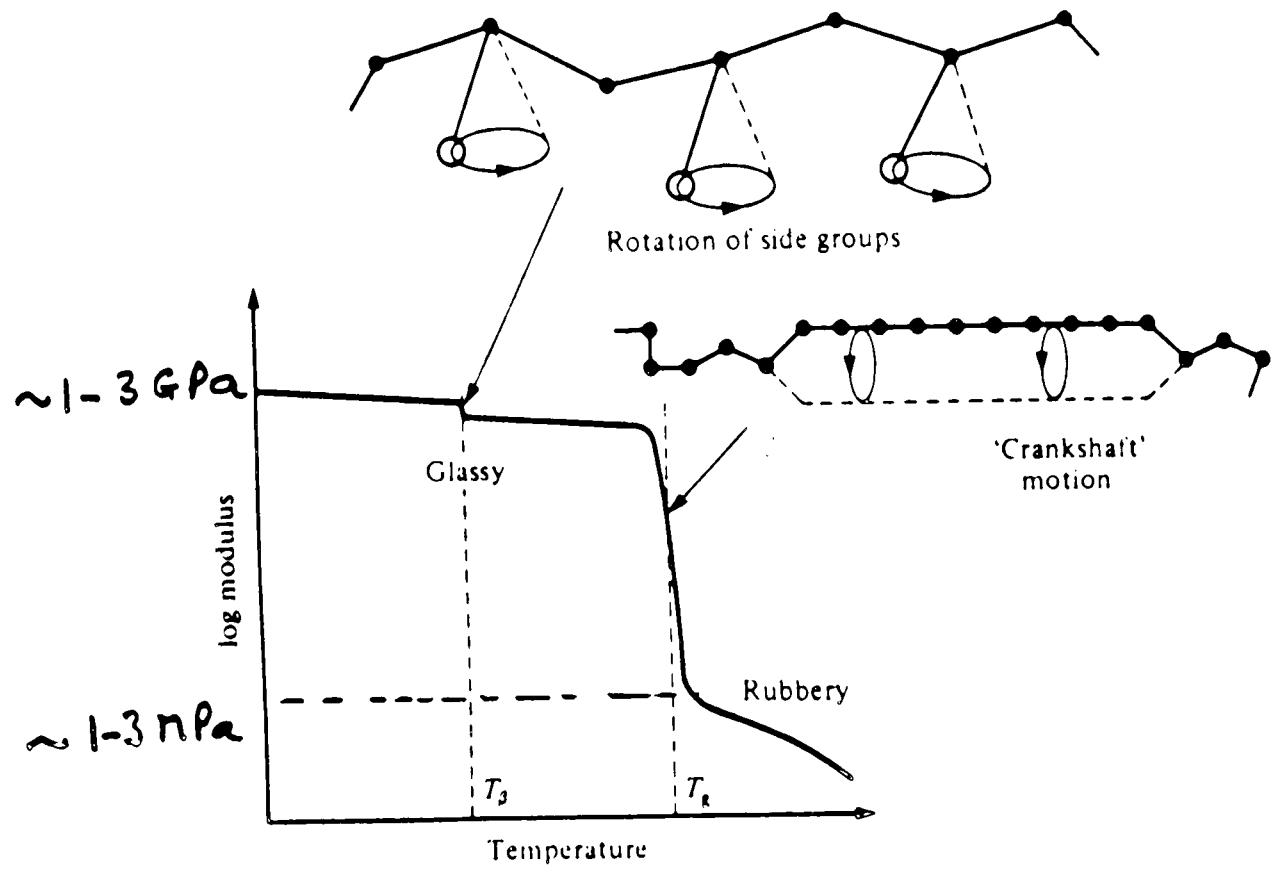
Polymers are a little stronger  $\approx 20\%$  in comp. than in tension.

