Engineering Tripos Part IA **First Year**

Paper 2 – MATERIALS

HANDOUT 1

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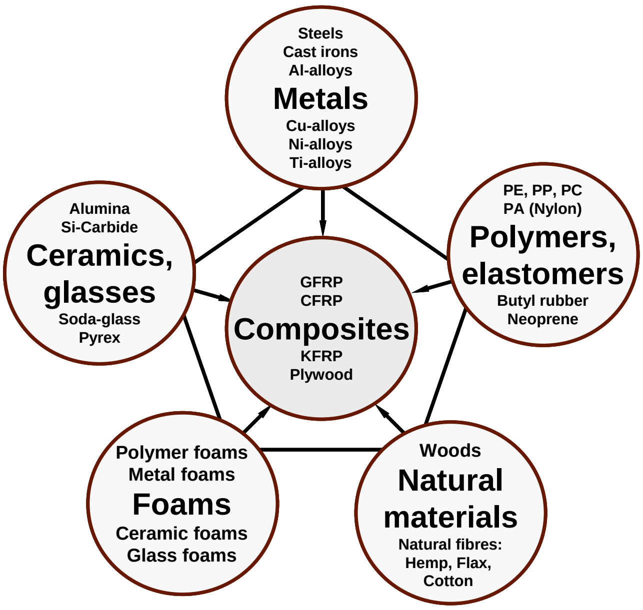
1. Introduction to Engineering Materials

1.1 Classes of Engineering Materials



Engineering materials can be classified into five generic groups. These are based primarily on similarities in

Composites can (in principle) be made by combining materials from any groups, giving them characteristics of both components – a rich source of "new" materials.

"Structural" Materials:

Part I Materials principally covers *structural materials*:

- materials used to resist mechanical loading
- sometimes also thermal and electrical loads
- not just "civil engineering" materials

Current drivers for development in structural materials:

- transport: lightweighting vehicles, engine efficiency
- energy: wind turbines, nuclear power
- life sciences: biomaterials - implants, artificial bone; medical devices
- sustainability: reduction in waste and packaging, greater recycling
- sports: high performance products (F1, racing yachts, athletics)

Engineering failures – a cautionary note:

Materials are not just enabling technologies – they are often at the centre of major disasters:

Liberty ships, Comet aircraft, Concorde, Columbia shuttle,
Hatfield rail crash, oil rig collapses …..

"Functional" materials:

Materials engineering also includes *functional materials* (i.e. optical, semiconductor, electronic, magnetic):

- Si-based chip technology, display technology, optical fibres, thin films, MEMS (micro-electro-mechanical-systems), nanotechnology …..

NB: design with "functional" materials overlaps with "structural":

- device density on a chip is constrained by the removal of heat
- speed of a hard disk is limited by inertia, vibration etc.
- overhead power lines are limited by strength and thermal expansion
- superconducting magnets produce fields which can break the magnet

And, the fundamental physics of *materials processing* (studied in IB) apply across structural and functional materials:

- solidification, heat flow, diffusion, microstructure control, etc.

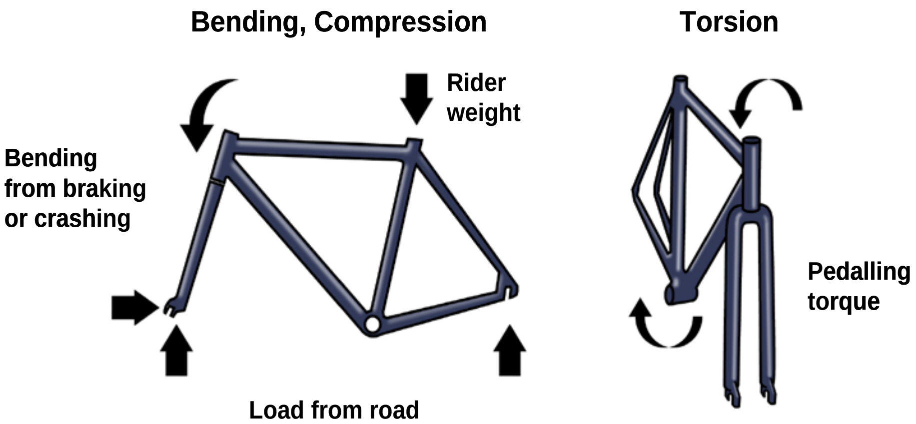
1.2 Materials in Design

Product Design and Material Selection

Designing a product or component involves specification of the *design requirements*, organised systematically into:

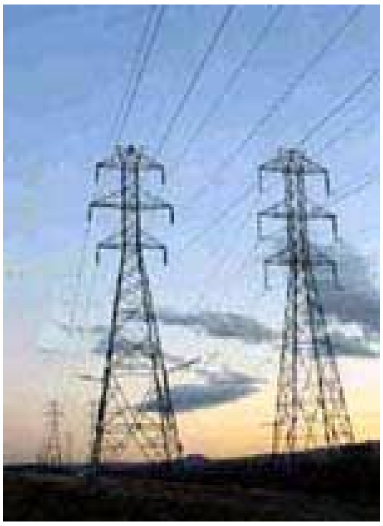
- *Function* (what the component does)
- *Constraints* (limits on geometry and performance)
- *Objectives* (design-optimising requirements)
- *Free variables* (parameters which can be adjusted by designer)

Example 1: Bicycle Design



- *Function*:
  - Support rider weight between the wheel axles, enabling comfortable, efficient pedalling action
- *Constraints*:
  - Geometric limits on span between axles, height and width
  - Specified *stiffness*: deflection under load
  - Resist *failure*: remains elastic – no permanent deformation, or fracture
  - Resist corrosion from water
  - Style, ability to decorate, add accessories, ease of maintenance …..
  - Weight or cost (upper limit, depending on user)
- *Objectives*:
  - Minimise *cost* (standard bikes) or *weight* (performance bikes)
- *Free variables*:
  - Cross-sectional shape and dimensions of structural members in frame
  - Materials and manufacturing processes

Example 2: Overhead Power Cables



- *Function*:
  - Carry electrical current at high voltage, above ground, and over long distances
- *Constraints*:
  - Span and dip between pylons, ground clearance
  - Must not fail under self-weight, wind and ice loads
  - Upper limits in cable dimensions and weight (for transport, installation, connections)
  - Operating temperature (due to ohmic heating)
  - Cost/km
- *Objectives*:
  - Maximum power transmission
- *Free variables*:
  - Cable size, cross-sectional winding pattern
  - Materials and manufacturing processes

Design Requirements - Overview

- *Function* (what the component does):
  - support loads on supports, store mechanical energy …..
  - conduct heat or electricity efficiently, prevent heat loss …..
- *Constraints* (limits on geometry and performance):
  - allowable dimensions, shape restrictions
  - allowable deflection, must not fail under load
  - resist corrosion or oxidation in service environment
  - limits on weight or cost
  - ergonomics, aesthetics, surface finish
  - ease of manufacture and recyclability
- *Objectives* (design-optimising requirements):
  - minimum weight or cost or environmental impact
  - maximum energy storage (per unit volume or mass)
- *Free variables* (parameters which can be adjusted by designer):
  - some dimensions
  - material(s) selected
  - manufacturing route

From Design Requirements to Material Selection

A material's ability to meet multiple design requirements depends on:

(1) *material properties*: response to *mechanical, electrical and thermal loads*, i.e. mostly numerical data.

(2) *secondary constraints*: imposed by *manufacturing, environmental impact and cost,* i.e. qualitative/quantitative information/expertise.

Material selection in design therefore involves *translation* of design requirements into a target *material profile.*

(1) ***Design-Limiting Material Properties***

Bicycle Frame:

Design requirement	Properties
Stiffness →	Young's modulus
Avoid failure →	Strength, fracture toughness
Weight →	Density
Cost →	Material price/kg

Overhead power cables:

Design requirement	Properties
Allowable sag →	Density, thermal expansion
Avoid failure →	Strength
Power transmitted →	Electrical resistivity

Summary: Design-Limiting Material Properties

General	*Mechanical*	*Thermal*	*Electrical*	*Resistance to service environment*
Density Price/kg	Young's modulus Strength Fracture toughness Ductility …..	Conductivity Expansion Maximum operating temperature	Electrical resistivity	Wear Corrosion

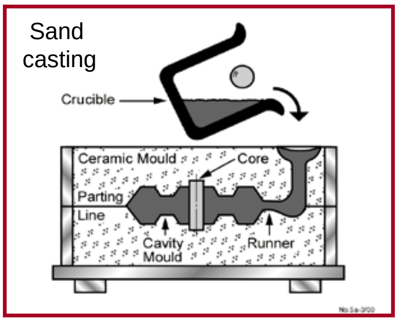
Property-based Material Selection – the technical challenges

- multi-physics: structures, mechanics, thermofluids, electrical ….
- 1000s of materials to choose from
- objectives and constraints often in conflict: an optimisation problem

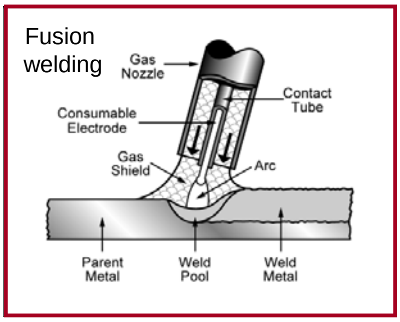
Design analysis (later) will show how to identify the right *combinations* of properties for a given problem.