# GLASS TRANSITION, $T_g$ , AND MELTING TEMPERATURES, $T_m$ , FOR POLYMERS

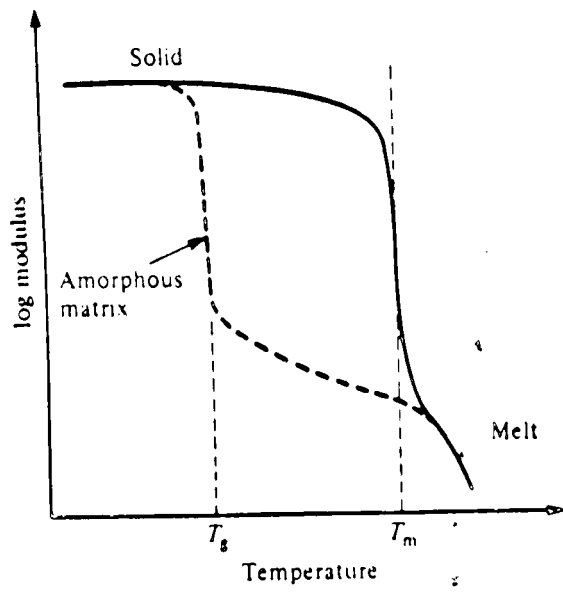


The glass transition temperature  $T_g$  is obtained from an experiment in which the specific volume  $v$  is measured whilst the specimen is cooled at a fixed rate, usually  $1^{\circ}\text{C}$  per minute. The construction for obtaining  $T_g$  from the data is shown. For polymer of low RMM,  $T_g$  marks the transition from glass to liquid; for high RMM  $T_g$  marks the transition from glass to rubber.

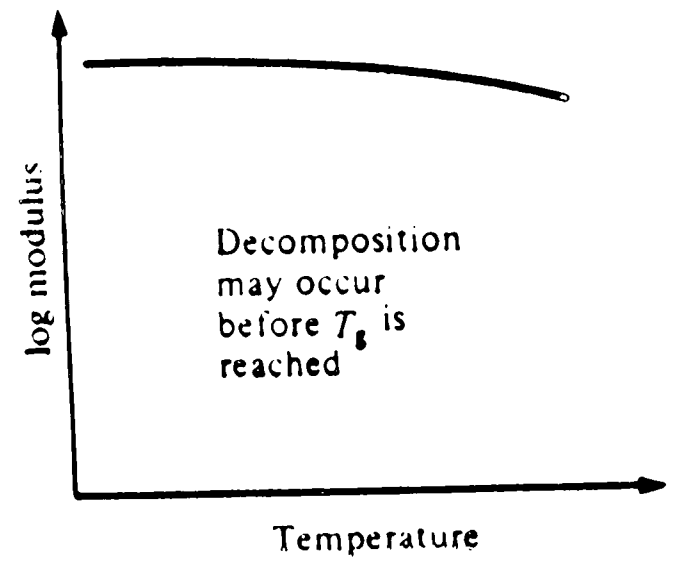




Transitions in amorphous polymers



Transitions in partly crystalline polymer

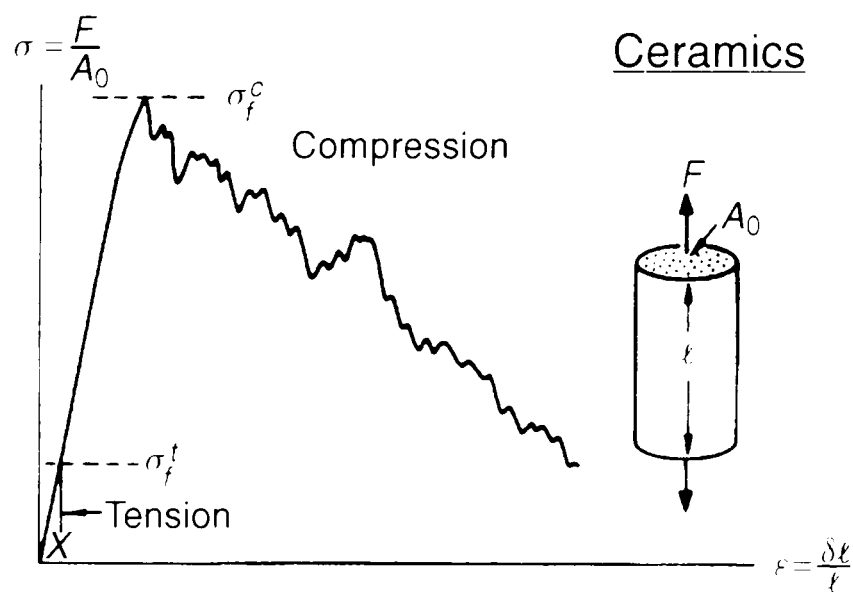


Transition in highly crosslinked polymer

## CERAMICS AND GLASSES

Strength for ceramics and glasses depends strongly on the mode of loading. In tension, “strength”  $\sigma_f$  means the fracture strength,  $\sigma_f^t$ . In compression it means the crushing strength  $\sigma_f^c$ , which is much larger, typically

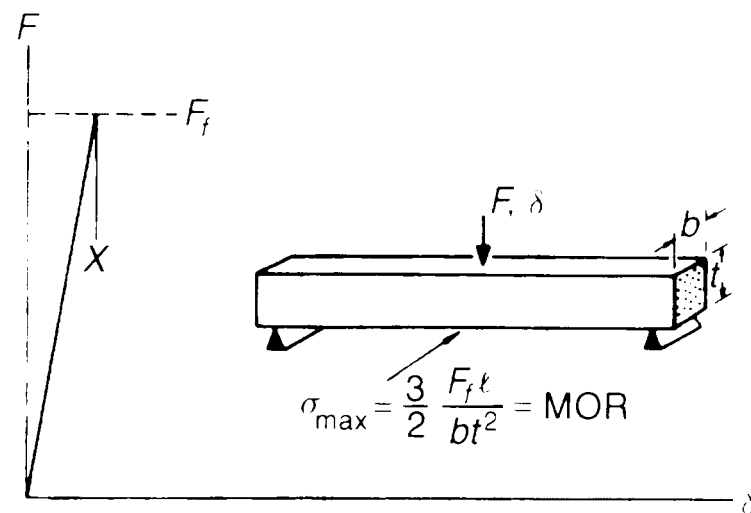
$$\sigma_f^c \approx 15 \sigma_f^t$$



## MODULUS OF RUPTURE, MOR — MPa

If the material is difficult to grip, as is the case with ceramics, its strength can be measured in bending. The **modulus of rupture**, MOR, is the maximum surface stress in a bent beam at the instant of failure.

In ceramics  $MOR \approx 1.3 \sigma_f^t$ .



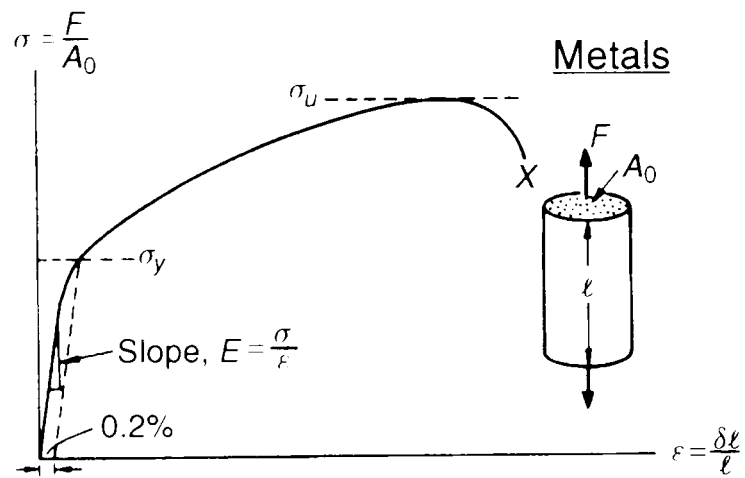
## **COMPOSITES**

The strength of a composite is typically defined by a set deviation, e.g. 0.5%, from linear elastic behavior.

The strength of long fibre composites is approximately 30 % lower in compression than in tension, because in compression the fibers buckle!.