(2) Secondary Design Constraints

(i) Manufacturing



Shaping



Joining

Manufacturing places many limits on design:

- significant contribution to product cost
- processability of material? (size & shape; melting point, ductility etc)
- ease of joining components?

(ii) Environmental Impact

Materials are increasingly evaluated for their *environmental impact*.

Possible environmental "properties" or "eco-indicators":

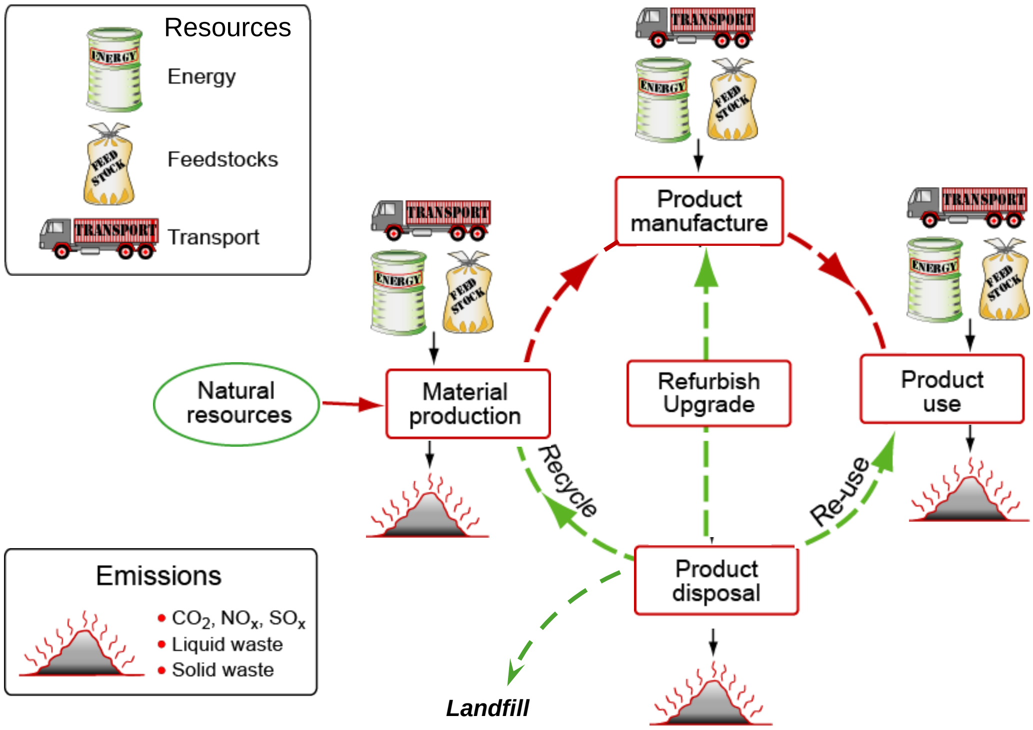
- "embodied energy" or CO_2 output per kg, in material production
- recyclability
- toxicity, NO_x production etc.

Life Cycle Analysis (LCA)

LCA captures the use of energy, materials and chemicals, and the output of CO_2 and waste, in four main stages in the life of a product:

- Production
- Manufacture, delivery
- Product use, maintenance
- Disposal

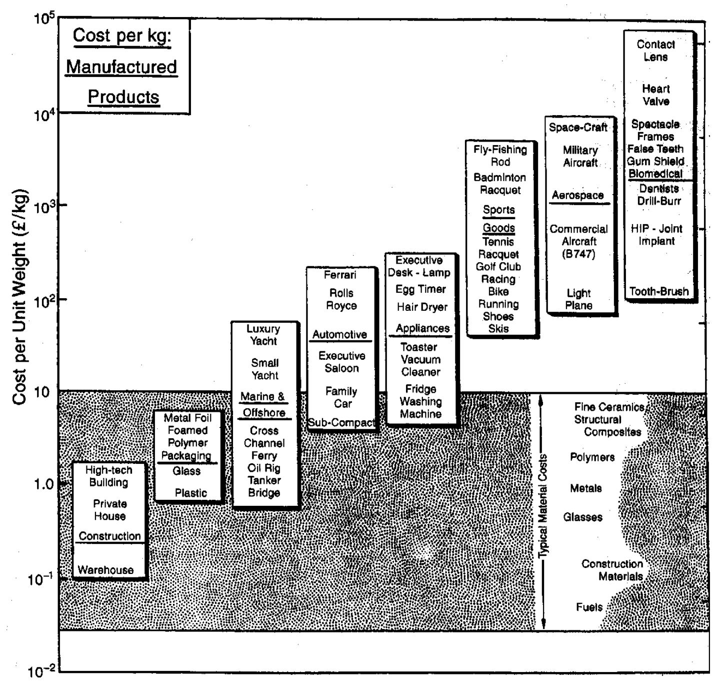
Product life-cycle



(iii) *Product and Material Cost*

Cost is (almost) always important, and includes:

- raw material costs
- manufacturing costs (capital, energy, manpower etc)
- prior research and development



Notes:

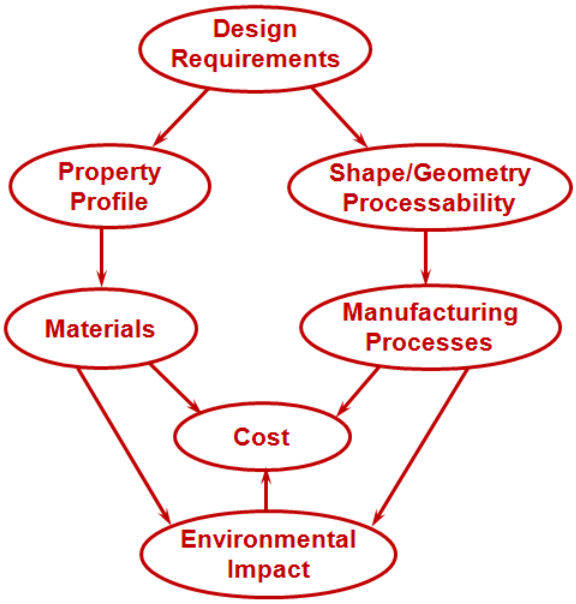
(1) Cost of most materials in range:

(exotic materials can be *much* more)

(2) Material cost significant in some products; others high "value added".

(3) High value sectors reflect:

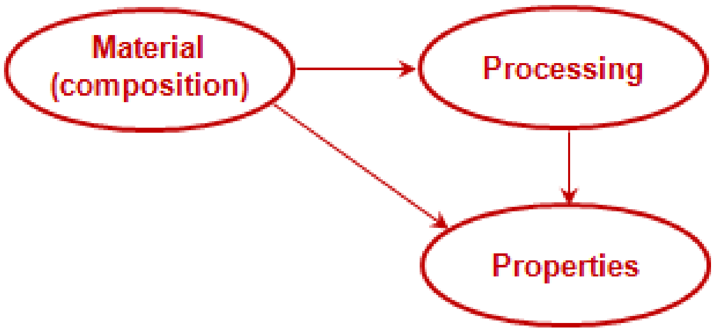
Summary: Materials in Design and Manufacture



Notes:

- selection of material and of process route are closely coupled
- material and processing contribute to cost and environmental impact
- material processing achieves two *simultaneous outcomes*:
  - shaping components and assembling them into products
  - manipulating the properties to give the required performance in service

• properties are controlled by material *microstructure* – so materials engineers are concerned with the interactions below:



1.3 Aims and Content of IA Materials Course

• To introduce the classes of structural engineering materials (metals, ceramics, polymers, composites);

• To introduce material properties relevant to engineering applications (stiffness, strength, toughness, corrosion resistance etc.);

• To relate material properties to atomic, molecular and microstructural features;

• To understand failure processes and mechanisms, and the application of mathematical models to describe material behaviour;

• To develop a systematic approach to optimal material selection in design, including manufacturing process and environmental impact.

Lent Term (12L) Dr H.R. Shercliff

1. Material Selection in Design/Elastic Properties of Materials (6L)
2. Plastic Properties of Materials/Material Selection (continued) (4L)
3. Process Selection, Environmental Impact of Materials (2L)

Easter Term (8L) Dr A.E. Markaki/Dr. A. Kabla

4. Fracture and Fatigue (5L)
5. Influence of service environment (corrosion, friction and wear) (3L)

Lent Term Examples Papers

1. *"Teach Yourself Microstructure"* (week 1)

2-4. Lecture material (weeks 1, 4, 6)

1.4 Reference texts, software, online resources

1. Ashby M.F., Shercliff H.R. and Cebon D., *Materials: Engineering, Science, Processing and Design*, Butterworth. *(1st, 2nd or 3rd edition).*
2. Callister W.D., *Materials Science & Engineering: An Introduction*, Wiley.
3. Ashby M.F. and Jones D.R.H., *Engineering Materials 1 + 2*, Butterworth.

The *Materials Data Book* is a key element of the course.

The course uses the *Cambridge Engineering Selector* (CES) software – available for free download to CUED students (details later).

<u>Online Resources</u>

via Teaching Webpages:

First Year > *Syllabuses and Course Notes* > *Paper 2 Materials*

- Filled handouts
- Audio-video extracts: key lecture topics and examples paper problems
- Audio-video CES Tutorials