## ULTIMATE TENSILE STRENGTH, $\sigma_u$ — MPa

This defined as the maximum engineering stress that can be achieved in an un-notched round bar of the material loaded in tension. For brittle solids — ceramics, glasses and brittle polymers it is the same as the “strength”  $\sigma_f$  in tension. For metals, ductile polymers and most composites it is larger than  $\sigma_f$ , by a factor of between 1.1 and 3. In metals  $\sigma_u$  is higher than  $\sigma_f$  because of work-hardening.



## **RESILIENCE, $R$ — J/m<sup>3</sup>**

This measures the maximum elastic strain energy per unit volume stored in a material. It is the area under the elastic part of the stress-strain curve:

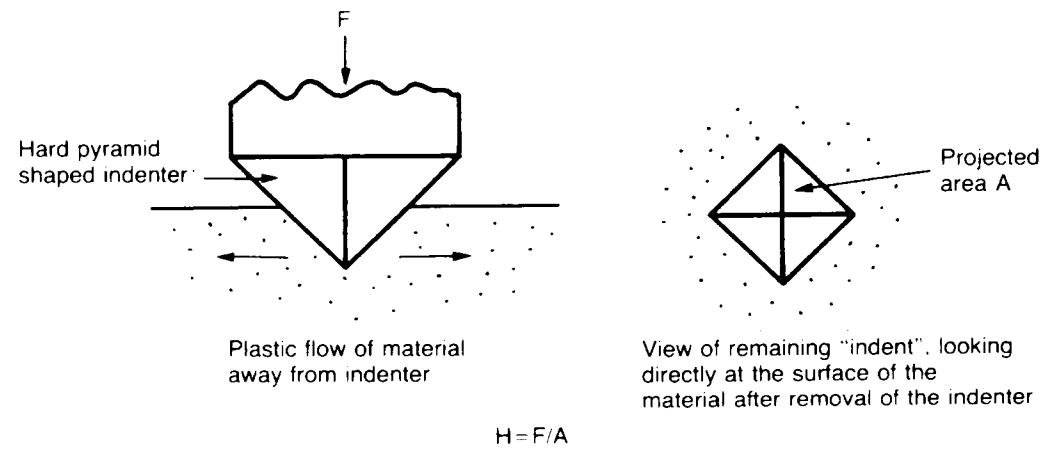
$$R = \frac{1}{2}\sigma_f\epsilon_f = \frac{\sigma_f^2}{2E},$$

where  $\sigma_f$  is the strength, as defined previously, and  $\epsilon_f$  is the corresponding strain for material with Young's modulus  $E$ .

Materials with large values of  $R$  make good springs.

## HARDNESS, $H$ — MPa

The hardness of material is a crude measure of its strength. It is measured by pressing a pointed diamond or hardened steel ball into the surface of the material. It is defined as the indenter force divided by the projected area of the indent.



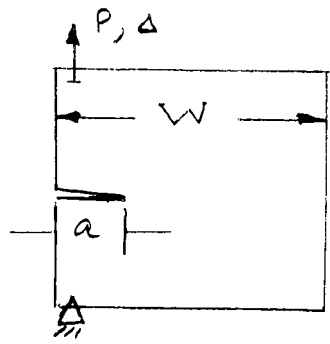
The hardness  $H$  is related to the strength  $\sigma_f$  by

$$H \approx 3\sigma_f$$



## **FRACTURE TOUGHNESS, $K_c$ — MPa $\sqrt{\text{m}}$**

The fracture toughness of a material is a measure of the resistance of the material to failure by parting of the solid into two (or more) pieces by the propagation of a macroscopic crack.



$P$  --- Load per unit thickness.

$$\sigma^{\infty} = \frac{P}{W}$$

$$K = Q\sigma^{\infty}\sqrt{\pi a} \text{ --- Stress Intensity factor}$$

$Q$  --- Configuration correction factor

$a$  = --- crack length

$K_c$  --- Critical stress intensity factor, material property

### **FRACTURE CRITERION:**

$$K \leq K_c$$

$K < K_c$  --- No fracture

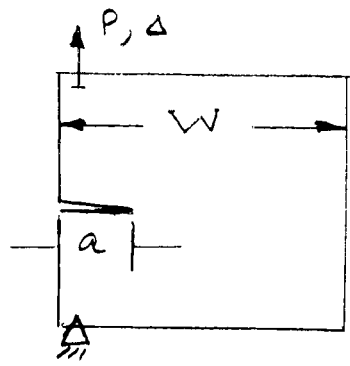
$K = K_c$  --- Fracture!

**TOUGHNESS  $\equiv$  CRITICAL STRAIN ENERGY RELEASE RATE,  $G_c$  — J/m<sup>2</sup>**

This is another measure of the resistance of a material to failure by propagation of a crack.  $G_c$  is a material property.

Relation between  $G$  and  $K$ :

$$G = \frac{K^2}{E(1 + \nu)}$$



$P$  -- Load per unit thickness.

$$U = \frac{1}{2} P \Delta$$

$$\frac{d}{da} U = P \frac{d}{da} \Delta - G,$$

$G$  = Energy absorbed by the crack tip as it extends by  $da$

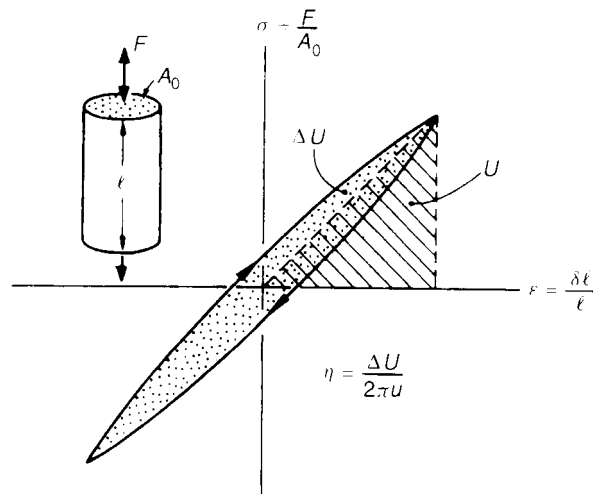
$$G = - \left\{ \frac{d}{da} U - P \frac{d}{da} \Delta \right\} \text{ "Energy release rate"}$$

**FRACTURE CRITERION:**

$$G \leq G_c$$

## LOSS COEFFICIENT – DAMPING, $\eta$ , dimensionless

The loss coefficient  $\eta$  is a measure of the degree to which a material dissipates vibrational energy.



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

The value of  $\eta$  usually depends on the frequency of cycling.

For  $\eta < 0.01$ ,

$$\eta = \frac{D}{2\pi} = \frac{\Delta}{\pi} = \tan \delta = \frac{1}{Q}$$

where  $D$ , specific damping capacity;  $\Delta$ , log decrement;  $\delta$ , phase lag between stress and strain;  $Q$ , resonance factor.

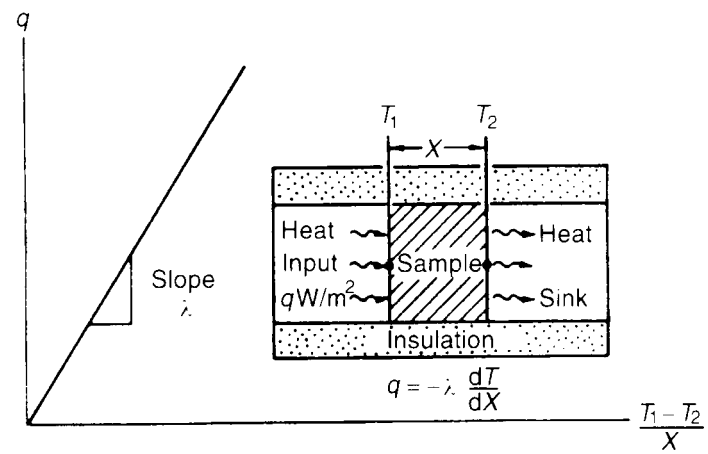
## **FATIGUE ENDURANCE LIMIT, $\sigma_e$ , MPa**

Cyclic loading not only dissipates energy; it can also cause a crack to nucleate and grow, culminating in fatigue failure.

For many materials there exists an **endurance limit**: a stress amplitude below which fatigue failure does not occur, or occurs only after a very large number ( $10^7$ ) of cycles.

## THERMAL CONDUCTIVITY, $\lambda$ , W/mK

The rate at which heat is conducted through a solid at steady state is measured by the thermal conductivity  $\lambda$ .



Fouriers law:

$$q = -\lambda \frac{dT}{dX}$$



## **THERMAL DIFFUSIVITY, $a$ , m<sup>2</sup>/s**

When the heat flow is transient, the differential equation for the temperature in one-dimension is

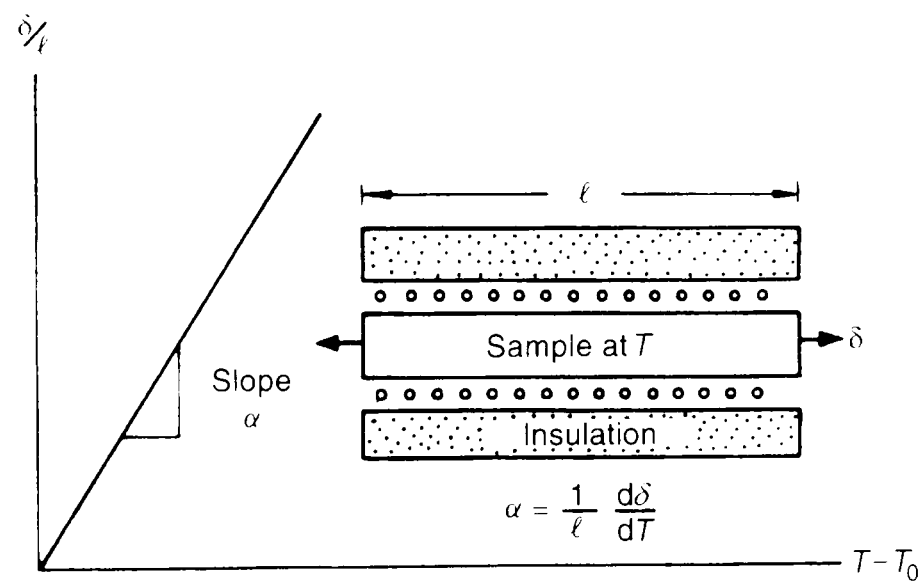
$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial X^2}$$

where

$$a \equiv \frac{\lambda}{\rho C},$$

is the **thermal diffusivity** and  $C$  is the **specific heat**.

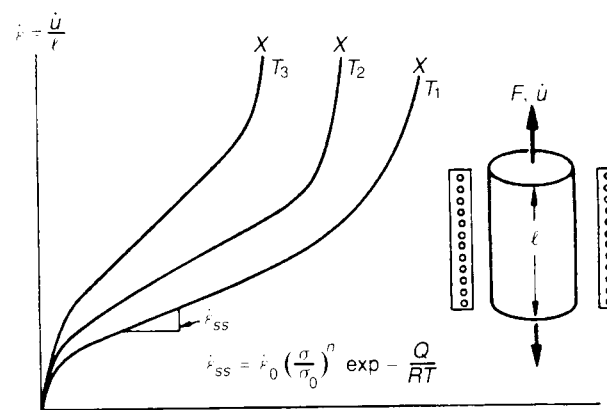
# COEFFICIENT OF THERMAL EXPANSION, $\alpha$



$$\epsilon^{\text{thermal}} = \alpha(T - T_0).$$

## CREEP

This is the slow time-dependent deformation that occurs when materials are subjected constant loads above about  $\frac{1}{3}T_m$  or  $\frac{2}{3}T_g$ . It is characterized by the creep constants  $\{\dot{\epsilon}_0, \sigma_0, n, Q\}$ .  $R = 8.314 \text{ J/(mol K)}$  is the gas constant.



$$\dot{\epsilon} = \dot{\epsilon}_0 \left( \frac{\sigma}{\sigma_0} \right)^n \exp \left( -\frac{Q}{RT} \right).$$

## WEAR

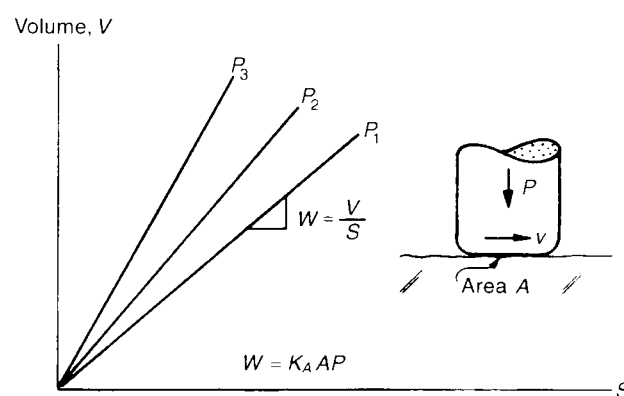
When two solids slide relative to each other, the volume of material lost from one surface, per unit distance slid, is called the **wear rate**

$$W = \frac{V}{S} \text{ wear rate, } mm^3 m^{-1} \equiv m^2.$$

The **specific wear rate** is

$$\frac{W}{A}, \text{ dimensionless,}$$

where  $A$  is the nominal area of contact.



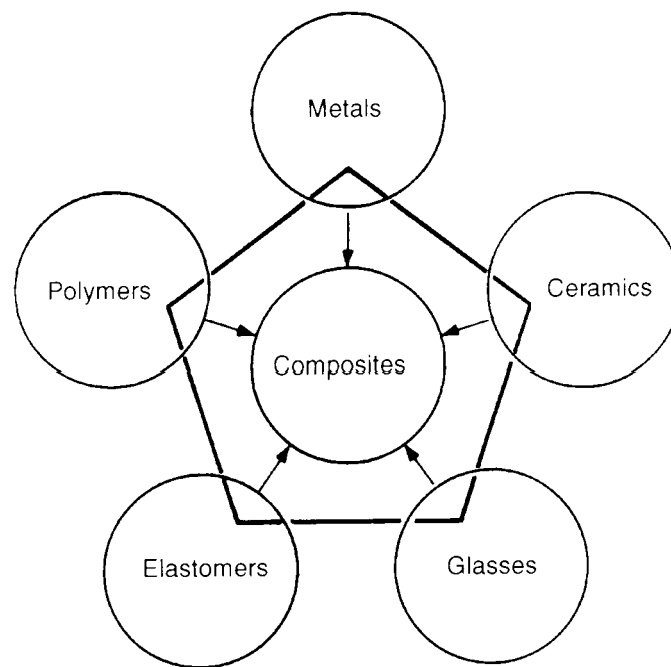
It is found that the specific wear rate increases linearly with the pressure  $P$  pressing the two bodies together:

$$\frac{W}{A} = k_A P.$$

The coefficient  $k_A$  is called the **Archard wear coefficient**, it has dimensions of  $\text{MPa}^{-1}$ , and always less than unity. Note that  $k_A$  is a property of the sliding couple, and not just one member of it.

## SUMMARY

- There are six important classes of materials for mechanical design: metals, polymers, elastomers, ceramics, glasses, and composites.



Within a class there is certain common ground:

- Ceramics as a class are hard, brittle, and corrosion resistant.
- Metals as a class are ductile, tough, and electrical conductors.
- Polymers as a class are light, easily shaped, and electrical insulators.
- etc.

This is what makes a classification of materials into classes useful.

- Importance of Material Properties versus Material Classes.
  - Each material has some **attributes**, its **properties**, e.g. density, modulus, strength, toughness, thermal conductivity, etc.
  - A designer does not seek a particular material, per se, but a specific combination of these attributes: a **property-profile**.
  - The material name is merely the identifier for a particular property-profile.

To this end we have identified the properties which are important in thermo-mechanical design.